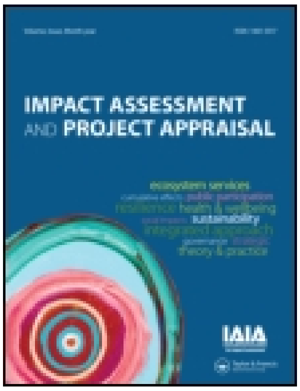

Impact Assessment and Project Appraisal
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tiap20

Adaptation, flexibility and project decision-making with climate change uncertainties

Andrew F. Colombo [a] & Philip H. Byer [a]
[a] Department of Civil Engineering , University of Toronto , Toronto , Ontario , Canada , M5S 1A4
Published online: 08 Oct 2012.

Impact Assessment and Project Appraisal
Vol. 30, No. 4, December 2012, 229–241

Adaptation, flexibility and project decision-making with climate change uncertainties

Andrew F. Colombo† and Philip H. Byer*

Department of Civil Engineering, University of Toronto, Toronto, Ontario, Canada M5S 1A4

(*Received 21 May 2012; final version received 11 September 2012*)

Project planning in the future must directly address both climate change and uncertainties about it. This paper presents the use of classical decision criteria, such as *maximin* and *minimax regret*, and approaches for adapting to climate change given the uncertainties. Adaptation strategies can help reduce the effects of uncertainties by allowing for adjustments in designs as the future climate evolves, although at a cost for such future flexibility. Adding such options and evaluating them against other design options using the decision criteria can provide valuable information to decision-makers and other stakeholders during project planning. A hypothetical example of a hydroelectric project illustrates the use of these approaches.

Keywords: adaptation; flexibility; climate change; decision-making; project evaluation; uncertainty

Introduction

In contemplating new infrastructure, project planners and engineers could traditionally base their designs on historic climate conditions, including the assumption that climate variability (e.g. frequency and intensity of storms) was *stationary*; that is, the probability distributions of key variables such as temperature and precipitation would not change throughout the life of the project. This century's major environmental challenge, climate change, will, however, modify the statistical parameters of historical climate, meaning that such data will no longer be a good basis for design of much future infrastructure (Byer et al. 2004, 2009; Byer & Yeomans 2007; IPCC 2007). Significantly complicating this issue is that we do not know how, to what extent or how fast future climate will change. Negotiating this uncertainty presents a significant challenge when finalizing designs, making investments and assessing environmental impacts. This, in turn, necessitates the development of decision-making approaches that account for such uncertainty in a systematic manner.

To illustrate the challenge, consider the example in Table 1 in which a decision-maker must select the appropriate design of a project on the basis of one impact in the face of climate change uncertainty. Three possible future climate scenarios are deemed to be representative of the range of uncertainty the project would encounter. These are: (1) no change in the current climate; (2) a moderate degree of climate change; and (3) severe climate change. Based on these scenarios, three project designs (A, B and C) were developed, with each matched to a corresponding scenario (1, 2 and 3, respectively) in order to realize the least adverse impact as represented by the values in the table. For example, if Design B is chosen and Scenario 2 occurs, the project will result in an impact level of 32. If Scenario 3 materializes instead, the impact (45) is greater and, in hindsight, Design C would have been preferred since it offers the least impact (40) for that scenario. The problem is that any of these scenarios could occur but the project design must be chosen now, before the eventual scenario is known, and there is no reliable information regarding the likelihoods of the scenarios.

This paper describes various ways in which infrastructure can be planned in such cases, using both criteria for decision-making under uncertainties and adaptation that builds in flexibility to help reduce the uncertainty. Full details are provided by Byer et al. (2011).

Adaptation

Adaptation and mitigation are two generalized responses for addressing climate change. Mitigation directly attempts to reduce greenhouse gas emissions and slow the rate of climate change through various approaches such as substituting fossil fuels with renewable energy or forest replanting to boost carbon assimilation. Adaptation, on the other hand, is the 'adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities' (IPCC 2007). Figure 1 presents a classification of various approaches for how a project might be adapted to address climate change. Each of these is briefly explained below.

The *Do-nothing* approach in this context refers to project design that is not influenced by climate change considerations. While not an actual adaptation method, it is always a possible course of action. Inability to predict future climate scenarios, lack of confidence in climate models, gaps in knowledge of climate processes, and the expectation that climate change impacts will be mostly felt after the project's life all can encourage this choice.

When contending with variability, one general practice in engineering is to design for larger than normal loads or conditions (e.g. applying safety factors). *Bolstering existing designs* can be useful for protecting against

*Corresponding author. Email: byer@ecf.utoronto.ca
†Present address: National Research Council of Canada, Ottawa, Ontario, Canada K1A 0R6.

ISSN 1461-5517 print/ISSN 1471-5465 online

http://dx.doi.org/10.1080/14615517.2012.731189
http://www.tandfonline.com

Table 1. Example impact matrix for different design options and climate scenarios.

Design options	Climate scenario: No change 1	Moderate 2	Severe 3
A	18	42	65
B	24	32	45
C	28	36	40

system failure, especially when uncertainty is not easy to characterize or quantify. Examples are stronger structures to withstand more extreme storms, or higher piers to allow for rising sea levels. *Variability management* involves design and operational measures that augment the capacity of the project to accommodate the increased climate variability. For example, a hydroelectric reservoir can be designed to handle larger inflows resulting from more intense storms. Project *reconceptualization* entails re-thinking the way a project is conceived, built and operated by considering hitherto unused or unusual design elements. An example of this is the shift away from mechanical means of cooling office buildings to architectural changes such as the use of green roofs.

