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TECHNICAL
REPORT

Lessons from RAND's Work on Planning Under Uncertainty for National Security

Paul K. Davis

Prepared for the Office of the Secretary of Defense

RAND NATIONAL DEFENSE RESEARCH INSTITUTE

The research for this paper was conducted within the RAND National Defense Research Institute, a federally funded research and development center sponsored by the Office of the Secretary of Defense, the Joint Staff, the Unified Combatant Commands, the Navy, the Marine Corps, the defense agencies, and the defense Intelligence Community.

Library of Congress Cataloging-in-Publication Data

Davis, Paul K., 1943-
Lessons from RAND's work on planning under uncertainty for national security / Paul K. Davis.
p. cm.
Includes bibliographical references.
ISBN 978-0-8330-7661-8 (pbk. : alk. paper)
1. National security—United States—Planning. 2. Interagency coordination—United States. 3. Strategic planning—United States 4. System analysis. I. Title..

UA23.D2877 2012
355'.033573—dc23

2012028666

Published 2012 by the RAND Corporation
1776 Main Street, P.O. Box 2138, Santa Monica, CA 90407-2138
1200 South Hayes Street, Arlington, VA 22202-5050
4570 Fifth Avenue, Suite 600, Pittsburgh, PA 15213-2665
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Preface

This short paper reviews selected highlights of RAND's treatment of uncertainty in national-security analysis over the last two decades. It is intended to be of interest to a broad audience concerned with strategy, planning, and related analytic methods. Much of the paper describes an evolution of thought regarding how to deal with what is called "deep uncertainty." As a whole, however, the paper describes how RAND has used a wide range of analytic methods to deal with diverse classes of uncertainty.

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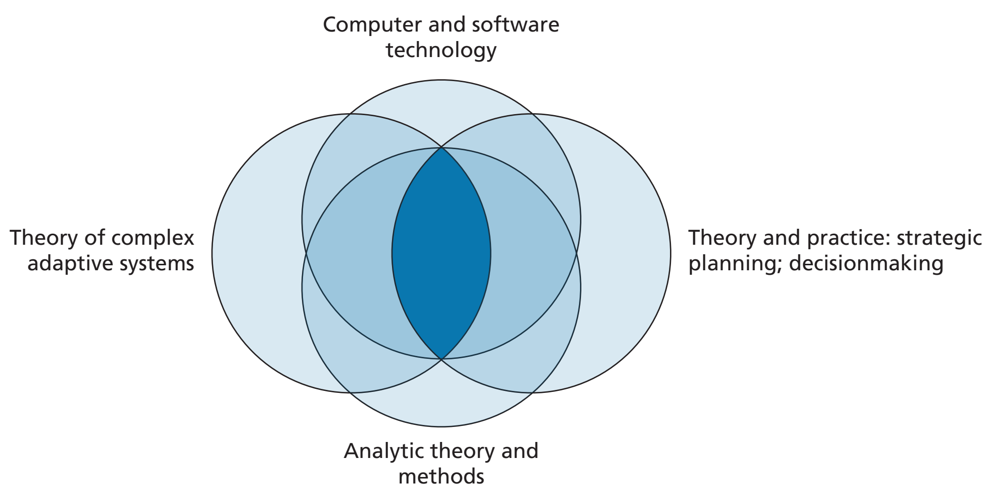
Summary

RAND's progress in dealing with uncertainty analysis for national security has benefited from a confluence of developments in four domains, as indicated in Figure S.1. Most familiar perhaps is technology: modern computers and software allow analysis that would have been inconceivable in the early days of systems and policy analysis, such as examining a vast possibility space when considering options for the way ahead. Technology, however, is only an enabler. Developments in understanding strategic planning and decisionmaking, and in analytic theory and methods, have also been fundamental. These, in turn, have been influenced by insights from the theory of complex adaptive systems, which recognizes that behaviors of such systems can be inherently difficult or impossible to predict with confidence. Nonetheless, the behaviors can often be analyzed, anticipated, nudged, and occasionally even controlled.

Much of the paper focuses on "deep" uncertainties, that is, important uncertainties that cannot be adequately addressed by normal versions of sensitivity analysis or probabilistic analysis. RAND's work has emphasized the following: facing up to deep uncertainty in many dimensions; performing exploratory analysis of the possibility space (also called scenario space); identifying regions of that space that pose special risks or opportunities; finding options

Figure S.1
Confluence of Influences



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to improve capabilities; and using portfolio analysis to conceive and compare strategic options for dealing with the diversity of challenges in an economically acceptable manner.

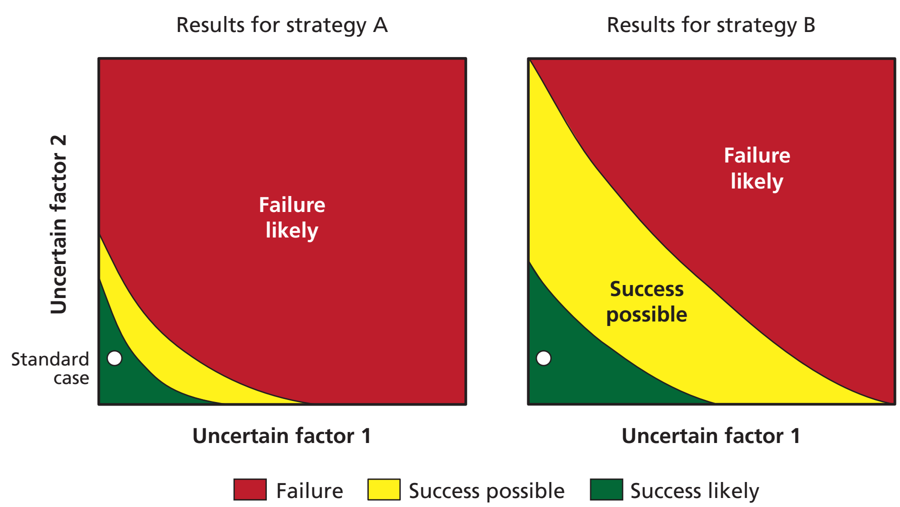
A cross-cutting theme (the "FARness principle") is that strategies should provide: future flexibility for taking on different missions or objectives, adaptiveness to deal with unanticipated circumstances, and robustness to shocks such as unanticipated adverse advents. RAND authors often use "planning for adaptiveness" or "robust decisionmaking" (with a different meaning of "robust") to cover all elements of FARness.

To illustrate this core philosophy with a simple example, Figure S.2 assumes two primary uncertainties, which creates a two-dimensional possibility space. How well a strategy will perform depends on the situation that actually arises, which could be anywhere in the space. Both strategies A and B are likely to succeed in a standard case (the point in the lower left, which is in the green area indicating likely success), but strategy B (right pane) is more likely to be successful or at least to make success possible (depending on other factors) in a much larger portion of the space (green and yellow regions) than is strategy A. That is, strategy B is more robust to uncertainty.

Ultimately, different problems call for different approaches to uncertainty. This is illustrated in the main text for applications to strategic planning, acquisition management, logistics, personnel management (manpower research), crisis decisionmaking, and organization and management. Looking across the research discussed, several themes stand out:

- Uncertainty analysis requires both creative, divergent work to understand the range of possibilities, as well as more convergent work to assist decisionmakers in conceiving and choosing among strategies. In both phases, there is need for both human-intensive work (e.g., brainstorming, gaming, and judgment) and more analytical methods, including computational discovery.

Figure S.2
Comparing Strategies A and B Across a Range of Conditions 1 and 2



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- Also, there is need for both theory-driven and data-driven approaches. Indeed, competition between such approaches can help stimulate progress.
- Experimentation and iteration are often crucial for uncertainty reduction and discovery.
- In practice, strategy will often be revisited and modified over time, despite the common assumption of once-and-for-all decisionmaking. Where possible, planning should anticipate the need for particular adaptations and identify signals that should trigger them.
- Because major surprises will nonetheless occur, planning should also provide general capabilities and organizational agility that allows for immediate adaptations to unanticipated developments. That is, part of good planning is ensuring the agility to "cope."
- Policymakers should demand analysis that aids them in finding strategies that lead to flexibility, adaptiveness, and robustness (in short, "robust strategies" or what some call "agile" capabilities). This would be quite different from settling for best-estimate analysis and a list of assumptions.

To elaborate on the last item, a common concept of good analytic practice for dealing with uncertainty when reporting to a policymaker is to show key assumptions, watch for the policymaker to acknowledge the assumptions, and then present results. Unfortunately, even if policymakers know the assumptions and believe them to be reasonable, the approach is inadequate. The appropriate standard for analysts should also include the following:

- Being sure that omitting considerations because of uncertainty does not critically affect study conclusions.
- Being sure that conclusions identify reasonable ways to hedge against consequences of uncertainty, to include preparing for adaptation.
- Sensitizing policymakers to the importance of such hedging, which is more valuable than final increments of fine-tuned optimizing for the baseline case.

The somewhat radical vision of RAND authors here is for policymakers to agree with this and then require their organizations to follow a corresponding analytic doctrine.

Acknowledgments

The constraint of writing a short paper, my uneven knowledge of the many strands of research mentioned, and my personal perspectives have undoubtedly affected the paper's structure and relative balance. Nonetheless, I hope to have done reasonable justice to the work of many colleagues. I benefited greatly from reviews of the draft paper by Richard Hillestad and Steven Popper and by comments on the draft paper or conversations over the years with Steven Bankes, James Bonomo, John Birkler, Paul Bracken, Lionel Galway, Ken Girardini, David Gompert, James Hosek, Michael Mattock, Richard Kugler, Robert Lempert, Louis (Kip) Miller, Russ Shaver, and Henry Willis. Finally, I benefited from interacting with students of the Pardee RAND Graduate School.

CHAPTER ONE

Introduction

For a half century RAND authors have lamented failure to deal well with uncertainty in analysis (Quade, 1968, pp. 355–356; Quade and Carter, 1989). This paper distills selected highlights of RAND research on improving performance in this area, primarily in the realm of national security, and also points readers to related publications.

It may be helpful to start with definitions and, because risk and uncertainty are tightly bound in common language, to introduce them together.

> *Uncertainty:* A primitive concept meaning a state of limited knowledge or of indecision.

