Integrating Multicriteria Decision Analysis and Scenario Planning – Review and Extension

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Abstract

Scenario planning and multiple criteria decision analysis (MCDA) are two key management science tools used in strategic planning. In this paper, we explore the integration of these two approaches in a coherent manner, recognizing that each adds value to the implementation of the other. Various approaches that have been adopted for such integration are reviewed, with a primary focus on the process of constructing preferences both within and between scenarios. Biases that may be introduced by inappropriate assumptions during such processes are identified, and used to motivate a framework for integrating MCDA and scenario thinking, based on applying MCDA concepts across a range of "metacriteria" (combinations of scearios and primary criteria). Within this framework, preferences according to each primary criterion can be expressed in the context of different scenarios. The paper concludes with a hypothetical but non-trivial example of agricultural policy planning in a developing country.

Keywords: multicriteria decision analysis, scenario planning, decision making under uncertainty

1. Background and Context

Our initial motivation for this paper was a concern that many quantitative decision analytic models do not adequately deal with the many uncertainties and risks

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that arise in long term strategic decision making contexts. We are particularly concerned with the use of multi-criteria value models and, to some extent, decision trees and influence diagrams, but the same difficulties occur in using other quantitative models: we would contend all other quantitative models. French [9] has written on the different forms of uncertainty that may arise in decision modelling and analysis and this paper to some extent extends that to thinking into the different contexts recognized by Snowden's Cynefin model discussed below. Belton and Stewart [1] provide a detailed discussion of the issues involved in dealing with uncertainties in multiple criteria decision analysis (MCDA); and French [10] discusses the varied roles of sensitivity analysis in addressing particular forms of uncertainty. There are, of course, many other discussions of how uncertainty might/should be addressed in decision analysis in the literature: for instance, Berkeley and Humphreys [2], Durbach and Stewart [7, 8], Graves and Ringuest [20], Jiménez et al. [22], Morgan [32], Morgan and Henrion [33], Papadopoulos and Karagiannidis [34], Roy [39], Walker et al. [48].

Given that some of the motivation for our work came from considerations of strategic energy planning [e.g., 16], it is interesting to note that problems of (multi-criteria) decision making under uncertainty have received particular attention in the area of power systems planning, for example in Crousillat et al. [5], Gerking [17], Gorenstin et al. [19], Linares [26], Millán et al. [27], Miranda and Proença [29]. This work recognized the need to balance risks by explicitly considering performance under different scenarios, and thus parallels much of our discussion below. The approach is primarily integrated into (multiobjective) mathematical programming rather than the discrete strategic choice including qualitative goals, which is our primary theme. We also seek a more formal basis for integrating performance under different scenarios with concepts of multi-criteria decision analysis.

Building primarily on work by Wright and Goodwin [51], Goodwin and Wright [18], Stewart [44], Montibeller et al. [31] and Schroeder and Lambert [40], we discuss here how the use of scenarios to articulate a family of related decision analyses may help address some gross uncertainties which can arise in dealing with strategic issues and/or long time horizons. Moreover, although our motivation grew from consideration of how uncertainties might be addressed, we also explore the use of scenarios to articulate discussion between different stakeholders, allowing each to explore their preferences between alternative strategies in the context of a range of future worlds: some representing how they would like their political and social environment to evolve, others less desirable futures.

Our broad aim in this paper is to review and explore synergies between two streams of management science: *quantitative decision analytic modelling*, particularly MCDA and multiobjective optimization approaches, and *scenario planning*. Although we refer to decision analytic modelling, we would emphasize that our discussion embraces process and behavioural issues in both of the streams to which we refer. We shall also use the term *scenario-thinking* to include any use of scenarios to inform analysis and deliberation, reserving the term *scenario-planning* for the approach and processes that derive from the work of Van der Heijden [46] and his colleagues at Shell. Our approach is to review various scenario based and multi-criteria decision making approaches, focussing particularly on integration of these concepts, after which we propose a framework for integrated decision analysis. In this approach, we shall address two general themes:

- **What does scenario-thinking offer to the practice of decision analysis, particularly MCDA?** Probability is used to model uncertainty in the formal quantitative decision models to which we usually subscribe, *viz.* Bayesian decision analysis based upon subjective expected multi-attribute utility models [15, 24]. However, the incorporation of complete multivariate probability distributions on performance measures (*attributes* or *criteria*) into formal multi-criteria models raises many implementation issues. We shall argue that the framework given by a well-chosen set of scenarios provides opportunities for circumventing some of these. For instance, if we can capture gross uncertainties through the differences *between* scenarios, then we may be able to articulate the uncertainties *within* scenarios through tractable and assessable probability distributions or even work with deterministic models and carefully structured sensitivity analyses. However, scenario thinking offers much more to the practice of quantitative decision analysis than simply a tractable way of addressing gross uncertainties. In the problem structuring, value elicitation and strategy construction phases, a focus on distinct scenarios can provide greater clarity of thought and communication to the process. It may help participants see and explore contingencies [15]. Moreover, there are circumstances in which preferences may be conditional on the structure, both in terms of the attribute tree and the form of the multi-attribute value function [14]. It may elucidate causes of conflict between participants, perhaps because each may have been thinking in terms of different scenarios. Above all, it can stimulate creative thinking, e.g. helping to design strategies which perform well in terms of goal achievement across scenarios, which can perhaps be viewed as robustness to uncertainty, although as we shall observe later, a mechanical interpretation of robustness in terms of variability across scenarios may not fully capture "robust" goal achievement concerns. Other concerns include accommodation of concerns of stakeholders and the representativity of the selected scenarios.