An appealing approach to dealing with uncertainties is to 'wait and see' how climate change unfolds and then adapt to those changes. Flexibility is the fundamental premise of this *adaptive management* strategy. It has its roots in the adaptive management processes developed and used over the past three decades in the natural resource sector, which Duinker and Trevisan (2003) describe as 'an experimental system of resource management that incorporates active learning'. Adaptive management may be particularly useful in the context of climate change since there is a significant amount of uncertainty in the prediction of future climate scenarios and outcomes (Hauser & Possingham 2008). Alternatively, it has been viewed as a way to defer the problem to a later date (Lee 1999). The European Climate Adaptation Platform (2012), an initiative of the European Union, describes adaptive management as involving

> the selection of a strategy that can be modified to achieve better performance as one learns more about the issues at hand and how the future is unfolding. A key feature of adaptive management is that decision makers seek strategies that can be modified once new insights are gained from experience and research … Learning, experimenting and evaluation are key in this approach and are actively planned for in decision-making.

As shown in Figure 1, adaptive management for climate change can be divided into three sub-classes: informational, operational and design flexibility. *Informational flexibility*, closely connected with *monitoring*, is a deliberate strategy of obtaining data in order to observe how climate-induced changes are occurring. Modular design and staged construction (described below) rely on acquired data before new components are added and project phases initiated. Monitoring can also provide valuable data for informing a project's operations, such as a reservoir release policy at a dam based on both upstream and downstream needs (water supply, power, navigation, irrigation, etc.), climate and local hydrology. Decision models can also be updated (especially scenarios and the probability of their occurrence) with such information. A meaningful wait-and-see approach requires, as a minimum, good data collection and interpretation.

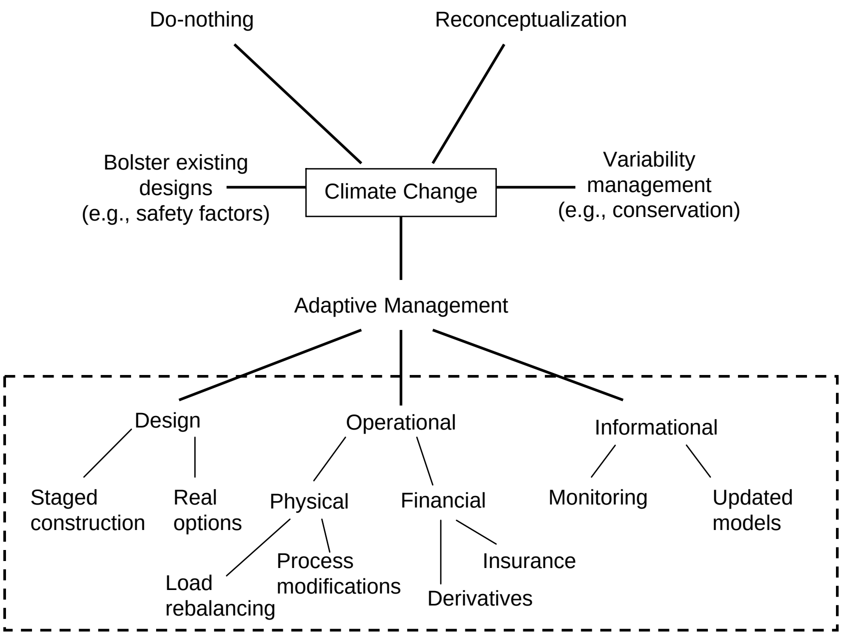

Figure 1. Classification of broad approaches for adapting to climate change at the project level.

Operational flexibility puts the emphasis of project-level climate change adaptation on the post-construction phase. There are two broad categories: flexibility in the operations of physical elements (e.g. machinery, through-put handling, worker shifts) and financial instruments. Flexibility in operations relates to how project assets are used and the decision rules governing their use, such as adapting to changes in river flow variation through modifications in the use of a spillway or running turbines at greater capacity. *Financial instruments* can also play a role by reassigning some of the monetary risk of a project. Insurance is a traditional way of reducing certain risks in exchange for the cost of the premium. Financial derivatives such as options and swaps are essentially risk management tools that can help shift risk to those with a greater appetite for it, typically commodity market investors.

Design flexibility is a conscious effort, at a cost (a flexibility charge), to design the project for potential future modification as climate change unfolds. An example is flood control embankments constructed with foundations so that retaining walls can be subsequently added as flood intensity increases over time. This is essentially the notion behind *real options*. As the name suggests, there is a resemblance to options in the financial sector whereby an investor buys the right, but not the obligation, to buy or sell a particular security at a given price (on, or by, a certain date). Dobes (2008) offers several examples of real options in the climate change context. Yang et al. (2008) employed real options for power capacity investments in the face of uncertainties about the future price of carbon emissions.

In the context of engineered projects, a real option is the ability to build extra capacity or undertake some other design modification as conditions change and new information becomes available. The option allows the decision-maker to avoid or put off some commitments now and wait to see what final investments are appropriate. Phased capacity expansion is a common example for engineering projects. Incremental design allows investors to engage fewer capital resources in the project at any moment, rendering project financing easier, and it minimizes expenses that might subsequently prove to have been unnecessary. However, it generally also involves up-front costs (essentially the option price) to allow for future modifications. De Neufville (2002, 2004) describes the economic analysis of tradeoffs involved in real options to reflect the time value of money.

Decision-making under uncertainty

Compendia of tools and methods for decision-making on adaptation to climate change are presented by Feenstra et al. (1998) and United Nations Framework Convention on Climate Change Secretariat (2008). The tools and methods they address include benefit–cost analysis, cost-effectiveness analysis, adaptation decision matrix and tools for environmental assessment and management. These and similar methods have also been discussed in the context of climate change by other authors, including de Bruin et al. (2009a, 2009b), Qin et al. (2008) and Bell et al. (2001, 2003). However, these methods address uncertainties primarily in the context of sensitivity analysis applied to the values assumed in the analysis, rather than explicitly and directly address uncertainties about future climate.

The focus in this paper is on methods that explicitly address uncertainties about the possible outcomes. These methods can be subdivided according to whether or not they assume estimates of the probabilities of the outcomes: if probabilities are assumed, criteria such as expected values or expected utilities or Bayesian analysis can be used, while other 'classical' decision criteria such as *maximin* or *minimax regret* can be used if the likelihoods of the outcomes are unknown (Kassouf 1970; Luce & Raiffa 1957).

