Unification of Seismic Performance Estimation and Real Estate Investment Analysis to Model Post-Earthquake Building Repair Decisions

Maryia Markhvida[a)] and Jack W. Baker[a)]

Post earthquake decisions on whether to repair or to demolish and rebuild a damaged commercial building can be influenced by factors other than repair costs. These factors include the property's ability to generate income and the conditions of the real estate market—factors not currently considered in seismic performance estimation models. This paper introduces a framework that unifies performance-based earthquake engineering and real estate investment analysis to model cases in which repair of damaged buildings is feasible, but redevelopment or leaving the building unrepaired and vacant might offer greater economic value. A three-stage approach for quantifying the likelihood of repair, redevelopment, or leaving the property vacant is proposed. First, building seismic performance analysis is conducted using *FEMA P-58* and Resilience-based Earthquake Design Initiative (REDi) methodologies; then, given repair and redevelopment costs and times, the net present value decision rule is used to evaluate alternative outcomes; and finally, the results from the two stages are integrated to quantify the probability of different decisions. An illustrative case study of four reinforced concrete buildings highlights the insights provided by the proposed framework. [DOI: 10.1193/030118EQS048M]

INTRODUCTION

Large earthquakes affecting urban areas can lead to severe loss of built environment, causing tremendous challenges in regional recovery. A recent, well-documented case of the loss of built environment occurred during the 2010–2011 Canterbury earthquake sequence. The Central Business District (CBD) of Christchurch suffered widespread damage that caused many instances of building demolition and a prolonged multi year cordon, resulting in displacement of 50,000 central city jobs (Chang et al. 2014). One important issue regarding the loss of built environment in the CBD was that many of the commercial buildings with relatively low damage were either demolished or left vacant for prolonged periods of time. Of the multistory reinforced concrete (RC) buildings in the CBD that had less than 30% damage ratio (measured by a visual estimate of the building damage expressed as a ratio of repair cost to replacement cost), 56% were demolished, 10% were left vacant (pending decision at the time of the study), and only 34% were repaired (Kim et al. 2017). Most of the buildings with damage ratio greater than 30% were demolished. Three years after the

a) Department of Civil and Environmental Engineering, Stanford University, Stanford, CA 94305-4020; Email: markhvid@stanford.edu (MM, corr. author)

Earthquake Spectra, Volume 34, No. 4, pages 1787–1808, November 2018; © 2018, Earthquake Engineering Research Institute

earthquakes, a survey of the office buildings in the CBD showed that most of the buildings were either demolished or left vacant with an unknown status, while only 8% of the original building stock area remained in use, 10% was rebuilt, and an additional 1.4% was being repaired (CBRE Research 2014).

Post earthquake decisions on damaged buildings can influence the course of regional recovery, where drastic changes in the supply of the commercial office space hinder regional business continuity and recovery, potentially leading to a permanent displacement of businesses from the area. In a survey of Christchurch businesses that had to relocate after the earthquakes, only 9% of business owners considered moving back to their pre-earthquake location (Bond et al. 2012). In addition, buildings that are left vacant for prolonged periods of time can lead to deinvestment in the neighborhood, reduction of the city's tax base by inducing devaluation and vacation of surrounding properties, and an increase in safety hazards because of lack of oversight and maintenance (Kraut 1999), which are all factors that can further impede regional recovery. Burton et al. (2015) showed that community resilience and the overall recovery time are a function of individual buildings' recovery, meaning that post earthquake decisions that lead to longer building recovery times hinder community recovery. A study on multifamily residential recovery during the Northridge and Loma Prieta earthquakes showed that the decision to demolish and rebuild led to an increased recovery time (average 3.6 years) as compared to the decision to repair (average 1.8 years; Comerio and Blecher 2010).

Following the 2010–2011 Canterbury earthquakes, several studies investigated factors that affected building owners' post earthquake decisions (Marquis et al. 2015, Kim et al. 2017, King et al. 2014). The studies concluded that while the level of damage and reparability were the primary factors influencing decisions, other significant factors included changes in the building regulations and associated compliance costs, price inflation because of demand surge, pre-earthquake real estate market conditions, high insurance penetration rate, and underinsurance. While many of the buildings in Christchurch were reparable, they were often deemed non economical to repair by the owners (Brown et al. 2013). The non-favorable pre-earthquake real estate market conditions that were marked by relatively low rental rates on commercial office spaces (as compared to other markets in New Zealand) and non competitive returns on investment caused several investors to leave the Christchurch CBD market after the earthquake (Chang et al. 2014, Marquis et al. 2015).

Decisions in commercial real estate are based on the property's ability to generate acceptable returns. Because of high transaction costs, real estate investments have long holding times, and techniques analogous to capital budgeting are used to make decisions related to development, purchase, upgrade, and redevelopment of real estate (Geltner et al. 2007, Brueggeman and Fisher 2001). One of the most commonly used decision rules is the net present value (NPV) rule, in which an investment that yields the maximum NPV out of all the mutually exclusive options is chosen. NPV is the difference between the present dollar benefits of an investment less the present dollar costs, and it can be calculated using discounted cash flow valuation.

Decision rules that are in line with real estate investment principals are not currently considered in the seismic risk assessment of commercial buildings. Seismic performance estimation techniques predict an individual building's repair cost and time (Moehle and Deierlein 2004, FEMA 2015, *FEMA P-58* 2012, Almufti and Willford 2013), but they do not consider the effect of real estate market conditions and the investors' required return on the ultimate fate of commercial buildings. This results in an incomplete understanding of the losses and recovery trajectories. This paper proposes a framework for incorporating real estate investment analysis into probabilistic seismic performance estimation in order to quantify the likelihood of repairing, redeveloping, or leaving a damaged building vacant. The differences between decision evaluation approaches in probabilistic seismic risk modeling and commercial real estate are investigated. Based on the findings, a framework is developed to model post earthquake commercial building outcomes that is consistent with how investors and building owners make decisions on income-generating properties. In this framework, the Performance Based Earthquake Engineering (PBEE) methodology is unified with the NPV analysis, in which NPV is used as the new decision variable. Such an approach brings real estate market insight into seismic performance evaluation and captures instances when repair is feasible, but redevelopment or leaving the property vacant might offer greater economic value. An illustrative case study of four office buildings in California highlights the effect of considering NPV in post earthquake decision analysis. Sensitivity of NPV and different decisions to real estate market parameters and other model inputs is investigated.

POST EARTHQUAKE BUILDING REPAIR DECISIONS

EARTHQUAKE ENGINEERING PERSPECTIVE

Earthquake engineering and seismic performance assessments typically consider two building states in the decision to demolish a damaged property. The first one is a state in which the building suffers extensive damage, such that repair is not feasible and demolition is required. In earthquake engineering literature, conditions leading to this building state are collapse (Aslani and Miranda 2005) and excessive residual story drift (Ramirez and Miranda 2012). In such cases, the direct loss (not considering losses associated with business interruption) is assumed to be the cost of demolition and building replacement.