- **What does decision analytic modelling, especially MCDA, offer the practice of scenario planning?** Just as the introduction of scenarios into a decision analysis can elucidate preferences and conflicts, so the explicit introduction of evaluation criteria into scenario planning can catalyse creativity and clarify the goals of the different participants. It introduces value focused thinking with all the ensuing benefits [23]. The practice of scenario planning includes evaluation of potential strategies in terms, for example, of

> their robustness in some sense, often not quantitatively defined across scenarios. This evaluation is typically not supported by formal analysis nor any checks on consistency. Decision modelling within each scenario could provide a template for more structured evaluation that may avoid the dangers of overlooking some important concerns or interests (criteria). As there certainly exist MCDA tools and models that can cope with ambiguity and imprecision of preferences, the appropriate MCDA could provide valuable support to the evaluation phase of scenario planning.

It is our contention then that the scenario-thinking which has underpinned the development of scenario planning can also bring huge benefits to decision modelling; and ultimately we seek a seamless integration of scenario planning and quantitative decision analysis. Taking the two approaches together may enrich deliberation by allowing the construction and evaluation of alternatives to include consideration of their advantages or disadvantages for different criteria under different scenarios. Ours is not the only work in this area and there are parallels with that of, *inter alia*, Goodwin and Wright [18], Wright and Goodwin [51], Montibeller et al. [31], Montibeller and Franco [30], Schroeder and Lambert [40].

Some of our thinking has been shaped by Snowden's Cynefin categorization of decision contexts [41], and illustrated in Figure 1. Cynefin is the Welsh for 'habitat', or at least that is its narrow translation; [41] indicates that it also contains connotations of familiarity. He originally developed the model to support discussions of knowledge management, but it has a much wider range of applicability [11, 12, 42]. Thus although his formulation is not commonly referenced in the literature on either decision analysis or scenario planning, we believe it provides a framework for thinking about the integration of these areas.

The Cynefin model roughly divides decision contexts into the four spaces indicated in Figure 1. In the *known space*, or the *Realm of Scientific Knowledge*, the relationships between cause and effect are well understood. All systems and behaviours can be fully modelled. The consequences of any course of action can be predicted with near certainty. In such contexts, decision making tends to take the form of recognising patterns and responding to them with well rehearsed actions. Klein [25] discusses such situations as recognition primed decision making; Snowden describes decision making in these cases as CATEGORISE, RESPOND. In the *knowable* space, the *Realm of Scientific Inquiry*, cause and effect relationships are generally understood, but for any specific situation there is a need to gather and analyse further data before the consequences of any action can be predicted with any certainty. This is the realm in which the standard methods of decision analysis as found in, say, Clemen and Reilly [4] apply. Snowden characterises decision making in this space as SENSE,RESPOND. In the *complex* space, often called the *Realm of Social Systems* though such complexity can arise in environmental, biological and other contexts, decision making situations involve too many interacting causes

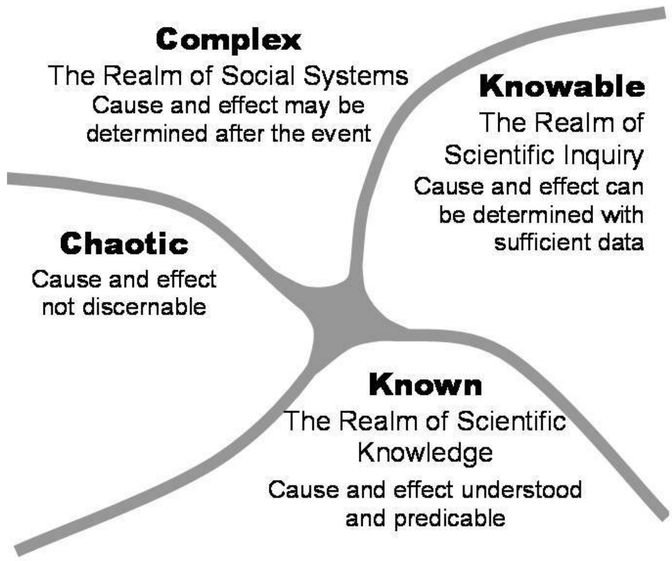

Figure 1: Snowden's Cynefin categorization of decision contexts

and effects for us with our present knowledge to disentangle particular causes and effects. There are no precise models to predict system behaviours such as in the known and knowable spaces. Decision analysis is still possible, but its style will be broader, with less emphasis on details, more exploration of judgement and an aim to develop broad strategies that are flexible enough to accommodate changes as the situation evolves. Analysis may begin and, perhaps, end with much more informal qualitative models and approaches to sense-making [49, 50], sometimes known under the general heading of soft modelling, soft OR or problem structuring methods [for example, the special issues of the *Journal of the Operational Research Society*, Vol. 57, No. 7, 2006 and Vol. 58, No. 5, 2007, as well as 28, 35, 38]. Scenario planning approaches are very relevant here. If quantitative models are used, then they are simple, perhaps linear multi-attribute value models [1], focused much more on exploring and evolving judgement, particularly preferences. Snowden suggests that in these circumstances decision making will be more of the form: PROBE, SENSE, RESPOND. Finally, in the *chaotic* space, situations involve events and behaviours beyond our current experience and there are no obvious candidates for cause and effect. Decision making cannot be based upon analysis because there are no concepts of how to separate entities and predict their interactions. Decision makers will need to take probing actions and see what happens, until they can make some sort of sense of the situation, gradually drawing the context back into one of the other spaces. Snowden suggests that such decision making can be characterised as ACT, SENSE, RESPOND. More prosaically, we might say 'trial and error' or even 'poke it and see what happens!'

The boundaries between the four spaces should not be taken as hard; the interpretation is much softer with recognition that there are no clear cut boundaries and, say, some contexts in the knowable space may well have a minority of characteristics more appropriate to the complex space.