Dessai and van der Sluijs (2007) identify Bayesian analysis as a potentially useful method for analysing climate change uncertainties pertaining to various infrastructure systems and projects. Hobbs (1997), which provides a thoughtful summary of the value and challenges of employing Bayesian analysis for improving decision-making when faced with climate change uncertainty, confronts the major issues of inference, subjective assessment and updating models given new information, and describes a framework based on a Bayesian Monte Carlo analysis for updating models of sea level rise. Hobbs et al. (1997) uses decision trees and Bayesian analysis to assess the value of incorporating climate change uncertainty into decisions about water resources infra-structure, applying the approach to an example of water level regulation and breakwaters for shoreline protection. The authors note that accounting for climate change uncertainty can help protect against significant opportunity losses and that, just as real options are used in a variety of contexts, the decision-making methodologies are no different in a context of climate change than for other forms of uncertainty commonly encountered in engineer-ing projects. Their analysis also provides estimates of the value of waiting for better information on climate change before making a decision. Since Bayesian analysis updates probabilities according to new information, it is a potentially useful tool for adaptive management. These approaches, however, are not easy or transparent to use and they require estimates of the likelihoods of how future climate will change that are highly subjective and often contentious. For these reasons, the focus here is on methods that do not use probabilistic estimates.

Several papers and reports have discussed the use of non-probability-based methods for decision-making with climate change. Bretteville (1999) applies classical decision criteria (e.g. *maximax*, *maximin*, *minimax regret*) at the policy level for climate change, offering a simplified example in which damage owing to climate change with or without policy action is assumed known, as is the cost of implementing the policy. Willows and Connell (2003) provide a simple hypothetical example of the use of these decision criteria for adaptation to climate change, where they structure a *payoff matrix* based on the degree of climate change that eventually materializes and the investment in adaptation. Clarke (2008) applies these criteria to assess the 'social insurance' of policies in minimizing regret and worst case outcomes (the precautionary principle) and evaluates the role of 'all weather' and mixed policies. Adaptive management is featured in an example of policy related to a river basin with two attributes (agricultural output and biodiversity); the policy integrates the classical criteria with utility theory in order to construct a payoff matrix having values derived from a social welfare function based on the two attributes.

Applying decision criteria in project planning under uncertainty

This section explains the use of decision criteria for the evaluation of alternatives with climate change uncertainty. They are illustrated through a hypothetical example of a hydroelectric project whose main purpose is to generate revenue from electricity sales while addressing potential environmental impacts. First, the decision criteria are applied to designs without flexibility, and only consider a single attribute (financial return). In later sections, flexibility options are considered, and finally this is expanded to consider two attributes (financial return and the probability of flooding).

These approaches first require the identification of candidate climate scenarios that capture the range of future climate-related impacts the project may face. How such scenarios are devised is not dealt with in this paper. Choosing the scenarios to consider is challenging. The IPCC (2001) recommended that 'users should ... apply multiple scenarios ... [that] span a range of possible future climates, rather than designing and applying a single "best guess" scenario', and the Canadian Institute for Climate Studies recommended that 'specific scenarios should be selected that represent the extreme ranges of the key variables required in the analysis, as well as a more moderate, intermediate scenario' (Canadian Institute for Climate Studies 2003). The relevant climate variables, such as precipitation, will depend on both the type of project and the impacts of concern. 'Archetype' scenarios can be developed to provide information suited to the needs of specific sectors and types of projects. Once scenarios are chosen, it is necessary to estimate the potential impacts that would result under each scenario for any project proposal. Byer et al. (Byer et al. 2004; Byer & Yeomans 2007) present methods that could be employed by EA practitioners to estimate the impacts under different future scenarios.

Setting up the decision framework

A hypothetical hydroelectric project facing climate change uncertainty is used to illustrate the framework for the application of the decision rules and options that allow for flexibility. As in the example in Table 1, there are three potential climate scenarios (1–3), and three project design options (A–C), each developed for one of the climate scenarios, but there are no probability estimates for the likelihood of the scenarios. The project is expected to last at least 60 years. Table 2 shows the project's initial cost and overall net financial return (in terms of present values in millions of dollars) for each combination of scenario and design option. The cost of each design option (25, 40, 62) is independent of the eventual scenario. The benefits (i.e. project revenues) can be determined from coupling the results of a scenario analysis with hydrologic watershed and facility hydraulic models in order to assess energy production. The design options represent different capacities to accommodate the streamflows associated with different climates (1 being the current climate, 2 representing a moderate change in streamflow, and 3 being a severe change from current climate). Thus, Design A is the design based on historical observation, while Designs B and C are increasingly larger facilities with greater capacity to accommodate more variability in streamflow and larger annual volumes of water, thus generating more revenue from power production. In this example the *payoffs* are financial, but the decision models could be applied to any other single metric of interest, such as hectares of arable land affected or probability of flooding, as shown later.

Decision rules for problems of uncertainty

Once the potential impacts under the various scenarios are estimated, decision rules that reflect attitudes toward risk

Table 2. Costs and net financial returns of a hypothetical hydroelectric project with three future climate scenarios.

	Up-front cost ($\times 10^6$ \$)			Net financial return ($\times 10^6$ \$)		
	Climate scenario			Climate scenario		
Design options	1	2	3	1	2	3
A	25	25	25	45	50	50
B	40	40	40	36	61	73
C	62	62	62	18	47	89

Table 3. Project payoff and regret matrices.

Net financial return ($\times 10^6$ \$)

Design options	Climate scenario 1	Climate scenario 2	Climate scenario 3
A	45	50	50
B	36	61	73
C	18	47	89

Maximin (45, circled) Maximax (89, circled)

Regret Matrix

Design options	Climate scenario 1	Climate scenario 2	Climate scenario 3
A	0	11	39
B	9	0	16
C	27	14	0

Minimax Regret (16, circled)

can be applied to determine the preferred option. Such rules include *maximin*, *maximax*, *Hurwicz-α* and *minimax regret*. Each of these is explained briefly before they are used with flexibility options.