The second building state that influences post earthquake decisions is the one in which repair of the building is technically feasible but might not provide the desired seismic performance once repaired. Extensive literature exists to support post earthquake decisions based on assessment of residual building capacity. *FEMA 306* (1998a) provides guidance for post earthquake building assessment aimed at determining the loss of building performance capability based on component damage for several types of structural systems. A companion report, *FEMA 308* (1998b), provides a framework for determining the appropriate scope of repairs for structural damage to achieve the desired seismic performance, and it guides policy decisions on whether to accept, restore, or upgrade earthquake-damaged buildings. Elwood et al. (2016) proposed a framework for assessing building reparability based on residual capacity of key building components and the expected performance of the repaired building, in which certain conditions might render a building with limited structural damage irreparable and will require demolition. Polese et al. (2017) have built on the *FEMA 308* methodology to consider repair costs in addition to performance levels in decision making. Their framework considers three decisions—repair, repair and upgrade, and demolition—which are functions of repair cost, initial performance index, and performance loss. The decision to demolish is assumed when total repair and upgrade costs exceed a specified fraction of demolition and new building construction costs. Similarly, *FEMA P-58* (2012), which is described in more detail below, considers a loss ratio (repair cost as a fraction of building replacement cost) threshold above which the decision to demolish and rebuild is triggered. While numerous frameworks employ a demolition-triggering loss threshold, engineering literature provides no basis for determining the value of this threshold, revealing a gap in understanding and modeling of building owners' post earthquake decisions. This in turn impedes the ability to accurately model the loss of built environment and recovery process after a large earthquake. In addition, no distinction is typically made between decisions for different types of building occupancies—a factor identified as important in post earthquake demolition (Kim et al. 2017).

Several studies have proposed empirical relationships for factors influencing post earthquake decisions and probability of demolition for multistory RC buildings (Kim et al. 2017, Polese et al. 2018). The studies have shown that occupancy type, heritage status, number of floors, construction year, cost of repair, and pre-earthquake safety level with respect to the new building code standards are significant variables when quantifying the probability of demolition.

Current seismic loss estimation methodologies that support the aforementioned frameworks originate from PEER's PBEE formulation (Moehle and Deierlein 2004, Porter et al. 2006). The probabilistic formulation incorporates analysis steps that integrate intensity measures, engineering demand parameters, and damage measures in order to quantify decision variables, which are typically repair cost, repair time, and casualties. One implementation of the PBEE formulation is *FEMA P-58* (2012), a state-of-the-art seismic building performance assessment framework. The building performance is evaluated by defining the earthquake hazard, analyzing building response, and assessing damages to the structural and non-structural components, while also taking into account potential collapse of the building. In addition, a complementary methodology, Resilience-based Earthquake Design Initiative (REDi), builds on *FEMA P-58* to more accurately evaluate the recovery time to partial and full functionality by considering modified labor allocations and repair sequencing and taking into account delay caused by impeding factors such as building inspection, engineering design, permitting, financing, and contractor mobilization (Almufti and Willford 2013).

The frameworks described above give little or no consideration to non engineering factors (other than repair cost) that have been found to influence building owners' decisions. A study of factors influencing post earthquake decision making proposes a conceptual framework for studying and understanding decisions (Marquis et al. 2015). It highlights the owner's strategy, externalities, building regulations, government decisions, financials, and insurance as factors that need to be further understood and integrated into the seismic assessment models. The next section considers several of these factors by providing an alternate perspective on decision making from a real estate investor point of view.

REAL ESTATE INVESTMENT PERSPECTIVE

In commercial real estate, investment decisions are made based on the value of a property, which is derived from its expected future income. Commercial office and retail properties generate income by leasing out space to tenants (Brueggeman and Fisher 2001). Therefore, the value of the property is highly dependent on the expected rental income. In real estate investment, one of the most commonly used decision rules is the NPV rule, which is based on the principle of investor wealth maximization (Geltner et al. 2007). NPV is the difference between the value of all the benefits (positive cash flows) in today's dollars (present value) and the present value of costs, and it can be determined using multi-period discounted cash flow valuation (DCF). According to the NPV rule, the investor should (1) choose the alternative that maximizes NPV out of all the mutually exclusive alternatives and (2) reject all alternatives with NPV < 0.

DCF is frequently employed by real estate investors by preparing standardized pro forma statements, or cash flow projections, which are legally required during acquisition and disposal of real estate. DCF typically involves the discounting of three main types of cash flows: capital expenditures, operating cash flows, and reversion cash flow. Capital expenditures consist of major investments into long-term physical assets that have income-generating value and provide a lasting benefit. Examples of capital expenditure include building purchase, renovation and retrofitting, and purchase of machinery or large equipment. It is common to cover the substantial costs of capital expenditures through debt or equity financing. In the case of earthquake damage, repair and redevelopment costs can be considered as capital expenditures.

Operating cash flows occur regularly throughout the lifetime of the investment and are usually assessed on an annual basis. The most widely used metric for operating cash flow is the net operating income (NOI), which is determined by subtracting the operating expenses from the effective gross income on the property. The effective gross income is the fully occupied rental revenue, calculated using projected market rental rates and other sources of revenue such as parking and billboards, less the expected vacancy. Operating expenses are ongoing costs associated with management and administration, repair, maintenance, utilities, insurance, and property taxes. Since NOI is a relatively stable metric and is easy to quantify, it is commonly used to empirically determine property yield by taking the ratio between annual NOI and property value.

Reversion cash flow refers to the amount of capital received when the property is sold, and it occurs once in the DCF, at the end of the investment holding period. The most common approach to calculating the reversion value is the direct capitalization approach, in which the value of the property at the time of sale is defined as the projected NOI the year after the sale divided by the terminal capitalization rate. In real estate investment, capitalization rate, a ratio of current earnings to asset value, is a widely used productivity measure that is analogous to current yield. Projecting terminal capitalization rate, or capitalization rate at the time of resale, can be a challenging task, where, in practice, it is common to assume that the terminal capitalization rate is similar to or greater than the going-in capitalization rate. A higher terminal capitalization rate is a reflection of the building's tendency to depreciate over time because of physical deterioration, and functional and external obsolescence (Brueggeman and Fisher 2001).

Lastly, future cash flows must be discounted to present day dollars by using a compounded discount rate. The discount rate in this case is the required return (or hurdle rate) of the investor, and it is a sum of a risk-free interest rate (rates of investments with no default risk) and a risk premium associated with the property. Furthermore, the discount rate accounts for both the current yield and capital growth of the investment, and, therefore, it is the sum of the capitalization rate and the projected NOI growth rate (Geltner et al. 2007).

With regard to real estate investment decisions, under normal circumstances (no earthquake damage), an owner can decide to hold, sell, or develop vacant land and hold, sell, or redevelop an existing property. Redevelopment (i.e., demolition and new development) is typically selected when the value of the building in its current use plus the demolition cost is less than the value of the vacant land (Munneke 1996). This is a consequence of the "highest and best use" (HBU) principle, under which the value of vacant land is estimated as the HBU property value minus the development costs. HBU is defined as "the reasonably probable and legal use of property, that is physically possible, appropriately supported, and financially feasible, and that results in the highest value" (Beckwith 2010). It reflects the current and the expected future market conditions and is often a benchmark value for investors. The valuation (i.e., calculation of the present value) of existing and HBU commercial properties can be done using DCF.

In a post earthquake environment, one can expect commercial real estate investors to make decisions according to principles similar to normal circumstances—to maximize their wealth. It should be noted that while the decision rule might remain the same, many of the cash flows will be significantly altered in a post earthquake environment. A damaged property might need significant capital expenditures to bring it back to an occupiable condition. In addition, the NOI can be significantly altered by a lack of access (Chang et al. 2014), lack of utilities, changes in the rental rates (Perdia and McNaughton 2014), and tenant relocation (Bond et al. 2012). Following a destructive earthquake, investors' risk perception can also change, a phenomenon observed after the Northridge earthquake, in which temporary and permanent increases in capitalization rates took place (Bleich 2003). A reduction in the Bay Area housing prices occurred as a result of changes in the risk perception following the Loma Prieta earthquake (Murdoch et al. 1993). After the Northridge earthquake, it was also observed that commercial properties with high earthquake risk were less likely to be financed through bank loans, thereby reducing capital availability of the investors (Garmaise and Moskowitz 2009).

