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Ethical Discounting for Intergenerational Life-cycle Risk Assessment

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ABSTRACT: In risk-informed decisions involving civil infrastructure facilities, the decision-maker often compares the immediate investments in design with the costs of maintenance or replacement of civil facilities during the facility service period. Certain civil infrastructure projects have substantially longer service periods than typical buildings and bridges. Conventional discounting methods for projects with service periods extending to a century or more raise ethical issues in terms of project risk shared between the current and future generations. To address these issues, several approaches to discounting have been suggested recently that aimed at sharing risk equitably between generations and at achieving long-term sustainable solutions for civil infrastructure projects. This paper explores recent developments in intergenerational discounting practices and examines how those methods might affect the optimal design solutions and long-term decision-making.

1. INTRODUCTION

Decisions for many civil infrastructure projects have consequences that may extend well beyond the traditional service lives of 50 to 75 years for buildings and bridges and may impact future generations. One extreme example of such a decision involves the disposal of nuclear waste; dams and flood control facilities, nuclear power plants and other critical facilities also may have design lives that span multiple generations. Customary risk-informed decision frameworks may not be applicable to such long-term event horizons. If expected cost (or expected utility) is used as the basis for intergenerational decision and future losses are discounted to present worth, severe events in the far-distant future may be found to have little impact on present value, leading to the conclusion that such events are unimportant in present decision–making. The ethics underlying current decision-making suggests that a decision-maker should maximize a weighted sum of his/her utility (or monetary value) and the utilities of future generations. However, when a constant discount rate tied to market interest rates (about 3% per year or higher) is used for this purpose, which is customary, the risk to life and property in the future is severely trivialized with respect to present value. To achieve intergenerational equity and sustainable decisions based on an equitable weighting of the preferences of present and future generations, improved intergenerational discounting methods are required. Indeed, the choice of the discounting method can significantly influence the optimal design and risk-informed decision. When the period of interest is a century or more, even slight differences in discounting can lead to vastly different decisions. The need for an appropriate discounting method derived from a fundamental ethical standard is required for inter-temporal efficiency and intergenerational equity.

Some approaches to address the dilemma of equitable sharing of risk have recently emerged. This paper explores some of these recent developments in intergenerational discounting used in risk-informed decisions for civil infrastructure involving time horizons extending to multiple generations. We begin with a brief review and appraisal of several approaches to discounting derived from inherently ethical considerations. We next propose a new way of incorporating sustainability mandates into discounting in the context of civil infrastructure. Finally, intergenerational discounting practices will be illustrated with a levee situated in a flood-prone zone, which has also been presented in Lind et al. (2009). We examine how different discounting methods might affect the optimal decision and show how a new approach can lead to sustainable decision-making by distributing the burden of the costs fairly between generations.

2. REVIEW OF LONG-TERM DISCOUNTING METHODS

Allocation of financial resources is essential for decision-making when demands on and response of a civil infrastructure facility are random, the effects of policies are expected to stretch out over a long period of time and costs and benefits accrue at random or non-uniform points in time. Expected costs generally are estimated using a discounting technique, which describes the value in present terms of future outcomes (measured in terms of damages, costs, benefits, or utility values). The discount factor, D(t), gives the value of one unit in the future in terms of its present value, and is used to convert future costs and benefits into their present equivalents. The discount rate, r(t), is the annual rate of decline of the discount factor, and gives the rate at which future value is discounted. In discrete and continuous time domains, the discount factor can be related to the discount rate shown in Eqs. (1a) and (1b), respectively (Hepburn 2007):

