1st Place Award Winner

# Applying Real Option Theory to the Evaluation of Climate Adaptation Investments

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## INTRODUCTION

Climate change has introduced unprecedented levels of uncertainty into the frequency, severity, and geographic distribution of extreme weather events (IPCC, 2021). Hurricanes, floods, heatwaves, droughts, and wildfires increasingly impose large and volatile costs on insurers, governments, and communities (Swiss Re Institute, 2025). In response, climate adaptation investments (also known as actions designed to reduce vulnerability and enhance resilience) have become a critical component of climate risk management. These investments include infrastructure upgrades, strengthened building codes, early warning systems, and community-based resilience programs.

Evaluating climate adaptation investments poses significant challenges. Traditional cost-benefit analysis (CBA), often based on discounted cash flow (DCF) methods, struggles to accommodate deep uncertainty, non-linear risk escalation, and managerial flexibility. Decisions are typically treated as irreversible, even though adaptation strategies can often be staged, expanded, delayed, or abandoned as conditions evolve.

Real option theory offers a powerful enhancement to conventional evaluation methods by explicitly valuing flexibility under uncertainty (Hayes, 2025). Actuaries, with their expertise in probabilistic modeling, long-term valuation, and risk management, are well positioned to apply real option techniques to climate adaptation decisions. This essay explores how real option theory can improve the evaluation of climate adaptation investments in an actuarial context, discusses practical modeling approaches, and highlights implications for actuarial practice.

## LIMITATIONS OF TRADITIONAL DISCOUNTED CASH FLOW ANALYSIS

Discounted cash flow analysis is a widely used tool for evaluating long-term investments. Under a DCF framework, expected future costs and benefits are projected and discounted to present value using a specified discount rate (Fernando, 2025). While this approach provides a clear structure, it has notable limitations when applied to climate adaptation.

First, climate risks evolve dynamically and non-linearly. Hazard frequency and severity can increase progressively with warming, while crossing biophysical or adaptation limits may lead to rapidly escalating risks and impacts (IPCC, 2023). Deterministic projections used in standard DCF analysis may fail to capture these dynamics.

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Second, under a standard DCF framework, investment value is assessed using a single forecast of expected future cash flows and a fixed discount rate, which does not explicitly account for decision flexibility over time (Fernando, 2025). In reality, adaptation investments are often incremental. For example, flood defenses can be built in stages, and building standards can be progressively strengthened. Ignoring this flexibility may lead to suboptimal conclusions, such as either overinvesting too early or underinvesting in the face of future risk escalation.

Third, uncertainty is typically handled through sensitivity testing rather than explicitly modeled as stochastic. This approach underrepresents tail risk and provides limited insight into downside outcomes—an issue of particular concern for actuaries focused on solvency, capital adequacy, and extreme events (Townsend, 2022).

These limitations motivate the use of alternative frameworks capable of valuing uncertainty and flexibility more rigorously.

## OVERVIEW OF REAL OPTION THEORY

Real option theory extends financial option pricing concepts to real (non-financial) investments. A real option represents the right, but not the obligation, to take a particular action in the future, such as expanding, delaying, scaling back, or abandoning a project, in response to new information (Dixit & Pindyck, 1994).

Unlike financial options, real options are embedded in physical assets or policy decisions and are not traded in markets. Their value arises from managerial flexibility under uncertainty. Common types of real options include:

- Option to defer an investment until uncertainty is reduced
- Option to expand capacity if conditions worsen or demand increases
- Option to contract or abandon if outcomes are unfavorable
- Staged investment options, where decisions are made sequentially

Climate adaptation investments naturally lend themselves to real option analysis because climate uncertainty evolves over time and learning occurs as new data become available.

## THEORETICAL FRAMEWORK: REAL OPTIONS VS. DISCOUNTED CASH FLOW

### DISCOUNTED CASH FLOW AS A STATIC VALUATION FRAMEWORK

Discounted cash flow (DCF) analysis evaluates an investment by computing the expected present value of future net benefits. Formally, the net present value (NPV) of an adaptation investment is given by

$$NPV_0 = \mathbb{E}\left[\sum_{t=0}^{T} \frac{B_t - C_t}{(1+r)^t}\right],$$

Where $B_t$ and $C_t$ denote benefits and costs at time $t$, respectively, and $r$ is the discount rate. The standard DCF decision rule is to invest immediately if $NPV_0 > 0$.