Against the backdrop of the Cynefin model, we may articulate our thinking as follows. Firstly, note that contexts which fall into the known and knowable spaces are necessarily repeatable or commonly occurring in some sense; otherwise we would not have developed sufficient understanding to infer and test scientific theories and hence build predictive models [11]. Contexts in the complex and certainly in the chaotic spaces tend to be novel. In this sense, the differing levels of repeatability relate to the varying levels of familiarity that are echoed in Snowden's adoption of the name Cynefin for his model. In the known and knowable spaces we have sufficient experience to build probability and value/utility models to represent our uncertainties and preferences respectively. In the complex region we lack that experience. However, by focusing on scenarios that are interesting in some sense we may reduce our unfamiliarity so that *within* each scenario we do have sufficient experience and knowledge to build models that can usefully inform our deliberations. Although we might categorize the overall context as complex, within each scenario behaviours and patterns fall much more into those categories that we find in the knowable or known spaces. Within each scenario we know enough to build more valid and useful models.

We might also use scenarios in the complex space to deal with value issues. Situations in the complex space are necessarily somewhat novel, since any previous occurrence would imply some element of repeatability. It is therefore probable that decision makers facing up to such situations would need to think though their preferences and values, perhaps catalysing their thinking through by seeking to construct an attribute or value tree [23]. Sometimes this might lead to an agreed set of values across a group of decision makers and stakeholders; but other times it may not. Disagreement may arise from many causes; but often it arises because we do not share the same fundamental values. Cultural theory [6, 45] have explored such differences finding that values are shared within broad subgroups in society but differ between them. If scenarios were constructed to represent an ideal future from the perspective of each of such subgroups, then this might support constructive debate and deliberations. Each subgroup could see how different strategies would play out against their ideal future and also against the ideal futures of other subgroups. The process would separate their concerns about the way they would like the world to change generally from the specifics of the given decision. In doing so it might clarify their values in relation to the decision.

There seems to us, therefore, to be considerable advantage in exploring how quantitative decision analytic modelling might be used within scenarios when deliberating on issues and decisions lying within the complex space.

For the remainder of the paper we focus on the interplay between MCDA and scenario thinking. In a companion paper on the modelling of the economic, environmental and social sustainability of nuclear energy in the context of UK power generation, we discuss some aspects of a similar interplay between decision tree and influence diagram modelling and scenario thinking [16].

2. Defining Scenarios

A key problem confronting any discussion of MCDA and scenario planning is that of appropriately defining the term *scenario*, which tends to have somewhat distinct meanings within scenario planning and the decision analytic disciplines. In everyday language, most dictionaries, including the *Oxford English Dictionary*, define a scenario as "A sketch or outline of the plot of a play, ballet, novel, opera, story, etc., giving particulars of the scenes, situations, etc." or a "A film script with all the details of scenes, appearances of characters, stage-directions, etc." Within scenario planning, scenarios are essentially a backdrop against which to frame strategic conversations. Within decision analysis scenarios are usually associated with future uncertainties, rather than future possibilities. For instance, Raiffa [36] identifies scenarios with paths along branches in a decision tree; French and Rios Insua [13] suggest that a scenario may be thought of as an ultimate consequence at the end of a branch in a decision tree, mindful of the costs and choices made in arriving at that consequence. We have suggested above that scenarios might be used to explore different value perspectives. A quite superficial scanning of the management literature reveals a number of other distinct definitions, each related to the specific purposes which the authors intend for the scenarios: Hughes [21] provides a useful overview. We outline some of these definitions, which are particularly relevant to our discussion, below, while a summary is given in Table 1.

Shell Scenario Planning Approach: This approach is well-documented by Van der Heijden [46]. The emphasis is on constructing a coherent story of the future context against which the consequences of policies or strategies will be worked out. The intention of having alternative scenarios is primarily seen to be that of providing the basis for a "strategic conversation" concerning pros and cons of strategic decision options. The scenario relates to external events against which policies are compared and evaluated. The Horizon Scanning Toolkit provided by the UK's Department for Business, Innovation and Skills is clear that[2]: "Scenarios are a way to structure, think about, and plan for, future uncertainties. It requires the articulation of more than one possible future (typically three or four). Scenarios do not predict the future. Rather they provide the means to consider today's policies and decision-making processes in light of potential future developments." It is stressed in this approach that policy options *do not* form part of the scenario.

[2] `hsctoolkit.tribalhosting.net/The-tools.html`, visited 13/3/2011.

Scenarios for exploring uncertainty: Scenarios may be used to explore how different uncertainties may play out, i.e. to explore a range of possible outcomes: see, e.g., Walker et al. [48]. In some senses this use of scenarios is similar to that within scenario planning described immediately above. The key difference is that there are no identified strategies needing to be evaluated against them. One simply explores possible futures, maybe to stimulate thinking about whether a change in strategy is necessary or whether there are opportunities that might be capitalised upon. Government Foresight studies are a good example of such a use: precursors to subsequent development and deliberation of specific strategies.

Scenarios for advocacy or political argument: This approach is closely allied to the previous two, but policy decisions or directions which are either being advocated or opposed are now explicitly included in the scenario, in order to emphasize plausible consequences of the policy directions. The purpose in producing the scenario is to create a story which highlights either the benefits or dangers of following one or other policy. Hughes [21] refers to utopian or dystopian perspectives being embedded in such uses of scenarios. The scenarios developed for South African political futures at a workshop involving a number of significant players during 1991/1992 are often held up as an example of this use of scenarios (and suggested as a major driver in the relatively peaceful transition which followed)[3]. Even the names chosen to describe the scenarios ("ostrich", "lame duck", "Icarus" and "flight of the flamingos") were chosen to evoke strong emotive responses. However significant these scenarios were in influencing the direction of negotiations in South Africa, they did not involve any analytical comparison of policy options . . . the "flight of the flamingos" was embraced as self-evidently the only desirable future.