A risk averse decision maker 'plays it safe' by paying more attention to the worst outcomes that might occur. For example, the decision-maker might select the alternative that has the best of the worst outcomes (i.e. the one that maximizes the minimum payoff deriving from the design options). This criterion, known as *maximin*, represents a very cautious or pessimistic outlook. In the example shown in the *payoff matrix* on the left side of Table 3, which is from the matrix on the right in Table 2, the worst outcomes for each of the options are 45 for A, 36 for B and 18 for C. Thus, using the *maximin* criterion, Design A would be chosen since 45 is the highest of these minimum payoffs.

Maximax is the opposite of *maximin* and represents a risk prone (optimistic) attitude. In such a case, the decision-maker focuses on the best outcome of each option, that is, 50, 73 and 89 in the example, and Design C with the best payoff would be chosen. This criterion, however, does not reflect the cautious approach generally considered appropriate for climate change. An attitude toward risk between these two extremes can be captured by another rule, the *Hurwicz-α* criterion, which provides for a balance, as represented by the α-value, between pessimism and optimism.

The *minimax regret* criterion tries to avoid making a bad decision in hindsight. It is applied by first determining the best payoff under each scenario and then referencing (subtracting) the payoff for each design (under the same scenario) from this best payoff value. For example, if Scenario 2 comes about, and Design B had been chosen, there would be no regret ($61-61=0$). However, if instead Design A had been chosen, then the project would yield 11 fewer payoff units ($61-50=11$). These values are shown in the *regret matrix* on the right side of Table 3. The maximum regret for each design option is then identified, and the option (B in the example) that results in the lowest of these is the preferred alternative.

Adaptation and the role of flexibility

The example above was restricted to making a single irreversible decision (an up-front commitment for the full investment and scope of the project) prior to project commencement. If, however, the project and its associated investment could be undertaken in more than one step, in accordance with how climate change is observed to unfold, different and potentially better payoffs might be achieved.

Phased construction and flexibility

As described earlier, strategies for flexibility can delay certain investments until climate change shows that they are necessary, but may require an additional initial cost to 'buy' the flexibility to permit such future actions to adapt to climate change, in essence paying to reduce uncertainty. This is illustrated in Figure 2 for the hydroelectric example, where time is on the horizontal axis and the present value (PV at time 0) of project costs is on the vertical axis.

In the example, the flexibility option involves designing for a smaller capacity (Design A for Scenario 1 – current climate) now with the additional flexibility charge to allow for future changes, and expanding to a larger capacity (Design B or C) depending on the degree of future climate change in order to increase electricity revenues. The up-front flexibility charge, X, reflects the incremental expenses associated with a more sophisticated design permitting future expansion. This would include the current costs of the various materials and services, such as bigger foundations and extra space for additional machinery, which would be needed to expand to one of the other design alternatives. It could also include expenses for monitoring equipment to assess the evolving climate. Such costs would, of course, depend on the specific nature

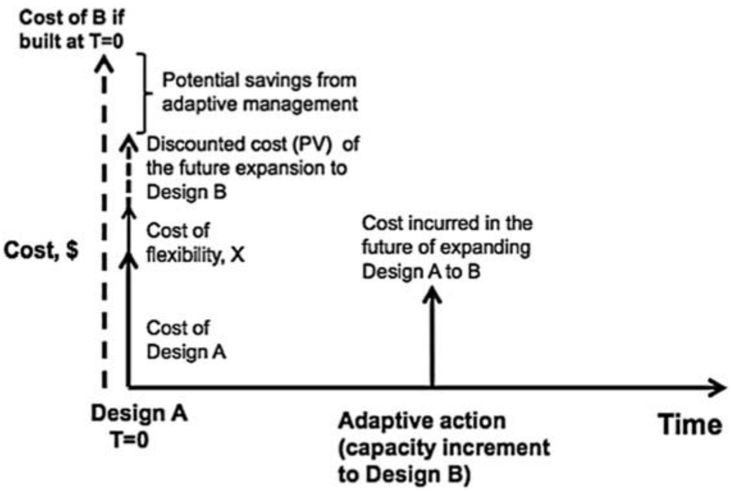

Figure 2. Costs with flexibility and phased construction.

of the project and could be determined in the same way that cost estimates are made for any engineering design.

The point in time when any adaptive action is undertaken would be when sufficient data has been collected and interpreted to indicate, with a predetermined confidence level, that the climate has reached, or will reach, a new scenario. By waiting longer, more confidence can be gained, but at the expense of having a design that does not match the changed climate.

If, for example, Scenario 2 becomes apparent, the cost of adaptation is the cost to expand from Design A to Design B, which is incurred in the future when the decision is made to adapt. With economic discounting, the present value (PV) of this additional, postponed cost is less than it would be at the time it is actually incurred. Depending on various factors, the cost of Design A plus the cost of flexibility plus the present value of the future cost of expanding to Design B may be less than the cost of implementing Design B initially.

The advantage of building in flexibility is to avoid potentially unnecessary charges for larger up-front costs that may never be needed. However, the cost of flexibility, the cost and time when adaptive action occurs and the discount rate are other factors that determine its overall economic value. Flexibility can also be used to address other impacts, as discussed later.

Flexibility offers new design options to be evaluated against other alternatives using the decision criteria discussed above. For example, Design A with the capability for future expansion constitutes a new option, Design F. Based on analyses explained in Byer et al. (2011), the present value of the net financial returns of this new option are $45 - X$, $65 - X$ and $100 - X$ for Scenarios 1, 2 and 3, respectively. These, together with the net financial returns from Table 2 for the original, non-adaptive options, are shown in Table 4.

