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Post-hazard Reconstruction of Building Portfolio Based on Portfolio Life-cycle Analysis

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ABSTRACT: The enormous social and economic impact from major natural hazards in recent years, e.g. Hurricane Katrina (2005) and the Great East Japan Earthquake and Tsunami (2011), attracts attention from decision-makers, researchers, and practitioners on how to rebuild communities' damaged building portfolio after a major hazard event to enhance its performance in future hazard events in a most efficient way. The concept of *Building Back Better* reflects a rebuilding philosophy that will enable the community to achieve higher performance level in future hazard events. This study demonstrates how to implement BBB under the concepts of life-cycle analysis and community resilience. It firstly scales the life-cycle analysis from the individual building to the building portfolio, which quantifies the impact of specific rebuilding decision over the entire life-cycle of the building portfolio in terms of expected building portfolio life-cycle cost and expected building portfolio cumulative prospect value. Specifically, in the latter methodology, the risk-aversion of typical decision-makers can be considered that the contribution of low-probability/high-consequence events is amplified. Further, it introduces the portfolio resilience performance goal which may be de-aggregated from higher level community resilience goal that could ensure controlled functionality loss and prompt recovery from extreme hazard events. The decision framework developed in this paper can be directly applied into the post-hazard reconstruction that could support building back better under seismic hazard (or other hazards with minor modification), and help communities finally achieve pre-defined resilience goals in a most efficient way.

1. INTRODUCTION

Natural hazards cause devastating damages, reveal the current hazard preparedness and resilience, and more importantly, provide a unique opportunity for communities to rethink and plan for more ideal communities that could perform as pre-defined in future hazard events and promote communities' sustainable economic growth. After the Indian Ocean Tsunami in 2004, Clinton (2006) proposes a new post-hazard recovery and reconstruction philosophy later known as Build Back Better (BBB). Recently, UNISDR (2017) stresses the importance of pre-disaster recovery and rebuilding planning and recommends developing an all-stakeholder, national-level disaster framework to effectively assess the post-disaster damage, formulate the strategy and revise policies, laws to promote the BBB.

The philosophy of Build Back Better (BBB) provides a new paradigm for the post-hazard rebuilding and recovery (Lin and Wang, 2017). Building environment, which constitutes most part of the physical system in a community, not only directly relates to the huge social-economic loss during hazard events, but also forms the basis supporting BBB. Within the building environment, Despite the great concept and prospect on BBB, few researchers give a tractable and quantified definition of BBB and the corresponding framework supporting the whole process that can eventually lead the community achieves the pre-defined BBB goal (i.e. resilience goal) in future hazards most efficiently. In practice, some researchers have found discrepancies between the BBB concept and real post-disaster rebuilding (e.g. Kennedy et al, 2008). Further, the huge investment required in the post-hazard rebuilding and its long-lasting impact requires that rebuilingd decisions should be made under the umbrella of Life-cycle Analysis (LCA). The renewal of the building portfolio under hazard is illustrated in Figure 1.

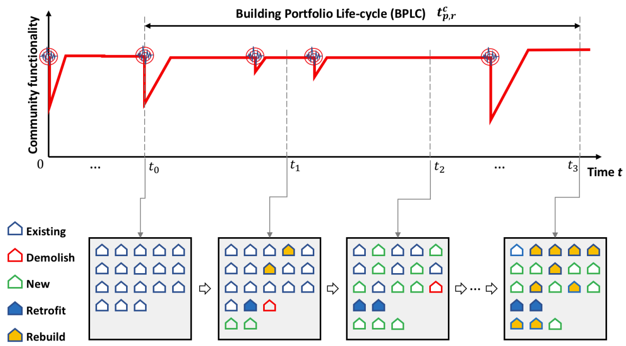

Figure 1 Illustration of portfolio renewal under natural hazard events over a long-time horizon