Representative sample of future states: This is perhaps a more technical approach. Future states are conceptualized in terms of a multivariate probability distribution on the state space. It is, however, recognized that the complete distribution may never be fully identified, and may in any case be too mathematically complicated to permit clear analysis of management options. For this reason, analysis will be based on a small number of representative outcomes in the sample space, but designed for good coverage as in experimental design, rather than selected randomly or because they seem "interesting".

French et al. [15] offer a 4-level categorization of the level of support offered by different decision modelling and analytic tools. Level 0 simply describes the cur-

[3] For a detailed description, see Global Business Network, paper accessed on 4 Jan 2011 from `http://www.generonconsulting.com/publications/papers/pdfs/Mont Fleur.pdf`.

rent situation; level 1 predicts how the current situation may evolve without any intervention or decision on the part of the decision makers; level 2 explores how different interventions may change that evolution; while level 3 changes perspective from simply being on possible futures and helps the decision makers explore their beliefs and preferences in relation to the potential intervention and the resulting outcomes. In these terms, the first and third uses of scenarios listed above seek to provide level 2 and, perhaps, qualitative level 3 support; whereas the second and fourth uses are restricted to level 1 support.

With few exceptions, discussions of scenario planning do not include formal methods of decision analysis. In fact, care needs to be exercised when attempting to apply decision analysis to issues arising from a scenario planning exercise. In the next section, we discuss requirements that would need to be placed on the formulation and structuring of scenarios for purposes of applying MCDA to the evaluation of policy options in this context.

3. Scenarios for Decision Analysis

Most of the tools of multicriteria decision analysis or multiobjective optimization are essentially deterministic in nature, i.e. for any specified course of action (a, say), a measure of performance ($z_j(a)$) is assumed to be determinable, and the process of MCDA is primarily aimed at reconciling conflicts between criteria. Any uncertainties in the performance measures (whether aleatory or epistemic) are frequently dealt with by forms of sensitivity analysis. Some approaches, e.g. interval programming [47] and others such as [22], do explicitly allow for moderate ranges of outcomes, but are often motivated by internal uncertainties (epistemic uncertainty, or imprecision) or to relatively moderate external uncertainties. The more substantial uncertainties regarding external factors which are the domain of scenario planning for strategic decisions, often including qualitatively different structures which may arise, would be more difficult to model in terms of simple performance intervals. Similar comments apply to the application of fuzzy sets to decision analysis [cf. 44].

The field of multiattribute utility theory (MAUT) [see, e.g., 24] provides a highly structured, fully axiomatized methodology dealing with uncertainties in outcomes, which should in principle at least be applicable to the strategic uncertainties we are discussing. MAUT is typically applied to discrete choice problems which is also our main context of discussion. For these reasons, we shall focus on MAUT for the purposes of the current paper, although many of the principles may well be applicable to other MCDM methods. MAUT, in essence involves two key features:

1. Denote by $Z_j(a)$ the measure of performance in terms of criterion j given action a, which is now viewed formally as a *random variable*. Let $\mathbf{Z}(a)$ be the vector of random variables $Z_j(a)$. At least marginal distributions on each

Table 1: Different Perspectives on Scenarios

Concept	Context	Purpose	Role of Formal Decision Analysis
External situations affecting consequences of policy actions	Emphasis on external uncertainties and future states; policy components excluded	To provide a *strategic conversation* between stakeholders, with consideration of the robustness of alternatives	No formal methods of evaluation used
Exploration of future conditions or environments	Creation of possible futures as a starting point for planning	To provide coherent "stories" of the future instead of statistical forecasts	No explicit comparison of alternatives
Advocacy of particular courses of action	Similar to that of exploring futures, but with the explicit inclusion of policy responses	To present arguments for or against particular policy directions	Policies are not formally compared, but may be fine-tuned within each scenario using conventional decision analytical approaches
Representative sample of future states	Discrete representation of a multivariate distribution describing current and/or future unknown states	Simplification of the assessment and analysis of inputs, especially for multiattribute utility models	Conventional decision analysis applied using the sample of states as the full distribution

$Z_j(a)$, but in most cases the complete multivariate probability distribution of $\mathbf{Z}(a)$ (see below) needs to be identified for each a.

2. A multiattribute utility function, say $U(\mathbf{z})$ is constructed such that a is preferred to b if and only if $\mathrm{E}[U(\mathbf{Z}(a))] > \mathrm{E}[U(\mathbf{Z}(b))]$. Keeney and Raiffa [24] establish forms of utility function which may arise under various axiomatic assumptions.

The key point to note in connection with multiattribute utility theory is that unless the very special property termed *additive independence* holds (which is difficult to verify but unlikely to hold in many instances), then evaluation of $\mathrm{E}[U(\mathbf{Z}(a))]$ does require a complete specification of the multivariate distribution of $\mathbf{Z}(a)$.

It is our view firstly that sensitivity analysis approaches are inadequate for dealing with complex multivariate structural uncertainties that confront much strategic planning. On the other hand, the elicitation of complete multivariate distributions, often at least partially by subjective evaluation, is typically cognitively and operationally too demanding to be a practical tool (and we note that very few applications of the full MAUT approach appear to have been reported in the literature). It is here that scenario thinking plays a role. Well-constructed scenarios can deal with complex inter-related futures, while not demanding complete probability distributions. The question, however, is to give operational meaning to the concept of "well-constructed" in the decision analytic context.

In common with scenario planning, the primary requirement of scenarios to be used in MCDA is to provide a description of the context within which the consequences of any policy action will be played out. As the purpose of the decision analysis is to evaluate and compare actions or policies, it is *essential* that the scenarios reflect external driving forces (events, states) which are separated from the policies or actions under consideration.

