Australian Climate Change Adaptation Network for Settlements and Infrastructure

Discussion Paper
February 2010

The incorporation of uncertainty associated with climate change into infrastructure investment appraisal

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Abstract

Conventional investment appraisal for infrastructure tends to be carried out deterministically, assuming that today's conditions will continue or trend into the future. This might be supplemented with sensitivity or scenario analysis in order to incorporate possible deviations. However with climate change, such steady state assumptions no longer hold. Infrastructure, in the future due to climate change, could be expected to have to deal with increased temperatures, altered rainfall patterns, altered frequencies of extreme weather events and sea level rise. These in turn will lead, for example, to changed demand patterns, increased maintenance and operation costs, decreased longevity, increased costs of retrofitting, changed land use and demographics, and more frequent disruption to use. And all of these consequences are only known to within defined probabilities. Future costs and benefits for infrastructure are now inherently probabilistic, and any investment appraisal must necessarily take into account the uncertainty. Deterministic appraisals can no longer be justified. Three main choices for new infrastructure are possible: (I) build for today's conditions and abandon in the future because of climate change, whereby the longevity of the infrastructure is restricted; (II) build for today's conditions with the view to being able to modify or upgrade in the future, such that the infrastructure is tailored to the changing climate or adapts to the changing climate; or (III) build for future conditions whereby the infrastructure is overdesigned in the near future but adequate for the longer term. Each choice represents different levels of feasibility. The paper explores the different possible mechanisms by which feasibility levels can be evaluated, including the feasibility associated with having flexible and adaptable infrastructure, such that rational investment decisions can be made within the uncertainty introduced by climate change.

1. Introduction

Commonly, economic feasibility of new infrastructure is based on a present worth (net present value) analysis, and this is done deterministically whereby all costs and benefits are assumed known, and the future is assumed to be a continuation of the present, or trend from the present. Where variability is anticipated in future costs and benefits, a sensitivity analysis or scenario analysis might also be carried out.

However with climate change, the future becomes less certain because of the underlying incomplete science and associated lack of confidence in prediction. Future benefits and costs and infrastructure lifespans cannot be predicted with any degree of accuracy, because of uncertainty associated with anticipated sea level and temperature rises, and changed occurrences and magnitudes of extreme weather events and rainfall patterns. Increases are expected in infrastructure maintenance, repair and operation costs, damage, and insurance premiums, while demands on infrastructure, energy, water and transport will change - both increase and decrease on a situation-by-situation basis. The locations of infrastructure needs will also change as demand changes. The operation of infrastructure will be disrupted more frequently. The longevity of infrastructure will decrease and external facades of infrastructure will experience accelerated degradation. Infrastructure will need to be replaced more frequently. Much has been written on this, for example [1], [2] and [3].

Climate change will expose vulnerabilities in existing infrastructure and infrastructure established along business-as-usual lines. And such vulnerability could be expected to vary between locations. Existing infrastructure could be expected to have limited ability or capacity to adapt, and may be found to be inadequate. Infrastructure intended for long term use may prove inadequate.

Clearly future benefits and costs will be best modelled as random variables rather than deterministic quantities as was the common practice in the past. This in turn means that present worth becomes a random variable, and feasibility has to be defined in terms of the probability that the present worth is positive [4], [5].

2. Background

The National Climate Change Adaptation Research Plan: Settlements and Infrastructure Consultation Draft of September 2009 by the National Climate Change Adaptation Research Facility (NCCARF) [3] highlights the background to the present paper. At pp. 14-15:

'There is considerable uncertainty about the timing and intensity of future climate change especially at regional and local scales. The economic situation contributes further uncertainty. Nonetheless decisions about developments, many irreversible, will continue to be made, and these need to increasingly take into account an awareness of both climate change and uncertainty about its specific local implications. One sensible approach for large investments is to undertake staged developments that allow for future expansion or additional adaptive features to be implemented contingent on certain climatic thresholds being surpassed. These so-called "real options" allow for learning and flexibility in planning and design decisions prior to any commitment of scarce resources. Optionality can add value to projects in a way that can be priced with modern financial tools that avoid the pitfalls associated with traditional [deterministic] Net Present Value calculations, often used for cost-benefit analysis.'

