Accounting for the slow pace that buildings are brought up to current code in benefit-cost studies

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Research Summary

Benefit-cost analysis of building codes has revealed significant long-term benefits. Prior traditional BCA mainly contemplates the benefits of a building or set of buildings adhering to a new building code at a single point in time, e.g., in the current year. This work, in contrast, focuses on a broader spatial scale (e.g., community), recognizing that the benefits of code compliance across the community will occur over time, driven by the typically slow pace of replacement or improvement of existing buildings and of new construction.

A new Community Benefit Discount Factor ($CBDF$) is introduced that can be used to adjust a traditional BCA to account for the timing of building code compliance for existing buildings. The CDBF addresses the economic discounting of the future costs and benefits of code compliance as they occur over time. The focus is on existing buildings undergoing replacement or substantial improvements that require compliance with current building codes for new construction. Building life (time to demolition), has previously been modeled stochastically with survival functions, the approach taken here to model the timing until replacement or substantial improvement. Assuming the common Weibull survival function, new formulas are developed for computing the $CBDF$. The formulas are developed for a single building, which can be extended to each building in the community. The application of the $CBDF$ is demonstrated under differing discount rates. Finally, limitations and potential future directions of this research are discussed.

The CBDF approach can be used to assess the benefit of adopting new building codes, or adding new local provisions to the model codes. Additionally, outputs of this process can be used as inputs to other assessment tools, such as the NIST Alternatives for Resilient Communities (ARC) Tool and the NIST Economic Decision Guide Software (EDGe$) Tool.

Research Advancement Details

Benefits and costs of code compliance have typically been evaluated from the perspective of a building owner and not the community. This is referred to below as the “traditional” benefit-cost assessment (BCA). In contrast, the goal here is to evaluate net benefits of

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improvements to local codes from the perspective of a community over a specified period of time. Factored into the analysis is a future period of time, typically decades, required for existing buildings to become compliant with the new code. The audience for this work are decision-makers or planners wanting to convey the benefits of code adoption or in deciding between alternative community investments.

This brief focuses on assessing the net benefits of the adoption of a code for a building location where an existing building resides. Code compliance at this location refers to the existing building complying with the codes for new construction, which can happened in two basic ways. Code compliance can occur with a rebuild, where the new building must comply with local building codes for new construction; the codes are adopted from international model codes (e.g., International Building Code (ICC, 2024a), International Residential Code (ICC, 2024c)) with amendments to address local considerations. Or, compliance may occur with an upgrade to the existing building. In codes for existing buildings (e.g., International Existing Building Code (ICC, 2024b)), a triggering event, e.g., substantial improvement, must occur to require existing buildings to comply with the codes for new construction. The response to a triggering event, rebuild or upgrade, depends on the decisions of individual owners. The construction of new buildings at a location where there is no building, in contrast, may depend on a much larger set of decisions, including community decisions pertaining to growth, and developer and parcel owner decisions on undertaking new construction, which may require a different cost-benefit methodology.

To assess the benefit of a code change to the community, a new multiplicative factor, the Community Benefit Discount Factor ($CBDF$) is introduced. The CBDF is to be applied to the traditional net benefit calculation. The formulas are developed for a single building, which can be extended to each building in the community. The CDBF accounts, in the economic discounting, for the time between when a building code becomes effective and the time each existing building undergoes rebuild/code-triggering substantial improvement.

There is a "building lifetime" literature that is relevant, but it does not address building codes (Aksözen et al., 2017; Aktas & Bilec, 2012; Bradley, 2005; Bradley & Kohler, 2007; Ianchenko et al., 2020; Kayo & Tonosaki, 2022; Kohler & Yang, 2007, 2007; Zhou et al., 2019, 2020). These studies have focused on assessing building lifetimes from data on the demolition of buildings. The aim of these studies was to assess and anticipate the future materials required and the environmental implications of their demolition and rebuild. In contrast, here, the goal of the lifetime analysis is to model the duration of time for a building at a location to remain unchanged with respect to code level.

To model this elapsed time, the approach used in building lifetime studies is adopted. In these studies, building lifetime has been statistically modeled using "survival functions"; more heavily parameterized system dynamics models have also been developed but also

typically employ survival functions (Zhou et al., 2019, 2020, 2022). Survival functions are most often used in reliability and related fields (NIST/SEMATECH e-Handbook of Statistical Methods, 2025). They are used here to model the timing of the triggering event requiring an existing building's compliance with building codes for new construction.

New formulas are developed that correspond to two special cases of the Weibull survival function, the exponential distribution, where the shape parameter $\gamma = 1$, and the Rayleigh distribution, where the shape parameter $\gamma = 2$; the formulas are applicable to all values of the scale parameter α. Inputs to the formulas include the discount rate *r*, and for the case $\gamma = 2$, time $\grave{t}$, which is the elapsed time between construction or the most recent substantial improvement triggering compliance and the time at which the code goes into effect. The $CBDF$ for these two cases will be shown to be solely a function of $r\alpha$ and $\grave{t}/\alpha$; isopleth maps are presented for each case to illuminate the $CBDF$'s sensitivity to these two quantities.

The organization of this research brief is as follows. First, the traditional assessment of the costs and benefits of building improvements, and then survival functions, are briefly described. Next, the $CBDF$ formulas that are used to adjust the traditional net benefits assessment are developed, with details provided in the Appendix. The *CBDF* formulas are applied in an example using data from the *Natural Hazard Mitigation Saves* study that represents a traditional BCA (Multi-Hazard Mitigation Council, 2019). The brief ends with a short discussion on limitations and potential future directions.