The multicriteria nature of the analysis requires that consequences contingent upon a specific action-scenario combination should be expressible in terms of the chosen set of decision criteria. It is thus important to capture the potential ranges of impact for all these criteria. In other words, scenarios for MCDA should be constructed to span the range of uncertainty in impacts for all criteria over all courses of action. Important (positive or negative) correlations between performance measures for the various criteria should also be captured. Since the uncertainties will include the epistemic, the ranges of perceptions of different stakeholder groups should also be spanned in some way.

Ultimately, actions need to be evaluated and compared on the basis of performance in terms of each criterion under conditions of each scenario. Practically, therefore, the product of number of criteria by number of scenarios needs to be cognitively manageable. We conjecture that this product should not exceed about 30–50. On the other hand, to capture ranges of uncertainties and potential interactions would surely require more than just 2 or 3 scenarios. These observations suggest around 4–6 scenarios would be expected in most multicriteria decision making problems, perhaps more in large studies involving several weeks or months of analysis (e.g. major reports to government).

In summary, therefore, we would suggest the following guidelines in constructing scenarios for (multicriteria) decision analysis.

1. About 4–6 scenarios need to be constructed.
2. The scenarios must be defined in terms of exogenous drivers.
3. The scenarios need to cover ranges of outcomes expected as well as key associations between the variables.
4. In circumstances in which there are substantial differences between the fundamental values of stakeholders there may be an advantage in using scenarios which represent different ideal worlds.

4. Applying MCDA to Scenario Structures

Some of the earlier multiobjective programming work in power systems planning previously cited do integrate scenario approaches in order to deal with uncertainties. For example, Miranda and Proença [29] discuss a problem involving three criteria under three load scenarios in a power system. The criteria are aggregated within each scenario, leading to a comparison of performances for each alternative strategy under each scenario. This representation is similar to that of Goodwin and Wright which we discuss below, but Miranda and Proença [29] include a structured min-max regret criterion for comparing across scenarios. A quite similar approach is adopted by Millán et al. [27], also in power systems planning, where the uncertainties modelled by the scenarios include demand growth, fuel and construction costs.

In some ways, the work of Linares [26] is closest to the context we discuss below. Alternative strategies are evaluated according to a set of criteria for each of a number of scenarios. Preferences within each scenario are assessed using AHP, and an optimal strategy selected for each scenario using goal programming. An interesting feature of this paper is the attention paid to potentially different preferences for different stakeholder groups. This stage of the analysis gives rise to a table of performance measures for alternatives x scenarios. This is again similar to the work of Goodwin and Wright discussed below, although Linares [26] seem to restrict attention to the best strategies under each scenario (rather than all strategies in Goodwin and Wright's approach).

The context which motivated our studies involved primarily discrete choices, necessitated by the fact that qualitative criteria played a significant role, so that performance evaluation will include a component of subjective judgement which is typically not possible in mathematical programming structures. This context is that discussed by Goodwin and Wright [18], which we shall shortly describe. First, however, we need to introduce some further formal notation.

For ease of presentation, suppose that we have a finite number n of alternatives indexed by $i = 1, 2, \ldots, n$. These are to be evaluated against m criteria ($j = 1, 2, \ldots, m$) under condition of p scenarios ($r = 1, 2, \ldots, p$). Let z_{ijr} be a suitable measure of performance of alternative i in terms of criterion j under conditions of scenario r (typically some natural attribute defining performance in an operationally meaningful manner). At this stage we do not assume anything more than ordinal properties in the sense that alternative i is preferred to alternative k (say) according to criterion j under the assumptions of scenario r if and only if $z_{ijr} > z_{kjr}$. Each alternative is thus differentiated from other alternatives in terms of a 2-dimensional ($m \times p$) array of performance measures. How then do we support comparative evaluation of alternatives?

Goodwin and Wright [18] in effect propose a three stage process:

1. Create an additive value function model across the m criteria, say $\sum_{j=1}^{m} w_j v_j(z_j)$, where the partial value functions $v_j(z_j)$ are defined over a range that includes z_{ijr} for all alternatives and scenarios.
2. For each alternative-scenario pair, calculate a "value" using this value function, say $V_{ir} = \sum_{j=1}^{m} w_j v_j(z_{ijr})$.
3. Display the $n \times p$ table of V_{ir} values to the decision maker for a final selection: Goodwin and Wright do not discuss the process behind this selection, nor requirements of associated decision support, but the implication seems to be that of seeking some form of robustness across scenarios. Possibly some form of min-max regret criterion as suggested in Miranda and Proença [29], Linares [26] and also by Montibeller et al. [31] could be adopted here, in order to minimize variability of outcomes across scenarios and/or to avoid extreme negative outcomes.

Perhaps the critical assumption in the above approach is that of a scenario-independent value function, i.e. that value trade-offs between criteria are the same under all scenarios. Such an assumption is by no means self-evidently true. Consider, for example, the evaluation of national development strategies (especially in a developing country context), where two important criteria may be socio-economic equity and environmental conservation, while scenarios relate to world economic conditions. It seems plausible that for many political decision makers, preference trade-offs between the two criteria would be different in a scenario of broad economic expansion (when costly conservation measures can be "sold" to the populace), than in a scenario of recession. Schroeder and Lambert [40] introduce scenario based weighting, though we remain to be convinced by their method of assessing the weights within a given scenario by considering difference with a base or "as planned" scenario. In similar vein, French et al. [14] discuss "event conditional attribute modelling" in the context of nuclear emergency management. The issues raised by Bordley and Hazen [3] also suggest that there is a danger in assuming too strong an independence between scenarios.