If climate does not change (Scenario 1), the financial return of Design F is simply the financial return of Design A minus the cost of flexibility, X, since flexibility would have been spent needlessly. If, however, Scenario 2 (or 3) occurs, the financial return of $65 - X$ (or $100 - X$) is the result of the initial cost for Design A, delayed costs of

Table 4. Net financial returns for the original three designs and flexibility option.

Design options	Net financial return ($\times 10^6$ \$) Climate scenario 1	2	3
A	45	50	50
B	36	61	73
C	18	47	89
F	45 - X	65 - X	100 - X

expansion to Design B (or C), revenues from Design A until the expansion and increased revenues from Design B (or C) after the expansion.

The decision criteria discussed above can be used to determine whether the flexibility option is preferred to the other options for any given value of X, the cost of flexibility. For example, the matrices in Table 5 show the net financial returns and associated regrets for all design-scenario combinations with $X = 5$, which was chosen for illustrative purposes, but is a reasonable estimate being 8–20% of initial costs. Under the *maximin* criterion, Design A with a minimum payoff of 45 (compared with minimums of 36, 18 and 40 for the other options) would be best, while Design F (flexibility option) would be best using the *minimax regret* criterion. The regret for Design F

Table 5. Net financial returns and regrets for the original three designs and flexibility option with $X = 5$.

Net financial return (x10⁶ $)

Design options	Climate scenario 1	Climate scenario 2	Climate scenario 3
A	45	50	50
B	36	61	73
C	18	47	89
F	40	60	95

Maximin (A, 45)
When flex charge X = 5

Regret matrix

Design options	Climate scenario 1	Climate scenario 2	Climate scenario 3
A	0	11	45
B	9	0	22
C	27	14	6
F	5	1	0

Minimax Regret (F, 5)

is simply the cost of flexibility, since such flexibility would not be needed if Scenario 1 occurs. The flexibility option, in this case, allows for a potentially high return (95) and choosing Designs A or B would lead to high levels of regret (45 or 22) if Scenario 3 were to occur. How beneficial this option is depends on the cost of flexibility. As X increases, the financial returns for Design F decrease and the maximum regrets for the other options decrease, and once the cost of flexibility is greater than 9 ($X > 9$), Design B is the preferred option under *minimax regret*.

Climate transitions

Thus far, only one transformation to a future climate scenario has been considered: that climate under Scenario 1 would either not change or would change to Scenario 2 or Scenario 3 at a particular point in time, as shown in Figure 3, with time on the horizontal axis and the climate-dependent design variable of interest, such as streamflows, on the vertical axis.

In reality, the climate will likely continue to change throughout the life of a project. Figure 4 illustrates how this might occur. There is relatively smooth transition

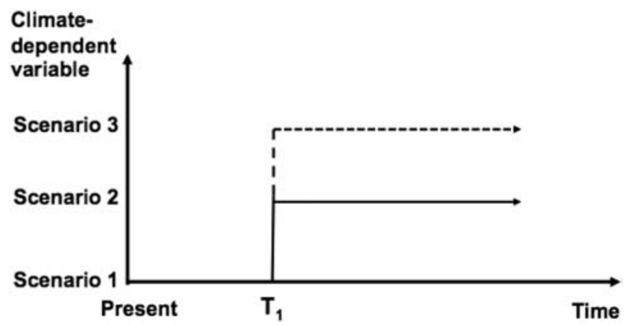

Figure 3. Single step transition from Scenario 1 to either Scenario 2 or Scenario 3.

from Scenario 1 to 2 to 3. Some adaptation measures can be undertaken on an essentially continuous basis (e.g. adjustments in reservoir release policy) while others, such as expanding capacity, can only be done in limited discrete increments due to practical considerations (e.g. how frequently construction equipment can be brought to the site), which requires assumptions about the specific times in the future when these decisions would be made. With the flexibility option (Design F), the facility is initially scaled to Scenario 1, permitting it to capture the streamflow (and associated electricity revenues) indicated in rectangle 1. When climate reaches Scenario 2, the design is modified to Design B, permitting it to capture the value of the increased streamflow indicated in rectangle 2 and, when it reaches Scenario 3, it is modified again to capture the value indicated in rectangle 3. Complicating this is the fact that it will not necessarily be clear when the climate has changed sufficiently to warrant a change in design; for example some extreme or turbulent events may appear incorrectly to be a sign of such change.

There are innumerable possible transition scenarios, and design options can be analysed for any given scenario. For example, Scenario 2–3 is a transition from Scenario 1 to Scenario 2 and then from Scenario 2 to Scenario 3, as shown in Figure 5.

Table 6 shows the net financial returns and regrets for the design options and scenarios considered so far as well as this new scenario. The analyses of the net financial returns and the assumed transition years are explained by Byer et al. (2011). Using the *maximin* criterion, Design A is best, while the *minimax regret* criterion results in Design F. These are the same results obtained without Scenario 2–3 (see Table 5). In this example, since Scenario 2–3 unfolds more slowly than Scenario 3, the delayed effects of climate change on the streamflows results in lower benefits to Designs B, C and F. However, because of this delay, the costs of expansion are spread over a longer period in

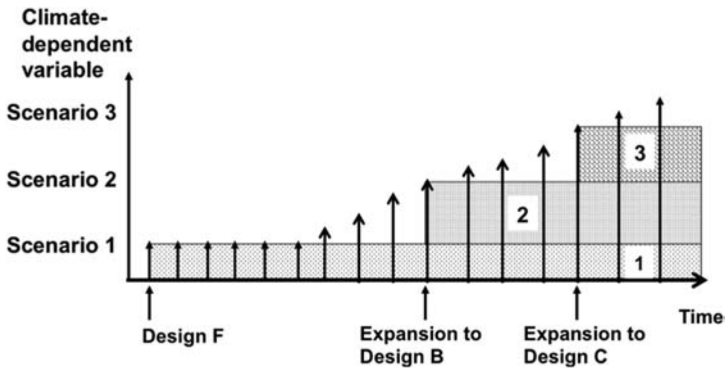

Figure 4. Smooth climate transition and phased expansion.