Net benefits traditional assessment

The traditional BCA assesses net expected benefits in the year that a change is considered. For example, even *Natural Hazard Mitigation Saves*, one of the few studies that aggregates benefits across a broad area, in that study at the national level, evaluates net benefits of new construction that takes place in year 1 of a new code (Multi-Hazard Mitigation Council, 2019). The traditional BCA expected net benefits are represented here by the function $\widehat{\boldsymbol{B}}(r)$. Function $\widehat{\boldsymbol{B}}(r)$ computes the net benefit on a present-value (at the time of compliance) and expected value basis. The net benefits reflect the present and future costs and benefits of an existing or new building being built to a new or proposed new code. Costs and benefits are discounted, using real discount rate r (unit:1/year).

While more general, the computation of $\widehat{\boldsymbol{B}}(r)$ is briefly described here in the context of hazard events. All costs and benefits discussed below are on an expected value basis. On the compliance cost side, there are additional upfront costs $\hat{C}$ from having to comply with a new standard. In addition, there are additional annual maintenance and replacements costs, expressible as annualized costs, $\bar{C}$; discounting of $\bar{C}$ to the time of compliance using continuous discounting, and assuming repeatability, yields $(1/r)\bar{C}$. On the benefits side,

this discussion assumes a finite set of hazard events E. $\tilde{B}_e$ refers to the avoided losses associated with the occurrence of hazard event $e \in E$. Assuming constant (through time) event probability density p_e (units:1/year) for each event e, the expected present value benefit associated with event e is defined by $\int_{t=0}^{t=\infty} p_e \tilde{B}_e e^{-rt} dt$ that solves to $p_e \tilde{B}_e / r$; the expected benefits across all events are $(1/r) \sum_e p_e \tilde{B}_e$. Accounting for all costs and benefits, as discounted to the time of compliance with the new code, the net expected benefits are:

$$\widehat{\boldsymbol{B}}(r) = \sum_e p_e \tilde{B}_e / r - \left(\hat{C} + \bar{C}/r\right) \qquad \text{Eq. 1}$$

Eq. 1 captures the essence of the traditional assessment of net expected benefits for a building subject to hazard events as assessed to the time the building adheres to the new code.

Weibull survival functions

Based on their use in building lifetime studies and more generally in reliability studies across several fields, Weibull probability functions are employed. The two-parameter Weibull probability density function (PDF) describes the time from first existence until "failure". The Weibull PDF, in time t, is:

$$f(t) = \left[e^{-\left(\frac{t}{\alpha}\right)^{\gamma}}\right]\left[\frac{\gamma}{\alpha}\left(\frac{t}{\alpha}\right)^{(\gamma-1)}\right] \qquad t, \gamma, \alpha > 0 \qquad \text{Eq. 2}$$

where γ is a shape parameter and α is a scale parameter. Here, "failure" refers to the existing building undergoing a rebuild or substantial improvement requiring compliance with the current codes for new construction. The Weibull parameters, of course, would be expected to be different for rebuilds than substantial improvements, with, for example, the scale parameter being higher for rebuilds as it is a larger undertaking.

While probability distributions (including the Weibull) are typically defined in terms of a probability density function (PDF), there are several related probability functions used in applications that have relevance here, in particular, the survival function and hazard function (*NIST/SEMATECH e-Handbook of Statistical Methods*, 2025). The expression for the Weibull survival function, $S(t)$, is the first bracketed term in the Weibull PDF (Eq. 2); at $t = 0$, $S(t) = 1$. The hazard function, $h(t)$, is the second bracketed term in the Weibull PDF. The hazard function is the failure PDF conditioned on having survived until time t.

The building-related studies that employ the Weibull report a wide range of values for (γ, α). The reported values are for building lifetimes as defined by demolition. Example reported values for (γ, α) are shown in Table 1. The table shows the wide variation of Weibull parameter assessments for different sets of buildings in different countries. Values of γ are greater than 1, which is to be expected as values of $\gamma < 1$ correspond to the

modeling of the lifetimes of 'assembly-line' type products that may be defective, i.e., with hazard rates highest initially, which is not the case for buildings constructed at a site, where defective products should be identified and corrected in the inspections that take place during construction. Also shown are the computed mean lifetimes, which range from 36 to 185 years. It should be noted that the studies generally note the lack of survival analysis of buildings and therefore there may be expected to be more variation in the parameter values than noted in the table for different building types and locales.

Table 1. Example reported Weibull survival functions for buildings. It is the survival until the building's demolition.

Study	Weibull			Reference
	γ	α	Mean lifetime	
An assessment of building lifetimes in the United States	2.70	150	133	Ianchenko et al., 2020
Chinese urban residential buildings	1.47	40	36	Zhou et al., 2019
German study in a largely (79%) residential area	1.29	200	185	Cord'homme et al., 2025

For illustration of the importance of the parameters of the Weibull for buildings, the Weibull PDF, survival, and hazard functions are shown in Figure 1 for two different sets of Weibull parameter values. The two sets of Weibull parameters (γ, α) are $\mathcal{W}(1, 60)$ (blue thinner line) and $\mathcal{W}(2, 67.7)$ (red thicker line). They vary most significantly with respect to the value of γ; for comparability of the influence of the shape parameter γ, the scale parameter α was adjusted to ensure that the two Weibull sets of parameters result in the same mean survival time of 60 years (mean = $\alpha\,\Gamma(1 + 1/\gamma)$ where Γ is the gamma function). These two sets will also be used in the example application of the derived CBDFs. Referring to the PDF, for $\mathcal{W}(1, 60)$ the time with the highest probability (density) of failure is at $t = 0$, whereas for $\mathcal{W}(2, 67.7)$ it is at approximately $t = 50$ years. The chance of survival for $\mathcal{W}(2, 67.7)$ is higher than $\mathcal{W}(1, 60)$ initially and until approximately $t = 75$ years where it then crosses the survival function for $\mathcal{W}(2, 67.7)$; survival chances for $\mathcal{W}(1, 60)$ approach zero much slower than $\mathcal{W}(2, 67.7)$, at 150 years reaching 8.2 % as

compared to 0.74 %, respectively. Driving these differences are the differences in their hazard functions (Figure 1c). The hazard function is a constant value through time for $\mathcal{W}(1, 60)$, whereas for $\mathcal{W}(2, 67.7)$ it linearly increases (from zero).