NCCARF raises this as a significant issue with respect to both building and for infrastructure financing. And at p. 27:

'Traditional [deterministic] Benefit/Cost analyses based on Present Worth method with relatively high discount rate and short planning periods are not appropriate to the long planning periods inherent in adaptation to climate change over the next century (and longer). Financial analyses for assessing infrastructure projects need to be modified to incorporate and take account of risks that are likely to change with climate over an extended timeline. Alternative financial and business models need to be investigated for use by government and private sectors for adoption in options assessment and investment decision making in the new climate era.'

The present paper addresses the concerns in both these quotations. The methodology advanced in this paper incorporates uncertainty and values options and flexibility.

3. Infrastructure development choices

Three main choices for new infrastructure are possible:

I. Build for today's conditions and abandon in the future because of climate change, whereby the longevity of the infrastructure is restricted.
II. Build for today's conditions with the view to being able to modify or upgrade in the future, such that the infrastructure is tailored to the changing climate or adapts to the changing climate.
III. Build for future conditions whereby the infrastructure is overdesigned in the near future but adequate for the longer term.

Each choice represents different levels of feasibility and value. Maintenance, if applicable, on the infrastructure for all three cases can be incorporated as an ongoing cost, and as such maintenance is not assumed to be a distinct case IV. The situation involving significant rectification work can be incorporated under case II.

Where existing infrastructure is being refurbished, the same options apply. The present worth calculations for each case can be made to fit under one general formulation, which is given in the next section. Costs, benefits and disbenefits are converted to cash outflows and cash inflows.

The cash flow diagrams for each of the three cases I, II and III might follow something like Figure 1. Variability in the benefits would remove the regularity implied by Figure 1.

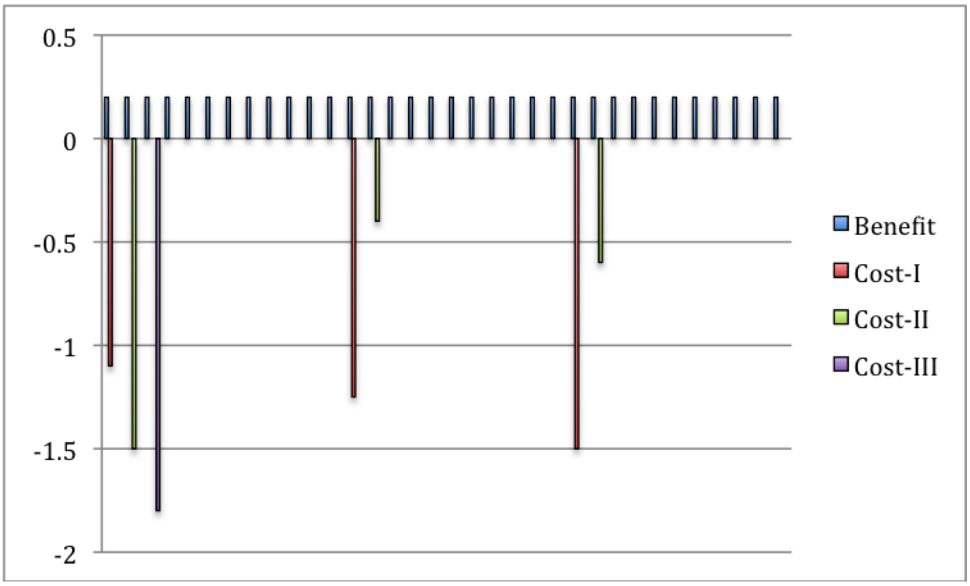

Figure 1 Schematic example cash flow diagrams (with variability in benefits removed) for the three possible infrastructure investment cases. Benefits are above the line. The costs below the line are in the order I, II and III at time now, while the costs are in the order I and II for later times.