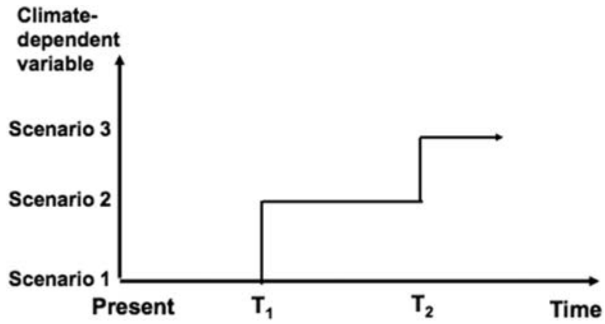

Figure 5. Scenario 2–3: dual step transition from Scenario 1 to Scenario 2 to Scenario 3.

Design F (two smaller expansions at times T_1 and T_2 instead of one larger expansion at time T_1).

Multiple attribute problems

Decisions about projects involve consideration of environmental and social consequences, as well the economic costs and benefits. In the hydroelectric example, one such impact is downstream flooding, and each of the design options can result in a different probability of flooding under each of the scenarios. Table 7 shows hypothetical annual probabilities of downstream flooding for each of the design options and three scenarios (for simplicity, Scenario 2–3 is not considered) along with the net financial returns. For each design option, increasing climate change leads to higher probabilities of flooding, and for each scenario, larger designs generally lead to lower probabilities. Table 8 shows the associated regret matrices.

The decision criteria can be applied for each impact separately to identify the preferred option for that impact. Ideally, the same design would be identified. If in our example the *minimax regret* criterion is applied to each attribute (see Table 8), Design F is the preferred alternative when considering net financial returns. When considering flooding, there is a tie among Designs B, C and F. Given this, Design F appears the best choice.

Such an evaluation may, however, result in a conflict between which alternative is best. When *maximin* is applied to the net financial returns, Design A is preferred. In order to apply the same criterion to flooding, where lower probabilities are desired, a *minimax* criterion would

Table 6. Net financial returns and regrets for the original three designs and flexibility option including transition Scenario 2–3.

Net financial return (x10⁶ $)

Design options	Climate scenario 1	2	3	2-3
A	45	50	50	50
B	36	61	73	70
C	18	47	89	74
F	40	60	95	83

Maximin

When flex charge X = 5

Regret Matrix

Design options	Climate scenario 1	2	3	2-3
A	0	11	45	33
B	9	0	22	13
C	27	14	6	9
F	5	1	0	0

Minimax Regret

Table 7. Net financial returns and annual probabilities of flooding.

Net financial return (x10⁶ $)

Design options	Climate scenario 1	Climate scenario 2	Climate scenario 3
A	45	50	50
B	36	61	73
C	18	47	89
F	40	60	95

Maximin (45) Maximax (95)

Probability of flooding

Design options	Climate scenario 1	Climate scenario 2	Climate scenario 3
A	0.02	0.06	0.15
B	0.015	0.08	0.09
C	0.01	0.07	0.11
F	0.02	0.08	0.11

Minimax (0.09)

Table 8. Regret matrices for net financial return and annual probability of flooding.

Regret matrices

Net financial return (x10⁶ $)

Design options	Climate scenario 1	Climate scenario 2	Climate scenario 3
A	0	11	45
B	9	0	22
C	27	14	6
F	5	1	0

Probability of flooding

Design options	Climate scenario 1	Climate scenario 2	Climate scenario 3
A	0. 01	0	0.06
B	0.005	0.02	0
C	0	0.01	0.02
F	0.01	0.02	0.02

be used, and this would result in a preference for a different option, Design B.

Visualization methods can help clarify these types of conflicts. As Bell et al. (2003) explained: 'Because of the large number of criteria and uncertainties in IA [impact assessment], the basic challenge is to portray highly dimensional data sets in such a way that users can grasp general trends and be stimulated to explore results further.' Data representation techniques such as bar charts, box plots, circle graphs, cartesian plots for the pairwise comparison of attributes for different policy alternatives, etc., were suggested as ways to present impact estimates and their associated uncertainties. Effective visualization and *tradeoff displays* offer simple and transparent ways to understand and communicate conflicts.

The matrices in Table 7 provide such a visualization method for the conflict between Design A and Design B when the *maximin* and *minimax criteria* are applied to financial return and flooding, respectively. As seen in the table, if Design B is chosen over Design A and:

- if Scenario 1 occurs, $9 (45–36) million is lost for a reduction of 0.005 (0.02–0.015) in the annual probability of flooding; or
- if Scenario 2 occurs, $11 (61–50) million is gained for an increase of 0.02 (0.08–0.06) in the annual probability of flooding; or
- if Scenario 3 occurs, $23 (73–50) million is gained in addition to a reduction of 0.06 (0.15–0.09) in the annual probability of flooding.

Understanding and presenting these tradeoffs and their relative importance to the various stakeholders can help determine the overall preferred option.

The above discussion applied the same decision criterion to each impact. This may not always be appropriate since the decision-maker may have different attitudes toward uncertainties for the different impacts. For example, the decision-maker may be risk averse with respect to uncertain flooding, but willing to take risks with respect to uncertain financial returns. In such cases, different decision criteria should be used for the impacts.

The above examples also used only quantitative measures, yet some criteria may be measured qualitatively. For example, if there is insufficient data to assign numerical estimates for the probabilities of flooding, as found in Table 7, there may be sufficient information to estimate the likelihoods qualitatively as illustrated in Table 9.

Some of the decision criteria, such as *minimax* and *maximin*, can be used with qualitative measures. For example, using Table 9, the *minimax* criterion results in Design B as the preferred option. A regret matrix can also be constructed for qualitative measures.