In civil engineering, LCA is usually employed to measure the cost (e.g. Dong and Frangopol, 2013) or environmental footprint (Carbon, Water etc.) (e.g. Padgett & Tapia, 2013) of a project during its service life. The life-cycle impact (e.g. monetary cost) of an engineered facility (e.g. a bridge or a power station) usually includes its initial design and construction, maintenance, repair, retrofit (if required), and salvage stage. LCA analysis provides a rigorous basis to support decision-making for engineering projects over a long-term horizon (Wen and Kang, 2001; Ellingwood and Wen, 2005). Such analysis has been applied to optimize the initial design of buildings (Wen & Kang, 2001), pre-hazard retrofit, and post-event rebuilt of bridges (Tapia & Padgett, 2015; Bocchini and Frangopol, 2012) exposed to environmental effects (e.g. corrosion) or natural hazards (e.g. earthquake and hurricane). However, little studies have been done to apply LCA to building the portfolio as a whole.

While life-cycle cost (LCC) is the most common basis in engineering decision-making, other decision models have been developed to reflect decision-makers' difficulties in monetizing risk. In these models, occurrence probabilities and economic consequences are mapped into perceived probabilities and utilities (or values), to better model the risk perception of the decision-makers. Among these models, Cumulative Prospect Theory (CPT) (Tversky & Kahneman, 1992) allow risk perceptions of decision-makers to be reflected in LCA and has been successfully applied in civil engineering decision-making in new construction and retrofit applications (e.g. Goda & Hong, 2008; Cha & Ellingwood, 2012). However, no attempt has been made for applying CPT-based decision making in the post-hazard rebuilding.

In this study, we extend the LCA from building level to portfolio level, i.e. Building Portfolio LCA (BPLCA) and propose a post-hazard rebuilding decision framework that could support BBB based on BPLCA and fulfill resilience requirement at the same time. To consider the risk-averse of typical decision makers, two metrics are employed, i.e. expected BPLLC (EBPLCC) and expected BP Cumulative Prospect Value (EBPCPV). The optimal post-hazard rebuilding strategy is that has minimum EBPLCC or maximum EBPCPV over portfolio's pre-defined life-time (BPLC) under portfolio level resilience requirement.

The organization of this paper is as follows. In Section 2, we formally introduce the proposed framework of BBB in the post-hazard rebuilding. In Section 3, the formulation of building portfolio LCA (BPLCA) is briefly introduced for application under seismic hazard. In Section 4, resilience goal is given under rebuilding context. The mathematical formulation of the decision problem is given in Section 5. We give the conclusion in the final section.

2. BUILD BACK BETTER IN POST-HAZARD REBUILDING

In this section, we propose a risk-informed decision framework enables the community to rebuild its damaged building portfolio to achieve pre-defined resilience and/or sustainability goals in the future in a most efficient way.

Firstly, we propose that BBB strategy should be defined by the efficiency in the post-hazard rebuilding process. Post-hazard rebuilding process is a large-scale investment issued by government agencies or private owners, in either way, decision makers seek to find a strategy that minimizes overall monetary cost or maximizes values depends on their risk-attitude. Due to long time-horizon of future life-cycle, we scale the LCA to portfolio level (BPLCA) to evaluate the total impact from the rebuilding, natural renewal, future hazard physical damage and human casualties (Wang et al., 2019a) during portfolio life-cycle (BPLC). The optimal post-hazard rebuilding strategy is the one that minimizes the expected building portfolio life-cycle cost (EBPLCC) or maximizes the expected building portfolio cumulative prospect value (EBPCPV).