4. Applicable tools

With such a probabilistic problem, available solution tools include Monte Carlo simulation (for example, [6]), fuzzy set approaches (for example, [7]) and second order moment analysis ([4] and [5]). The first two are numerical and only give a little insight into underlying behaviour. Black-Scholes and binomial lattices (for example, [8]), as used in financial options theory, could also be used but lack intuitive appeal to many. Second order moment analysis is used in the following because of its ease of use and requires very little adjustment for those familiar with conventional discounted cash flow (DCF) analysis. The method gives equivalent results to real options analysis via Black-Scholes or binomial lattices.

Conventional deterministic approaches would commonly use a risk-adjusted discount rate, leading to a high discount rate, which in turn leads to future cash flows having little value in present worth terms. As such, deterministic approaches effectively ignore any long term climate change impacts, and decisions would favour projects with short lifespans and short term returns. Probabilistic approaches on the other hand, because the uncertainty is already encapsulated within the future cash flows, use the lower risk-free discount rates, which give value (in present worth terms) to the future. With many of climate change impacts being long term and infrastructure lifespans being long term, it is accordingly more rational to adopt a probabilistic approach; this is on top of the issue as to what a risk-adjusted discount rate means in present worth calculations.

Deterministic approaches hide the fact that there is potential downside to any investment, while probabilistic approaches acknowledge that there is always a finite probability that the present worth of any investment can turn out to be negative.

5. DCF formulation covering infrastructure choices

Infrastructure choices I, II and III can be incorporated under a general model that has cash flows at each time period. The nature, magnitude and sign of these cash flows will differ between the three choices.

Let the net cash flow at each time period, i = 0, 1, 2, ..., n, be the result of a number of cash flow components Y_{ik}, k = 1, 2, ..., m. The cash flow components are benefit, disbenefit and cost related. There may be correlation between the cash flow components at the same period.

The net cash flow X_i in any period can be expressed as,

$$X_i = Y_{i1} + Y_{i2} + \ \dots + Y_{im} \tag{1}$$

where Y_{ik}, i = 0, 1, 2, ..., n; k = 1, 2, ..., m, is the cash flow in period i due to component k, with mean E[Y_{ik}] and variance Var[Y_{ik}].

The expectation and variance of X_i become,

$$E[X_i] = \sum_{k=1}^{m} E[Y_{ik}] \quad (2)$$

$$Var[X_i] = \sum_{k=1}^{m} Var[Y_{ik}] + 2\sum_{k=1}^{m-1} \sum_{\ell=k+1}^{m} Cov[Y_{ik}, Y_{i\ell}] \quad (3)$$

where Cov[ ] is the covariance. Alternatively, the variance expression can be written in terms of the component correlation coefficients, $\rho_{k\ell}$, between Y_{ik} and $Y_{i\ell}$, $k, \ell = 1, 2, \ldots, m$,

$$Var[X_i] = \sum_{k=1}^{m} Var[Y_{ik}] + 2\sum_{k=1}^{m-1} \sum_{\ell=k+1}^{m} \rho_{k\ell} \sqrt{Var[Y_{ik}]} \sqrt{Var[Y_{i\ell}]} \quad (4)$$

The present worth, PW, is the sum of the discounted X_i, i = 0, 1, 2, ..., n, according to,

$$PW = \sum_{i=0}^{n} \left[\frac{X_i}{(1+r)^i} \right] \quad (5)$$

where r is the discount rate. The expected value and variance of the present worth become ([9], [10], [11]),

$$E[PW] = \sum_{i=0}^{n} \frac{E[X_i]}{(1+r)^i} \quad (6)$$

$$Var[PW] = \sum_{i=0}^{n} \frac{Var[X_i]}{(1+r)^{2i}} + 2\sum_{i=0}^{n-1} \sum_{j=i+1}^{n} \frac{Cov[X_i, X_j]}{(1+r)^{i+j}} \quad (7)$$