Changes in impacts over time

With the transitions in climate, there will also be transitions in the impacts. The transition in financial costs and benefits was incorporated into net present values through standard engineering economic calculations, as explained in Byer et al. (2011). This is not possible with non-economic measures. For example, as climate changes, streamflows and associated probabilities of flooding will change. But for simplicity, the example in Table 7 used probabilities that apply after the step transition as shown in Figure 3. However, before the transition, there would be different probabilities, ones that would be associated with the climate condition before the transition. Therefore, there are probabilities of flooding before and probabilities of flooding after the transition for Scenarios 2 and 3, as shown in Table 10. (In reality, these transitions would be smoother.) For example, if Design B is chosen and the climate changes to Scenario 3, the probability of flooding before Scenario 3 materializes is 0.015 (the probability under Scenario 1) and 0.09 thereafter. In the case of the flexibility option, Design F, the flooding probability is initially that of Design A, and then changes to those associated with Designs B and C for Scenarios 2 and 3, respectively.

Table 9. Qualitatively expressed likelihoods of flooding.

Probability of flooding

Design options	Climate scenario 1	Climate scenario 2	Climate scenario 3
A	L	L-M	VH
B	VL-L	M	M-H
C	VL	M	H
F	L	M	H

Minimax

VL = very low, L = low, M = medium, H = high, VH = very high

Table 10. Transitions in annual probabilities of flooding.

Probability of flooding

Design options	Climate scenario 1	Climate scenario 2	Climate scenario 3
A	0.02	0.02 0.06	0.02 0.15
B	0.015	0.015 0.08	0.015 0.09
C	0.01	0.01 0.07	0.01 0.11
F	0.02	0.02 0.08	0.02 0.11

Some of the decision criteria, such as *minimax* and *minimax regret*, can be applied in these cases. For example, since the maximum probabilities for Designs A, B, C and F are 0.15, 0.09, 0.11 and 0.11, respectively, the *minimax* criterion would result in Design B being chosen. This approach could be modified to account for the sets of before and after transition probabilities under some of the design/scenario combinations, for example, using a time-averaged value of the two probabilities.

A different design focus

As explained above, each design option was based on optimizing financial return for one of the climate scenarios. There are, however, other designs that could be considered including those that optimize a different attribute, such as flood control, for each scenario, or that try to balance multiple impacts. Table 11 shows Designs B′, C′ and F′ that are aimed primarily at flood control for the different scenarios; Design A remains the alternative designed for the current climate. The adaptive strategy in

Table 11. Net financial returns and annual probabilities of flooding for designs focused on flood control.

Design options	Net financial return (x10^6 $) Climate scenario 1	2	3
A	45	50	50
B′	29	48	58
C′	14	38	71
F′	35	53	75

Design options	Probability of flooding Climate scenario 1	2	3
A	0.02	0.02 0.06	0.02 0.15
B′	0.012	0.012 0.03	0.012 0.06
C′	0.008	0.008 0.02	0.008 0.04
F′	0.02	0.02 0.03	0.02 0.04

Table 12. Net financial returns and annual probabilities of flooding for all options.

Design options	Net financial return (x10^6 $) Climate scenario 1	2	3
A	45	50	50
B	36	61	73
C	18	47	89
F	40	60	95
B′	29	48	58
C′	14	38	71
F′	35	53	75

Design options	Probability of flooding Climate scenario 1	2	3
A	0.02	0.02 0.06	0.02 0.15
B	0.015	0.015 0.08	0.015 0.09
C	0.01	0.01 0.07	0.01 0.11
F	0.02	0.02 0.08	0.02 0.11
B′	0.012	0.012 0.03	0.012 0.06
C′	0.008	0.008 0.02	0.008 0.04
F′	0.02	0.02 0.03	0.02 0.04

this case (Design F′) follows the same pattern as for its financial counterpart (Design F): it begins as Design A with flexibility to adapt to B′ or C′ depending upon observations about climate change. Since Designs B′, C′ and F′ are designed for flood control, the probabilities of flooding and the net financial returns are lower than for Designs B, C and F, respectively.

These options should be evaluated and compared to each other as well as to Designs B, C and F, as shown in Table 12. The same decision criteria applied above can be used. For example, using the *maximin* criterion for financial return and the *minimax* criterion for flooding results in preferences for Designs A and C′, respectively, and hence a conflict. Presentation of this type of information could assist the decision-maker and other stakeholders to identify a potential compromise from among these design options, as well as other designs that could be considered. In this example, the flexibility option Design F′, which achieves reasonable returns and low probabilities of flooding compared with the other options, appears to be a promising compromise.

Conclusions

When we go outside in cloudy weather and are uncertain about whether or not it will rain, we make a decision about taking a raincoat or umbrella based on the risks of getting wet vs the extra effort involved in taking the raincoat or umbrella. Or we might decide to 'play it safe' with little inconvenience, by putting a small umbrella in a pocket in case it rains. Most of the time, this is not a difficult or significant decision. However, it is the opposite when decisions are being made about development projects that will last many decades and have environmental, social and economic consequences that depend on the shape of the future climate. For many projects, we can no longer make proper decisions based on historical climate data. Yet, with all of the information and discussion about climate change over the past several decades, there has been very little discussion about how to make such decisions in the face of the inherent uncertainties about the future climate, where we know that climate is changing but are uncertain how, how much and how quickly, and do not have reliable probability estimates about this.

This paper has tried to help rectify this by setting out a framework and explaining the use of well-established criteria for making decisions in the face of uncertainties. Their use would require that the implications of climate change uncertainties and attitudes toward risk be confronted and understood before decisions are made. We have also discussed how adaptation strategies with flexibility can help reduce the effects of uncertainties by allowing for adjustments in designs as the future climate evolves. Given the potentially high environmental, social and economic costs of making a 'wrong' decision, building in flexibility has its advantages. However, by necessity, our work has made a number of simplifying assumptions, and more work is clearly needed to further develop, test and share better methodologies and approaches.