It is useful to distinguish between *normal* uncertainty and *deep* uncertainty. The former applies when we understand a phenomenon and how to value outcomes. Under this condition, we can address uncertainty with standard versions of sensitivity analysis or probabilistic analysis—as when changing one parameter value, calculating the odds in poker, or predicting something using soundly determined subjective probabilities. Deep uncertainty is the condition where we do not know with confidence (1) the model by which to describe the phenomenon of interest, (2) the relevant probability distributions, or (3) how to value the outcomes.[1]

> *Risk:* The potential for something adverse to happen. The extent of risk depends on the likelihood of bad developments and the consequences if they occur. (This definition is used in this paper, as in natural English.)

Other definitions exist, as indicated in Table 1.1. Definitions 2 and 3 are used in the financial community; definition 4 is common in the risk literature. The U.S. Department of Defense (DoD) sometimes uses definition 5, which blurs the distinction between saying "we will reduce capabilities for B because we no longer believe as much is needed" with "but there is always the risk of being wrong."

At least seven broad approaches exist for addressing uncertainty, as indicated below. The first four are classic (Madansky, 1968; Quade and Carter, 1989); the last few, although precedented throughout history, are especially difficult and are methods to which RAND has contributed significantly over the last two decades (Davis and Finch, 1993; Davis, 1994d; Lempert, Schlesinger, and Bankes, 1996; Lempert and Schlesinger, 2000; Davis, 2002; Lempert, Popper, and Bankes, 2003; Groves and Lempert, 2007):

[1] This definition is slightly different from that in earlier publications. Also, other authors have variously referred to aspects of deep uncertainty as ambiguity, epistemic uncertainty, future-challenges risk, future uncertainty, real uncertainty, strategic uncertainty, scenario uncertainty, state-of-the-world uncertainty, and unknown unknowns.

Table 1.1
Varied Meanings of "Risk"

Meaning	Comment
1. Risk as potential for harm or damage	Natural-language meaning. Risk is then a function of both likelihood and consequences. This definition is used throughout this paper.
2. Risk as volatility	Used in financial-world portfolio analysis. A stock's risk is measured by the variance in price to be expected from past fluctuations.
3. Risk as *bad* volatility	Also used in financial portfolio analysis, but with recognition that only the drops in value are of concern.
4. Risk as uncertainty characterized probabilistically	Commonly used in the literature on risk. In this construct, "uncertainty" is distinguished from risk by the absence of a probability distribution.
5. Risk as less capability or more potential vulnerability	Commonly used in the U.S. government. If money is shifted from B to A, it is said that the decision is to accept more risk in B.

1. Buy time (defer decisions until more is known).
2. Buy information (e.g., research, intelligence, experimentation).
3. Take a conservative approach (e.g., plan against a worse-than-expected threat).
4. Buy flexibility and insurance as hedges.
5. Anticipate, and plan accordingly. Use creative forms of research and analysis to anticipate potential problems and opportunities.
6. Prepare to cope. "Surprises" will assuredly occur despite planning efforts, so prepare for FARness: flexibility to take on different missions, adaptiveness to new circumstances, and robustness to shock.[2] This includes developing the organizational *agility* for timely coping.
7. Preemptively deal with potential roadblocks, as by shaping the international environment through alliances, forward presence, and international activity.

Against this background, the remainder of this paper discusses RAND's work on addressing uncertainty, which includes most or all of the seven approaches listed above. Section 2 introduces the cross-cutting concept of exploratory analysis. Sections 3 through 7 address examples in strategic planning, acquisition management, logistics, staffing, and crisis decision-making. Section 8 touches upon matters of organization and implementation. Section 9 gives brief conclusions.

[2] These three attributes are different, but overlapping. Further, the terms "flexible," "adaptive," and "robust" have mulitple meanings and are often seen as synonyms. In the context of FARness, the meaning of "robust" is as in "as resistant to storm as a robust oak tree." Elsewhere in the report "robust" is used as in "a robust conclusion holds up across a wide range of assumptions." Connotation should be evident from context.

CHAPTER TWO

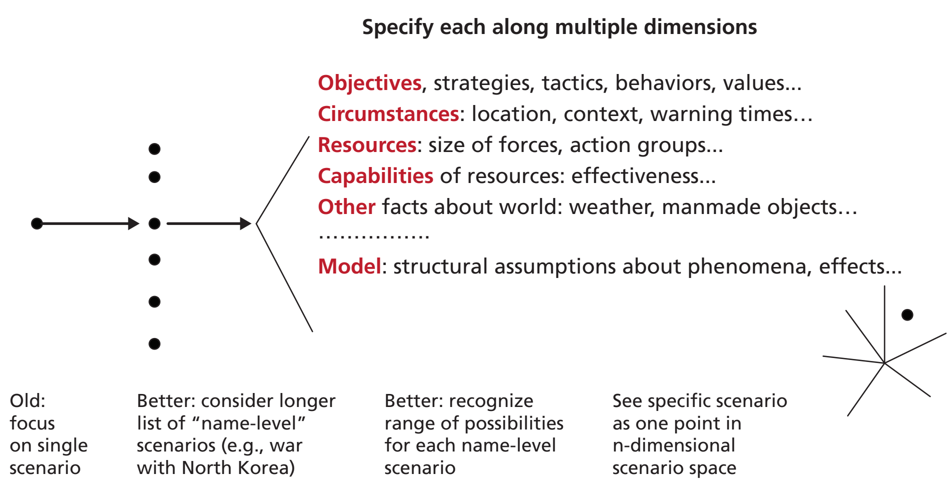
A Cross-Cutting Analytic Method: Exploratory Analysis

The Concept

Exploratory analysis is an outgrowth of multiscenario analysis (Davis and Winnefeld, 1983) and is closely related to exploratory modeling (Bankes, 1993). RAND authors have used both terms frequently since 1992–1993, more or less interchangeably (Anderson et al., 1993; Bankes, 1993; Davis, 1994a; Davis, 1994b).

A first step in dealing with uncertainty is to confront its existence, ubiquity, and magnitude. A second step is to deal with it when informing assessments and decisions. Doing so *requires* models, whether implicit mental models or explicitly defined models expressed using mathematics or computer programs. The models generate outputs, but those outputs depend on the models themselves and the values assumed for each and every input to the models, across many dimensions of uncertainty. What, then, are the "dimensions" of uncertainty? Figure 2.1 is a schematic of the concept describing a left-to-right progression from ignoring uncertainty (using only a single scenario) to recognizing a number of scenarios but expressing them in vague terms such as "war with North Korea," and then to recognizing that each such name-level scenario could have an infinite number of variations. In what follows, "scenario"

Figure 2.1
Schematic of Possibility Space (also called Scenario Space)



SOURCE: Adapted from Davis (1994, 2002).
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refers to a fully defined set of assumptions used to feed a model (mental or computational). Such a full definition means thinking about all of the generic dimensions of uncertainty shown on the right side of Figure 2.1 (Davis, 1994b; Davis, 2002).

The generic dimensions are intendedly comprehensive, thus improving rigor. In Figure 2.1, the items above the dotted line are *parametric uncertainties* because, in principle, they can be reflected in variable inputs. Below the line, we see reference to the model itself. How does it represent the world? What does it include and exclude? What cause–effect relationships does it embrace? These are *structural uncertainties*.

The intent in exploratory analysis is to examine as much of the possibility space (that is, scenario space) as possible. This is enabled by modern technology. As mentioned earlier, the intent is often to find flexible, adaptive, and robust strategies (FAR strategies), referred to in shorthand as robust strategies (Davis, 2002). Significantly, exploratory analysis examines cases that vary all of the inputs simultaneously, rather than one by one as in traditional sensitivity analysis. Often, no baseline case is given particular credence because, given the uncertainties in play, no baseline case is more likely than other cases, including some that are drastically different.

Exploratory analysis is now common at RAND, either with modern commercial modeling software such as Analytica™ or a powerful software environment (Computer Assisted Reasoning, CAR™) specifically developed for such purposes by RAND researchers through Evolving Logic Inc. (Bankes, Lempert, and Popper, 2001). RAND licensed CAR and has used it in many studies and doctoral dissertations.

Making Exploratory Analysis Feasible and Convergent

Exploratory analysis helps greatly in recognizing possibilities, but conducting analysis across a complex and infinite scenario space can be daunting. RAND has worked diligently on the challenge and has found the following five themes to be especially valuable (Davis, 2002).

Start with a Broad View

As indicated in Figure 2.1, it is valuable to conceive the entire possibility space when first starting a study and thinking about uncertainties. Doing so requires a period of creative, divergent work. That period may last for days or weeks, but is important in any case.

Narrow the Analysis for the Study at Hand

Although "possibility space" may be infinite in general, a given study need consider only *some* aspects of uncertainty. A study does not usually involve learning everything about a broad phenomenon, but rather involves aiding policymakers with particular responsibilities. No general formula exists on how to do the narrowing, but past studies provide some examples. Some studies considered broad balance-of-power considerations and did not address intricacies of war fighting (Shlapak, et al., 2009); others, in contrast, were specifically focused on war fighting capability against an adversary that might use creative and stressful strategies (Davis, 1988), including cyber attacks against military networks; still other studies addressed weapon-mix issues and focused on uncertainties in weapon reliability, sortie rate, and deployment schedule (Brooks, Bankes, and Bennett, 1997).

Another way of narrowing the space is to use game theory. For example, RAND developed the SAGE algorithm for a game-theoretic version of combat simulation that assessed military strategies for the cases in which the adversary either employed forces optimally (as judged by the combat model) or doctrinally. This bounded the possibilities and reduced substantially the dimensionality of analysis (Hillestad and Moore, 1996). In a similar vein, even modest initial exploration quickly reveals that many uncertain considerations are relatively insignificant and that huge portions of the "possibility space" are irrelevant to analysis.

A crucial admonition in the narrowing phase is that *narrowing should not be based on conventional wisdom or the desire to avoid controversy*. To be sure, client representatives sometimes resist analysis that goes beyond standard cases, but policymakers themselves are more open to uncertainty analysis—if, but usually only if, it helps them reach decisions.