Alternatively, the variance expression can be written in terms of the intertemporal correlation coefficients between X_i and X_j, namely ρ_{ij}, rather than the covariance of X_i and X_j,

$$Var[PW] = \sum_{i=0}^{n} \frac{Var[X_i]}{(1+r)^{2i}} + 2\sum_{i=0}^{n-1} \sum_{j=i+1}^{n} \frac{\rho_{ij} \sqrt{Var[X_i]} \sqrt{Var[X_j]}}{(1+r)^{i+j}} \quad (8)$$

For independent cash flows X_i,

$$Var[PW] = \sum_{i=0}^{n} \frac{Var[X_i]}{(1+r)^{2i}} \quad (9)$$

For perfect correlation of the cash flows X_i,

$$Var[PW] = \left(\sum_{i=0}^{n} \frac{\sqrt{Var[X_i]}}{(1+r)^i} \right)^2 \quad (10)$$

Var[PW] is smaller for the assumption of independence compared with the assumption of correlation.

6. Feasibility and upside value

Having characterized the present worth in terms of its moments, some measure is needed to establish the suitability of an investment. Feasibility is one appropriate measure.

Feasibility, Φ, is defined as the probability that the present worth is positive ([4], [5]).

$$\Phi = P[PW > 0] \qquad (11)$$

This may be readily evaluated where present worth follows a normal distribution. A normal distribution is commonly held to be a good representation of present worth ([9], [12], [10], [13])

Where competing infrastructure choices exist, that with the largest feasibility might be preferred.

Feasibility is a probability, and some people may not feel comfortable working with this measure. The question arises as to what is a level of feasibility acceptable to the investor, that is, what is an acceptable level of probability that the present worth will turn out to be positive. The answer to this will depend on whether the investor is risk prone, risk averse or risk neutral, and hence requires knowledge of the investor's values.

An alternative deterministic measure is to use the mean of the present worth upside, that is the mean of the portion of the present worth distribution that is positive. This is referred to as the upside value, UV, in this paper.

$$UV = E[PW \text{ upside}] \qquad (12)$$

The Black-Scholes formula and binomial lattices calculate something similar.

For a given Var[PW], a larger E[PW] means higher feasibility and higher upside value, while a lower E[PW] means a lower feasibility and lower upside value. That is for a given Var[PW], as Φ increases/decreases, so too does UV increase/decrease respectively. Accordingly the preferred infrastructure, where alternatives exist, is that with the largest UV. With an individual investment, what is considered a minimum upside value will depend on other circumstances and intangibles surrounding the infrastructure. It is noted that there will always be an upside value because of the positive tail of the normal distribution representing PW. However the upside value will approach zero for investments with low feasibility. And so investors might like to make a decision based on both the upside value in conjunction with the feasibility.

What feasibility and the upside value are telling is that all investments may turn out as losses and also turn out as gains, with probabilities attached.

7. Example

To demonstrate the types of results obtained, consider three investments of the form shown in Figure 1. The numbers and correlation type assumed are not important; rather it is the methodology that is being demonstrated. Uncertainty in the benefits and costs is assumed to increase with time. The standard deviations of the benefits and the costs are taken to increase respectively at 0.01 and 0.02 times the mean for each additional year. Having basic infrastructure is taken to cost 1.1 initially with replacement costs being 1.25 and 1.5 in 10 and 20 years respectively; having adaptable infrastructure is taken to initially cost 1.5, with upgrades costing 0.4 and 0.6; having infrastructure that will last the full period is taken to cost 1.8. Benefits are 0.2 annually. Benefits and costs are in a unit of money. A discount rate of 10% is used. Benefits are assumed correlated. Costs are assumed correlated. Benefits and costs are assumed uncorrelated.