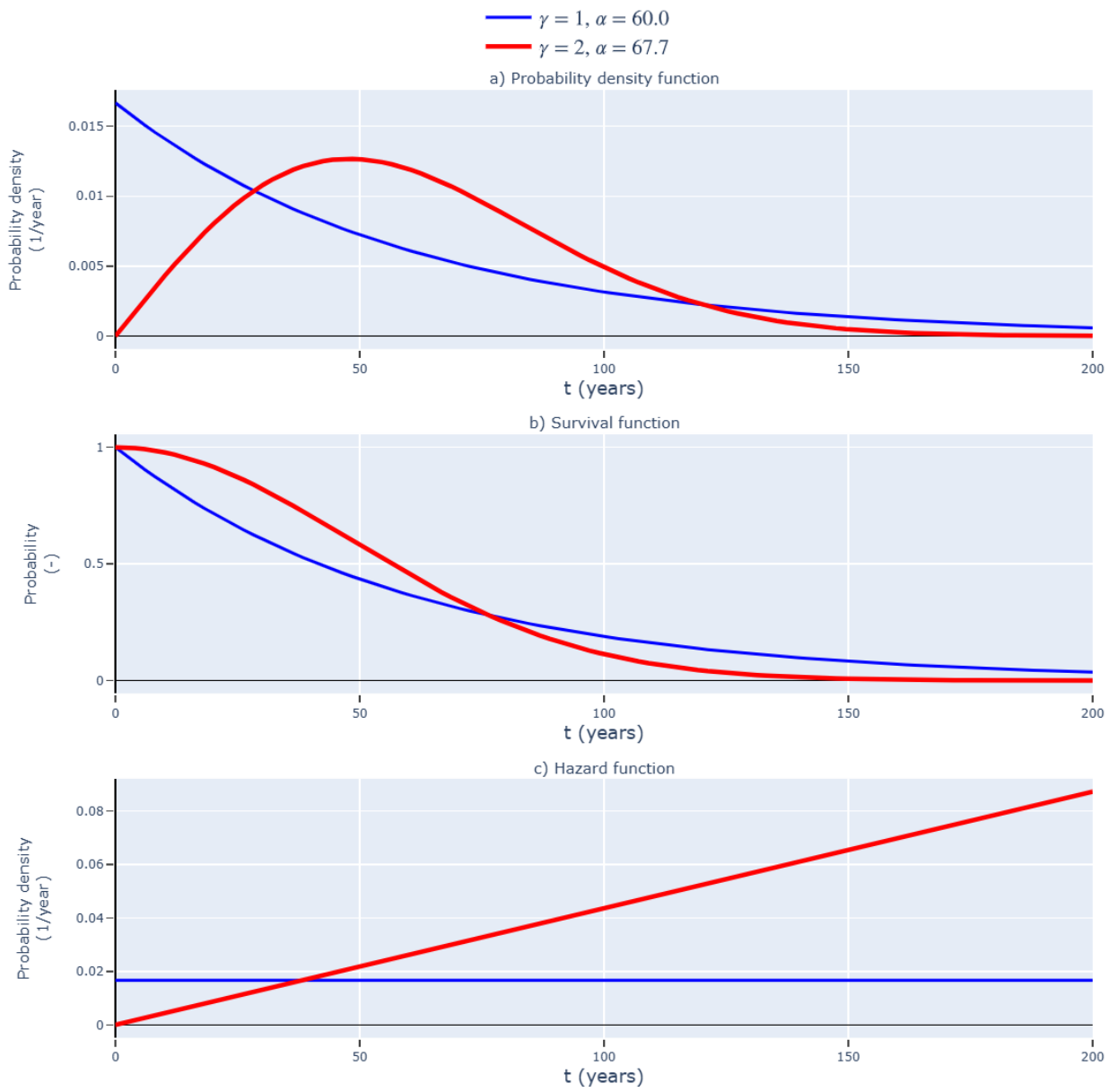

Figure 1. Weibull probability functions for two different sets of parameter values having the same mean survival time of 60 years: ($\gamma = 1$, $\alpha = 60.0$) (blue thin line) and ($\gamma = 2$; $\alpha = 67.7$) (red thick line). The probability functions include: a) probability density function, b) survival function, and c) hazard function.

Community Benefit Discount Factor

The goal is to evaluate the expected community (net) benefit of compliance with the building codes for new construction at locations where existing buildings currently are located. This compliance will be achieved through rebuild or a substantial improvement to the existing building. The formulas are developed for a single existing building turning over to new code with the knowledge that the approach can be scaled up to the full set of the community's existing buildings, provided that the data are available on which to develop Weibull parameter values. The variable representing a single building's community benefit is denoted as $\mathcal{B}^{CMTY}$. It is to represent the expected net benefits as discounted to the code's effective date, with accounting of the stochastic timing of the triggering events for code compliance, as dictated by its survival function.

For clarity in describing the methodology, some conceptual shorthands are used. "Building age" is used to represent the time since construction or last significant improvement that required compliance with codes for new construction. Similarly, "building lifetime" is to refer to the time since construction/rebuild/significant improvement to the next rebuild or significant improvement. It is likely that the survival parameters are dependent on whether the last event was construction/rebuild or substantial improvement; this is addressed in the discussion section.