$$D(t)=\frac{1}{(1+r(t))^{t}} \tag{1a}$$

$$D(t)=\exp\left(-\int_{0}^{t}r(\tau)\,d\tau\right) \tag{1b}$$

While no consensus exists on the appropriate rate for discounting, cost-benefit analysis customarily uses one rate and holds it constant over the time horizon involved in the decision. A constant positive discount rate implies that the discount factor declines exponentially, D(t) = exp(-rt), valuing an increment in future consumption less than an increment in present consumption. The relative value of future events is extremely sensitive to the discount rate, as shown in Figure 1 which illustrates discount factors corresponding to several annual constant discount rates. A higher discount rate implies that we place a lower value on future gain or loss than on the same gain or loss occurring now. To illustrate, the value of a dollar 100 years in the future would be valued at 0.37 dollar today if the discount rate were 1%, while it would have negligible value (present value of 0.00007 dollar) if the discount rate were 10%. Exponential discounting with a constant discount rate (often corresponding to a market interest rate or the rate on long-term US government bonds) may be sensible over the short to medium term. For longer time frames however, it appears to be inconsistent with intergenerational equity and sustainable development (Weitzman 1998; Gollier 2002), diminishing the importance of consequences of present decision-making to future generations.

On the surface, the simplest approach to value future generations might be to use very low discount rates. For instance, the Stern review on the Economics of Climate Change (Stern 2006), which is one of the most comprehensive surveys of the economics of climate change, employs a relatively low discount rate of 1.4%, suggesting more rapid reduction in greenhouse gas emissions than had been suggested in previous UK reports. But this suggestion solves one problem by creating another: with a discount rate this low, the current generation may sacrifice too much to reduce risks faced by future (and presumably wealthier) generations. Conventional discounting practices for projects spanning multiple generations conflicts with our moral intuitions; the intergenerational approach to discounting should explicitly incorporate the perspectives of both the current and future generations.

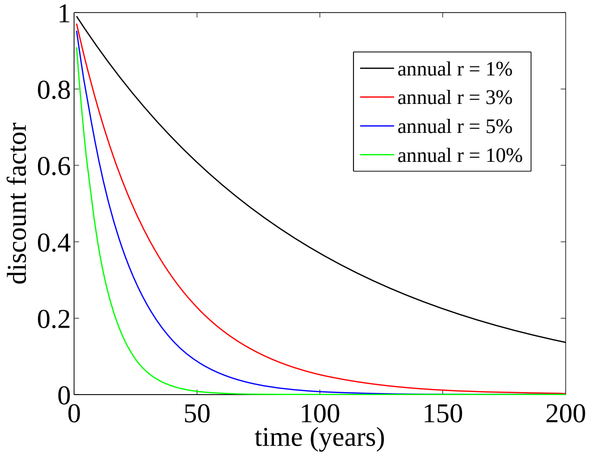

Figure 1: Discount factors corresponding to different annual discount rates.

For discounting over a century or more, a number of economists have suggested that the discount rate should decrease over time. For example, Weitzman (1998, 2001) shows that certainty-equivalent discount rates, which are obtained from an averaging procedure over uncertain states of future return to capital, decline over time and, as time goes to infinity, converge to some minimum discount rate associated with the economic scenario considered. Such declining discount rates have been officially accepted in some countries to achieve a fair weighting of the preferences of present and future generations; the rate used to discount events in the near future (at higher/ observable market rates) is substantially higher than for events in the far-distant future. Figure 2 shows the schedules of such rates used in France and the United Kingdom. France has recommended a time-declining discount rate that starts at 4% for below 30 years and decreases to 2% for longer horizons. It corresponds with discount factors of $(1.04)^{-t}$ for time horizons less than 30 years and $(1.04)^{-30}(1.02)^{-(t-30)}$ for horizons longer than 30 years. The government of the UK uses a stepwise declining discount rate: 3.5% for 1-30 years, 3% for 31-75 years, 2.5% for 76-125 years, 2% for 126-200 years, 1.5% for 201-300 years, and 1% for longer periods. The constant discount rate used in both approaches for periods less than 30 years is consistent with current practices in financial markets, in which the time horizon seldom exceeds that value.