Figure 2 shows the present worth distributions for cases I, II and III. In summary, greatest feasibility is demonstrated by II and least by I (the three values are 0.83, 0.97 and 0.96 respectively for I, II and III); I demonstrates highest upside value, with III the lowest (the three values are 0.37, 0.35 and 0.29 respectively for I, II and III);. It is seen that with increasing uncertainty, the upside value, UV, increases. This is consistent with options analysis. For comparison, a conventional deterministic analysis (using expected values only, and ignoring variability, but using the same discount rate) gives present worths for I, II and III of 0.27, 0.33 and 0.27 respectively, with III slightly greater than I; that is II performs the best and I the poorest. The deterministic approach hides the fact that there is potential downside to any investment, while the probabilistic approach acknowledges that there is always a finite probability that the present worth of any investment can turn out to be negative. Table 1 gives a comparison performance of each of the investment choices.

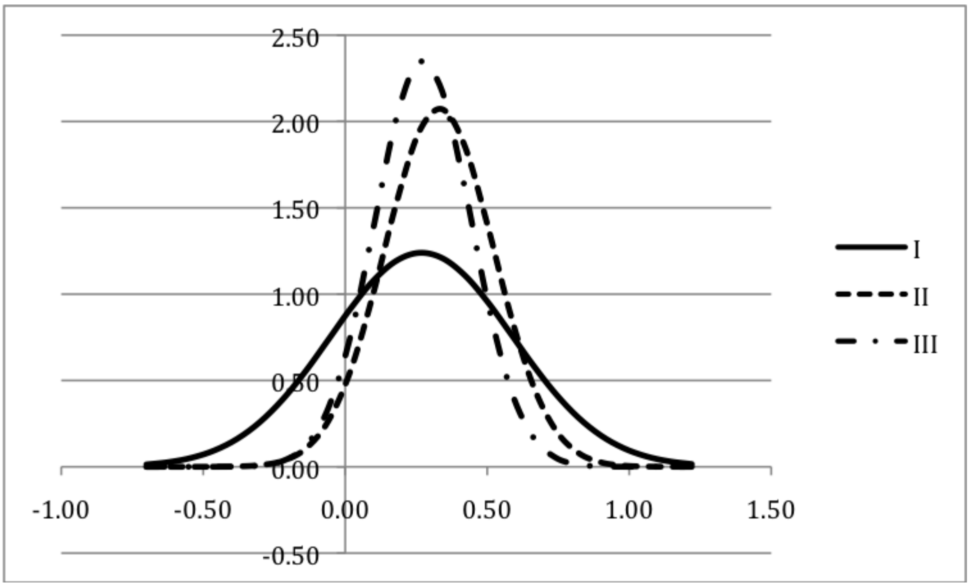

Figure 2. Present worth density functions (frequency of occurrence of present worth versus money) for infrastructure choices I, II and III; example values.

	Φ	UV	E[PW]
I	0.83	0.37	0.27
II	0.97	0.35	0.33
III	0.96	0.29	0.27

Table 1. Comparison of choices I, II and III for the example calculations. Highest value preferred for Φ, UV *and* E[PW].

8. The value of building in flexibility

Building in flexibility to infrastructure may take many forms including defending, modifying (retrofitting, alteration), retreating, relocating and abandoning. ‘The likely impacts of climate change need to be recognised and an adaptive management approach to designing and managing investment is essential. Climate conditions will change considerably over the life of long-lived infrastructure … The capacity for such assets to incorporate adaptation treatments or adjustments to their maintenance regime will in part determine their resilience to accelerated degradation of materials and fatigue of structures due to increased intensity and frequency of extreme events (storms, wind, rainfall, bushfire). … Integrating … renewal options in long-lived infrastructure would also help enable periodic improvements to these assets as knowledge improves.’ ([3], p. 23)

The value of building in the capacity to be flexible may be viewed as is done in real options analysis. In the real options literature, the techniques of Black-Scholes and binomial lattices are used, but can be criticized for their lack of intuitive appeal, particularly in needing to define a volatility term, which has meaning in a share price sense but not a project sense. Instead of Black-Scholes and binomial lattices, the authors prefer to use the results of the probabilistic DCF analysis outlined above, to value the option to adapt.