The unit of analysis here is a single survived building of age $\grave{t}$ at the time the code becomes enforceable (i.e., its effective date). Given this unit of analysis, the appropriate distribution for modeling the timing of rebuild or significant improvement after $\grave{t}$ is a left-truncated distribution with interval $(\grave{t}, \infty)$:

$$\mathrm{f}_l(t) = \frac{\mathrm{f}(t)}{1-\mathrm{F}(\grave{t})} = \frac{\mathrm{f}(t)}{\mathrm{S}(\grave{t})} \qquad t > 0 \qquad \text{Eq. 3}$$

The following integral defines $\mathcal{B}^{CMTY}$:

$$\mathcal{B}^{CMTY} = \int_{t=\grave{t}}^{t=\infty} \frac{\mathrm{f}(t)}{\mathrm{S}(\grave{t})} \left[\widehat{\mathrm{B}}(r)\, e^{-r(t-\grave{t})}\right] dt \qquad \text{Eq. 4}$$

The integral is evaluated from $\grave{t}$ through a long-time horizon, approximated here by infinity. The second bracketed term is the result of the rebuild or substantial improvement: compliance with the current codes for new construction and the benefits that come with it, i.e., $\widehat{\mathrm{B}}(r)$, as discounted to the code effective date $(t - \grave{t})$ years prior using continuous discounting (the factor $e^{-r(t-\grave{t})}$).

Assuming a Weibull probability distribution, the integral to be evaluated is defined as $\mathcal{B}_{\mathcal{W}}^{CMTY}$:

$$\mathcal{B}_{\mathcal{W}}^{CMTY} = \int_{t=\grave{t}}^{t=\infty} \left[\frac{e^{-\left(\frac{t}{\alpha}\right)^{\gamma}} \frac{\gamma}{\alpha^{\gamma}} t^{(\gamma-1)}}{e^{-\left(\frac{\grave{t}}{\alpha}\right)^{\gamma}}} \right] \left[\widehat{\mathrm{B}}(r)\, e^{-r(t-\grave{t})} \right] dt \qquad \text{Eq. 5}$$

Equation 5 could be solved with methods of numerical integration. To examine the role of the Weibull parameters, closed-form solutions were developed to gain general understanding of the influence of the shape parameter, γ, and the scale parameter, α. Recognizing that actual values of γ for building survival, as shown in Table 1, will be greater than 1, two cases are considered, $\gamma = 1$ and $\gamma = 2$. The terms $\mathcal{B}_{\gamma=1}^{CMTY}$ and $\mathcal{B}_{\gamma=2}^{CMTY}$ are defined, respectively, for these two cases. The exponential case ($\gamma = 1$) is important to examine as there are cases in which building lifetimes were found to be nearly independent of age (Bradley & Kohler, 2007), for the convenience of its application (e.g., lower data requirement), and as it has been the assumption in some resilience studies concerning buildings (Wang et al., 2020).

The results of the integrations, the details of which are in Appendix A, respectively, are:

$$\mathcal{B}_{\mathcal{W}_{\gamma=1}}^{CMTY} = \left[\frac{1}{r\alpha + 1} \right] \widehat{\mathrm{B}}(r) \qquad \text{Eq. 6}$$

$$\mathcal{B}_{\mathcal{W}_{\gamma=2}}^{CMTY} = \left[1 - \frac{1}{2}\sqrt{\pi} r\alpha\, e^{\left(\frac{r\alpha}{2} + \frac{\grave{t}}{\alpha}\right)^2} \operatorname{erfc}\left(\frac{r\alpha}{2} + \frac{\grave{t}}{\alpha}\right) \right] \widehat{\mathrm{B}}(r) \qquad \text{Eq. 7}$$

where $\operatorname{erfc}(x)$ is the complementary error function: $\operatorname{erfc}(x) = 1 - \operatorname{erf}(x)$.

Defining $CBDF_{\mathcal{W}_{\gamma=1}}$ and $CBDF_{\mathcal{W}_{\gamma=2}}$ as the coefficients to be applied to $\widehat{\mathrm{B}}(r)$ to yield the net benefits of a code change yields:

$$\mathcal{B}_{\mathcal{W}_{\gamma=1}}^{CMTY} = CBDF_{\mathcal{W}_{\gamma=1}}\ \widehat{\mathrm{B}}(r) \qquad \text{Eq. 8}$$

$$\mathcal{B}_{\mathcal{W}_{\gamma=2}}^{CMTY} = CBDF_{\mathcal{W}_{\gamma=2}}\ \widehat{\mathrm{B}}(r) \qquad \text{Eq. 9}$$

where

$$CBDF_{\mathcal{W}_{\gamma=1}} = \frac{1}{r\alpha + 1} \qquad \text{Eq. 10}$$

$$CBDF_{\mathcal{W}_{\gamma=2}} = 1 - \frac{1}{2}\sqrt{\pi} r\alpha e^{\left(\frac{r\alpha}{2} + \frac{\grave{t}}{\alpha}\right)^2} erfc\left(\frac{r\alpha}{2} + \frac{\grave{t}}{\alpha}\right) \qquad \text{Eq. 11}$$

Equations 10 and 11 assume a time scale where *t*=0 represents the beginning of the building's life. This time scale was selected as it typically is the form of the survival function. The equations can, however, be expressed in calendar time with substitution of $\grave{t}$ with $t^{eff} - t^0$ where t^{eff} is the effective date of the code and t^0 is the beginning of the building's life:

$$CBDF_{\mathcal{W}_{\gamma=1}} = \frac{1}{r\alpha + 1} \qquad \text{Eq. 12}$$

$$CBDF_{\mathcal{W}_{\gamma=2}} = 1 - \frac{1}{2}\sqrt{\pi} r\alpha e^{\left(\frac{r\alpha}{2} + \frac{t^{eff} - t^0}{\alpha}\right)^2} erfc\left(\frac{r\alpha}{2} + \frac{t^{eff} - t^0}{\alpha}\right) \qquad \text{Eq. 13}$$

The community benefits as evaluated with Eq. 9 and Eq. 9 are as discounted to the code effective date. The benefits, however, could easily be expressed also at different dates (e.g., code adoption date, a common year of comparison with other community investments) using present/future value calculations, or may be expressed in equivalent annual terms.