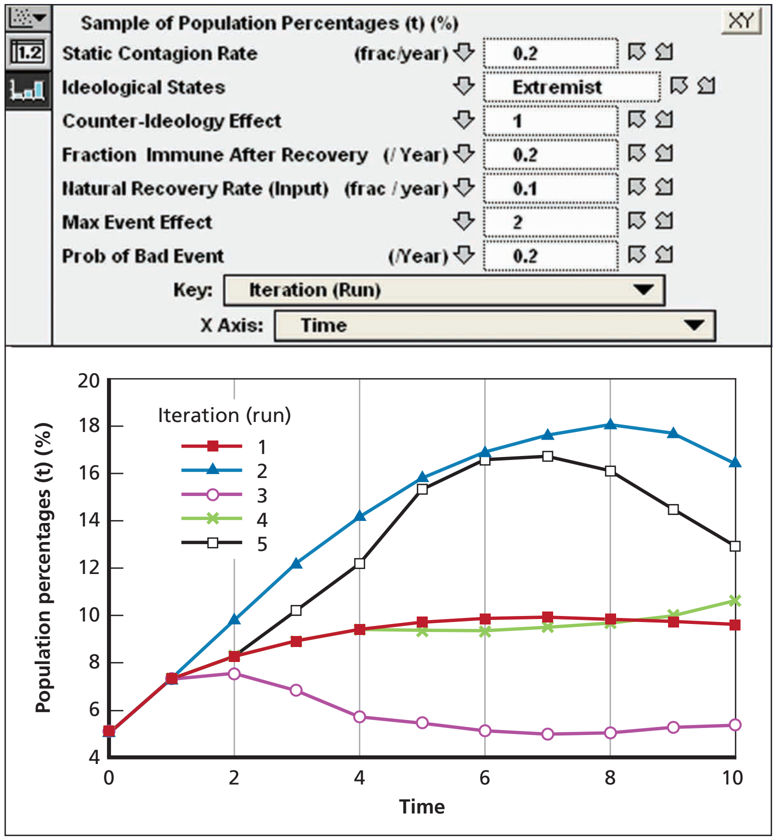
Use Multiresolution Modeling

To describe a nontrivial system may require identifying tens, hundreds, or even thousands of variables. If all are uncertain, the curse of dimensionality looms large, even with fast and tireless computers. However, RAND has exploited an important modeling insight: the variables characterizing a system can usually be modeled in layers of increasing detail, that is, with more abstract, higher-level variables optionally determined by lower-level variables. This is multiresolution modeling (Davis and Hillestad, 1993; Davis and Bigelow, 1998). Typically with this type of modeling, systems can be described most simply with perhaps 3 to 12 variables. Such a description can be relatively comprehensive (subject to the quality of imagination), albeit shallow. Reasoning with the smaller set of variables can be rigorous and understandable. The uncertainties in those variables can be inputted directly. This said, the ability to understand and reason well about a system and its uncertainties at a given level of detail depends on having a reasonably good understanding of phenomena at least one level deeper. If a high-level factor proves important, then drilling down to explore the ways in which it can take on favorable and unfavorable values is necessary. The driling down can continue through several layers of detail.

As an illustration of exploratory analysis at the highest level, Figure 2.2 shows results from a simple model that characterized terrorism's spread by analogy with that of disease, that is, with an epidemiological construct. All important assumptions are explicit on the display. The analyst can change the values of the variables at the top of the display by selecting from a menu. With an hour's work in the office with the door closed, the analyst can have a good sense of where the interesting regions of the possibility space lie, for example, what combinations of assumptions most often lead to early eradication of the "disease." To understand how something like infection rate relates to more concrete matters would require delving into considerably more depth.

There is no formula by which to accomplish multiresolution modeling; further, the relationships among levels are usually approximations. However, if relatively detailed models exist, the primary ways to develop corresponding lower-resolution models are (Davis, 2003a): (1) start from scratch in building a simple model, but with knowledge of the higher-resolution models so that linkages can be created or changes mandated in the detailed models to permit the linkages; (2) derive a simplified model from the more detailed model by a series of approximations; and (3) use high-level insights (perhaps informed by empirical information) to hypothesize a crude but meaningful low-resolution model structure (e.g., "the quality of outcome ought to be proportional to the *product* of the variables reflecting effectiveness of the operation's critical

Figure 2.2
Illustrative Multidimensional Display for a Simple Model



SOURCE: Adapted from Davis, Bankes, and Egner (2007).
NOTE: The Y axis displays the projected extremist percentage of a population at a given time (X axis), assuming rates of "infection" by the extremist ideology, a natural recovery rate, the fraction of recovered people who are subsequently immune, the effect of counter-ideology strategic communication (a multiplier of contagion rate and recovery rate), the probability of world events that stimulate extremism, and the magnitude of such effects (a multiple of contagion rate). Such events occur randomly, so in different runs of the model, the trajectories are very different. Typically, the "epidemic" worsens for some years and then dies down, but does not disappear.
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components") and to then fit the coefficients of that structure with results from the higher-resolution model. The third approach is called *motivated* meta modeling.

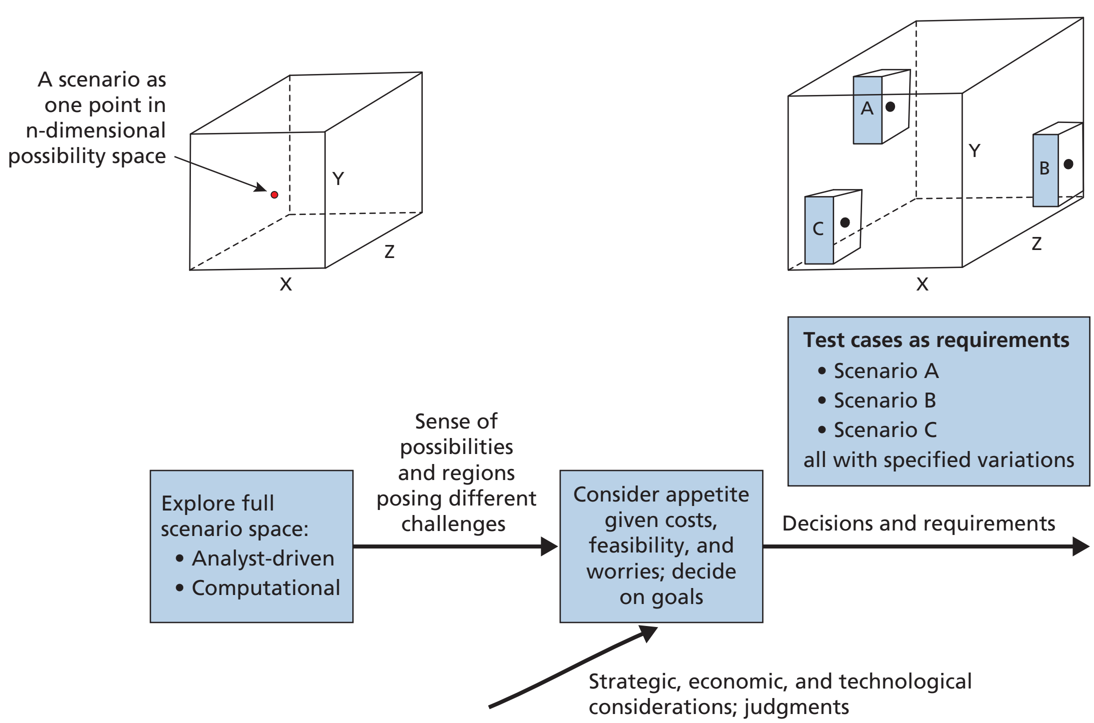
It might seem that multiresolution modeling is not necessary if a good high-resolution model exists. After all, computers are fast, sampling techniques are effective, and statistical methods can sometimes find important variables amidst a great deal of complexity. However, such statistical analyses will usually not find the all-important abstractions that are central to high-level reasoning unless those abstractions are inserted into the analysis, as in the example of motivated meta modeling above, which reasoned that a product of certain variables would be especially important. If such abstractions are inserted and are indeed important, that will be confirmed by the statistical analysis.

Narrow to a Test Set of Scenarios

Full-blown exploratory analysis is not feasible for analysts using large, standardized complex models and databases that are arrived at by coordination and compromise, as is common in government and other large organizations. Recent work for a DoD under secretary connected the need for exploratory analysis with the need for standardized analysis. The key concept is that initial exploratory analysis of the full scenario space that is relevant to an application area can often identify a small set of scenarios such that, if options are successfuly tested against each scenario, the capabilities provided by the options will likely allow success in any scenario that actually arises. This is called a "spanning set" to suggest that the set of scenarios covers the range of possibilities of concern. The spanning set can then be used subsequently throughout an organization to test and compare options (Figure 2.3).

Finding a spanning set is a problem-specific challenge, but the generic idea is to recognize that different classes of challenge exist in different regions of the possibility space. This was illustrated in a recent study on prompt conventional global strike (Davis, Shaver, and Beck, 2008). What capabilities might be needed for such strikes in different scenarios? Exploratory analysis identified three classes of scenarios that led to test cases stressing the following: timelinesss of response; the quality of intelligence, surveillance, and reconnaisance for finding mobile targets; and the ability to attack hard, buried facilties. The different "regions" of the possibility space were found by imaginative analysis and insights from human games and history. The approach was subsequently used in a recent National Academy study (National Academy of Sciences, 2008), and something conceptually similar was used in the most recent Quadrennial Defense Review (Gates, 2009).