In addition, optimal rebuild strategy should also fulfill the performance requirement on resilience and/or sustainability. Resilience requirement ensures that functionality loss and economic cost immediately after extreme hazard events are under control (Robustness) and the recovery process is in a prompt manner (Rapidity) to reduce indirect social-economic impact and avoid the grave result of population permanent outmigration (Bruneau et al, 2003). Similarly, sustainability requirement (e.g. CO2 emission) could be introduced to ensure that the rebuilding strategy does not enforce excessive environmental pressure. For illustration purpose, in this study, we only discuss the resilience goal in detail. However, the sustainability requirement can be incorporated without any technical difficulties. It should be noted that resilience and sustainability of certain strategy are evaluated in different time-frame. For resilience assessment, only extreme events (e.g. M 8 earthquake) are employed to evaluate the performance of a portfolio with no "time" involved. On the other hand, for sustainability assessment, BPLCA over BPLC is generally required.

Figure 2 illustrates the workflow of the post-hazard rebuilding decision framework. The framework begins with the given post-hazard damage state of each building in the portfolio as well as the hazard model of the geological location. Then, a rebuilding strategy (e.g. strategy for a certain type of building in certain damage state) is generated (can be arbitrary at first). After that, the feasibility of the strategy is checked in resilience aspect. If resilience goal is not fulfilled, the current rebuilding strategy is infeasible, thus a new strategy is generated; otherwise, the strategy is feasible and approaches to the BPLCA module. In BPLCA, the EBPLCC, $E[C_{LCC}^{P}(\boldsymbol{X})]$ or EBPCPV, $E[V_{CPV}^{P}(\boldsymbol{x})]$ for the portfolio are evaluated with the portfolio life-cycle (BPLC) and building portfolio renewal rate (BPRR) introduced in Wang et al (2019a). Lastly, the decision framework stops if it finds the strategy that relates to minimum $E[C_{LCC}^{P}(\boldsymbol{X})]$ or maximum $E[V_{CPV}^{P}(\boldsymbol{X})]$ and at the same time fulfills the resilience goals, otherwise a new strategy is generated by some algorithm (e.g. genetic algorithm (GA)) and the aforementioned steps are repeated until optimal strategy is found.

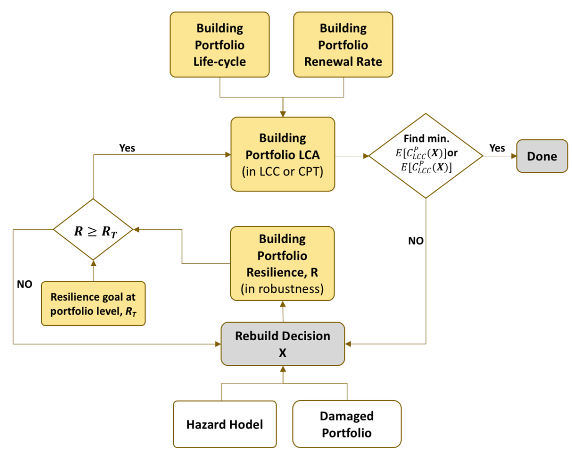

Figure 2 Illustration of the BBB decision framework

3. BUILDING PORTFOLIO LIFE-CYCLE ANALYSIS

As introduced in Section 2, the BPLCA lays the rational foundation for optimal rebuilding decision as it put the perspective from the building portfolio life-cycle (BPLC), and quantifies the overall impact from the post-hazard rebuilding, portfolio natural renewal, and future hazard impact. This section briefly introduces the BPLCA framework developed in Wang et al. (2019a).

We define the post-event rebuilt decision variable matrix $\boldsymbol{X}$, where element $x_{ij} \in$

$(0,1,2, \dots, n_x)$ is the performance target for Type i building in j-th damage state, $i \in (1, 2, \dots I)$ and $j \in (1,2,3,4)$. The building type here is defined by structural and occupancy type.