Visualization of the CBDF

As the two quantities $r\alpha$ and $\grave{t}/\alpha$ appear repeatedly in the factors (Eqs. 10 and 11) and solely determine them, the surfaces for $CBDF_{W_{\gamma=1}}$ and $CBDF_{W_{\gamma=2}}$ are visualized in Figure 2.

The quantity $\grave{t}/\alpha$ on the horizontal axis is the building age $\grave{t}$ as normalized to the scaling parameter α, which is related to building lifetime; $\grave{t}/\alpha$ essentially can be interpreted as how "young" the building is at the code effective date. For reference, $\gamma = 2$, $\grave{t}/\alpha = 1$ corresponds to approximately the 63rd percentile of ages until which a building "lives" (here, "remains untriggered") and $\grave{t}/\alpha = 2$ represents an "old" building, approximately the 98th percentile. On the vertical axis is the product $r\alpha$.

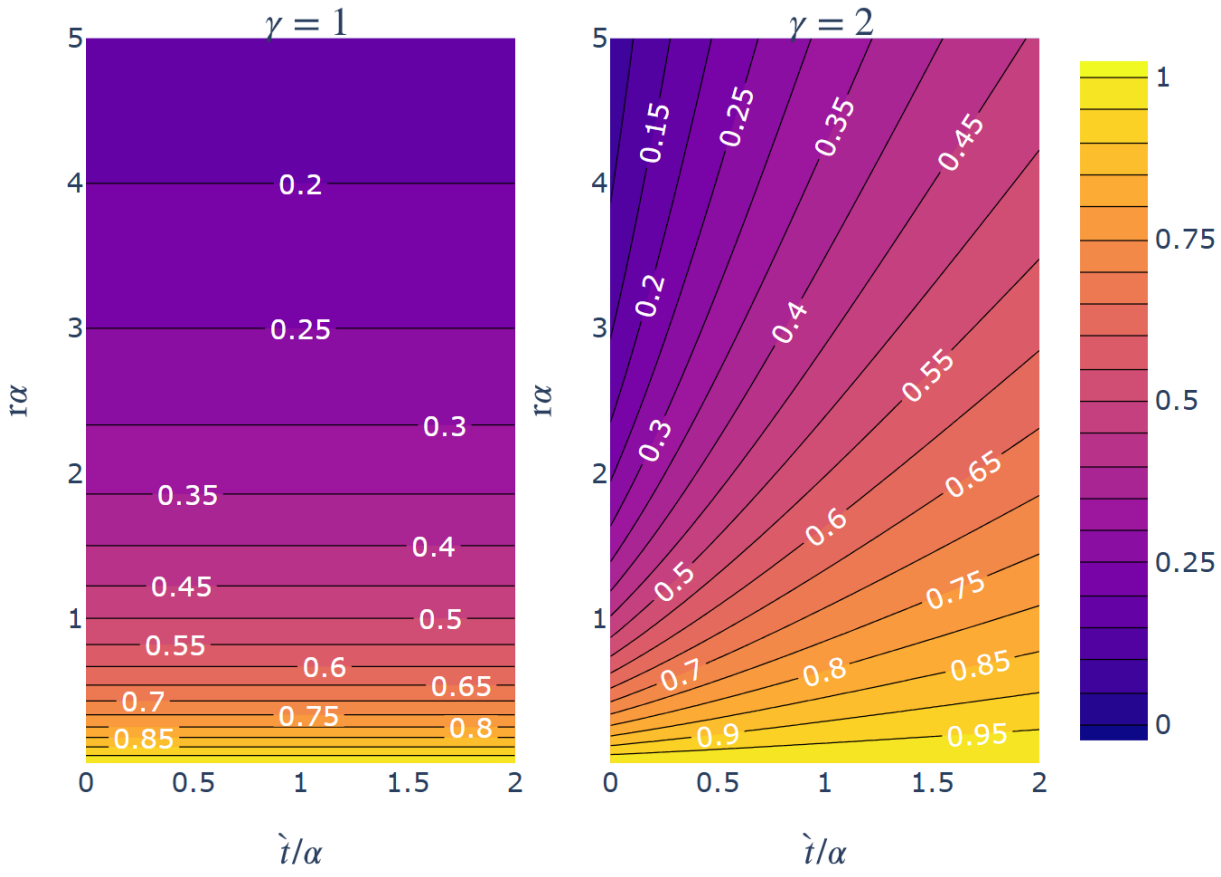

Figure 2. Community Benefit Discount Factor (CBDF) as a function of, on the vertical axis, the product of the discount rate r and the Weibull scale parameter α, and, on the horizontal axis, the ratio of the building age when a new building code comes into effect, $\grave{t}$, to the scale parameter α. The factors are shown for $\gamma = 1$ (left pane) and $\gamma = 2$ (right pane). The multiplicative CBDF is to be applied to the estimate of net benefits as assessed from the building owner at the time of code compliance.

To interpret the figure, first consider a fixed value of the scale parameter α. The plots indicate that, as expected, increasing r decreases both $CBDF_{\mathcal{W}_{\gamma=1}}$ and $CBDF_{\mathcal{W}_{\gamma=2}}$; the rate of decrease slows as r increases. However, whereas the building age ($\grave{t}$) has no effect on $CBDF_{\mathcal{W}_{\gamma=1}}$, an increase in building age increases $CBDF_{\mathcal{W}_{\gamma=2}}$. The explanation is that, unlike $\mathcal{W}_{\gamma=1}$, the probability of encountering the code trigger increases with age under $\mathcal{W}_{\gamma=2}$ (see the hazard function in Figure 1c). Under $\mathcal{W}_{\gamma=2}$, the older buildings will encounter the benefits sooner than the younger buildings, and so will be less heavily discounted (i.e., have a higher CBDF).