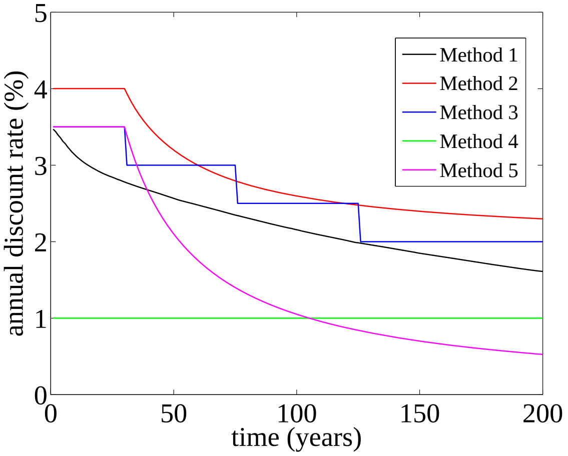

Figure 2: Different types of discount rates (each method corresponds to Table 1).

Lind (2007) suggested a different approach to support sustainable decision-making, using the notion of a *financing horizon*. The financing horizon is the duration for which the project is to be financed. It is project-specific: the financing horizon for some civil facilities may equal the design life, while for others, including bridges, tunnels, toll highways, etc., it may correspond to the amortization period of the initial investment. Lind (2007) postulated that the financing horizon for public infrastructure projects should equal the remaining mean life expectancy of the current population in order to avoid imposing risk on future generations. Once a specific discount rate is selected for a project, it is applied only during the financing horizon. No further discounting subsequent to the end of the financing horizon implies that risk incurred beyond the financing horizon should be valued as if it occurred at the end of the financing horizon. This principle yields an effective discount rate, which is constant over the financing horizon and decreases hyperbolically with time after the financing horizon (Lind 2007). Figure 3 illustrates the effective discount rates when different lengths of financing horizons are assumed. Shorter financing horizons induce more dramatic decrease in discount rates, and at the end of a 200-year service period, lead to much lower discount rates.

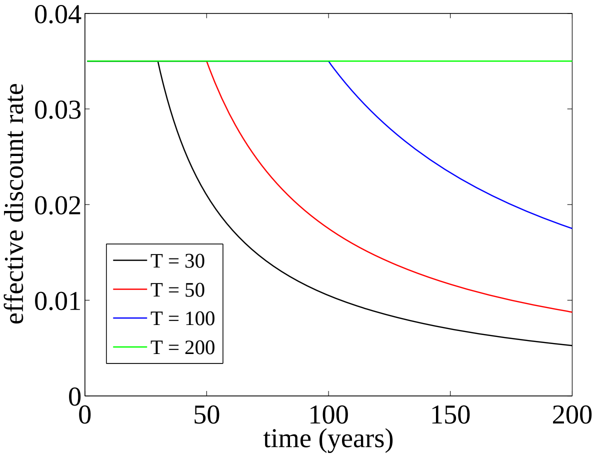

Figure 3: Sensitivity analysis of effective discount rate to financing horizon.

3. DEVELOPMENT OF IMPROVED INTERGENERATIONAL DISCOUNTING METHOD

As indicated in Section 2, a declining discount rate has been widely accepted as a method to support sustainable and intergenerational decision-making. The theoretical rationale for such decreases with time should include uncertainty about the future. Substantial uncertainties and lack of confidence in economic and non-economic forecasts (such as the rate of economic growth, the amount of capital that will be accumulated, the level and pace of technological progress, the state of the environment, political events, etc.) in the distant future require that such uncertainties be reflected in the discount rate. The scenarios associated with future discount rates and probabilities assigned to them play an important role in determining the particular shape of their decline with time. Two different sources of uncertainty – embedded in discount rate itself and in the future growth of the economy - have been considered over the last decade. The former approach forecasts future discount rates based on past market interest rates. Unfortunately, few markets exist for assets with maturities exceeding 30 years, making the interest rate beyond that horizon even more uncertain. To develop a new method of intergenerational discounting for civil infrastructure, therefore, we will focus more on the underlying uncertainty inherent in economic growth rates and will examine the implication of this uncertainty on discounting practices (Lee and Ellingwood, 2015).