Montibeller et al. [31] describe experiences in applying the Goodwin and Wright model, and argue that problems do arise in the simultaneous assessment of outcomes of all alternative-scenario combinations on the same basis. They thus proposed a modification to the Goodwin-Wright model by applying MCDA (multiattribute value theory) *within* each scenario. It is accepted that, for example, weights associated with different criteria may, and quite typically do vary from scenario to scenario. This provides an evaluation of alternatives separately for each scenario. Montibeller et al. do not seek any formal aggregation across scenarios, but do seek to identify alternatives which are robust across scenarios in a sense which again emphasizes variability across scenarios.

Focussing on the Goodwin-Wright formulation, we observe that choice between alternatives on the basis of the V_{ir} is not an elementary process, and that "robustness" across scenarios is not necessarily either well-defined or desirable when defined mainly in terms of variability alone as the following example illustrates[4].

Example: We have two alternatives (a_1 and a_2), two criteria (C_1 and C_2), two scenarios (S_1 and S_2) and two possible outcomes (expressed as 0 or 1) on each criterion. Consequences for each action and scenario in terms of each criterion are given in Table 2.

Table 2: Description of consequences for the simple example

Alternative	Scen. S_1		Scen. S_2	
	Crit. C_1	Crit. C_2	Crit. C_1	Crit. C_2
a_1	0	0	1	1
a_2	1	0	0	1

The important distinction between the two alternatives is that a_1 results in equal performance on both criteria under either scenario, while a_2 results in diametrically opposing performances on the two criteria under either scenario. In consequence of this distinction:

- In contexts where considerations of equity between criteria are dominant (e.g. where the criteria are linked to interests of different stakeholders), a_1 would be preferred to a_2;

[4]Forebears of this example may be traced back to Raiffa's seminal RAND Memorandum [37] and beyond

- In contexts in which tradeoffs between criteria are permissible, a risk averse decision maker would prefer a_2 to a_1.

The important point which we are emphasizing is that either alternative could be preferred by rational decision makers, depending on the underlying value structures. Of course, a full MAUT analysis would resolve these issues completely, but it is not clear that simpler aggregation methodologies would capture the relevant preferences. We do acknowledge that any methodology should never be applied mechanically, and should rather facilitate discussion, often between stakeholders. Nevertheless, it is critical to ensure that any decision analytic and/or support methodology which is adopted should not in its structure eliminate potentially desirable conclusions from consideration irrespective of inputs from the decision maker(s), for example by suppressing possible issues such as a concern for equity. In the context of the above example, the methodology should therefore in its structure allow, with the appropriate inputs, any of the three possible conclusions, namely a_1 preferred, a_2 preferred, or indifference between a_1 and a_2. We shall observe that all three conclusions are not necessarily allowed by some approaches.

Now, without loss of generality, the marginal value functions can be defined such that $v_j(0) = 0$ and $v_j(1) = 1$ for both criteria. For the Goodwin-Wright approach, the V_{ir} table becomes:

Alternative	Scenarios	
	S_1	S_2
a_1	0	1
a_2	w_1	w_2

This representation now obscures any equity issues, and conventional robustness considerations seem likely to bias evaluation towards a form of risk aversion which would favour a_2. It is not evident that the Montibeller et al. modification would change this outcome for the present example.

In both [18] and the earlier work of Miranda and Proença [29], Linares [26], there is clear recognition of a need for preference aggregation across both criteria of evaluation and scenarios, although this aggregation has to a large extent been performed separately for criteria and scenarios. What we seek is a framework for structuring these aggregation steps in a simple manner, but without obscuring issues such as those identified in the above example. A clear starting point must be the recognition that in a scenario-based MCDA structure, alternatives do fundamentally need to be evaluated and compared in terms of all $m \times p$ performance measures. In other words, at some point attention needs to be given to how well an alternative performs in terms of each criterion under the conditions of each scenario. Although this recognition is implicit in the cited work, we propose to make it explicit by reference to each criterion-scenario combination as a *metacriterion*. Each metacriterion then represents a dimension on which preferences can and need to be formed and stated[5]. In the above simple example, there are thus 4 metacriteria, corresponding to the last four columns of Table 2. Assuming that there is no alternative that is simultaneously best in terms of all $m \times p$ metacriteria, any decision made will reflect a balance between better performance on some metacriteria and lesser performance on others, i.e. there is an inevitable trade-off between performances on each metacriterion, even if this may be difficult to express explicitly.

We recognize that in some applications, it would not be necessary to aggregate across scenarios in an explicit fashion, and it would be sufficient to display the within scenario analyses to decision makers and to leave it to their judgement to come to a final decision. However, in introducing metacriteria in this paper we seek to explore the form of analysis that would result if they chose some more formal and explicit aggregation. Under these conditions we would treat metacriteria as conventional criteria, and in principle, any technique of MCDA could be applied to the metacriterion structure. For illustration purposes, we discuss the use of value function methods. Provided that the metacriteria are preferentially independent, standard results [e.g., 24, Chapter 5] imply that the alternatives may be ordered on the basis of an additive value function which can here be expressed in the form:

$$V_i = \sum_{j=1}^{m} \sum_{r=1}^{p} w_{jr} v_{jr}(z_{ijr}) \tag{1}$$

where according to our structure, separate partial value functions need to be established for each criterion-scenario combination. Let us observe how this concept may applied for the above simple example.

Example (Continued). We can without loss of generality scale each marginal value function such that $v_{jr}(0) = 0$ and $v_{jr}(1) = 1$. It thus follows that $V_1 = w_{12} + w_{22}$ and $V_2 = w_{11} + w_{22}$, and thus alternative 1 is preferred to alternative 2 if and only if $w_{12} > w_{11}$, and *vice versa* (with indifference if $w_{12} = w_{11}$).