Consider the situation for cases I and II, at the time where a first decision is necessary (after 10 years in the example), but before the second decision becomes necessary. Case I involves rebuilding anew; case II involves adapting the initial infrastructure. The present worth of this flexibility is shown in Figure 3. It has an upside value of 0.14 for I and 0.37 for II. This is equivalent to the Black-Scholes option value. The option to be flexible in the future has a value. The total value of the infrastructure is based on its value up to the point where a decision is necessary together with this option value.

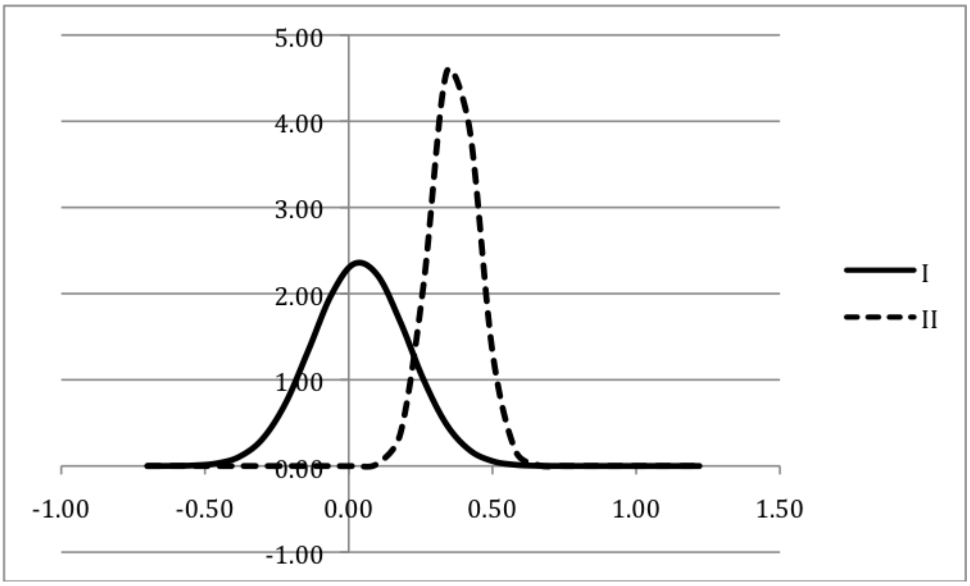

Figure 3. Probability density functions of present worths (frequency of occurrence of present worth versus money) for upside value calculation for choices I (build anew) and II (adapt); example values.

9. Conclusions

With climate change comes increasing uncertainty. With increased uncertainty comes the need for rethinking feasibility studies of infrastructure investments. Flexible and adaptable infrastructure may offer the potential to give better financial feasibility over existing non-flexible approaches because of this uncertainty. The paper offers a sound methodology for not only incorporating future uncertainty but also allowing investors to price flexibility.

The intent of the paper was not to imply that any one of the three choices for infrastructure listed, namely I (design for today), II (design for adaptation) or III (over-design for tomorrow) is better than any other. Which is best will be determined by the particular circumstances. Rather the paper offers a sound methodology for establishing which choice is best in any particular situation.

Acknowledgement

The assistance in developing this discussion paper provided by Associate Professor Ron Cox from the School of Civil and Environmental Engineering at the University of New South Wales, and the Australian Climate Change Adaptation Network for Settlements and Infrastructure is thankfully acknowledged.

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