Figure 2.3
Exploratory Analysis to Define a Spanning Set of Test Scenarios



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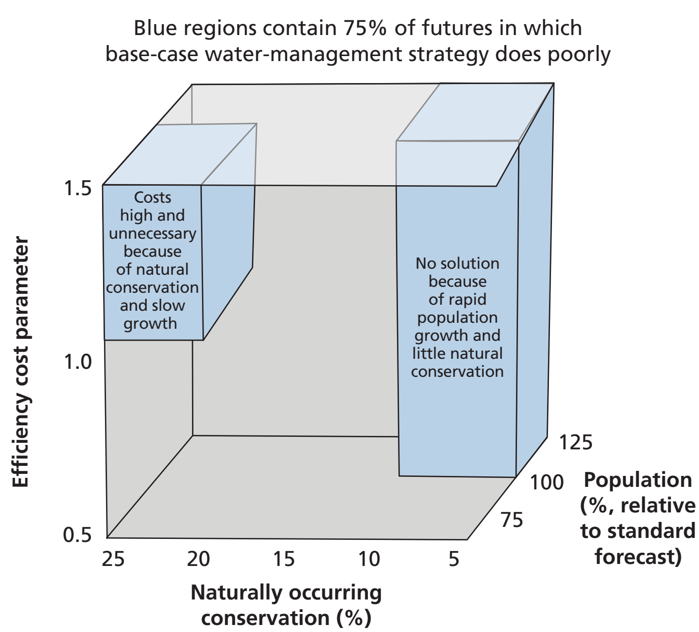
Use Computational Experiments for Scenario Discovery

An exciting new approach has become feasible for scenario discovery as the result of RAND research on robust decison making for finding the distinct regions. In this approach one builds an experimental design, conducts computational experiments, and then uses advanced search methods, referred to as "data mining," to characterize the scenario space. This is sometimes called question-driven analysis (Bankes, 1993) or scenario discovery, as in discovering the combinations of input values that lead to results of particular interest, such as success or failure of a strategy or system across the possibility space (Groves, 2006; Groves and Lempert, 2007; Davis, Bankes, and Egner, 2007; Bryant and Lempert, 2010). Figure 2.4 illustrates this, drawing from a social-policy study of water management strategy. After testing a baseline strategy for water management across a space of possible futures, data analysis showed that 75 percent of the scenarios that the strategy could *not* deal with appear in the two blue regions shown, where the axes of the three-dimensional structure are the extent of conservation that would occur independent of the strategy, the growth rate in population relative to a standard forecast, and the value of an efficiency cost parameter. These regions capture only 75 percent of the failure cases because failures could occur elsewhere due to the effects of other variables.

With this background of definitions and cross-cutting methods, the following sections touch upon application areas: strategic planning, acquisition management, logistics, personnel management (manpower research), and crisis decisionmaking.

Figure 2.4
Illustrative Computational Search to Find Regions of Special Concern



SOURCE: Adapted schematically from Groves and Lempert (2007); Figure 4. Current work by the authors uses the term "robust decision making" (RDM)

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CHAPTER THREE

Strategic Planning

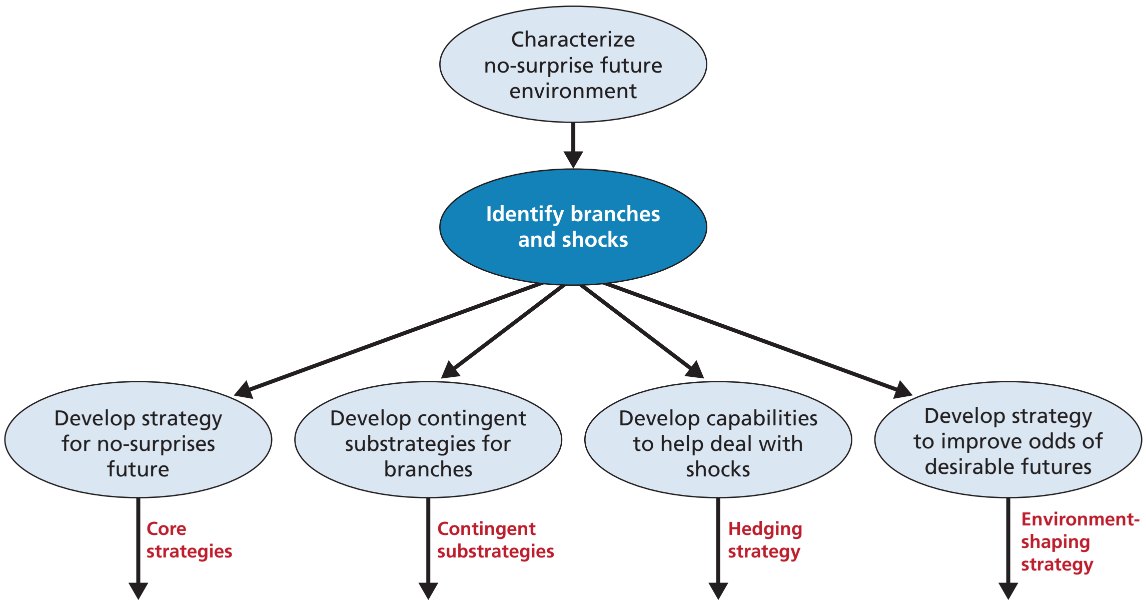
Many consultant companies exist to help organizations with their strategic planning—often using scenario-based methods that trace back to Herman Kahn's RAND work in the 1950s. Subsequent years brought many enrichments, variations, and new ideas such as RAND's Day-After Exercises (Molander, Wilson, Mussington, and Mesic, 1998), which have been used in planning exercises relating to, for example, cyberwar, nuclear proliferation, and peace planning (Molander et al., 2009). In these exercises, participants (senior officials, in some instances) stand in a decisionmaker's shoes at three points in time: first, with a possible crisis looming; then after one has actually occurred with dire consequences; and then back in today's context with the challenge of taking actions to reduce the likelihood of such a crisis or to mitigate its consequences.

The maze of strategic-planning methods is confusing, and it is helpful to distinguish among various planning functions when selecting a method. Sometimes an organization needs divergent thinking to open minds and contemplate out-of-the-box futures and strategies. Sometimes the organization needs convergent thinking that will lead to decisions and *action*. Other times an organization has already built a strategic plan but needs to have it critiqued, tightened, and otherwise improved. These different functions require different methods for addressing uncertainty (Davis, 2003b). The following discusses each of these.

Uncertainty-Sensitive Strategic Planning and Assumptions-Based Planning

As the Cold War waned, RAND developed new planning methods that moved away from traditional scenario building to ways of sketching the no-surprises future, listing known branch-style uncertainties, and stretching the imagination to build a long list of potential shocks (good or bad). Historical shocks have included: the fall of the shah of Iran, the disintegration of the Soviet Union, Saddam Hussein's invasion of Kuwait, and the terrorist attacks of September 11, 2001. Although such individual events are typically deemed unlikely, it is *very* likely that at least one of the identified possibilities will occur—but we don't know which. A good strategy, then, is to attend to the expected future, attempt to *shape it*, include relatively detailed contingent planning for the anticipated branch points, and include a variety of hedges to deal with the various potential shocks that cannot practically be planned for in detail (Figure 3.1) (Davis, Gompert, and Kugler, 1996). Hedges include reserve capabilitites, vigorous research and development, and thinking through how various crises could be dealt with (Davis, 1994c; Davis, 2003b). An application of this approach contributed significantly to the thinking represented

Figure 3.1
Elements of Uncertainty-Sensitive Planning



SOURCE: Adapted from Davis, Gompert, and Kugler (1996); based on earlier work of Davis and Bracken.
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in the DoD's 1996 Quadrennial Defense Review 1996, its strategy of *Shape, Respond, Prepare Now*, and its (then-tentative) embrace of what came to be called transformation (Cohen, 1997).

Independently, a very similar approach was taken in RAND work for top leadership of the U.S. Army; it became a well-honed and frequently used methodology called Assumptions-Based Planning for which a textbook exists (Dewar, 2003). The basic concept is for fierce critics to study a plan, identify the implicit assumptions on which it depends, identify vulnerabilities of those assumptions, and identify signposts or indicators of when the assumptions might be failing.

Variants of these planning methods have been developed in several lines of recent RAND work. All address deep uncertainties and seek robust strategies. Some envision rather detailed use of subjectively based probabilities, as in an ambitious study on managing risks for the Air Force (Camm et al., 2009); others do not (Kent and Ochmanek, 2003; Kent, 2008; McGinn et al., 2002). Each has its strengths and weaknesses.

Planning Specific Adaptations

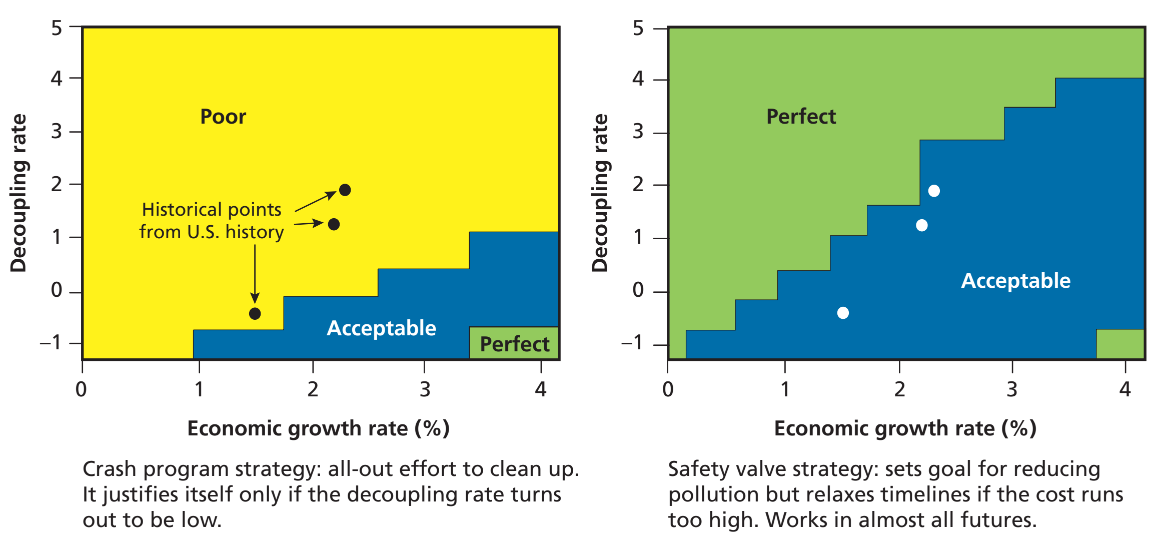
An important paradigm-level point arose in RAND's work on climate change rather than national security: although discussions often assume that decisions are of a once-and-for-all variety, the reality is that strategic decisions are usually revisited and tuned over time. This means that we should build strategic adaptation into options. Doing so is challenging but feasible (Lempert, Schlesinger, and Bankes,1996). Further, adaptive strategies frequently turn out to be superior to "pure" strategies motivated by a particular concept of the future. Figure 3.2 shows schematically a comparison of two strategies for dealing with climate change. The crash-program approach (left pane) proves good or very good (blue or green) only in one corner where economic growth turns out to be high and the natural decoupling of energy production from carbon dioxide emissions is low. In contrast, the "safety-valve" strategy (right pane) begins with a crash program but relaxes the pace of change if economic development is slower or natural decoupling is faster than expected. This avoids unnecessary spending. The results are reasonably good in almost all of the anticipated development scenarios. The concept has proven valuable in numerous subsequent studies, most in social-policy areas but also in, for example, the interplay between economic and national-security issues (Popper et al., 2009).