Turning to the role of α, for $CBDF_{\mathcal{W}_{\gamma=1}}$, increasing α increases the average building lifetime. This decreases benefits by pushing them further into the future where they are more heavily discounted. A percentage increase in α has the same effect as a percentage increase in the discount rate r. The magnitude of this effect is irrespective of building age ($\grave{t}$). For $CBDF_{\mathcal{W}_{\gamma=2}}$, however, while increasing α also pushes benefits further out into the future leading to more discounting, the magnitude of this effect is dependent on building age ($\grave{t}$). For a building of a particular age ($\grave{t}$) at the time the code becomes effective, a higher value of α effectively makes the building younger. As younger buildings have a lower hazard rate (i.e., the probability density of encountering a triggering event is lower) than older buildings, benefits are pushed even farther into the future, resulting in an even lower CBDF.

Example application

The example involves a community considering the adoption of a new code that exceeds 2015 I-Code requirements for buildings. The analysis considers the community net benefit of requiring the seismic retrofit of soft-story wood-frame multifamily dwellings that were built between 1970 and 1980 and had remained at the code level to which they were built. For the sake of the example, it is assumed that there are 10,000 housing units in such dwellings, not all of which will be cost-effective to retrofit. It is desired to know the community benefit at the time of enforcement of the code, which is assumed to be 1/1/2028.

The example draws from the 2019 *Natural Hazard Mitigation Saves* study (Multi-Hazard Mitigation Council, 2019) that addressed multiple hazards (riverine flooding, hurricane surge, hurricane wind, earthquake, and wildland-urban interface fires). In the study, avoided losses beyond property loss were considered, including deaths and nonfatal injuries, loss of employment, and in some cases other types of losses (e.g., financial, social, cultural). Long-term costs and benefits were considered. They were estimated at the time of the new construction or retrofit. While results were aggregated across buildings at the national level, they were estimated for changes to the building stock in year 1 only. Hence,

the issue that is addressed here, that of discounting to a common year for building changes that extend into the future, was not addressed in the *Natural Hazard Mitigation Saves* study.

The example applies the study's assessment of the net benefits of seismic retrofits of soft-story wood-frame multifamily dwellings (Multi-Hazard Mitigation Council, 2019; Table 5-33). For three different discount rates, a cost-of-borrowing discount rate of 2.2 %, and the OMB values of 3 % and 7 %, the study provided the associated benefits and costs.

Importantly, the number of housing units with cost-effective retrofit (i.e., positive net benefit) is dependent on the discount rate. The study had reported that, nationally, at the discount rates of 2.2 %, 3 % , and 7 %, the number of housing units in dwellings that were cost-effective to renovate were 1.4, 0.9, and 0.7 million, respectively. In the example here, the number of housing units in dwellings assumed cost beneficial to retrofit at 2.2 % are 1,000 of the 10,000 housing units. The number at 3 % and 7 % are assumed in the same proportion as the study had reported, and therefore 640 housing units at 3 %, and 500 at 7%.

The net benefits in the example assume the average soft-story net benefit reported in the study at the three rates. The net benefit per housing unit is inflated from the study's 2018 USD to 2024 USD using the approach taken by the study (World Bank GDP per capita, PPP, for the United States). Per housing unit, this results in \$164K, \$203K, and \$119K, at 2.2 %, 3 %, and 7 %, respectively.

The discount rate, age of the building at the code effective date, and Weibull distribution parameters were used to compute the CBDF, which was then applied to the traditional benefit assessment to arrive at the community net benefit. The same two sets of Weibull parameter values as considered earlier, for which the PDF, survival, and hazard functions were shown in Figure 1, and with the same mean lifetime of 60 years, are applied here: $\mathcal{W}(1, 60.0)$ and $\mathcal{W}(2, 67.7)$. A construction date of 1/1/1975 was assumed for the 1970's era multifamily soft-story multifamily dwelling and effective date of the code, 1/1/2028. Applying Equations 12 and 13, using the discount rates 2.20 %, 3 %, and 7 %, respectively, the CBDFs for $\mathcal{W}(1, 60.0)$ are computed as 0.43, 0.36, and 0.19, and for $\mathcal{W}(2, 67.7)$ 0.58, 0.50, and 0.28. Finally, the CBDFs were applied to the traditional assessment to yield the results shown in Table 2.

Assuming immediate code compliance, as it appears the study did, leads to net benefits of 60 M\$ to 164 M\$ for the community, with the greatest benefits at the lowest discount rate as future benefits are least heavily discounted and as the number of dwellings for which retrofit is cost-effective is greatest. Factoring in the time for the current existing building locations to come into compliance with the 2015 I-Code requirements, the community benefit assessment, instead is from 11 M\$ to 95 M\$.

Table 2. An example application of the Community Benefit Discount Factor (CDBF) to a traditional net benefit evaluation. The example considers the enforcement of code requiring cost-effective soft-story wood-frame multifamily dwelling seismic retrofits that exceed 2015 I-Code requirements. The net benefits are shown on a per housing unit basis for an average multifamily dwelling constructed in the 1970s. Dollars are denominated in 2024 USD.