The starting point of this approach can be derived from the classical Ramsey formula for the social discount rate (Ramsey, 1928):

$$r_t = \rho+\eta g_t \tag{2}$$

where ρ is the utility discount rate (or the rate of pure time preference) explaining impatience, η is the elasticity of marginal utility of consumption describing by how many percent marginal utility changes if consumption increases by one percent, and g_t is the rate of growth of consumption per capita describing how fast consumption increases. Under the assumption that the utility function has a constant relative risk aversion (CRRA) factor, the discount rate is a function of consumption growth rate, g_t; increasing (or decreasing) future consumption growth rate implies a higher (or lower) discount rate. Considering the uncertainty embedded in the rate of growth in consumption causes the classical Ramsey formula to be modified (Gollier, 2008):

$$r_t = \rho + \eta \frac{E(G_t)}{t} - 0.5\eta^2 \frac{Var(G_t)}{t} \tag{3}$$

in which G(t) = ln(c_t) - ln(c_0), the natural log consumption growth between date 0 and date t; c_t = consumption at date t; and c_0 = consumption at date 0. The last term in Equation (3) is termed the *precautionary effect*. This term contains the notion of prudence; a prudent decision-maker is willing to save more in the present by lowering the discount rate. If growth is subject to random shocks that are identically distributed and statistically independent, discount rate is independent of the time horizon. Gollier (2008) proves that positively correlated shocks to the growth rate of the economy can justify using a decreasing term structure of discount rate. To illustrate the effect of correlated shocks on aggregate consumption, the change in log consumption is assumed to follow an autoregressive process (Gollier 2012; Bansal & Yaron 2004):

$$\begin{aligned} &\ln(c_{t+1}/c_t) = x_t \\ &x_t = \mu + y_t + \sigma_t \eta_t \\ &y_t = \phi y_{t-1} + \rho_e \sigma_t e_t \end{aligned} \tag{4}$$

where μ = the trend of growth; σ_t = time-varying volatility; ϕ = the degree of persistence in the expected growth rate process; ρ_e = the ratio of time-varying volatility in y_t to the one in x_t; and η_t and e_t = identically distributed and statistically independent normal random variables with mean of zero and variance of unity. When $0 < \phi < 1$, $Var(G_t)/t$ increases over time and converges to $\rho_e^2\sigma^2/(1-\phi)^2+\sigma^2$ as t goes to infinity. The precautionary term becomes sizeable for long horizons, leading to declining discount rates. For the growth of consumption that is positively correlated, risk and uncertainty accumulate over time, causing smaller discount rates for longer horizons.

The intergenerational discount rate adopted in this paper is based on the extended Ramsey formula, with positively correlated shocks to the growth rate of the economy shown in Equation (4). The parameters of this highly uncertain process have been obtained by Bansal and Yaron (2004) based on the annual observations of the United States from 1929 to 1998. In addition to the accumulated uncertainties over time, the additional increase in uncertainty with time should be incorporated in the consumption growth rate in order to ensure intergenerational equity in engineering decisions (Lee & Ellingwood, 2015). The model of time-varying volatility, defined by the term σ_t in Equation (4), determines the shape and extent of decline in discount rates over time. An exponentially increasing volatility in the change in log consumption growth shown in Equation (5) is considered in this study (Lee & Ellingwood, 2015).

$$\sigma_t = \sigma(2 - \exp(-\alpha t)) \tag{5}$$

where σ is the initial volatility and α is the annual rate of increment in volatility. For the purpose of achieving an inter-generationally acceptable discounting method, we use 2 as the elasticity of marginal utility of consumption, which is close to the mean value when considering a reasonable range is from 0.5 to 4, and a low rate of pure time preference close to zero, 0.1 percent per annum (corresponding to the Stern's value). The newly developed intergenerational discount rate with additional uncertainty is shown in Figure 2, for comparison with others discussed previously.