While repair costs will be a significant factor in the owner's decision, as it is often a large capital expenditure, the NPV of different alternatives will ultimately depend on the property's ability to generate future income. This consideration is currently missing from PBEE-based decision rules. The rest of this paper focuses on the proposed framework that attempts to unify the PBEE approach to repair cost and time estimation with the NPV decision rule in order to model earthquake consequences in a manner consistent with real estate decision-making principles.

UNIFIED FRAMEWORK FORMULATION

The NPV decision rule is a natural continuation of PBEE, in which the resultant repair costs and times can be used as inputs into the NPV analysis by considering the repair costs as capital expenditure and the repair times as interruption to income generation. The preferred post earthquake decision on a damaged property would correspond to the one with the highest NPV. With this perspective, NPV is a new decision variable in the PBEE analysis. This approach is in line with the decision-making process of real estate investors, who consider not only the required capital expenditures but also the returns that the investment is able to generate.

The proposed framework is subdivided into three computational stages: (1) building seismic performance analysis that quantifies building state probabilities and estimates the joint probability distribution of repair cost, repair time, and redevelopment time conditioned on the building state and the shaking intensity; (2) NPV analysis for all plausible combinations of repair cost, repair time, and redevelopment time to determine the financially preferable decisions; and (3) integration of the building state probabilities, the joint probability distributions of repair cost, repair time, and redevelopment times, and the results of the NPV analysis to obtain the probability of different post earthquake building outcomes. The variables involved in each stage of the analysis are illustrated in Figure 1, and details on each of the stages are provided in the following section.

The framework considers three potential decisions for a damaged commercial property: repair, redevelopment, and leaving the building vacant. Repairing a building entails bringing the building to pre-earthquake condition by repairing the damaged structural and nonstructural components based on the current construction sector prices. Additional costs related to the necessary seismic upgrades and/or bringing the building in compliance with the current building codes should also be considered (Marquis et al. 2015). Redevelopment necessitates demolition of the damaged structure and construction of a new building in accordance with the HBU principles (i.e., a building that yields the highest returns in current market conditions). One would expect the per-square-foot income of a new building to be greater than or equal to that of a repaired building because of the physical and functional improvements in a new property. The last potential decision considered in this framework is to leave the building damaged and vacant—a decision not considered by previous seismic loss models. In this case, it is assumed that the building is left unrepaired and unoccupied until the financial circumstances of the current owner change, the property is sold to a new investor, or the market conditions improve (e.g., rental rates increase or investor risk perception changes), making repair or redevelopment more desirable. A number of other outcomes or combination of outcomes, such as repair and change of building use, exist and can be evaluated using this framework, for which only the inputs into Stage 2 of the analysis would have to be changed. However, for the purposes of this paper, we limit the number of decisions to the above three.

Finally, it should be noted that the calculations are performed on a before-tax basis, meaning that the valuation is done on a property level (i.e., market value of the property asset) and not the level of the owner's equity. Borrowed funds and debt service payments are also not considered in property level valuation. Incorporating property taxes and financing schemes can impact the NPV of the decisions because they would be included in the discounted cash flow calculation. However, it is typical in real estate investment analysis to consider both analyses (with and without taxes and financing) when making a decision. While the described framework is shown on a before-tax basis and without consideration of financing and debt, future models will investigate the influence of these factors on post earthquake decisions.

STAGE 1: BUILDING SEISMIC PERFORMANCE ANALYSIS

This stage of the analysis uses *FEMA P-58* and REDi methodologies to calculate two conditional probability distributions—the probability of being in various building states and

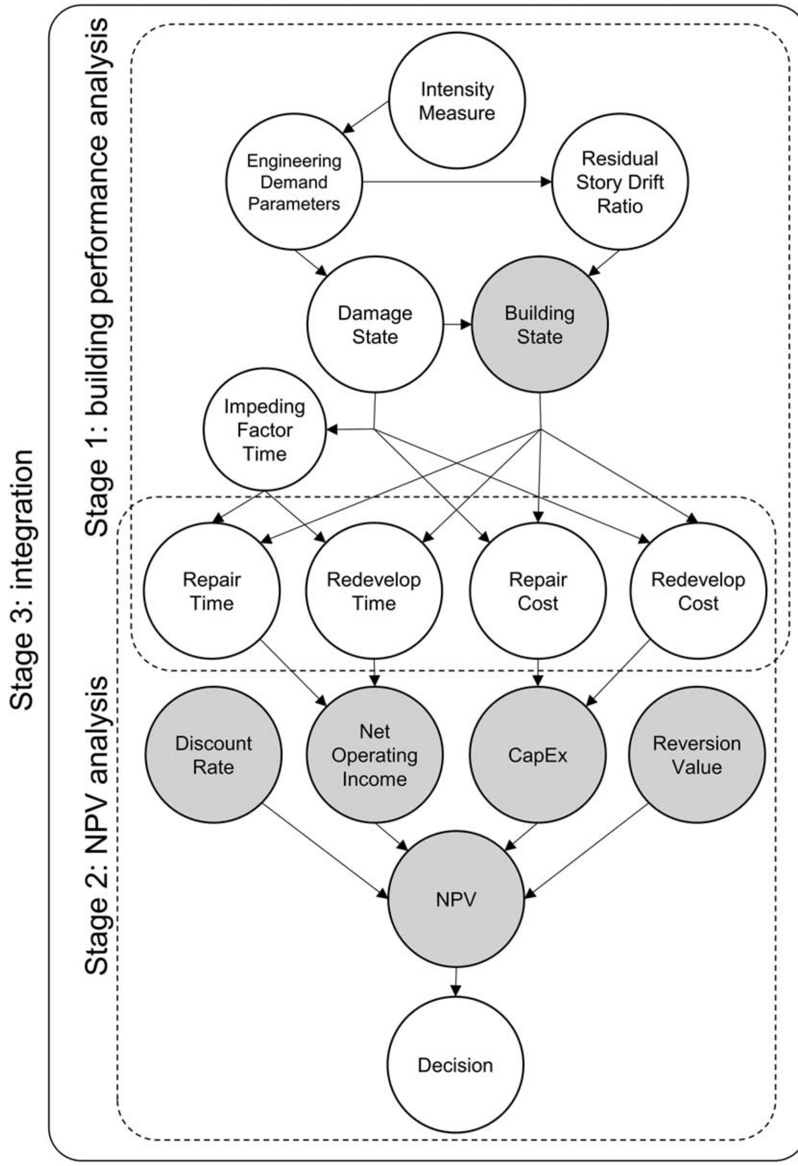

Figure 1. Three-stage framework for evaluating post earthquake decisions on damaged commercial buildings. Non shaded circles represent variables that have been considered by *FEMA P-58* and REDi methodologies. Shaded circles are new variables considered in the proposed framework. Arrows indicate probabilistic dependencies.

the joint probability distribution of loss ratio, repair time, and redevelopment time. In order to quantify these probabilities, several intermediate variables must be estimated for a given level of shaking intensity (or intensity measure) following the *FEMA P-58* approach.