A very different instance of planning strategically for adaptation appeared in a congressionally mandated study of how to draw down U.S. forces in Iraq, amidst a great many uncertainties that posed considerable risk. The study methodically identified risks and measures to mitigate those risks, including plans for specific adaptations (Perry et al., 2009).

Capabilities-Based Planning and Portfolio Analysis

In 2001, DoD introduced "capabilities-based planning" (Rumsfeld, 2001). RAND's definition, adopted by many in the defense community, is that capabilities-based planning is "planning, under uncertainty, to provide capabilities suitable for a wide range of modern-day challenges and circumstances, while working within an economic framework" (Davis, 2002). The primary concepts were developed in the 1990s, resurrecting classic tenets but adding concepts of exploratory analysis, multiresolution modeling, and portfolio analysis. DoD's implementation of this method has had major effects. Also, there were also some unfortunate twists in

Figure 3.2
Robustness of Explicitly Adaptive Strategy



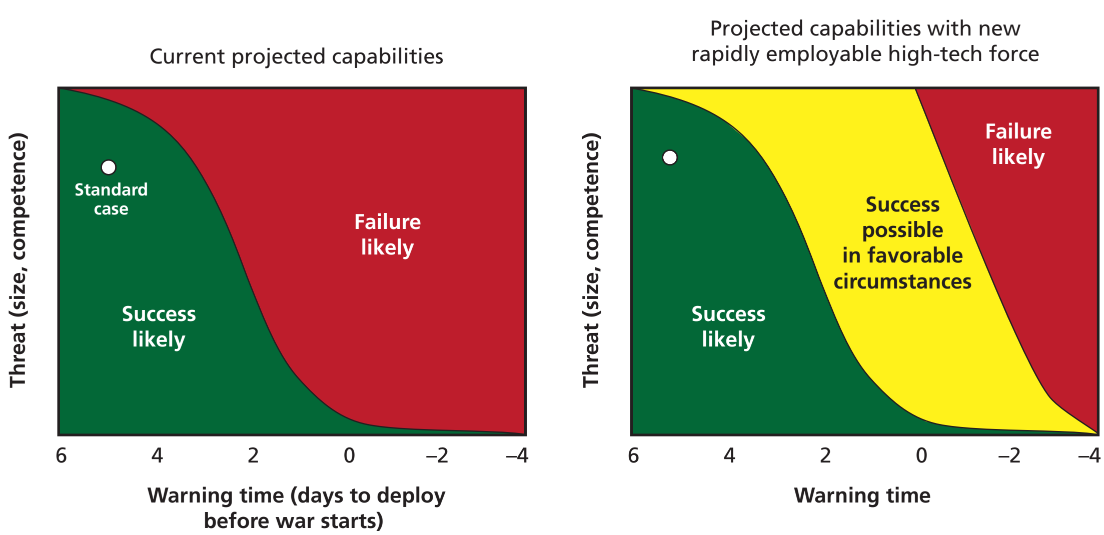
SOURCE: Schematic adaption from Popper, Lemert, and Bankes (2005).
RAND *TR1249-3.2*

the early days, such as rejecting discussion of adversary-specific scenarios and often not getting around to making choices to live within the budget available (Davis, 2010a). The term itself now has some "baggage," but the basic concept is accepted and implementation has improved.

An important aspect of the concept is seeing that the purpose of planning is to provide broad capabilities that will make it possible to deal with a wide range of future challenges. Figure 3.3 illustrates schematically the planning capabilities for a large scenario space covering a wide range of warning times and levels of adversary capability. The "standard case" shown as a black dot is just one of the infinite possible scenarios. The left panel of the figure is a version of a graphic used with numerous senior audiences; it illustrates that (as of the mid-to-late 1990s) the U.S. military would have been unable to deal effectively with scenarios that provided short warning times for decision and deployment of forces. By investing in even relatively small forces that could be on the scene quickly with precision weapons (right pane), U.S. capabilities would be sufficient to cope with many more cases, although only if circumstances were favorable, as with having effective and responsive allies. As in Figure 3.2 , the point is to measure the value of an option by how it deals with uncertainty, rather than how it improves performance marginally for a standard case (the dot in the upper left).

One aspect of capabilities-based planning is portfolio analysis, the essence of which is recognizing multiple objectives and multiple instruments with which to address them. DoD does not have the luxury of, say, ignoring the Far East or the Middle East, nor of ignoring future balance-of-power issues by focusing strictly on present-day irregular warfare. Planning can be seen as achieving a partially subjective *balance* in the way the various objectives are addressed. The DoD and the U.S. government have multiple instruments that can be used to do this. The result should be a portfolio of investments to attend to a variety of needs. National-security portfolio analysis is metaphorically related to financial portfolio analysis that recommends holding a mixture of stocks, bonds, and real estate to ensure capital preservation and increase wealth (limit downside volatility while growing capital). The national-security version of port-

Figure 3.3
Planning Capabilities for a Large Scenario Space, Circa 1995-2000



RAND *TR1249-3.3*

folio analysis deals with more and softer criteria (e.g., reassurance of allies and deterrence of adversaries); it necessarily depends more on strategic judgements about balancing the portofolio. "Objective" optimization is not possible because there is no a priori utility function, although optimization methods can be very helpful as part of the overall exploration.

RAND's work on portfolio analysis dates from the late 1990s in work for the Office of the Secretary of Defense (Davis, Gompert, and Kugler, 1996) and more recent work for the Missile Defense Agency and the Under Secretary of Defense for Acquisition, Technology, and Logistics (Davis et al., 2008). The concept is now well accepted and was articulated by Secretary of Defense Robert Gates, who noted that U.S. military forces and defense investments were focused almost exclusively on a class of "traditional wars." After two decades of experience with lesser conflicts and counterterrorism, he argued that the United States should "rebalance" its planning (Gates, 2009). It is proceeding to do so.

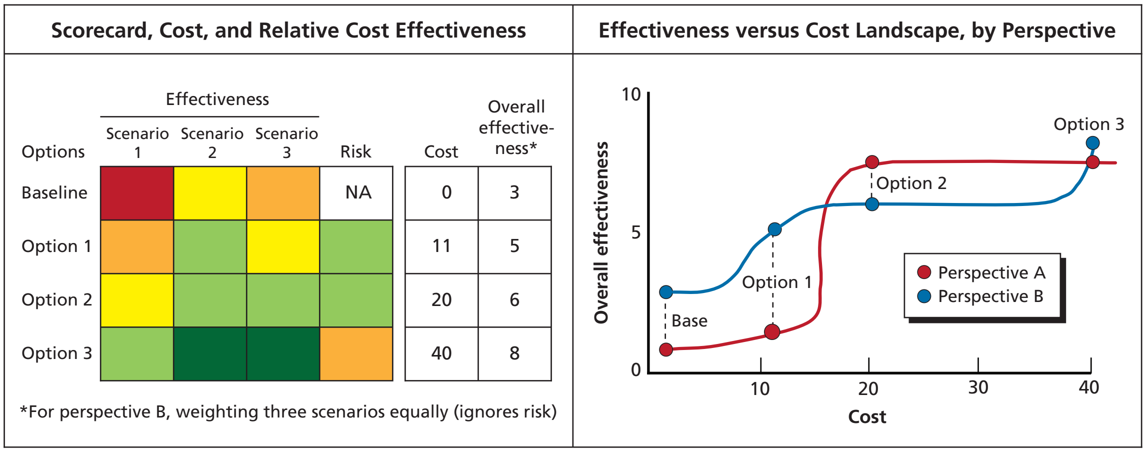
When conducting portfolio analysis, it is necessary to estimate how well alternative strategies attend to the various objectives. Evaluating strategies for particular scenarios can be useful, but the scenarios should be chosen systematically and analytically. As discussed earlier, initial exploratory analysis can identify a small set of test-case scenarios. Policymakers can then be shown results for all of these in the simple form of colored scoreboards (left side of Figure 3.4). They can first view results at the scorecard level to see balances or imbalances, engage in discussion, and guide iteration of options. They can also and sometimes do drill down into details to understand or question selected results (not shown here).

Ultimately, portfolio balancing depends on policymakers' judgments. In 2011–2012, for example, a key national-security issue was the balance of investments between irregular-warfare capabilities and capabilities affecting the longer-term balance of power in the Far East, something discussed in earlier RAND work (Gompert, Davis, Johnson, and Long, 2008; Davis, et al., 2008). *After* policymakers address the higher-level matters of balance, it can be useful to "add up" effectiveness scores across criteria and then plot simplified effectiveness versus cost landscapes (right side of Figure 3.4). A RAND innovation is to do so as a function of strategic *perspectives*, that is, sets of assumptions about values, beliefs, and judgments. Policymakers with different perspectives will weigh balance-of-power considerations and near-term counterinsurgency capabilities differently and may also evaluate prospects for accomplishing missions differently (e.g., manpower-intensive intervention may be seen as both risky and potentially counterproductive or as likely to succeed, depending on who is doing the assessing). In Figure 3.4, option 3 looks good under perspective B (blue line), although it is expensive, but in perspective A (red line), option 2 looks best and option 3 looks wasteful. More generally, benefit-cost analysis turns out to depend strongly on matters about which there are strategic disagreements and uncertainties, which are more important than the precision of analysis.

With this in mind, RAND developed a methodology (not discussed here) that generalizes classic efficient-frontier analysis so as to identify options that are "near" (rather than on) the efficient frontier by any of several alternative perspectives and across uncertainties (Davis, et al., 2008).