4. BENCHMARK PROBLEM: FLOOD CONTROL FACILITY

Flooding is among the most devastating and costly natural disasters impacting civil infrastructure and affecting the economic, social and political well-being of modern society. It accounts for the majority of natural catastrophic losses in the developed world and is the leading cause of death and injury among natural disasters (Swiss Re, 2010). Moreover, flood control facilities have service periods of 100 years or more, which are substantially longer than those typically considered in life-cycle engineering of buildings or bridges and may extend across many generations. Intergenerational risk sharing in risk-informed decision-making for flood control facilities thus is an important and timely research challenge.

To compare different intergenerational discounting methods in the context of equitable transfer of risk across multiple generations, we examine a newly constructed levee situated in a flood-prone city, which has 100,000 inhabitants and has been severely damaged by flooding at least twice since 1900. A similar structure has been considered previously for the purpose of studying the societal capacity to commit resources to sustainable risk reduction (Lind et al. 2009). Five alternative discounting methods considered in the present study are summarized in Table 1 and are illustrated in Figure 2.

Table 1: Five methods of discounting.

	Type
Method 1	Discount rate with additional uncertainty (Eqs. (2) – (5))
Method 2	Discount rate used in France
Method 3	Discount rate used in UK
Method 4	Low constant discount rate of 0.01
Method 5	Effective discount rate with a financing horizon = 30 years (Lind, 2007)

The service period of the levee is 200 years and the alternatives are determined by the crest elevation H (m) of the levee. The demand on the levee structure is based on 98 years of flood data; it was found that the Gumbel distribution provided the best fit to these data, with parameters $\alpha = 0.549\ m^{-1}$ and $u = 5.939m$ estimated using the method of moments (Lind et al. 2009). However, this fitted distribution is overly influenced by low and central values of data. In order to refine the upper tail of the distribution, which governs the failure probability of the levee, the cross-entropy method was used to estimate the upper tail of the cumulative distribution function describing flood elevation (see Lind et al. 1989):

$$G(x) = 1-c[1-F(x)] = 1-c(1-\exp\{-\exp[-\alpha(x-u)]\}),\quad x>x_n \qquad (5)$$

For each structure with crest elevation H, the conditional annual probability that the flood exceeds level H is $p = 1 - G(H)$. The initial cost for each alternative is also approximated as a function of H. The construction cost is estimated as $C = C(H) = a(H^3-b^3)$, where $a = \$100{,}000/m^3$ and $b = 13m$ are constants. Economic losses upon failure (including reconstruction cost) are assumed to be \$400M + C. For simplicity, levee failure is assumed to occur only once during the design life (with the failure event uniformly distributed over 200 years) and to cause a loss of 300 lives. The estimates of risk trade-offs that people make with regard to life safety in the US are in the range of \$4M to \$9M (Viscusi & Aldy, 2003), and in this problem, \$4M is allocated to the value of one human life.

The calculated values of total expected life-cycle cost for the five discounting methods in Table 1 are illustrated in Figure 4. For the purpose of comparison, total expected life-cycle costs with a single discount rate of 0.035 are also shown in Figure 4. This value of 0.035 corresponds to the average market interest rate and is commonly used in cost-benefit analyses involving time horizons of less than 50 years. Even though discount rates used in France give slightly higher costs than the constant discount rate of 0.035, their optimal design heights are almost the same; this result implies that discount rates used in France do not address future generations very well, at least in this example. On the other hand, a very low discount rate of 0.01 and effective discount rates with a financing horizon of 30 years yield much higher optimal crest elevations compared to the elevation obtained using the constant 3.5% annual discount rate. It should be noted that a high value of optimal design does not always guarantee equitable risk-sharing over generations. Rather, it could impose an excessive burden and sacrifice on the current generation, which is more apparent in Figure 5. Figure 5 illustrates the optimal crest elevations as a function of design life obtained from five discounting methods. All forms of discount rate indicate an increase in optimal design with service life, which means that all methods (except that used in France) consider, in some way, future generations in decision-making. Little difference in optimal levels exists for service lives less than 100 years, except when the discount rate is very low. Beyond 100 years, however, the optimal design levels do not approach an asymptotic value, but increase dramatically when employing effective discount rates with a 30-year financing horizon. This implies that the current generation places too much value on the preferences of future generations; a financing horizon of 30 years cannot support an equitable distribution of resources between generations. The use of the intergenerational discount rates accounting for additional uncertainty developed in Section 3 lead to optimal crest elevations that increase modestly and asymptotically after 100 years, and appear to allocate costs and benefits between the current and future generations in more equitable fashion.