These variables include engineering demand parameters such as story drift ratios and peak floor accelerations, residual story drift ratios, and damage states of various structural and nonstructural components of the building.

During the course of the analysis, the intermediate random variables are marginalized to quantify the probability of being in a particular building state conditioned on the spectral acceleration at the first-mode period, $S_a(T_1)$, which is an intensity measure commonly used to predict earthquake building response and damage. The building state is a variable that indicates whether a building has no damage, is reparable, or is irreparable following an earthquake. While the building states can be further subdivided into categories such as reparable and safe to occupy or reparable and unsafe to occupy, such differentiations can be captured by adjusting the time to reoccupancy. Therefore, for the purposes of this study, the building states are limited to the three. The building state probability, $P(BS_i \mid S_a(T_1))$, is represented by a categorical distribution, with categories $BS_i \in \{\text{no damage, reparable, irreparable}\}$. The irreparable building state is intended to identify buildings for which repair is unfeasible and repair costs become irrelevant in the decision making. If the building is irreparable, the possible building decisions are restricted to redevelopment and leaving the building vacant. In this model, the building is considered irreparable if it collapses or the residual story drift ratio is above a certain threshold (Ramirez and Miranda 2012). It is recommended that Monte Carlo techniques be used to estimate the probability of different building states conditional on spectral acceleration (Gentle 2006).

Next, the joint probability distribution of loss ratio (LR), repair time (T_R), and redevelopment time (T_{DEV}), conditional on the building state, BS_i, and spectral acceleration, $S_a(T_1)$, is estimated using a combination of *FEMA P-58* and REDi. Loss ratio is the repair cost expressed as a fraction of the replacement cost of the building, and repair time is the time required to bring the damaged building back to a fully functional state, including delay time because of impeding factors. Redevelopment time refers to the time it takes to carry out demolition and build a new structure, also including the delay because of impeding factors. The resultant joint conditional probability distribution is denoted as $P(LR,T_R,T_{DEV} \mid BS_i,S_a(T_1))$, and it can be approximated by estimating the joint probability mass function using Monte Carlo techniques.

STAGE 2: NPV ANALYSIS

NPV is used to determine the preferred building outcome (repair, redevelopment, or leaving the building vacant) for commercial, income-generating properties. The calculations are made on a pre tax basis, not considering borrowed funds or debt servicing. For each LR, T_R, and T_{DEV} combination in Stage 1, the NPV for each of the decisions is calculated. For each decision $D \in \{\text{repair, redevelop, leave vacant}\}$, NPV_D is evaluated as per Equation 1, where $CapEx$ is the required capital expenditure, NOI_t is the net operating income at time t, REV is the reversion value of the property at the investment holding period N, and r is the discount rate:

$$NPV_D = -CapEx_D + \sum_{t=1}^{N} \frac{NOI_{t,D}}{(1+r)^t} + \frac{REV_D}{(1+r)^N} \tag{1}$$

If the NPV of repair and redevelopment are less than zero, it is assumed that the owner would choose to leave the building vacant because the other options would result in a net loss. Therefore, for the purposes of this model, $NPV_{\text{leave vacant}}$ is represented by 0. It should be noted that the owner will likely incur costs associated with keeping the property, such as property taxes, but because the model is evaluated on a pre tax basis, the costs are assumed to be negligible. The preferred decision is chosen in accordance with highest NPV (Equation 2):

$$Decision = \underset{D}{\text{argmax}}\ NPV_D \quad \text{where } D \quad \in \{\text{repair, redevelop, leave vacant}\} \tag{2}$$

The $CapEx$ for the case of repair is the repair cost, which is evaluated as LR times the replacement cost. For the case of redevelopment, $CapEx$ is the demolition cost plus the cost of the new building. Any value of the damaged building that can be recuperated in the redevelopment (e.g., reuse or sale of existing equipment) can be reflected by reducing the $CapEx$ or including an additional positive cash flow stream.

The NOI should be estimated for each year during the holding period based on the anticipated effective gross income and operating expenses. When evaluating NPV_{repair} and $NPV_{\text{redevelop}}$, the NOI should be adjusted for the duration of T_R and T_{DEV} to reflect the reduction in income when the building is unoccupied during recovery. For commercial buildings that generate income by leasing space, building closure affects the rent collection. While in reality, rent collection following closure because of earthquake damage will depend on the terms of the lease, for the purposes of this model, it is assumed that no rent is collected during the closure. We expect the NOI of the redeveloped property to be equal to or greater than the repaired property for two reasons. On one hand, the new development will reflect the current market demand such that it will maximize the income. On the other, the repaired building is subject to depreciation because of functional obsolescence that can result in lower rental rates and higher operating expenses (Brueggeman and Fisher 2001).

In this model, the sale price at the holding period, or REV, is determined using the direct capitalization approach as per Equation 3, where R_{cap^T} is the terminal capitalization rate. The reversion value of the redeveloped property will tend to be higher than the repaired one because of a higher NOI and a lower R_{cap^T}:

$$REV = \frac{NOI_{N+1}}{R_{cap^T}} = \sum_{t=1}^{\infty} \frac{NOI_{N+1}}{(1 + R_{cap^T})^t} \tag{3}$$

The final variable in Equation 1 is the discount rate, r. In the Real Estate Investment Perspective section, the discount rate was presented as a composition of a risk-free interest rate and the risk premium. It was also discussed that the discount rate is the sum of the capitalization rate and the NOI growth rate, and therefore the discount rate can be approximated by the capitalization rate under the assumption of zero growth rate. In this model, it is assumed that there is no growth rate in the income and that the capitalization rate stays constant for the duration of the holding period; therefore, the discount rate can be approximated as $r = R_{cap} = R_{cap^T}$. The capitalization rate for the repaired building is expected to be higher, reflecting the risk perception associated with an older building with previous damage (Bleich 2003).

STAGE 3: INTEGRATION

The final stage of the framework integrates the results from Stages 1 and 2 to obtain the marginal probability of repair, redevelopment, or leaving the building vacant, conditioned on spectral acceleration. Because the estimated probability distributions are probability mass functions, the marginalization becomes a summation over all values of BS, LR, T_R, and T_{DEV}, as in Equation 4:

$$P(Decision \mid S_a(T_1)) = \sum_i \sum_j \sum_k \sum_l P(Decision \mid LR_l, T_{R,k}, T_{DEV,j}) \times P(LR_l, T_{R,k}, T_{DEV,j} \mid BS_i, S_a(T_1)) \times P(BS_i \mid S_a(T_1)) \tag{4}$$

Currently, the model does not consider uncertainty in real estate market parameters, NOI, REV, and r; therefore, $P(Decision \mid LR_l, T_{R,k}, T_{DEV,j})$ evaluates to 1 for the decision with the highest NPV and 0 for the other two decisions. To consider uncertain market parameters, additional marginalization over the market parameter values would be needed.