The portfolio-analysis methodology also examines numerous risk factors, such as strategic risk (e.g., world reaction to collateral damage), technical risk, program-cost risk, and political risk (as when a development might be especially subject to second-guessing by Congress or a new administration). The principles are documented and a portfolio-analysis tool is available to the public (Davis and Dreyer, 2009). Such tools are not created overnight; this one evolved over the period of a decade (Hillestad and Davis, 1998).

Figure 3.4
Scorecards and Cost-Effectiveness Landscapes by Perspective



NOTE: The left-pane scoreboard compares options 1-3 with a baseline. Each option (row) has capabilities measured by effectiveness in scenarios 1, 2, 3 (columns). The colors red, orange, yellow, light green, and green denote very poor, poor, medium, good, and very good effectiveness, respectively. Each option has risks and costs. An option's overall effectiveness depends on the relative weights of the four columns on the left and on the decisionmaker's perspective. The right pane shows overall effectiveness versus cost for perspectives A and B. Each curve is a smoothed "efficient frontier" (no option exists that would be more effective for a given cost or less expensive for a given effectiveness. Perspective B (blue) sees considerable value in Options 1 and 2, and even more value in Option 3. Perspective A, however (red), sees modest value in Option 1, a great deal of value in Option 2, and no additional value to Option 3.
RAND *TR1249-3.4*

In recent times, related methods that recognize the differences in "stakeholder perspective" have also been used to evaluate options for social issues, such as rebuilding in New Orleans. These methods make good use of both optimization methods and comparison of results from different perspectives (Fischbach, 2010).

System Thinking in Strategic Planning for Complex Adaptive Systems

System thinking has been a hallmark of RAND work since its creation, but the meaning has changed over the decades, especially with appreciation of complex adaptive systems (Holland and Mimnaugh, 1996) and the implications of complex adaptive systems theory for modeling and analysis. For example, the study of complex adaptive systems phenomena and methods strengthened RAND's emphasis on exploratory analysis/modeling (Bankes, 2002), multiresolution modeling, and agent-based modeling for research in contexts involving social dynamics (e.g., stabilization and irregular warfare). Two manifestations in national security work are described below.

Border Control for Drug Smuggling

Recent work for the Department of Homeland Security defined measures and metrics for addressing border control (Willis, Predd, Davis, and Brown, 2010). Researchers found themselves having to address the complex and changing interactions between border control actions and, for example, the state of the U.S. and Mexican economies, the effectiveness of internal

U.S. law enforcement agencies, the effectiveness of the judicial system in punishing criminals, and trends in domestic demand for drugs (affected by social cycles, education, and demography). These "other" matters are to some extent unpredictable because of the complexity of the overall social system, including the adaptations of drug smugglers. However, analysis dramatized the point that overall success is unlikely without *simultaneous* initiatives by several government agencies (e.g., more effective interdiction of smugglers *and* punishments sufficient to change their behavior).

Despite uncertainties, a good deal can be done to analyze such problems, as illustrated by early RAND work (Rydell, 1994) in which a system dynamics simulation was developed to relate components of a problem to estimate where marginal investments could most usefully be made (e.g., in educational efforts to dissuade current or potential drug users rather than even greater efforts to interdict drug smugglers). The work was applauded for its contributions to structuring the problem and debate, despite using data beset with uncertainties. Interestingly, the same trade-offs are being discussed in 2012, almost two decades later.

Counterterrorism and Counterinsurgency

A second example of dealing with complexity involved RAND work on counterterrorism and counterinsurgency. In both domains, deep uncertainties dominate. Also, such subjects cannot be addressed with the kinds of "kinetic-oriented" thinking that dominated previous DoD planning (that is, thinking focused on physical destruction of armies or facilities). Further, as predicted in what is now seen as groundbreaking work on "networks and netwar" (Arquilla and Ronfeldt, 2001), it has become necessary to think constantly about complex adaptive networks rather than simple systems. In the months after 9/11, a RAND study laid out principles for the "deterrence and influence" components of a counterterrorism strategy. It argued against seeing al-Qaeda as a monolith, instead suggesting a system view that decomposes al-Qaeda into components (including public supporters), many of which *are* subject to influence and even some versions of deterrence (Davis and Jenkins, 2002). The study concluded that efforts to find a single critical point of vulnerability were misguided because of complex-adaptive-system considerations. The study concluded that the United States should instead conduct a broad-front attack on all elements of the al-Qaeda system, reinforcing successes when they occur (sometimes by good fortune, as when al-Qaeda overreaches and antagonizes populations). Recent work on deterring terrorism has gone farther in stressing the importance of measuring options by their high-leverage *potential* rather than the certainty of their success and by exploiting terrorists' dislike of operational failure (Morral and Jackson, 2009; Davis, 2010b).

One consequence of the uncertainties that dominate counterterrorism has been DoD's request for social science research to better understand issues and courses of action. A new generation of RAND social scientists is contributing to that endeavor, as illustrated by a recent integrative survey (Davis and Cragin, 2009) that exploited qualitative and quantitative empirical work as well as simple integrative models. Subsequent empirical studies have largely validated the qualitative models to include—as predicted—demonstration of country-specific differences in the relative importance of factors. The most recent study has moved from a purely qualitative conceptual model of public support for insurgency and terrorism to an uncertainty-sensitive computational model that should improve the ability to elicit expert information and assess counterterrorism options under deep uncertainty (Davis and O'Mahony, unpublished). The authors constructed the model to support contingent, context-sensitive assessment and planning, rather than more traditional generation of "best-estimate" predictions.

Strategic Forecasting and Expert Elicitation

A traditional input to strategic planning is forecasting. One recent example was a study for the National Intelligence Council (Silberglitt, Antón, Howell, and Wong, 2006) that looked at the global technology revolution in far-reaching topics such as biotechnology, nanotechnology, materials, and information trends; drivers of change; barriers to change; and social implications.

An issue that arises in such work is how to elicit expert judgment; this topic affects all domains of policy analysis, not just strategic planning. RAND's work from a half century ago became the well-known Delphi technique (Helmer-Hirschberg, 1967). Currently, RAND research is tapping the so-called wisdom of crowds (not randomly chosen crowds, however) through a combination of traditional sessions, social media, and distributed activities on the worldwide web. This research exploits modern technology to improve the ability to find best-estimate forecasts of diverse and independent experts, improve those forecasts by discussion and iteration, and also keep track of significant points of disagreement where minority views could be of particular value and even prescient (Dalal, 2011).

CHAPTER FOUR
Acquisition Management

Acquiring weapon systems involves huge investments and intense scrutiny. Even when the decision to acquire something (e.g., a new tanker aircraft) has been reached, managing the acquisition is challenging. Despite conventional wisdom that identifies such alleged core issues as the need for competition, the need to use commercial off-the-shelf technology, or the need to have greater (or lesser) oversight, it is difficult to know what to believe, which creates a need for research. A few examples illustrate relationships with this paper's theme of uncertainty.

Deciding on Whether to Arrange for Competition

It is accepted in the United States that competition is essential for innovation, quality, and cost control. We see confirmatory examples in our day-to-day lives. Managing competition in DoD's acquisition domain, however, involves difficult and unusual issues, especially as the result of unique defense-sector consolidations.

Consider early days in the acquisition of the Joint Strike Fighter. How much competition should be required in the proposal, prototype, and production phases? Why? What difference would competition make and how do we know? If there were enough relevant and diverse acquisitions over a long enough period of time, the problem could be addressed as one of statistical uncertainty. Acquisitions, however, are less numerous than in earlier decades, technologies and industrial methods have changed, and the past is not obviously prologue. Major disagreements exist about how to proceed. Consequently, RAND has struggled with how to use a combination of methods to inform decisions.

In one Joint Strike Fighter project (Birkler et al., 2001), RAND assessed prospects of competition for reducing overall program costs. First, it developed an economic model using program-office information to estimate the break-even point: how much would have to be saved through competition to pay for the cost of having it? The answer was 30 percent. Researchers then augmented these data with extensive discussions with contractor teams, consultants, and the program office. Discussions addressed, for example, the real-world feasibility and desirability of various competition strategies. As emerged clearly during these discussions, such a strategy would create new incentives and disincentives for both the lead contractor and the competitors, some of which might have perverse consequences. Also, the pace of technological developments was so great that paying to preserve the option to shift contractors in the future for building a system conceived and designed in the past would not obviously be valuable.

This work included traditional analysis, but depended heavily on creative brainstorming with experts to anticipate possibilities. The recommendations were to (1) stick with the winnertake-all strategy for near-term development and production, but (2) consider *funding a potential future competitor* that would be capable of competing to develop and manufacture the next major upgrade of the mission system equipment. This strategy would mean that future managers would have the option of a competitive second source, something that might not otherwise be available (Arena and Birkler, 2009).

Reducing Risk by Taking Risk

To taxpayers it may seem that DoD is always taking risks. After all, acquisition programs frequently run into trouble and price tags rise. However, a frequent theme in RAND acquisition work has been the need, in part of its portfolio, for DoD to take *more* risks in experimenting with new technology and novel operational concepts. The Defense Advanced Research Agency certainly pushes the envelope, but actual defense acquisition is remarkably conservative because of concern about costs and the personal and organizational consequences of failure. This increases the possibility that at some point in the future, major aspects of U.S. military capability will be rendered obsolete, as occurred when aircraft carriers replaced battleships. That is, there is high strategic risk in reducing acquisition risk.

Forecasts of obsolescence have often proven wrong or premature, but transitions do eventually occur. In work done for the U.S. Air Force, RAND has been candid in noting the need for new concepts of operations in East Asia (Shlapak, 2010). A 2011 study for OSD discussed "looming discontinuities" in defense planning (Davis and Wilson, 2011), anticipating the changes of U.S. grand strategy announced early in 2012 and calling for new concepts of operation.