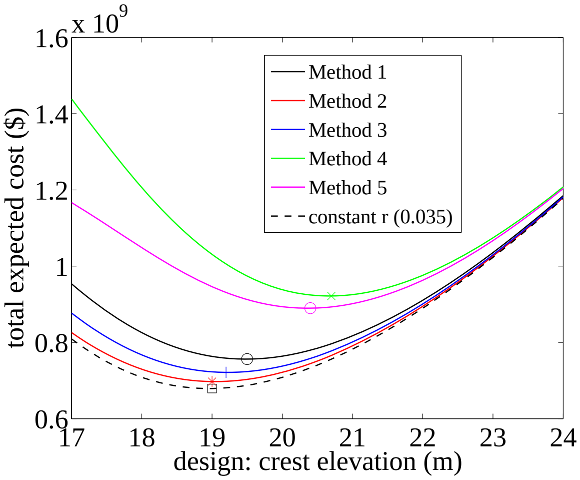

Figure 4: Sensitivity of total expected LCC and the optimal design level to different discounting methods.

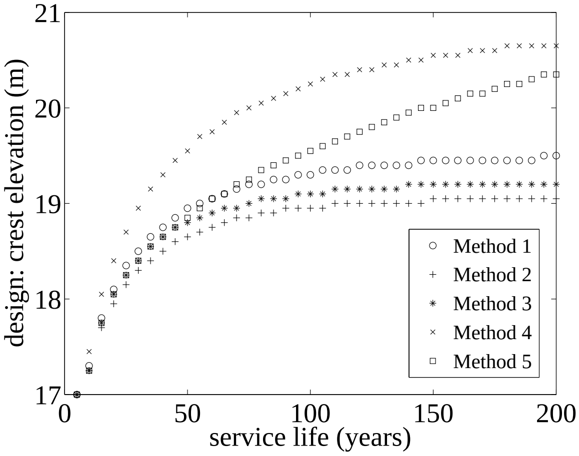

Figure 5: Comparison of optimal crest elevations as a function of design life obtained from five discounting methods.

5. SUMMARY AND CONCLUSIONS

The Brundtland Report, also known as "Our Common Future", asserts that "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs." Decision support frameworks for socio-economic sustainable civil infrastructure are urgently needed. This paper has explored several discounting methods that promote such intergenerational equity in risk-informed decisions, and has illustrated those methods in evaluating a new levee by minimum life-cycle cost analysis. While all discounting practices take into account future generations in decision-making in some fashion, some practices tend to impose too much responsibility on current generations. The newly suggested discount rate in previous research (Lee & Ellingwood 2015), where uncertainty about future economic growth is incorporated, overcomes the ethical issues of conventional discounting methods and achieves a goal of socio-economically sustainable solutions.

The approach in the present study to reflect intergenerational transfers of risk in decision frameworks has focused on discounting practices used in life-cycle cost analysis. Aversion to intergenerational inequality can be reflected in the utility or value functions, by presenting a decision-maker with a range of different functions, or by adjusting the weights placed on consumption flows at each point in time. The Life Quality Index (LQI) incorporates preference-related parameters in risk-informed decision frameworks and can be an alternative to reflect risk aversion to loss of life or personal injury of future generations (Nathwani et al. 1997). However, additional research is necessary to incorporating time-dependent factors and intergenerational equity into the LQI. The intergenerational discount rates presented herein have been designed for risk sharing over several generations. While discounting methods may be adapted to reflect risk aversion to low-probability high-consequence events or aversion to spatial inequality in different contexts, methods to do so require further research. Discounting alternatives should be investigated to establish a more comprehensive framework for incorporating various kinds of decision-makers' preferences in engineering decisions.

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