Firstly, we introduce the expect building portfolio life-cycle cost (EBPLLC)-based methodology. The EBPLCC can be expressed as

$$E[C_{LCC}^{P}(\boldsymbol{X})] = E[C_{Re}(\boldsymbol{X})] + E[C_{int}^{C}(\boldsymbol{X})] + (\omega + 1) \cdot E[C_{Dam}^{C}(\boldsymbol{X})] + E[C_{Cas}^{C}(\boldsymbol{X})] \quad (1)$$

In which $C_{Re}(\boldsymbol{X})$ denotes the cost of rebuilding and repair of the damaged building portfolio immediately after current hazard event; $C_{int}^{C}(\boldsymbol{X})$ denotes the cumulative initial construction cost of new buildings during the entire BPLC; $C_{Dam}^{C}(\boldsymbol{X})$ denotes the cumulative cost of building damages due to future hazard exposure during the BPLC; $C_{Cas}^{C}(\boldsymbol{X})$ denotes the cumulative monetary cost of human casualty due to future hazard exposure during the BPLC; $C_{Ind}^{C}(\boldsymbol{X})$ denotes the cumulative indirect loss due to disruptions in the local economy and social well-being caused by functionality loss of building portfolio due to future hazard exposure during BPLC. For the preliminary study, in Eq. (1), we employ ω to consider the indirect loss due to disruptions of the local economy and social well-being. All the items in Eq. (1) are formulated under the decision of $\boldsymbol{X}$.

For the $E[C_{Item}^{C}(\boldsymbol{X})]$, $Item \in (Dam, Cas)$, considering the different occurrence rate of different hazard levels, we bin hazard level into K intervals, with each level k represented by the hazard level at the center $k \in (1,2, \dots, K)$. For application in earthquake hazard, the $E[C_{Item}^{C}(\boldsymbol{X})]$ can be expressed as (Takahashi et al, 2004)

$$E[C_{Item}^{C}(\boldsymbol{X})] = \sum_{k=1}^{K} E[C_{Item}(\mathrm{k}, \boldsymbol{X})] \cdot E[N_E(\mathrm{k})] = \sum_{k=1}^{K} E[C_{Item}^{C}(\mathrm{k}, \boldsymbol{X})] \quad (2)$$

Where $C_{Item}(k, \boldsymbol{X})$ is the portfolio damage item due to magnitude interval k under decision X; $N_E(\mathrm{k})$ is the number of magnitude interval k earthquake in BPLC.

Next, we introduce the expected building portfolio cumulative prospect value (EBPCPV)-based methodology to reflect risk perception in the formulation. For typical risk-averse decision-makers, they trend to overemphasis the low-probability, high-consequence (LPHC) events in both probabilities and consequences, which can be modeled by cumulative prospective theory (CPT). In this paper, the reference point of the value function is set equal to $V = 0$. Further, only weighting function (adjust probability) is considered to reflect the risk-averse of decision-makers and assume the value function $v(y) = y$. Thus, the EBPCPV under decision $\boldsymbol{X}$, $E[V_{CPT}^{P}(\boldsymbol{X})]$ is

$$E[V_{CPV}^{P}(\boldsymbol{X})] = C_{Re}(\boldsymbol{X}) + C_{Ini}^{C}(\boldsymbol{X}) + (1 + \omega) E[V_{Dam}^{C}(\boldsymbol{X})] + E[V_{Cas}^{C}(\boldsymbol{X})] \quad (3)$$

In which $V_{Item}^{C}(\boldsymbol{X})$ denotes the cumulative prospect value under decision $\boldsymbol{X}$. In Eq. (3), we assume the rebuilding cost $C_{Re}(\boldsymbol{X})$ and $C_{Ini}^{C}(\boldsymbol{X})$ are deterministic and the event of rebuilding and renewal are events with probability 1. It should be noted that since only the loss is considered in Eq. (3), the $E[V_{CPV}^{P}(\boldsymbol{X})]$ is a negative one that decision makers seek to minimize its absolute value. For simplicity, we neglect the negative sign "$-$" in $E[V_{CPV}^{P}(x)]$.