This framework implicitly assumes that the investment decision is made once, at the outset, and that the investment is irreversible. Uncertainty enters only through expected values or deterministic sensitivity

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analysis applied to model inputs. As a result, DCF reduces the decision problem to a comparison of mean outcomes, abstracting from the timing of decisions, learning over time, and the distribution of outcomes.

These assumptions are particularly restrictive for climate adaptation investments, where uncertainty is persistent, information improves over time, and decisions can often be staged or adjusted as risks evolve.

## STOCHASTIC INVESTMENT UNDER UNCERTAINTY

Real option theory reframes investment as a dynamic decision made under uncertainty. Rather than assuming that benefits are known with certainty, the value of an adaptation investment, such as avoided climate damages, is modeled as a stochastic process. A common representation assumes that the underlying benefit process $V_t$ follows a geometric Brownian motion:

$$dV_t = \mu V_t dt + \sigma V_t dW_t,$$

where $\mu$ is the expected growth rate of benefits, $\sigma$ measures volatility, and $W_t$ is a standard Brownian motion. Volatility here reflects uncertainty in climate outcomes, including changes in hazard frequency, severity, and exposure.

Let $I$ denote the irreversible cost of undertaking the adaptation investment. The decision-maker holds an option to invest and chooses the optimal timing to exercise this option. Under real option theory, the value of the investment opportunity, denoted $F(V)$, satisfies the Bellman equation:

$$F(V) = \max\{V - I, \mathbb{E}[e^{-rdt} F(V_{t+dt} | V_t = V)]\}.$$

This expression captures the tradeoff between exercising the option immediately (and receiving net payoff $V - I$) and waiting for additional information. Solving this problem yields an optimal investment threshold $V^*$ such that investment occurs only when $V_t \geq V^*$, where

$$V^* = \frac{\beta}{\beta - 1} I, \quad \beta = \frac{1}{2} - \frac{\mu}{\sigma^2} + \sqrt{\left(\frac{\mu}{\sigma^2} - \frac{1}{2}\right)^2 + \frac{2r}{\sigma^2}}.$$

Because $\beta > 1$, it follows that $V^* > I$. This result has a critical implication: even when the expected net present value is positive, it may be optimal to delay investment. The gap $V^* - I$ represents the option value of waiting.

## INCREMENTAL ADAPTATION AS A COMPOUND OPTION

Many climate adaptation investments are not single, all-or-nothing decisions but rather sequences of incremental actions. Examples include staged flood defenses or progressively strengthened building codes. Real option theory models such strategies as compound options, where each stage creates the option, but not the obligation, to proceed to the next stage.

Let $F_t(V_t)$ denote the value of holding the option at stage $t$. Then

$$F_t(V_t) = e^{-r\Delta t} \mathbb{E}_{\mathrm{t}}[\max(0, F_{t+1}(V_{t+1}) - I_{t+1})]$$

With terminal condition:

$$F_T(V_T) = \max\,(V_T - I_T, 0)$$

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where $I_{t+1}$ is the cost of next-stage investment. This recursive structure explicitly captures learning and sequential decision-making. In contrast, DCF typically collapses staged investments into a single expected cash flow stream, thereby ignoring the informational and strategic value of staging.

### DISTRIBUTIONAL RISK AND TAIL OUTCOMES

Finally, DCF focuses on expected values, whereas real option analysis naturally accommodates distributional concerns. Climate-related losses are often heavy-tailed, and downside outcomes are particularly relevant for actuaries concerned with solvency and capital adequacy.

Within a real options framework, valuation can be extended to incorporate risk-sensitive criteria, such as tail risk measures:

$$Value = \mathbb{E}[X] - \lambda * TVaR_\alpha(L), L = -X$$

Where $X$ represents net outcomes and $TVaR_\alpha$ captures extreme losses beyond a specified confidence level. The ability to delay, scale, or abandon investments reduces exposure to extreme downside scenarios—an effect that DCF, which collapses outcomes to a single expected value, cannot represent.

### OPTION TO EXPAND UNDER ESCALATING CLIMATE RISK

When climate damages may escalate rapidly, the ability to expand protective measures represents a valuable real option. Let $V_t$ denote avoided damages from an expanded adaptation measure at time $t$, and suppose

$$\frac{dV_t}{V_t} = \mu\, dt + \sigma_t dW_t$$

where $\sigma_t$ captures uncertainty in future climate outcomes. Let $K$ denote the expansion cost. The payoff from expansion is

$$\max(V_t - K, 0)$$

so, the value of the option to expand is

$$\mathbb{E}[\max(V_t - K, 0)].$$

Under standard real option assumptions, option value is increasing in volatility:

$$\frac{\partial}{\partial \sigma_t} \mathbb{E}[\max(V_t - K, 0)] > 0.$$

This result reflects the asymmetric payoff structure of real options. Higher uncertainty increases the likelihood of high-damage realizations in which expansion yields substantial benefits, while unfavorable outcomes are bound by the decision not to exercise the option.