It is then instructive to consider how the assessment of w_{12} and w_{11} might proceed. In this case we have that performance on criterion 2 is independent of action within each scenario, so that the performance on criterion 2 becomes a defining feature of the scenarios. The question to the decision maker is thus whether good performance on criterion 1 is more important in scenario 1

[5]In an earlier conference presentation [43] we had used the term *pseudocriteria*, but this term has been used elsewhere in a different context

(characterized by poor outcomes on criterion 2 irrespective of action taken) or in scenario 2 (characterized by good outcomes on criterion 2). When inter-criterion compensation is beneficial, the first is more important; under concerns for equity, the second is more important. The necessity for such value judgements regarding compensation and equity concerns are clearly surfaced by the proposed methodology.

More generally, the metacriterion weights could be assessed by some form of swing-weighting. However, the number of metacriteria likely to be involved would be too large to perform the swing-weighting simultaneously for all, so that some form of hierarchical assessment may be needed. Two potential approaches are the following:

Approach 1.

- For each scenario r, compare the importance swings for each of the m criteria within this scenario, giving estimates of the ratios w_{jr}/w_{kr} for all pairs of criteria j, k;
- Then for one or two of the more important criteria, compare the relative importance of the swings for these criteria across each of the p scenarios.

Approach 2.

- For each criterion j, compare the importance swings of criterion j within each of the p scenarios, giving estimates of the ratios w_{jr}/w_{jt} for all pairs of scenarios r, t;
- Then for one or two selected scenarios, compare the relative importance of the swings for each of the m criteria.

Neither approach differentiates in essence between the evaluation of importance of metacriteria *within* scenarios (comparisons of the initial criteria in a standard MCDA approach), or *between* scenarios (comparisons of scenarios). The distinction between the approaches is a matter of the timing of the comparisons during the analytical process. At this stage, we have not formed any clear conclusions as to which approach is preferable, which should form the topic of future empirical research.

Schroeder and Lambert [40] suggest a third approach which relies on identifying a base or "as planned" scenario, but we are not convinced that developing a range of scenarios as described in the preceding section would create such a distinct scenario.

In the above simple example, either approach would recognize that $w_{2r} = 0$ for both scenarios (a zero swing having zero importance), leaving just the comparison of w_{11} and w_{12} to be undertaken, as indicated in the example (with the implied focus on importance of equity versus compensation).

5. Illustrative Example

In order to illustrate the approach, we consider a small hypothetical example, but one which we believe contains many of the key components of strategic decision making with macro-uncertainties. The example relates to changes in subsistence agriculture policies in a developing country, in response to potential climate changes. Three broad policy directions have been tabled for discussion, namely: Do nothing, i.e. retain current crop mixes (A1); Introduce genetically modified (GM) varieties of the current crop mixes (A2); and Change to more robust crops, but which have lower productivity under current conditions (A3).

There are two key uncertainties. Firstly, there is the uncertainty regarding the climatic changes which may be faced, with a realistic prospect that mean annual rainfall might drop, but with an accompanying increase in inter-annual variance. Then, an important area of concern is that the introduction of GM crops can lead to the genetically modified genes jumping species to cause unspecified environmental damage[6]. We construct four scenarios to reflect these major uncertainties as follows:

S1: Rainfall patterns unchanged and GM crops exhibit no cross species contamination

S2: Rainfall patterns unchanged and GM crops cause genetic changes in other vegetation

S3: Mean annual rainfall falls, while inter-annual variability increases; GM crops exhibit no cross species contamination

S4: Mean annual rainfall falls, while inter-annual variability increases; GM crops cause genetic changes in other vegetation

We note, to avoid possible confusion, that *the decision* includes consideration of whether or not to introduce GM crops, but that the extent of the propensity of such crops to cause genetic mutations elsewhere is a property of GM crops which exists irrespective of decisions made. Such propensity is thus an external unknown which affects consequences of decisions, and has therefore to be incorporated into the definition of scenarios.

In practice, it would be necessary to define the scenarios somewhat more quantitatively and with greater detail in order to give operational meaning to the context

[6] We do not claim expertise in the microbiology, but whether or not cross-species contamination is deemed by experts to be possible or likely, the fear of this happening is very real in communities.

in which value judgements need to be made, but the above should suffice for illustrative purposes.

Finally suppose that three criteria have been identified as follows:

C1: Costs of maintaining and/or changing crop mixes

C2: Per capita food production in rural areas

C3: Loss of farming and conservation land through environmental damage

For ease of illustration and discussion, we have expressed these criteria in quite simple and quantifiable terms. In practice, criteria in strategic contexts will include many qualitative features. It should be evident that the analysis described below (based on ranking alternatives for each metacriterion and placing the alternatives along a possibly subjective scale) is well-suited to dealing with qualitative issues. See chapter 5, for example, of Belton and Stewart [1] for further discussion.

Suppose further that for each metacriterion, the preference orders shown in Table 3 have been elicited. These are provided purely for purposes of illustration and do not necessarily represent the value judgements of any actual decision maker.