Exhortations about taking risks to stay ahead have been common, but being able to do so depends on management policies. RAND has argued that major reforms are needed if the United States is to improve its ability to pursue novelty. These include (1) creating the requisite organizational environment; (2) monitoring civilian developments for ideas and opportunities; (3) permitting testing and even provisional fielding of less-than-fully-mature novel systems and approaches so that operational commanders can "see" and feel what is possible and can significantly influence subsequent emphasis and convergence based on real-world experience; (4) decentralizing decisionmaking so that energetic young officers and officials can pursue promising ideas without having to persuade superiors; and (5) systematically accumulating lessons about managing experiments with and acquisition of novel systems (Birkler, 2009). Analysis, then, concludes that analysis is not enough.

Reducing Uncertainty by Researching the Facts

A second acquisition-management example of dealing with uncertainty illustrates the value of research to discover the "true facts." Advocates of acquisition reform, for example, have long claimed that burdensome statutes and regulations are a major hinderance to the efficiency of the acquisition process. A RAND project went beyond horror-story anecdotes to quantify and document these effects empirically. Researchers used a web-based tool to collect information on actual time spent on the various activities. They collected information for one year from 316 people such as program managers and personnel within the functional areas of interest. The results were surprising (Drezner et al., 2007):

- The total reported time spent on compliance activities in the five statutory and regulatory areas addressed was less than 5 percent.
- Most compliance-related activities were responding to a service request or requirement, rather than one from OSD, the Government Accountability Office, or other program stakeholders.
- Participants recognized that many of these compliance activities must be accomplished whether or not they are mandated.
- There was little evidence of actual consequences to program execution or outcomes as a result of the compliance activities we tracked.

Clearly, some compliance activities are burdensome and add little value. However, the study concluded that no evidence supports the perception that compliance activities substantially raise costs or lengthen the process. The study had other thoughtful observations, but the relevant point here is that, if focused, research can materially reduce uncertainties about where problems are and are not most severe.

Scientific Cost Estimation

One aspect of acquisition management is estimating the future cost of weapon systems. This might seem to be in the realm of "normal" uncertainties, but matters are simple only if the past is prologue and a great deal of relevant empirical data exist. From comparing case-history insights to empirical data, it is clear that the forecasting of costs involves numerous deep uncertainties. One consequence is the need to draw upon subjective expert judgment, such as that of experienced program managers, technologists, and acquisition managers.

RAND recently conducted an interdisciplinary review of the scholarly literature to identify best practices for doing drawing upon such judgment (Galway, 2007). Common practices are highly varied and frequently problematic. RAND sought to identify a better way of doing this by reviewing and synthesizing scholarly material from statistics, psychology, and cost-estimating. Not surprisingly, the review found strong evidence of worrisome human biases that undercut usual judgment elicitation. Prescriptions were harder to find, but they emerged after synthesizing across reports. Prescriptions included: (1) elicit probability distributions rather than point estimates; (2) use multiple independent experts; (3) ask experts to provide at least lower, upper, and most-likely values (to be used in a triangular distribution from .05 to 0.95) and more if possible (e.g., 25th and 75th percentile values); (4) provide feedback to the original experts and discuss; and (5) document the entire process. These are perhaps most remarkable for the degree to which they diverge from common practices.

CHAPTER FIVE

Logistics

Background

RAND's logistics researchers have long worried about uncertainties and mechanisms for minimizing bad consequences. The usual distinction has been between stochastic and state-of-the-world uncertainties—i.e., between statistical and deep uncertainties. For example, the parts of a weapon system are subject to random failures characterized by empirical probability distributions. They may also be replaced if humans decide to change out a group of parts because they are thought to be due for change. The consequences can be represented by simulation models that incorporate consumptions, failures, responses, and adaptations, in addition to changes in the parameters used in the distributions that occur over time (e.g., a part's mean time to failure may increase slowly over time or may be relatively large initially and much smaller thereafter). "State-of-the-world uncertainties" refer to the actual war in which logistics will be tested and all of the detailed circumstances of that war that are affecting and have been affected by logistics.

Stochastic uncertainties exist on both the supply side and the demand side. Early work focused on forecasting demand and depended on simplifying assumptions that made the mathematics tractable. Analysis with modern computers relaxed these assumptions and revealed, for example, that actual demand for spare parts is not well described by simple Poisson distributions. Also, analysis showed that distinctions were not being made properly between demands based on consumption or the need for replacement on the one hand, and demands resulting from part failure on the other. Experience also showed that with enough recent data, more complicated distributions could be inferred and used to forecast future demand. Indeed, it has become increasingly possible to represent complex real-world processes of work flow and to reflect likely adaptations that can in some cases mitigate and in other cases exacerbate problems (Adams, Abell, and Isaacson, 1993). Such work can be described generally as *dynamic stochastic programming*. Many advances have been made in this area as far back as the late 1970s and early 1980s, including development of the influential Dyna-METRIC model (Hillestad, 1982). They continue to this day.

RAND's 1980s Uncertainty Project

A troublesome aspect of early logistics work was that it focused unduly on optimizing economic efficiency in peacetime. Later RAND work remedied this by assessing logistical issues for *wartime* conditions (Rich and Drezner, 1982) as proxied by warfighting scenarios. Convincing DoD clients to adopt the wartime emphasis was an uphill struggle because it led to inconveniences and expense and because it required more complex modeling that represented the interactions between combat and logistical systems. That said, emphasis on state-of-the-world uncertainty in wartime was an important part of what was called the "Uncertainty Project" within RAND's Project Air Force. The project sought to better understand problems that had long been obfuscated in stochastic modeling that oversimplified by imagining single processes and stationarity. The project also included early aspects of what became a major theme of RAND work—finding ways to deal with highly variable demand by such *coping* mechanisms as cannibalization, lateral supply and repair, priority repair, responsive intertheater and intratheater transportation, and responsive depot repair.

This work brought out a competition of paradigms and fierce arguments between those who sought to make better forecasts and those who sought to prepare for adaptiveness. Both are necessary, but the premium had been on forecasting. Indeed, it was taken for granted that "everything" was slow—months to deploy forces to a distant theater or even to supply unanticipated parts. Attitudes began to change during the 1980s, driven in significant part by developments in the commercial sector, which inspired RAND's initiatives in the 1990s for the Air Force and Army referred to as Lean Logistics (Air Force) and Velocity Management (Army).

Despite considerable advances, debates continued within RAND because only some aspects of state-of-the-world (deep) uncertainty were being addressed, In addition, the inertial tendency was to slip back to the more familiar and well-defined analysis that involved standard scenarios (albeit, with complex database work and computation). The results of such analysis can be counterproductive by obfuscating actual uncertainty. The gauntlet was thrown in a 1990 paper (Hodges, 1990), elements of which had much in common with the research described in Chapter 2 by highlighting two main shortcomings of past work: omitting crucial sources of uncertainty and neglecting systems' ability to respond to the unexpected. These relate to both deep uncertainty and adaptation.

By this time, however, model-based logistics work was beginning to improve decision tools, better reflect operational concerns, and generate results more quickly (e.g., with the DRIVE algorithm). The logistics challenge was seen as a control problem. One aspect of this work—a classic example of something eminently sensible in retrospect but disruptive at the time—was to focus on aircraft availability as a key measure of effectiveness (rather than, say, part shortages per se) (Abell, Miller, Neumann, and Payne, 1992).

A review of the uncertainty project began with a statement of objectives that was very much in keeping with the entirety of this paper. Paraphrased, these objectives were to (1) improve understanding of the magnitude and extent of variability; (2) increase the flexibility, robustness, and responsiveness for better readiness and sustainability in unpredictable peacetime and wartime circumstances; and (3) improve infrastructure to support "real-time" needs of combat forces (Cohen, Abell, and Lippiatt, 1991, p. v).

Recent Developments

Recently a great deal of logistics work has gone into planning worldwide stockage of war reserve materiel by using multiple capability-test scenarios to improve system robustness (Amouzegar et al., 2006). RAND has been suggesting rather drastic overhauls to U.S. Air Force logistics for worldwide operations, emphasizing both planning under uncertainty and "agility." This can mean revisiting decisions or changes in execution more frequently, including decision support. For example, decision support can be more rapid and adaptive if it is based on relatively simple models that can be exercised quickly over a range of scenarios and for only a short time horizon, which is appropriate if decisions will be revisited frequently.

Looking back, it is clear that RAND's Velocity Management work for the U.S. Army had major effects. Recently, the Army used the Six Sigma approach to reduce variance in supply-side performance. Also, some of RAND's recent uncertainty-related logistics work provided a much more dynamic and cost-sensitive approach to suggest inventory levels for Army support activities based on a combination of recent experience and contingency-related constraints (Girardini et al., 2004). Affected strongly by wartime experience, the approach makes it easier for small, inexpensive items with high-priority requisitions to be stocked in enough depth so as to be available when customer requests arrive. Other recent work for the Army has also exploited empirical-demand information. One project focused on setting tactical and theater inventory levels during such ongoing conflicts as the wars in Iraq and Afghanistan. The combination of unit-specific, theater-specific, and Army-wide data has been especially valuable. The demand data contains both stochastic elements and aspects of deep uncertainty. The demand streams are processed with statistical filtering to remove outliers and without assuming any underlying probability density function because of the large number of low-demand items and effects of deep uncertainty reflected in the demand data. Heuristic and mixed-integer programming approaches have been used to make estimates.

Longer-term research has also considered inventory planning, but for future contingencies. Deep uncertainty dominates such planning; RAND has used specific scenarios associated with Southwest and Northeast Asia, but has combined forecasts from multiple models.

Looking across efforts, the newer logistics projects have exploited technology to provide and analyze massive amounts of raw data, including current data. Doing so has been a major factor in the great successes of Lean Logistics and Velocity Management, as well as responsiveness to warfighters in Iraq and Afghanistan. Thus, in contrast with most of the items discussed in this paper, recent logistics work has been less about dealing with deep uncertainty than about exploiting rich data in fast-turnaround empirical (but theory-informed) modeling. That said, thoughtful system modeling of the entire supply chain and its bottlenecks has greatly improved the Army's ability to sustain warfighters in Iraq and Afghanistan (Peltz, Halliday, Robbins, and Girardini, 2005; Peltz, Girardini, Robbins, and Boren, 2008; Girardini, Fan, and Miller, 2010). These authors concluded that despite the complexity of the supply-chain system, it is possible to manage it well given (1) a strategic vision of how it should operate, (2) effective monitoring (the crucial point about data, above), and (3) coordination among major players to work toward the same goal. Some of the resulting changes involved significant shifts in the airlift/sealift mix, implementation of new algorithms within the increasingly responsive supply chain, and better forecasting and budgeting.