ILLUSTRATIVE CASE STUDY: RC COMMERCIAL OFFICE BUILDINGS

To illustrate the insight provided by the proposed approach, four RC buildings were analyzed: four- and eight-story non ductile perimeter moment-frames built in 1967 (herein referred to as 4-1967 and 8-1967, respectively) and four- and eight-story ductile special perimeter moment-frames designed and built in 2003 (referred to as 4-2003 and 8-2003, respectively). The buildings are Haselton and Liel archetype designs (Haselton et al. 2011, Liel et al. 2011), with key building properties summarized in Table 1. The buildings were assumed to be located in Commerce, California (Los Angeles County), with soil conditions corresponding to NEHRP soil category D (256 m/s average shear wave velocity over

Table 1. Input model parameters for the four buildings

Building	4-1967	4-2003	8-1967	8-2003
Gross area, A_{gr} (sf)	86,400	86,400	115,200	115,200
First-mode period, T_1 (s)	0.62	0.62	1.16	1.16
Yield base shear coefficient, V_y	0.067	0.133	0.033	0.067
Replacement cost[a], per square foot ($ psf)	160	160	193	193
Replacement cost, total ($ mil.)	13.9	13.9	22.2	22.2
Redevelopment cost[b] ($ mil.)	15.7	15.7	25.1	25.1
Rentable area[c], A_r (sf)	64,800	64,800	86,400	86,400
Repaired rental rate, RR^R ($ psf/yr)	20	25	20	25
Redevelop rental rate, RR^{DEV} ($ psf/yr)	30	30	30	30
Vacancy rate (%)	15	15	15	15
Repaired capitalization rate, R_{cap}^R (%)	9%	9%	9%	9%
Redevelop capitalization rate, R_{cap}^{DEV} (%)	7.5%	7.5%	7.5%	7.5%

[a] Calculated using 2016 RSMeans psf costs.
[b] Equivalent to replacement cost plus demolition cost, which was assumed to be 13% of the replacement cost.
[c] Assumed to be 75% of A_{gr}.

the top 30 m). The shaking intensities at various return periods were determined using 2008 USGS Unified Hazard Tool (USGS 2008). The replacement costs were taken from the 2016 RSMeans square foot costs for RC commercial office buildings with brick veneer (RSMeans 2016). The demolition costs were assumed to be 13% of the replacement costs, in line with the observed costs for Christchurch commercial office buildings (Marquis et al. 2015).

The real estate market parameters used in this example are summarized in Table 1. The assumed rental rates are net of operating expenses and are in line with the 2016 Greater Los Angeles market reports (Cushman & Wakefield 2016). The lower net rental rate for buildings built in 1967 reflects the building depreciation because of functional obsolescence and the increased operating expenses associated with aging infrastructure. The redevelopment rental rates are higher than the rental rates of repaired buildings because new development caters to current market conditions in accordance with the HBU principles, resulting in better returns than the previous building. The NOI is calculated by multiplying the net rental rate by the rentable area and adjusting it to account for vacancy. The capitalization rate of the repaired property is 1.5% higher than the redeveloped one, reflecting the risk premium associated with the uncertainty of the repair cost and the building performance in future earthquakes. As discussed in the previous section, it was assumed that the discount and terminal capitalization rates are equal to the capitalization rate. Finally, a ten-year holding period was selected, as real estate is typically regarded as long-term investment in which frequent sales are avoided in order to minimize transaction costs.

STAGE 1: BUILDING PERFORMANCE ANALYSIS

First, the probability of the three building states (no damage, reparable, and irreparable) is estimated for each of the shaking intensities using 15,000 Monte Carlo simulations. The results are summarized in Figure 2, which shows the probability of a building being in a

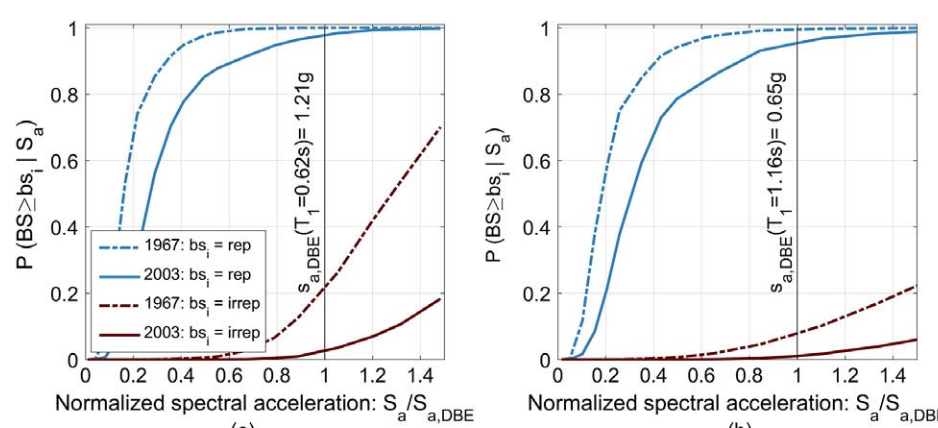

Figure 2. Probability of being in a building state, bs_i or worse for buildings (a) 4-1967 (dashed) and 4-2003 (solid), and (b) 8-1967 (dashed) and 8-2003 (solid), as a function of spectral acceleration, S_a, normalized by spectral acceleration of design basis earthquake, $S_{a,DBE}$. The order of building states from best to worst is no damage, reparable, and irreparable.

given or worse building state conditioned on a spectral acceleration, $P(BS \geq bs_i \mid S_a(T_1))$. In the figure, the spectral acceleration in normalized by the spectral acceleration of the design basis earthquake. As expected, the older buildings (1967) suffer larger levels of damage and have a higher probability of being irreparable than the newer buildings (2003), since they are not designed to modern code standards. In addition, for a given normalized shaking intensity, the four-story building has a higher probability of being in an irreparable building state because of larger story drifts.

Once the building state probabilities are calculated, conditional joint probability distributions of loss ratio, repair time, and redevelopment time, $P(LR, T_R, T_{DEV} \mid BS, S_a(T_1))$, are estimated using *FEMA P-58* and REDi analyses. For the purposes of calculating the delay caused by impeding factors, the buildings are considered to be non essential facilities, whose repair and redevelopment are financed through insurance, and there is no pre-existing contract with a general contractor, as per the REDi methodology (Almufti and Willford 2013). This analysis results in the estimation of multivariate probability mass functions for a given building state and shaking intensity. Figure 3 shows the estimated distributions (marginalized over the redevelopment time) for a design basis earthquake given that the buildings are reparable. For all of the buildings, the loss ratio and repair time show a high level of correlation (~0.8). The more vulnerable 4-1967 building has a more uniformly distributed probability mass, with a higher probability of large loss ratios and repair times. Conversely, most of the probability mass for the 8-2003 building is

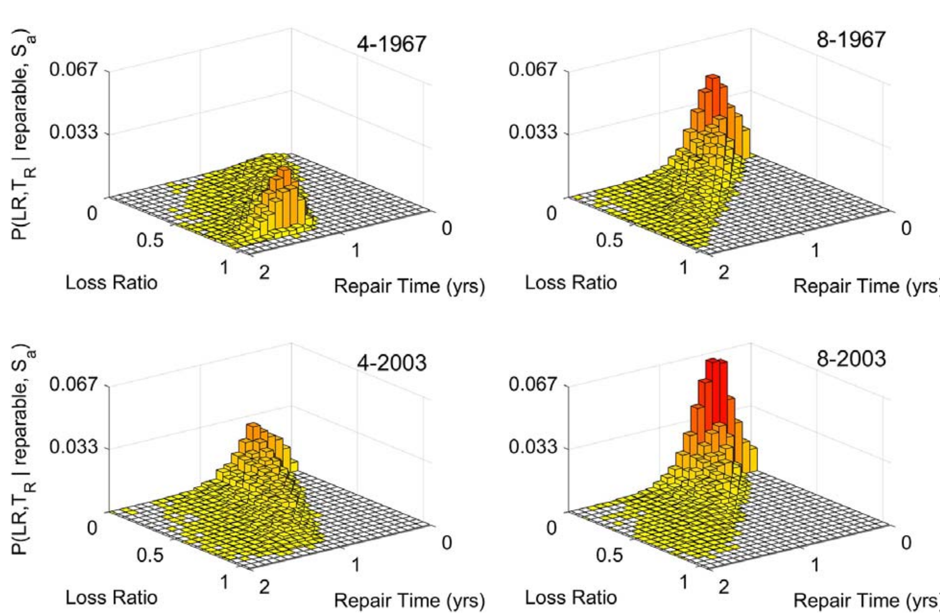

Figure 3. Estimated joint probability mass functions of loss ratio (LR) and repair time (T_R) for the four buildings conditioned of reparable building state (BS = reparable) and spectral acceleration for design basis earthquake ($S_{a,DBE}$).