Climate change is expected to increase both the expected level of climate-related damages ($\mu$µ) and their volatility ($\sigma_t$). Consequently, the value of retaining expansion flexibility rises not only with higher expected damages, but also with greater uncertainty, which widens the distribution of possible outcomes. In this sense, adaptation investments embed an exposure to uncertainty analogous to positive volatility sensitivity in financial options: greater uncertainty enhances the value of waiting and responding conditional on realized outcomes.

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From an actuarial and risk-management perspective, this logic aligns with established practice. Instruments whose payoffs respond positively to tail risk are valued for their role in managing extreme losses, supporting capital adequacy, and preserving solvency. Real option analysis thus provides a rigorous framework for valuing flexibility in climate adaptation decisions under increasing uncertainty.

## INTUITIVE EXAMPLES: WHY FLEXIBILITY HAS VALUE

Climate adaptation decisions are rarely one-time, irreversible commitments. Instead, they often involve adaptive pathways. For example, a coastal municipality may initially construct moderate flood defenses while retaining the option to heighten them if sea-level rise accelerates. Similarly, insurers may invest in improved risk modeling or loss mitigation incentives, with the option to expand programs as climate risks become clearer.

### EXAMPLE 1: THE VALUE OF WAITING

Real option theory captures the value of waiting and learning. Under high uncertainty, delaying irreversible investments can be optimal, even when expected net present value is positive.

Consider a city deciding whether to build a flood barrier at cost $I = 110$ (million dollars). Once completed, the barrier permanently prevents flood damage, but construction requires one year. Annual flood damage depends on the underlying climate regime, which is uncertain at time $t = 0$ but is revealed at the end of Year 1 based on observed losses. With equal probability $\pi = 0.5$, the city may face a high-risk climate state with annual damages $D_H = 24.2$, or a low-risk state with annual damages $D_L = 6.05$. The city discounts future costs and benefits at rate $r = 10\%$.

If the city invests immediately at $t = 0$, it pays the cost $I$ upfront. Because construction takes one year, the barrier becomes operational in Year 2, so only damages for $t \geq 2$ are avoided. Let

$$PV_{t=0}(D_s, t \geq 2)$$

denote the discounted present value of avoided damages from Year 2 onward under climate state $s \in \{H, L\}$, evaluated at time $t = 0$. Using the damage streams implied by the annual losses above, these values are

$$PV_{t=0}(D_H, t \geq 2) = 220$$

$$PV_{t=0}(D_L, t \geq 2) = 55.$$

The net present value of immediate investment in each state is therefore

$$NPV_{\mathrm{t=0}}(D_H, t \geq 2) = 220 - 110 = 110$$

$$NPV_{\mathrm{t=0}}(D_L, t \geq 2) = 55 - 110 = -55$$

Taking expectations across climate states yields the standard discounted cash-flow valuation:

$$\mathbb{E}[NPV_{\mathrm{t=0}}] = 0.5(110) + 0.5(-55) = 27.5.$$

Under traditional DCF rules, the city would invest immediately because the expected net present value is positive.

Now suppose instead that the city has the option to wait until $t = 1$ before deciding whether to invest. By the end of Year 1, realized flood damages reveal whether the climate state is high-risk or low-risk. If the

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high-risk state is observed, the city builds the barrier at $t = 1$. Because construction still requires one year, flood damages are avoided only for $t \geq 3$. The discounted value of avoided damages in this case is

$$PV_{t=0}(D_H, t \geq 3) = 200,$$

implying a net present value (measured at $t = 0$) of

$$NPV_{\mathrm{t=0}}(D_H, t \geq 3) = 200 - \frac{110}{1.1} = 100.$$

If the low-risk state is observed, the city optimally chooses not to invest, because avoided damages from $t \geq 3$ would equal

$$PV_{t=0}(D_L, t \geq 3) = 50.$$

This amount is insufficient to justify the construction cost $I = \frac{110}{1.1} = 100$ evaluated at $t = 0$, so the city exercises its option not to build. The realized payoff in the low-risk state is therefore zero rather than negative.