Acknowledgements

The paper is based on a report by the authors prepared with the financial support of the Canadian Environmental Assessment Agency's Research and Development Program. The authors gratefully acknowledge the Agency for this support. The views and conclusions expressed herein are those of the authors and do not represent the views of CEAA or the Government of Canada. We also thank two anonymous reviewers for their useful suggestions.

References

Bell ML, Hobbs BF, Elliott EM, Ellis H, Robinson Z. 2001. An evaluation of multi-criteria methods in integrated assessment of climate policy. J Multi-Criteria Decision Anal. 10:229–256.

Bell ML, Hobbs BF, Ellis H. 2003. The use of multi-criteria decision-making methods in the integrated assessment of climate change: implications for IA practitioners. Socio-Econ Plan Sci. 37:289–316.

Bretteville C. 1999. Decision criteria under uncertainty and the climate problem. Working Paper 1999:10. Oslo: CICERO – Center for International Climate and Environmental Research.

Byer PH, Colombo AF, Sabelli A, Ches C. 2011. Decision making under uncertainties for adapting to climate change in project environmental assessments. Report prepared for the Canadian Environmental Assessment Agency.

Byer PH, Lalani MJ, Yeomans JS. 2009. Addressing and communicating climate change and its uncertainties in project environmental impact assessments. J Environ Assess Policy Mgmt. 11(1):29–50.

Byer PH, Yeomans JS. 2007. Methods for addressing climate change uncertainties in project environmental impact assessments. Impact Assess Project Appraisal. 25(2):85–99.

Byer PH, Yeomans JS, Lalani M. 2004. Addressing climate change uncertainties in project environmental assessments. Report prepared for the Canadian Environmental Assessment Agency.

Canadian Institute for Climate Studies. 2003. Canadian climate impacts scenarios [cited 2003 Apr 24]. Available from: http://www.cics.uvic.ca/scenarios/index.cgi.

Clarke H. 2008. Classical decision rules and adaptation to climate change. Austr J Agric Resource Econ. 52:487–504.

de Bruin KC, Dellink RB, Tol RSJ. 2009a. AD-DICE- an implementation of adaptation in the DICE model. Climat Change. 95:63–81.

de Bruin K, Dellink RB, Ruijs A, Bolwidt L, van Buuren A, Graveland J, de Groot RS, Kuikman PJ, Reinhard S, Roetter RP, Tassone VC, Verhagen A, van Ierland EC. 2009b. Adapting to climate change in The Netherlands: an inventory of climate adaptation options and ranking of alternatives. Climat Change. 95:23–45.

de Neufville R. 2002. Architecting/designing engineering systems using real options. MIT Engineering Systems Symposium on the Intellectual Foundations of Engineering Systems.

de Neufville R. 2004. Uncertainty management for engineering systems planning and design. Engineering Systems Monograph, Engineering Systems Symposium, 2004 Mar 29–31. Cambridge (MA): MIT.

Dessai S, van der Sluijs J. 2007. Uncertainty and climate change adaptation – a scoping study. Utrecht: Copernicus Institute for Sustainable Development and Innovation.

Dobes L. 2008. Getting real about adapting to climate change: using 'real options' to address the uncertainties. Agenda. 15(3):55–69.

Duinker PN, Trevisan LM. 2003. Adaptive management: progress and prospects for Canadian forests. In: Burton PJ, Messier C, Smith DW, Adamowicz, WL, editors. Towards sustainable management of the boreal forest. Ottawa: NRC Press. p. 857–892.

European Climate Adaptation Platform [Internet]. 2012. How to factor uncertainty into adaptation decision-making? [cited 2012 Aug 21]. Available from: http://climate-adapt.eea.europa.eu/web/guest/uncertainty guidance/topic2?p_p_id=56_INSTANCE_qWU5&p_p_lifecycle=0&p_p_state=normal&p_p_mode=view&p_p_col_id=column-1&p_p_col_count=1 What+are + different + types + of + adaptation + options %3F.

Feenstra JF, Burton I, Smith JB, Tol RSJ, editors. 1998. Handbook on methods for climate change impact assessment and adaptation strategies, version 2.0. Amsterdam: United Nations Environment Programme and the Institute for Environmental Studies, Vrije Universiteit.

Hauser CE and Possingham HP. 2008. Experimental or precautionary? Adaptive management over a range of time horizons. J Appl Ecol. 45(1):72–81.

Hobbs BF. 1997. Bayesian methods for analysing climate change and water resource uncertainties. J Environ Mgmt. 49:53–72.

Hobbs BF, Chao PT, Venkatesh BN. 1997. Using decision analysis to include climate change in water resources decision making. Climat Change. 37:177–202.

IPCC. 2001. Climate change 2001: impacts, adaptation, and vulnerability. McCarthy JJ, Canziani OF, Leary NA, Dokken DJ, White KS, editors. Contribution of Working Group II to the third assessment report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

IPCC. 2007. Climate change 2007: impacts, adaptation and vulnerability. Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE, editors. Contribution of Working Group II to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

Kassouf S. 1970. Normative decision making. Englewood Cliffs (NJ): Prentice-Hall.

Lee KN. 1999. Appraising adaptive management. Ecol Society. 3(2):3.

Luce RD, Raiffa H. 1957. Games and decisions. New York: John Wiley & Sons.

Qin XS, Huang GH, Chakma A, Nie XH, Lin QG. 2008. A MCDM-based expert system for climate-change impact assessment and adaptation planning – a case study for the Georgia Basin, Canada. Expert Syst Applic. 34:2164–2179.

United Nations Framework Convention on Climate Change Secretariat. 2008. Compendium on methods and tools to evaluate impacts of, and vulnerability and adaptation to, climate change.

Willows RI, Connell RK, editors. 2003. Climate adaptation: risk, uncertainty and decision-making. Technical Report. Oxford: United Kingdom Climate Impacts Programme.

Yang M, Blyth W, Bradley R, Bunn D, Clarke C, Wilson T. 2008. Evaluating the power investment options with uncertainty in climate policy. Energy Econ. 30(4):1933–1950.