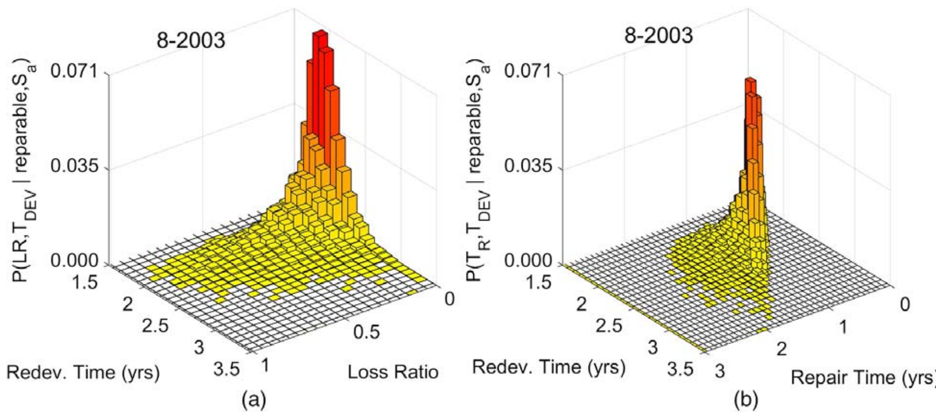

Figure 4. Estimated joint probability mass functions of (a) redevelopment time (T_{DEV}) and loss ratio (LR) and (b) redevelopment time and repair time (T_R) for building 8-2003 given reparable building state ($BS =$ reparable) and design basis earthquake spectral acceleration ($S_{a,DBE}(T_1 = 1.16\,\mathrm{s}) = 0.65\,\mathrm{g}$).

concentrated around low loss ratios, in which the repair time dispersion is mostly a result of impeding factors causing delay in the repair works.

The results can also be visualized as bivariate probability mass functions of loss ratio and redevelopment time, and repair time and redevelopment time, by marginalizing over the repair time and loss ratio, respectively. Sample results for building 8-2003 are as shown in Figure 4. As expected, redevelopment time and loss ratio are not correlated, as demolition is required for redevelopment, and therefore the extent of damage in the building is irrelevant. On the other hand, redevelopment and repair times (Figure 4b) are correlated because of the effect of the shared impeding factors; for simplification purposes, the delay because of inspection, engineering and contractor mobilization, financing, and permitting is assumed to be the same for repair or redevelopment. The lower bound of redevelopment time is the demolition and reconstruction time with no impeding factors delays, which is 1.3 and 1.6 years for the four- and eight-story buildings, respectively.

STAGE 2: NPV ANALYSIS

Using the market parameters defined in Table 1, NPV analysis was conducted for each possible combination of loss ratio, repair time, and redevelopment time in order to determine and compare the NPV's of repair and redevelopment. Sample results of the NPV surfaces for different decisions are shown in Figure 5, in which for visualization purposes, the redevelopment time is kept constant assuming a 0.5-year delay because of impeding factors. For a given combination of loss ratio, repair time, and redevelopment time, the preferred decision is marked by the highest NPV (i.e., the surface in the figure that is on top). Several observations can be made from these results. For zero loss ratio and repair time, the repair NPV is equal to the undamaged building value. The undamaged value is lowest for the smaller, older building (4-1967) and highest for the larger, newer one (8-2003). As the loss ratio and repair

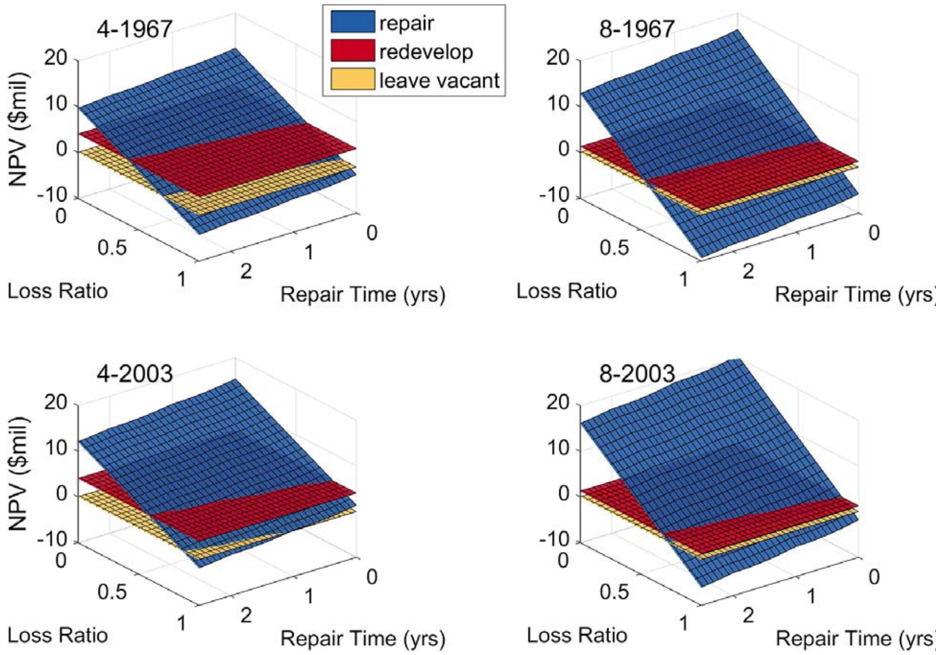

Figure 5. NPVs of repair, redevelop, and leave vacant decisions for different loss ratios and repair times. The redevelopment time is held constant, where T_{DEV} is equal to 1.8 and 2.1 years for the four- and eight-story buildings, respectively.

time increase, the NPV of repair decreases at a fast rate, as more capital must be invested in order to repair to pre-earthquake condition, and the building is unoccupied for a longer period of time. It should be noted that the NPV of repair is much more sensitive to the loss ratio than to the repair time. This is a consequence of the fact that the forgone income because of vacancy during repair, accounts for a relatively small portion of the NPV as compared to the capital expenditures required to repair the building.

Furthermore, the redevelopment NPV surface in Figure 5 is constant across all loss ratios and repair times, as the NPV of redevelopment is not a function of these two variables. It should be noted that the random variables (loss ratio, repair time, and redevelopment time) are not independent, and their dependence is considered in the next stage of the analysis. The redevelopment NPV is lower for larger buildings because of a longer time to reoccupancy and a higher per-square-foot replacement cost that results in a higher per-square-foot capital expenditure relative to the rental income. The NPV for leaving the buildings vacant is zero because in the model, this decision is assumed to bear no cost and generate no income.