The expected value of the wait-and-see strategy is thus

$$\mathbb{E}[NPV_{t=0}^{\mathrm{wait}}] = 0.5(100) + 0.5(0) = 50.$$

Comparing this to the value of immediate investment, the option value of waiting can be expressed as

$$\text{Option Value} = \mathbb{E}[NPV_{t=0}^{\mathrm{wait}}] - \mathbb{E}[NPV_{\mathrm{t=0}}] = 50 - 27.5 = 22.5.$$

This option value arises because waiting preserves flexibility. Immediate investment forces the city to commit irreversibly before uncertainty is resolved, exposing it to the risk of overinvestment in the low-risk state. By delaying the decision, the city sacrifices some avoided damages in the high-risk state due to the construction lag but gains the ability to condition the investment on newly revealed information. Traditional discounted cash-flow analysis overlooks this trade-off because it treats investment as both immediate and irreversible. Real option theory makes explicit that, under uncertainty, the ability to wait and learn has economic value—even when the expected net present value of immediate investment is already positive.

## EXAMPLE 2: INCREMENTAL ADAPTATION BEATS ALL-AT-ONCE INVESTMENT

Consider two alternative strategies for flood protection:

1. Build a large barrier now at a cost of $220 million.
2. Build a smaller barrier now for $80 million, with the option to expand later for an additional $140 million if flood risk increases.

Assume:

- Flood risk escalates with 40% probability.
- If risk escalates, total avoided damages from a large barrier are $300 million.
- If risk does not escalate, avoided damages are only $100 million.

Under traditional DCF, the expected avoided damages:

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$$0.4 * 300 + 0.6 * 100 = 180.$$

The Net Present Value is

$$NPV_{large} = 180 - 220 = -40.$$

Under traditional DCF analysis, the project is rejected because the expected net present value is negative. The city would conclude that flood protection is not economically justified.

However, under the staged strategy, the city makes a modest initial investment and retains the option to expand protection if flood risk increases.

In the high-risk scenario (40% probability), flood damage escalates substantially. The city expands the barrier, incurring total costs of $220 million (initial investment plus expansion), while avoiding $300 million in damages. The resulting net payoff is $80 million.

In the low-risk scenario (60% probability), flood risk remains moderate. The city does not expand the barrier, incurring only the initial $80 million cost and avoiding $100 million in damages, yielding a net payoff of $20 million.

Weighing these outcomes by their probabilities gives an expected net present value of

$$0.4 \times 80 + 0.6 \times 20 = 44.$$

Therefore, the staged, flexible strategy delivers a positive expected NPV of $44 million. This result highlights how flexibility improves outcomes across both scenarios by avoiding unnecessary investment while preserving protection against severe risk.

## ACTUARIAL MODELING OF REAL OPTIONS IN ADAPTATION INVESTMENTS

Stochastic modeling of climate risk is a foundational step in applying real option theory to adaptation investments. Actuaries can use stochastic climate scenarios to represent a wide range of plausible future hazard pathways. These scenarios are informed by climate science and catastrophe models and may reflect changes in the frequency, severity, and geographic distribution of extreme events (IPCC, 2023; Geneva Association, 2021). Instead of producing a single expected outcome, each scenario generates a distribution of potential future losses and benefits, providing the probabilistic structure required for real options analysis.

This probabilistic framework is critical because real options valuation depends on understanding uncertainty and flexibility over time. By capturing the range of possible climate outcomes, actuaries can better evaluate how adaptation investments perform under different conditions and assess the value of making decisions dynamically as new information emerges.

A variety of techniques are available to value real options in climate adaptation settings. Decision trees and binomial lattice models represent investment decisions at discrete points in time, with branches reflecting alternative future states. These approaches are intuitive and particularly well suited to staged or phased infrastructure investments where decisions can be revisited as uncertainty resolves (Brandão, Dyer, & Hahn, 2005).

Monte Carlo simulation offers a more flexible approach by modeling uncertainty continuously rather than at discrete intervals. This method is especially valuable when multiple risk drivers interact and is well aligned with actuarial practices commonly used in capital modeling and reserving. Dynamic programming

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provides another powerful tool, enabling the identification of optimal decision rules across time and supporting the analysis of complex, multi-stage adaptation pathways (Dixit & Pindyck, 1994).

The selection of an appropriate valuation method depends on the complexity of the investment, the quality and availability of data, and computational constraints. Actuaries need to balance analytical rigor with practical considerations to ensure that real options analyses are both robust and usable for decision-making.

## ADVANTAGES OVER TRADITIONAL APPROACHES

Real option theory provides several important advantages over traditional discounted cash flow (DCF) analysis when assessing climate adaptation investments. One of its key strengths is the explicit valuation of flexibility. Rather than treating flexibility as a qualitative consideration or ignoring it altogether, real option theory recognizes managerial and strategic flexibility as an asset that can add measurable value to an investment.