			Discount rate		
			2.20%	**3%**	**7%**
Number of housing units in dwellings that are cost-beneficial to retrofit			1,000	640	500
Net benefit (million$)	**Assuming immediate code compliance**		164	130	60
	Community (uncertain time of compliance; discounted to code effective date)	$\mathcal{W}(1, 60.0)$	70	46	11
		$\mathcal{W}(2, 67.7)$	95	65	17

Discussion

There are several limitations to the CDBF formulas. One, after the code effective date the approach assumes a single code compliance triggering event or that the additional costs and benefits of subsequent triggering events, when discounted, would be negligible. An additional limitation is that the need to rebuild after a hazard event (not to be confused with the hazard probability density function for code-triggering events) may itself result in new code compliance. Of the entire building stock this is a very small fraction, but in some locations, such as hurricane-prone or repeat flooding areas, this may be a significant path to code compliance. Finally, the probability of a triggering event requiring code compliance may not be independent of the costs of construction. Owners will be less likely to take up building improvements or replacement if they are more costly. This impact, however, may be small as it has been estimated that the construction costs of hazard-resistant provisions are small. Applying 2018 I-Codes, for example, was estimated to result in an additional 0.7 % in cost over 1988 seismic requirements, 1.7 % for adding 1 foot of freeboard for flooding, and 1% compared to 1990 requirements for hurricane wind (Federal Emergency Management Agency, 2020).

Applying the basic approach identified here, i.e., developing the CBDF to apply to the traditional assessments, to the full building stock imposes formidable data challenges. It is widely acknowledged that building stock dynamics are poorly understood (Bradley & Kohler, 2007; Kohler & Yang, 2007; Kurvinen et al., 2021). Weibull (or other) survival function parameter values would need to be developed for buildings grouped by, for example, archetype, construction date, the timing of their last code compliance triggering event, and could depend on the kind of prior triggering event, that is, the time to the next

triggering event may be dependent on whether the last trigger was rebuild or substantial improvement.

While close-formed solutions were developed here for two Weibull survival functions to explore the importance of the CBDF and for its analytical convenience, solutions for any other Weibull parameter set or hazard function could be found with numerical integration. Given the number and complexity of factors impacting the triggering, including building age, the type of structure, its location, type of use (e.g., residential or commercial), and a range of other technological, economic and social factors (Bradley & Kohler, 2007; Zhou et al., 2020), other methods may find application. This may include machine learning and other AI in addition to other statistical approaches to augment or replace the survival function approach. Also, the CBDF approach could be applied to new construction given a model for predicting new construction patterns and amounts. The hope is to develop community-scale benefits of building code adoption for communication to the public and for decision-makers to weigh against other public investments.

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Appendix A

For the case $\gamma = 1$:

$$\mathcal{B}_{\gamma=1}^{CMTY} = \int_{t=\grave{t}}^{t=\infty} \left[\frac{e^{-\left(\frac{t}{\alpha}\right)} \frac{1}{\alpha}}{e^{-\left(\frac{\grave{t}}{\alpha}\right)}} \right] \left[\widehat{\mathrm{B}}(r)\, e^{-r(t-\grave{t})} \right] dt$$

$$\mathcal{B}_{\gamma=1}^{CMTY} = \frac{\widehat{\mathrm{B}}(r)}{\alpha e^{-\left(\frac{\grave{t}}{\alpha}\right)}} e^{-r\grave{t}} \int_{t=\grave{t}}^{t=\infty} e^{-\left(\frac{1}{\alpha}+r\right)t} dt$$

$$\mathcal{B}_{\gamma=1}^{CMTY} = \frac{\widehat{\mathrm{B}}(r)}{\alpha e^{-\left(\frac{\grave{t}}{\alpha}\right)}} e^{-r\grave{t}} \left[\frac{e^{-\left(\frac{1}{\alpha}+r\right)t}}{-\left(\frac{1}{\alpha}+r\right)} \right]_{t=\grave{t}}^{t=\infty}$$

$$\mathcal{B}_{\gamma=1}^{CMTY} = \frac{\widehat{\mathrm{B}}(r)}{\alpha \left(\frac{1}{\alpha}+r\right) e^{-\left(\frac{\grave{t}}{\alpha}\right)}} e^{-r\grave{t}} e^{-\left(\frac{1}{\alpha}+r\right)\grave{t}}$$

$$\mathcal{B}_{\gamma=1}^{CMTY} = \frac{\widehat{\mathrm{B}}(r)}{(1+r\alpha) e^{-\left(\frac{\grave{t}}{\alpha}\right)}} e^{-\frac{\grave{t}}{\alpha}}$$

$$\mathcal{B}_{\gamma=1}^{CMTY} = \frac{\widehat{\mathrm{B}}(r)}{(1+r\alpha)}$$

For the case $\gamma = 2$:

$$\mathcal{B}_{\gamma=2}^{CMTY} = \int_{t=\grave{t}}^{t=\infty} \left[\frac{e^{-\left(\frac{t}{\alpha}\right)^2} \frac{2}{\alpha^2} t}{e^{-\left(\frac{\grave{t}}{\alpha}\right)^2}} \right] \left[\widehat{\mathrm{B}}(r)\, e^{-r(t-\grave{t})} \right] dt$$

$$\mathcal{B}_{\gamma=2}^{CMTY} = \frac{1}{e^{-\left(\frac{\grave{t}}{\alpha}\right)^2}} \int_{t=\grave{t}}^{t=\infty} \left[e^{-\left(\frac{t}{\alpha}\right)^2} \frac{2}{\alpha^2} t \right] \left[\widehat{\mathrm{B}}(r)\, e^{-r(t-\grave{t})} \right] dt$$

$$\mathcal{B}_{\gamma=2}^{CMTY} = \frac{\widehat{\mathrm{B}}(r)}{e^{-\left(\frac{\grave{t}}{\alpha}\right)^2}} \int_{t=\grave{t}}^{t=\infty} \left[e^{-\left(\frac{t}{\alpha}\right)^2} \frac{2}{\alpha^2} t \right] \left[e^{-r(t-\grave{t})} \right] dt$$

The integration by parts formula, i.e., $\int u\, dv = u\, v - \int v\, du$ is applied. As the above is a definite integral, $\int_a^b u\, dv = [u\, v]_a^b - \int_a^b v\, du$.