Looking across different buildings, the smaller, older building (4-1967) has a higher range of loss ratios and repair times under which the building is redeveloped. This is a consequence of the higher rental benefit from redevelopment as compared to the newer building (4-2003) and the higher redevelopment NPV as compared to the larger buildings (8-1967 and 8-2003). Conversely, the newer, larger building (8-2003) has a higher range of variables for

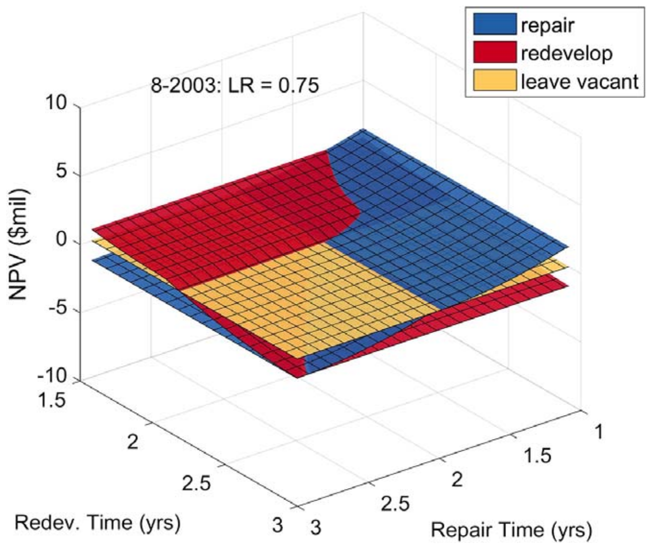

Figure 6. NPVs of repair, redevelop, and leave vacant decisions for building 8-2003 considering different redevelopment and repair times. The loss ratio is held constant at $LR = 0.75$.

which repair is preferred because of the relatively low redevelopment NPV and a lower rental benefit increase from redevelopment, since the building is newer.

While the NPV of repair is more sensitive to changes in loss ratio than to changes in repair and redevelopment times, these times can still influence the NPV. Figure 6 shows how decisions can vary for a fixed loss ratio of 0.75. At lower repair times, repair is preferred. As repair time increases, either redevelopment (for low redevelopment time) or leaving the building vacant and unrepaired (for high redevelopment time) is preferred.

While the examples above consider NPV calculations for a wide range of loss ratios and repair and redevelopment times, only combinations of variables in which the joint probability distribution is non zero need to be considered.

STAGE 3: INTEGRATION AND THE RESULTING PROBABILITY OF REPAIR, REDEVELOPMENT, AND LEAVING A BUILDING VACANT

The last step of the analysis consists of integrating the joint probability distribution with the results from the NPV analysis to obtain the likelihood of the three building outcomes, as per Equation 4. Figure 7 shows the resultant probabilities of repair, redevelopment, and leaving the building vacant for increasing levels of shaking intensity conditioned on the building being damaged (i.e., reparable or irreparable). For all buildings, the probability of repairing a damaged building using the proposed model is lower than if only the *FEMA P-58* criteria (collapse or large residual story drifts) are used. The lower likelihood reflects cases in which repair is feasible but is not financially preferred to other decisions. The probability of redevelopment is generally higher than for *FEMA P-58* results, and it increases with

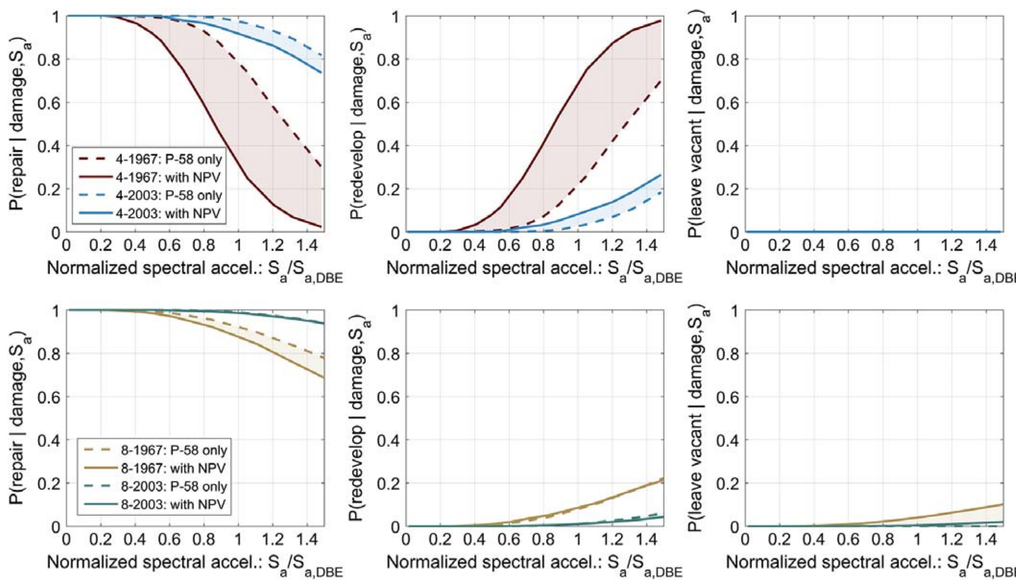

Figure 7. Probabilities of repair, redevelopment, and leave vacant decisions conditioned of damage ($BS =$ reparable ∪ irreparable) and spectral acceleration, using *P-58* criteria (*P-58* only) and the proposed model (with NPV). The top row shows results for the four-story buildings and the bottom row for the eight-story buildings.

increasing levels of shaking intensity. The smaller, older building (4-1967) is the most likely to be redeveloped because of the combined effect of higher damage leading to higher repair cost and larger rental benefit from redevelopment. In addition, it can be seen that for taller buildings, the probability of leaving the building vacant becomes non zero as shaking intensity increases—a case that current seismic risk models do not capture. For larger buildings, the NPV of redevelopment is relatively low, and when the capital expenditure for repair becomes too large, both repair and redevelopment lead to a net loss. In this case, doing nothing with the building and waiting for the market conditions or the owner's financial circumstances to change is the financially preferable option.

SENSITIVITY OF BUILDING OUTCOMES TO MARKET PARAMETERS AND OTHER INPUTS

The case study demonstrated how the inclusion of market parameters can influence the likelihood of post earthquake outcomes. Real estate market parameters, however, can vary depending on the property location, economic conditions, interest rates, and other factors. In addition, the real estate market might experience changes following a destructive earthquake. Therefore, it is of interest to investigate how the NPVs of different post earthquake decisions change with varying market parameters and other inputs.

Figure 8 shows how the NPVs of repair and redevelopment investments for building 8-2003 change as input parameters are varied. The baseline parameters are $LR = 50\%$,

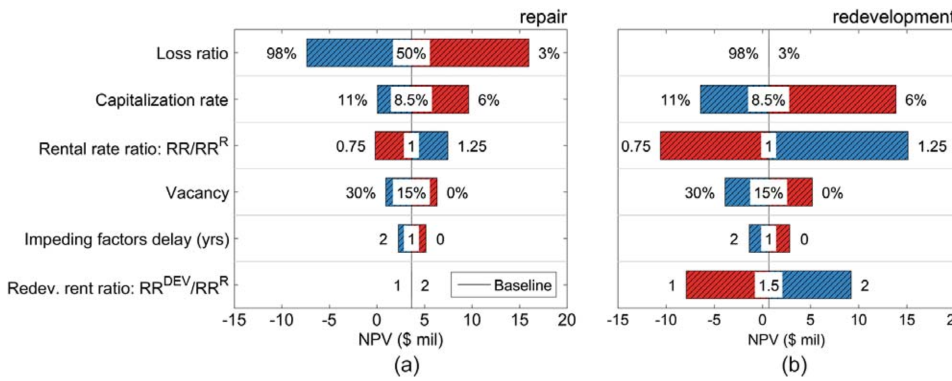

Figure 8. Graphical representation of the sensitivity of (a) repair NPV, and (b) redevelopment NPV to changes in several input parameters for building 8-2003. Red bars indicate a decrease in input parameter and blue bars, an increase. Parameter ranges used in these calculations are shown to the left and right of each bar, and baseline parameter values are shown in the middle.