Table 3: Illustrative Preference Orders for the Agricultural Policy Example

Scenario	Criterion	Preference order
S1	C1	$A1 \succ A3 \succ A2$
S1	C2	$A2 \succ A1 \succ A3$
S1	C3	$A1 \succ A2 \succ A3$
S2	C1	$A1 \succ A3 \succ A2$
S2	C2	$A2 \succ A1 \succ A3$
S2	C3	$A1 \succ A3 \succ A2$
S3	C1	$A3 \succ A1 \succ A2$
S3	C2	$A2 \succ A3 \succ A1$
S3	C3	$A3 \succ A2 \succ A1$
S4	C1	$A3 \succ A1 \succ A2$
S4	C2	$A2 \succ A3 \succ A1$
S4	C3	$A3 \succ A1 \succ A2$

In some instances, convenient measures of performance may be established for each criterion, utilizing operationally well-defined attributes. For example, one might choose monetary impact for C1, food value provided per capita for C2 and expected loss of land through environmental damage for C3. It would not in general be legitimate to assume, however, that value functions expressing decision maker preferences are linear in these measures (attributes), so that subjective assessment of a value function would be necessary whether the underlying criteria are quantifiable in terms of such attributes or are more qualitative in nature (as described in Chapter 5 of Belton and Stewart [1]). The application of a value measurement approach in this context then requires (1) an assessment of a cardinal value function for each metacriterion, and (2) an assessment of the weights w_{jr}, which we now describe.

Partial value functions: Since there are only three possible outcomes for each metacriterion, it is sufficient to specify partial values v_{ijr} for each alternative under each metacriterion, and to allocate values of 100 and 0 to the best and worst performing alternatives respectively. If performance is measured in terms of quantitative attributes, then $v_{ijr} = v_{jr}(z_{ijr})$ as previously defined. But in any case, we only require a single intermediate value to be assessed, corresponding to the middle ranking alternative on this metacriterion. Consider, for example, C2 under scenario S3. The most preferred alternative is A2, so that $v_{223} = 100$, while $v_{123} = 0$ (the worst alternative). This leaves only the assessment of v_{323} (for A3) to be judged by the decision maker.

Still only for purposes of numerical illustration, suppose that the middle values for each metacriterion were assessed in this way as shown in Table 4.

Swing weights: In the previous section we suggested two possible approaches. It is possibly easier in the context of this problem to adopt the second approach. Thus we start with the ranges of outcomes for C1 represented by the three alternatives, and compare importances of the implied swings in each of the four scenarios. Suppose that the decision maker rates these in a relative sense (with the most important swing given a score of 10), as indicated in the relevant row of Table 5, which also shows similar illustrative judgements for the other two criteria. The interpretation, for example, of the second row (C2) is that the weights $w_{21} : w_{22} : w_{23} : w_{24}$ are in the proportions 10:8:8:6.

The decision maker now needs to compare the swings for C1, C2 and C3 under conditions of one selected scenario; for illustration suppose that S4 is selected, perhaps because it represents the worst case scenario. Suppose that the relative scores on these three swings are given as 6, 10 and 8 respectively. These imply that the weights $w_{14} : w_{24} : w_{34}$ are in the proportions 6:10:8. Taking any one criterion under scenario 4 (say C3), we may now assess the ratios w_{jr}/w_{34} for any (j, r) by:

$$\frac{w_{jr}}{w_{34}} = \frac{w_{jr}}{w_{j4}} \cdot \frac{w_{j4}}{w_{34}}.$$

The elements in the first ratio come from Table 5, and those in the second ratio from the within-scenario swings. Thus for example, w_{22}/w_{34} would be given by $(8/6) \times (10/8) = 1.667$. Following convention, the weights displayed in Table 6 have been further standardized to sum to one (but it is easily confirmed that $w_{22}/w_{34} = 0.1417/0.085 = 1.667$).

Table 4: Illustrative values for middle alternatives

Metacriterion	Middle alternative	Middle value
C1/S1	A3	70
C1/S2	A3	80
C1/S3	A1	90
C1/S4	A1	90
C2/S1	A1	30
C2/S2	A1	40
C2/S3	A3	30
C2/S4	A3	50
C3/S1	A2	50
C3/S2	A3	80
C3/S3	A2	50
C3/S4	A1	90

Table 5: Swing weights across scenarios for each criterion

Criterion	Scenarios			
	S1	S2	S3	S4
C1	8	10	7	8
C2	10	8	8	6
C3	1	8	1	10

Table 6: Standardized weights for metacriteria

Criterion	Scenarios			
	S1	S2	S3	S4
C1	0.0638	0.0797	0.0558	0.0638
C2	0.1771	0.1417	0.1417	0.1063
C3	0.0085	0.0680	0.0085	0.0850

A final aggregate value can then be calculated for each alternative. For example, using the illustrative values from Tables 4–6, the aggregate value for A1 is found to be:

$$
\begin{aligned}
&[0.0638 \times 100 + 0.0797 \times 100 + 0.0558 \times 90 + 0.0638 \times 90] \quad \text{(cost)} \\
+&[0.1771 \times 30 + 0.1417 \times 40 + 0 + 0] \quad \text{(food production)} \\
+&[0.0085 \times 100 + 0.0680 \times 100 + 0 + 0.0850 \times 90] \quad \text{(environmental damage)} \\
=&51.40
\end{aligned}
$$

The aggregate values for the other two alternatives are found in similar fashion to be 57.54 (A2) and 47.16 (A3), favouring alternative A2 (use of GM crops). Of course, this example is purely illustrative (and we make no claims for the efficacy of GM crop policies in any real world setting). In reality the results would be subject to extensive sensitivity analysis. We have only attempted to demonstrate the applicability of our proposed approach.

6. Conclusions

We believe that synergies between scenario-planning and quantitative decision modelling can be exploited to considerable advantage in addressing complex decision contexts. Confining attention to well structured scenarios which 'take-out' gross uncertainties may allow tractable quantitative analyses which do not require, e.g., the elicitation of non-additive multiattribute utility functions and probability distributions over highly correlated variables. We have illustrated this in the context of MCDA using multiattribute value functions, but recognize that the same approach may be applied with Bayesian expected multiattribute utility analyses; and, indeed, with many other forms of quantitative decision analysis. In future papers we shall explore this approach in the context of more realistic or actual decision analyses such as those relating to the sustainability of nuclear power.

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