As in EBPLCC-based approach, $V_{Item}^{C}(k, \boldsymbol{X})$, can be expressed as

$$E\left[V_{Item}^{C}(k, \boldsymbol{X})\right] = E[C_{Item}(k, \boldsymbol{X})] \cdot \eta_k \cdot E[N_H(k)] \quad (4)$$

Where η_k is the probability adjustment factor for level k hazard. From comparison to Eq. (2), it is found that the original $v_K^E(t, t_0)$ and $E[N_E(k)]$ are replaced by $\eta_k \cdot v_K^E(t, t_0)$ and $\eta_k \cdot E[N_E(k)]$ in Eq. (4), everything else is the same. The quantification of η_k can be found in Wang et al. (2019a).

In sum, we briefly introduce the two BPLCA methodologies that support the post-hazard rebuilding decision, namely, EBPLCC and EBPCPV. Notably, only one probability adjustment factor η_k is needed to convert the EBPLCC into EBPCPV, which is convenient for potential practical applications.

4. RESILIENCE GOAL

To avoid the tremendous socio-economic consequence in communities from extreme hazard events, rebuilding portfolio to achieve certain resilience goal is desirable. The resilience of a community is defined by its ability to withstand and recover promptly from the external perturbation (NIST, 2015). Resilience goal usually can be defined by certain performance objective regarding economic metrics (e.g. direct and indirect loss (Cutter et al, 2014)), social well-being metrics (e.g. security and sense of belonging (Burton, 2015; Cutter et al, 2014)) or combined metric (e.g. permanent population dislocation (Peacock et al, 2014)) in probability form conditioned on certain return period (e.g. 10% in 50 years) (Wang et al, 2018).

Because of the uncertainties involved in hazard and building performance, it is desirable to express the community level resilience goal in probability form (Wang et al, 2018).

$$P\left(M_{l,k} < G_{l,k} \,\middle|\, m_k\right) = a\% \tag{5}$$

where $M_{l,k}$ represents a community resilience metric l evaluated under hazard level k, $G_{l,k}$ is the prescribed resilience goal corresponding to $M_{l,k}$, and the $a\%$ is a prescribed confidence level. An example of the goal statement expressed in Eq. (5) is $P\left(M_{DLR,3} < 20\% \,\middle|\, m_3 = 7.5\right) = 95\%$, meaning "with 95% probability, the direct loss in the residential buildings are less than 20% of the overall portfolio replacement cost in any earthquake event related to $m_3 = 7.5$. The presence of the $a\%$ in the goal statement acknowledges the uncertain nature associated with any community resilience assessment, reflects the risk level that a community is willing to tolerate, and should be allied with a community's preferences.

5. DECISION FORMULATION

Optimal rebuilding strategy of building portfolio after a deterministic hazard event should be determined such that the summation of rebuilding cost and discounted future hazard loss (summation of cumulative prospect from the rebuilding and discounted future hazard loss) during the BPLC would be minimized in the EBPLCC–based (EBPCPV-based) framework. As mentioned in Section 4, resilience performance is implicitly embedded in the framework.

Ideally, after a major earthquake event, there is optimal rebuilding decision for each building *k*. To simplify the optimization problem and considering the situation in the real-world implementation, we assume that for each building type i under j damage state j, $i \in (1, \ldots, I), j \in (1,2,3,4)$, there is only one rebuilding decision $x_{ij} \in \{0,1,\ldots,n_x\}$. In other words, the rebuilding decision of specific building is determined by its type i and post-hazard damage state j. More details of the decision formulation can be found in Wang et al (2019b).

6. CONCLUSIONS

The urge needs of reconstructing the building portfolio after major hazard event as well as potential threats from future hazards begs the need to develop optimal rebuilding strategy based on BPLCA considering the rebuilding cost, natural updating cost, and social, economic loss from future hazard events. In addition, the need for quick post-hazard recovery and eliminating loss of functionality require the portfolio resilience goal to be satisfied, such portfolio level goal is usually derived from community resilience goal. Future work is needed to unify the resilience and sustainability consideration in post-hazard rebuilding process.

7. ACKNOWLEDGEMENT

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