$R_{cap} = 8.5\%$, $RR^R = \$20$ psf, $RR^{DEV} = \$37.5$ psf, 15% vacancy rate, and one-year delay because of impeding factors. Two additional ratios are also varied—ratio of the rental rate to the baseline rental rate (rental rate ratio) and the ratio of rental rate for redeveloped property to the repaired one (redevelopment rent ratio). The first ratio is a proxy to reflect the conditions of the real estate market and the profitability of development, and the second one indicates how obsolete the original property is in current market conditions. All of the parameters are varied within reasonable ranges.

Several observations about NPV sensitivity can be made from Figure 8. Given the same variations in input parameters, the changes in the NPVs of repair and redevelopment are different, where, in general the redevelopment NPV is more sensitive (with the exception of changes in the loss ratio). Because the relative sensitivities to individual parameters vary between the repair and redevelopment cases, a change in an input parameter can change the decision on whether to repair, redevelop, or leave a damaged building vacant. For both repair and redevelopment, an increase in capitalization rate, vacancy, or a delay because of impeding factors will decrease the NPV, and an increase in rental rate ratio will increase the NPV. Repair is very sensitive to changes in the loss ratio because it directly affects the $CapEx_{\mathrm{repair}}$, whereas the redevelopment NPV does not depend on the repair cost because demolition is necessary for any loss ratio. On the other hand, the redevelopment rent ratio affects only the redevelopment NPV because it causes changes in the *NOI* and *REV* of the redeveloped property.

Next, the effect of changes in the loss ratio, rental rate, and capitalization rate on the ultimate outcome of building 8-2003 is investigated. Figure 9a shows how the decision changes as loss ratio and rental rate vary. If the loss ratio is low (<50%), the decision will always be to repair, as the relatively low capital expenditure will be recovered through generated income and sale at the holding period. For higher loss ratios, the decision can change depending on the rental rate. High rental rates signal increased demand and a

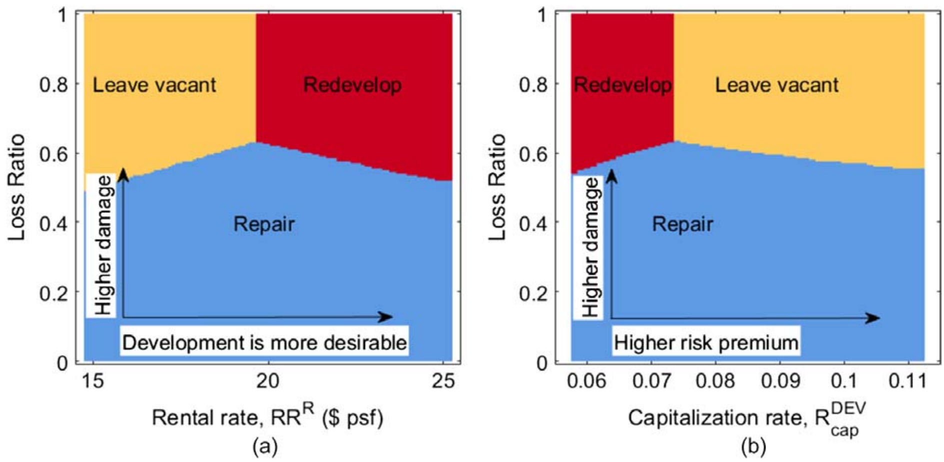

Figure 9. Boundaries for repair, redevelop, and leave vacant decisions for building 8-2003 as a function of loss ratio: (a) rental rate and (b) capitalization rate.

more desirable development environment, in which enough income can be generated to justify the redevelopment investment. Conversely, lower rental rates are typically a consequence of rental space oversupply and high vacancy rates. In a case where the rental rates are low and a large capital expenditure is required to restore building functionality, the owner might choose to do nothing because the investment will not pay off. On the other hand, if the rental rates are high and a newly developed building can generate relatively high income, the owner might decide to invest the additional capital required for redevelopment.

With regard to the capitalization rate (Figure 9b), in a stable, less risky market (low capitalization rate), a high loss ratio might cause the owner to redevelop in order to capitalize on the benefits of the new property. However, in a high-risk market or when the opportunity cost of capital is high, the returns on the property might not justify the investment needed for repair or redevelopment, and leaving the building as is might be the preferred option.

SUMMARY AND CONCLUSIONS

This paper proposes a model that unifies seismic building performance assessment and real estate investment analysis to determine the likelihood of various post earthquake decisions—repair, redevelop, or leave vacant—for commercial properties. A three-stage framework was presented, which (1) leveraged *FEMA P-58* and REDi methodologies to estimate the probability of being in different building states and the joint probability distribution of loss ratio (repair cost expressed as a percentage of the replacement cost), repair time, and redevelopment time; (2) evaluated the financially preferred option using the NPV decision rule for all plausible combinations of loss ratios and repair and redevelopment times; and (3) integrated the results to obtain the probabilities of different decisions. The proposed framework is of most value when repair is feasible, but other decisions might yield greater economic value.

The illustrative case study showed that incorporating NPV analysis into *FEMA P-58*, as compared to using *P-58* alone, yields lower repair probabilities and higher redevelopment and leaving the building vacant probabilities, which is consistent with the decisions made (e.g., following the 2010–2011 Canterbury earthquakes). The change in probabilities was most significant for the smaller, older building.

The sensitivity analysis showed that in addition to repair cost, post earthquake decisions are sensitive to real estate market conditions. When capitalization rates are low and rental premiums on redeveloped property are high, redevelopment is the preferred option, while in a depressed real estate market with low rental rates and high capitalization rates, leaving the building vacant can be the financially preferred option. Both of these situations reflect decisions that previous seismic risk assessment models would fail to capture.

This novel approach toward modeling decisions on commercial buildings allows one to consider post earthquake impacts beyond building damage, bringing insight into building recovery trajectories that will in turn impact economic activities in the region. Being able to model and understand factors affecting decisions can also facilitate the design of policies and mitigation measures aimed at reducing the loss of built environment and enhancing community resilience. In addition, this research unifies the terminology and concepts from the fields of earthquake engineering and real estate investment and finance to enrich and arrive to a common understanding of post earthquake building consequences. Future research will focus on the incorporation of debt and after-tax investment analysis into the framework in order to understand how access to capital and different policies can affect building owners' decisions. In addition, the framework will be extended to a regional level to understand the potential loss in the built environment and the subsequent recovery at a community scale.

ACKNOWLEDGMENTS

The authors would like to thank Richard Carr, Brent Nahkies, Christine Boyd, and Lydia Tan for their valuable insight into real estate investment analysis. The authors would also like to acknowledge Ken Elwood for the thoughtful comments and advice on the topic. An academic license of the SP3 software was utilized to perform the *P-58* analyses in this work.

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(Received 1 March 2018; Accepted 7 May 2018)