Let $u = e^{-r(t-\grave{t})}$, so $du = -re^{-r(t-\grave{t})} dt$

And $dv = e^{-\left(\frac{t}{\alpha}\right)^2} \frac{2}{\alpha^2} t\, dt$, so $v = e^{-\left(\frac{t}{\alpha}\right)^2}$

Then:

$$\mathcal{B}_{\gamma=2}^{CMTY} = \frac{\widehat{\mathrm{B}}(r)}{e^{-\left(\frac{\grave{t}}{\alpha}\right)^2}} \left(\left[e^{-r(t-\grave{t})} e^{-\left(\frac{t}{\alpha}\right)^2} \right]_{t=\grave{t}}^{t=\infty} - \int_{t=\grave{t}}^{t=\infty} \left[e^{-\left(\frac{t}{\alpha}\right)^2} \right] \left[re^{-r(t-\grave{t})} \right] dt \right)$$

$$\mathcal{B}_{\gamma=2}^{CMTY} = \frac{\widehat{\mathrm{B}}(r)}{e^{-\left(\frac{\grave{t}}{\alpha}\right)^2}} \left(\left[e^{-r(t-\grave{t})-\left(\frac{t}{\alpha}\right)^2} \right]_{t=\grave{t}}^{t=\infty} - r \int_{t=\grave{t}}^{t=\infty} e^{-r(t-\grave{t})-\left(\frac{t}{\alpha}\right)^2} dt \right)$$

$$\mathcal{B}_{\gamma=2}^{CMTY} = \frac{\widehat{\mathrm{B}}(r)}{e^{-\left(\frac{\grave{t}}{\alpha}\right)^2}} \left(e^{-\left(\frac{\grave{t}}{\alpha}\right)^2} - re^{r\grave{t}} \int_{t=\grave{t}}^{t=\infty} e^{-\left(\frac{t}{\alpha}\right)^2 - rt} dt \right)$$

Now, substituting $-\left(\frac{t}{\alpha}\right)^2 - rt = -\left(\frac{t}{\alpha} + \frac{r\alpha}{2}\right)^2 + \left(\frac{r\alpha}{2}\right)^2$

$$\mathcal{B}_{\gamma=2}^{CMTY} = \frac{\widehat{\mathrm{B}}(r)}{e^{-\left(\frac{\grave{t}}{\alpha}\right)^2}} \left(e^{-\left(\frac{\grave{t}}{\alpha}\right)^2} - re^{r\grave{t}} \int_{t=\grave{t}}^{t=\infty} e^{-\left(\frac{t}{\alpha}+\frac{r\alpha}{2}\right)^2 + \left(\frac{r\alpha}{2}\right)^2} dt \right)$$

$$\mathcal{B}_{\gamma=2}^{CMTY} = \frac{\widehat{\mathrm{B}}(r)}{e^{-\left(\frac{\grave{t}}{\alpha}\right)^2}} \left(e^{-\left(\frac{\grave{t}}{\alpha}\right)^2} - re^{r\grave{t}} e^{\left(\frac{r\alpha}{2}\right)^2} \int_{t=\grave{t}}^{t=\infty} e^{-\left(\frac{t}{\alpha}+\frac{r\alpha}{2}\right)^2} dt \right)$$

Let $z = \left(\frac{t}{\alpha} + \frac{r\alpha}{2}\right)$, so $dt = \alpha dz$. Now, the limits of the integral change from $[\grave{t}, \infty)$ to $\left[\frac{t}{\alpha} + \frac{r\alpha}{2}, \infty\right)$.

$$\mathcal{B}_{\gamma=2}^{CMTY} = \frac{\widehat{\mathrm{B}}(r)}{e^{-\left(\frac{\grave{t}}{\alpha}\right)^2}}\left(e^{-\left(\frac{\grave{t}}{\alpha}\right)^2} - r\alpha e^{r\grave{t}+\left(\frac{r\alpha}{2}\right)^2}\int_{z=\frac{t}{\alpha}+\frac{r\alpha}{2}}^{z=\infty} e^{-z^2}dz\right)$$

Using the definition of the complementary error function, i.e., $\mathrm{erfc}(x) = \int_x^\infty e^{-z^2}dz$

And following $r\grave{t} + \left(\frac{r\alpha}{2}\right)^2 = \left(\frac{\grave{t}}{\alpha} + \frac{r\alpha}{2}\right)^2 - \left(\frac{\grave{t}}{\alpha}\right)^2$

$$\mathcal{B}_{\gamma=2}^{CMTY} = \frac{\widehat{\mathrm{B}}(r)\, e^{-\left(\frac{\grave{t}}{\alpha}\right)^2}}{e^{-\left(\frac{\grave{t}}{\alpha}\right)^2}}\left(1 - r\alpha e^{\left(\frac{\grave{t}}{\alpha}+\frac{r\alpha}{2}\right)^2-\left(\frac{\grave{t}}{\alpha}\right)^2}\left[\frac{\sqrt{\pi}}{2}\mathrm{erfc}\left(\frac{\grave{t}}{\alpha} + \frac{r\alpha}{2}\right)\right]\right)$$

$$\mathcal{B}_{\gamma=2}^{CMTY} = \widehat{\mathrm{B}}(r)\left(1 - \frac{1}{2}\sqrt{\pi}r\alpha e^{\left(\frac{\grave{t}}{\alpha}+\frac{r\alpha}{2}\right)^2}\mathrm{erfc}\left(\frac{\grave{t}}{\alpha} + \frac{r\alpha}{2}\right)\right)$$