Another major advantage is its improved treatment of uncertainty. By relying on stochastic modeling, real option analysis aligns closely with actuarial best practices and allows for a more complete understanding of risk, including tail risk and extreme outcomes. This is particularly relevant in the context of climate change, where uncertainty and low-probability, high-impact events play a critical role.

Real option theory also enhances decision-making around the timing of investments. Instead of focusing solely on whether an investment should be made, it helps determine when it is optimal to invest, defer, expand, or abandon a project as conditions evolve. This dynamic perspective is especially valuable for adaptation measures that can be staged over time.

Finally, the real options framework aligns well with risk-based decision-making. It supports evaluations that consider not only expected value but also downside risk and volatility, which are central concerns for actuaries. Together, these strengths make real option theory particularly well suited for actuaries advising insurers, governments, and infrastructure stakeholders on climate adaptation strategies.

## IMPLICATIONS FOR ACTUARIAL PRACTICE

Applying real option theory to climate adaptation investments expands the actuarial role beyond traditional pricing and reserving. In property and casualty insurance, real option analysis can inform decisions about underwriting strategies, risk mitigation incentives, and capital deployment in climate-exposed regions. In public-sector and infrastructure contexts, actuaries can support long-term investment planning under deep uncertainty.

Furthermore, real option thinking aligns closely with enterprise risk management (ERM), where flexibility, stress testing, and adaptive strategies are central themes. As climate risk increasingly influences financial stability, actuaries equipped with real option tools can provide valuable guidance to decision-makers.

## CHALLENGES AND FUTURE RESEARCH

Despite its advantages, real option analysis faces practical challenges. Data limitations, model complexity, and computational demands can hinder implementation. Additionally, translating climate science into probabilistic financial inputs remains an evolving area of research.

Future work could focus on developing standardized actuarial frameworks for real option valuation in climate adaptation, improving integration with catastrophe models, and exploring regulatory applications.

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Enhanced collaboration between actuaries, climate scientists, and policymakers will be essential to advance this field.

## CONCLUSION

Climate adaptation investments are essential for managing the growing risks associated with climate change. Traditional evaluation methods, while useful, often fail to capture the value of flexibility under uncertainty. Real option theory provides a robust framework for enhancing cost–benefit analysis by explicitly valuing adaptive decision-making.

Actuaries are uniquely equipped to apply real option techniques, combining stochastic modeling, long-term valuation, and risk management expertise. By incorporating real option theory into the evaluation of climate adaptation investments, actuaries can support more resilient, efficient, and forward-looking decisions in an increasingly uncertain climate future.

## REFERENCES

Brandão, L. E., Dyer, J. S., & Hahn, W. J. (2005). Using binomial decision trees to solve real-option valuation problems. *Decision Analysis, 2*(2), 69–88.

Dixit, A. K., & Pindyck, R. S. (1994). *Investment under uncertainty*. Princeton University Press.

Fernando, J. (2025, October 17). Discounted cash flow (DCF) explained with formula and examples. *Investopedia*. https://www.investopedia.com/terms/d/dcf.asp

Geneva Association. (2021). *Climate change risk assessment for the insurance industry*. The Geneva Association.

Hayes, A. (2025, August 22). Real options explained: Definition, valuation, and examples. *Investopedia*. https://www.investopedia.com/terms/r/realoption.asp

Intergovernmental Panel on Climate Change (IPCC). (2021). *Climate change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (V. Masson-Delmotte et al., Eds.). Cambridge University Press. https://doi.org/10.1017/9781009157896

Intergovernmental Panel on Climate Change (IPCC). (2023). *Sixth assessment report: Impacts, adaptation and vulnerability*.

Rockafellar, R. T., & Uryasev, S. (2000). Optimization of conditional value-at-risk. *Journal of Risk, 2*(3), 21–41.

Swiss Re Institute. (2025, April 29). *Natural catastrophes: Insured losses on trend to USD 145 billion in 2025 (Sigma Report 1/2025)*. Swiss Re. https://www.swissre.com/institute/research/sigma-research/sigma-2025-01-natural-catastrophes-trend.html

Townsend, L. (2022, September 28). Deterministic vs. stochastic models: A guide to forecasting for pension plan sponsors. *Milliman*. https://www.milliman.com/en/insight/deterministic-vs-stochastic-models-forecasting-for-pension-plan-sponsors

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