CHAPTER SIX

Manpower Research

RAND's research on managing human capital (manpower research) has long been used by OSD and related services. Recent work builds on ideas developed in the 1980s before computing power allowed such ideas to be exploited. In particular, a continuing challenge is to understand personnel retention well enough to tailor policies and incentives so as to maintain requisite levels of experience. Here the uncertainties are of a different character than in force-structure or weapons-acquisition problems. Whether to re-enlist or leave the service is an individual decision dependent on myriad factors such as the state of the economy, the nature of service experiences generally (whether in times of peace or conflict), and individual circumstances. Some aspects of personnel policy such as incentive pay can, however, be adjusted adaptively much faster than, say, the time scale for developing and acquiring a new major weapon system or for revising warfighting doctrine.

RAND continues to use and modernize a method using stochastic dynamic programming *at the individual level* (Gotz and McCall, 1984; Asch, Hosek, Mattock, and Panis, 2008). The core concept is that individuals make choices each year as if they were rational in the economist's sense, but with value functions that show considerable variation in individual natural preferences for life in the military or civilian world, as well as individual preferences dictated by a changing personal-level or general "environment." Choices include leaving service, signing up for short additional tours, or signing up for longer additional tours. If all else were equal and constant, longer-term reenlistments would have the highest economic value. However, circumstances change and make staying in the military more and less attractive to the individual. The model represents explicitly the value of maintaining the flexibility to leave service earlier rather than later. Empirically, it does a good job in explaining and predicting behavior.

At a more technical level, an individual in the model considers, in each time period (yearly), the expected future value of each possible choice, taking into account that the future value will depend on both future random events (e.g., an event next year, or the year after that, which would make continuing service more or less attractive to the individual) and future choices. Analytically, the model can be understood in terms of a decision tree unfolding into the future. Empirical data establish the parameters of the model, which can be adjusted routinely as data are updated. This approach is very different from merely using empirical data to fit an unmotivated statistical regression model because the variables and parameters of the model are understandable in terms of rational decisionmaking. Thus, if the model "works" empirically, it also has a built-in explanation capability.

Many other staffing-related projects have dealt with uncertainty, sometimes in the context of logistics, for example, setting requirements for maintenance staffing in the U.S. Air Force using the Logistics Composite Model (Dahlman, Kerchner, and Thaler, 2002).

CHAPTER SEVEN

Crisis Decisionmaking

Deep uncertainty is never more consequential than in crisis decisionmaking, which RAND has studied since the Cold War, with recent contributions adding new insights. Interdisciplinary research drew on literature from general decisiomaking theory, presidential decisionmaking, cognitive psychology, and crisis preparation in industry, including poliycmakers' accounts of crisis decisionmaking from Eisenhower through Clinton. Only portions of the work in the early 2000s were issued formally because the conclusions, if published at the time, would have inevitably been seen as "political" criticism of then-current matters related to the Iraq war. Instead, core points were published in an integrating review that stuck with the science (Davis, Kulick, and Egner, 2005).

A contribution of this work was to strike a synthesis between the extensive research on cognitive biases and newer research on naturalistic (intuitive) decisionmaking. The synthesis took the view that decisionmaking should draw from both the rational–analytic and intuitively driven paradigms and should be tailored so as to assist a given decisionmaker's style while making an effort to help mitigate against its predictable shortcomings. The following are summary recommendations for decision support that came out of that work. Many are efforts to overcome the *tyranny of the best estimate*, which so often undercuts the quality of decisionmaking.

Recommendations

- Ensure that two or more alternative "stories" (essentially models) are articulated early when discussing interests, adversary intentions, and strategy.
- Build the requirement to create such alternative models and stories into doctrine in order to protect and raise the status of disparate views (potentially more effective than attempting to use the devil's advocate approach).
- Use multiple communication modes, from discussion to point papers and graphics.
- Routinely provide best-estimate, best-case, and bad-case assessments (that is, pay attention to both upside potential and downside risks).
- Routinely conceive and protect explicitly adaptive strategies that hedge against errors in the best estimate.

A common theme in the recommendations above involves "doctrine" for decision support at the National Security Council level, especially doctrine designed to strongly nudge deliberations toward choosing a course of action with the same virtues as those highlighted earlier (that is, flexibility, adaptiveness, and robustness), especially related hedging. Prescriptively, the admonition is to go far beyond the practice of ensuring that decisionmakers know the assumptions underlying analysis and to instead *routinely* add elements to the emerging strategy to hedge against error, especially fundamental errors such as misunderstanding the adversary. Much more could be done on this subject on an applied basis, but the primary intellectual ideas have been published (Davis, Kulick, and Egner, 2005; Davis and Kahan, 2007).

CHAPTER EIGHT

Organization and Implementation

Organizing to Cope

As anticipated in Chapter 1 and mentioned in Chapter 6, some of RAND's most important work on uncertainty relates to *coping* with surprise developments. Many strands of RAND research have exhorted organizations to organize so as to achieve the virtues mentioned in early sections of this paper, variously described in terms such as flexibility, adaptiveness, and robustness. A highly readable book reviews such RAND work in the context of characterizing high-performance organizations (Light, 2004). The primary themes abstracted in the review are: (1) thinking in terms of plural futures, (2) organizing for lightening of the organization (so as to be flexible and adaptive), (3) challenging prevailing wisdom, and (4) focusing and organizing around mission (which leads to tight "alignment").

It should be noted that any initiative for planning under uncertainty can be seen by some elements of an organization as a threat to more general norms and activities, that is, it can be seen as what organization theory refers to as a "precarious value."

Anticipating Organizational Behavior Undercutting Intentions

RAND has learned a great deal over the last 20 years about how difficult it is for the DoD and other organizations to implement policies for dealing with uncertainty. Some of the interesting conclusions are

- Implementation of good concepts such as capabilities-based planning can be undercut by sloppy thinking and unwise organizational changes. Adaptations occur, but time is lost. Also, a key element of capabilities-based planning is making choices when budgets are limited. Without budget pressures, it is too easy to defer choices. In the extreme, capabilities-based planning can become an exercise in finding shortfalls and seeking blank checks.
- The natural tendency of successful leaders is often to enforce priorities (first-things first), but a naive priority-list focus can be at odds with taking a portfolio-balancing approach to address multiple enduring objectives and to build in hedges.
- Organizations that might be expected to pursue capabilities-based planning are sometimes recalcitrant. Well-established analytic organizations, for example, may be wedded to routinized analysis with big, complex models and standardized scenarios decided upon by committee. They may not be able to address uncertainty effectively or respond quickly to decisionmaker questions.

- DoD's emphasis on consensus-building makes planning under uncertainty extremely difficult, not only because of the number of people involved but also because the representatives are charged with protecting their offices' programs, not with being good long-term strategic planners.
- The separation between "requirements" and "acquisition," which resulted from Goldwater–Nichols legislation, has created profound organizational and process problems that make planning under uncertainty difficult. A planning style is needed in which strategists, technologists, operators, and analysts (and cross-cutting individuals) work efficiently together to creatively solve problems using forward-looking thinking (Kent, 2008; Davis et al., 2008).

The primary conclusion is that if the theory of planning under uncertainty and preparing to cope with surprise effectively is difficult and complex, implementing and maintaining corresponding changes is even more difficult. Policymakers will require constant vigilance or their initiatives will be undercut or allowed to wither.

CHAPTER NINE

Conclusions

Even this short review of uncertainy analysis for national-security applications demonstrates the wide range of uncertainties that arise, the variety of techniques that need to be applied, and the progress that has been made in dealing with deep uncertainty.

Looking across the research discussed, several themes stand out for planning under uncertainty:

- There is need for a combination of creative work to understand the range of possibilities, and more convergent analysis to assist decisionmakers as they seek economically accepable strategies that are likely to be acceptably effective for the diverse challenges that may actually arise. Diverse methods, some of them human intensive (including gaming and brainstorming), and some of them analytic and even computational, are needed.
- Experimentation and iteration are often essential for both uncertainty reduction and discovery.
- In practice, strategy will often be revisited and modified, despite the common assumption of once-and-for-all decisionmaking. Where possible, planning should anticipate the need for adapation and identify the signals that should trigger adaptation.
- Because major surprises will nonetheless occur, planning should also provide general capabilities and organizational agility for adapting to such unanticipated developments, both positive and negative.

To elaborate on the last point, a common concept of good analytic practice for dealing with uncertainty when it is included in a report to a policymaker is to show key assumptions, watch for the policymaker to acknowledge the assumptions, and then present results. Unfortunately, even if policymakers know the assumptions and believe them to be reasonable, this approach is inadequate. RAND work argues that analysts should also do the following:

- Be sure that omitting considerations because of uncertainty does not critically affect study conclusions.
- Be sure that conclusions identify reasonable ways to hedge against consequences of uncertainty, including preparing for adaptation.
- Sensitize policymakers to the importance of such hedging, which is more valuable than final increments of fine-tuned optimizing for the baseline case.

RAND's somewhat radical vision is that policymakers agree with this process and then require their organizations to follow a corresponding analytic doctrine (Davis, 2002).

APPENDIX

More General Literature

This paper summarizes highlights of RAND work relating to uncertainy analysis for national-security applications. A substantial general literature also exists. The following are suggested entry points to that more general literature.

A good advanced text on dealing with uncertainty analytically is a book by Granger Morgan and Max Henrion (Morgan and Henrion, 1992). Another text, by John Hammond, Ralph Keeney, and Howard Raiffa, updates thinking about multicriteria decisionmaking and value-focused thinking (Hammond, Keeney, and Raiffa, 2002).

The literature on scenario-based planning is considerable, dating from Herman Kahn's pioneering work at RAND in the 1950s and later at the Hudson Institute and from Pierre Wack's famous work at Shell Oil (Kahn, 1962; Schwartz, 1995; Senge, 2006). Nassim Taleb's recent book on deep uncertainty is particularly enjoyable and discusses uncertainty through the metaphor of "black swans" (Taleb, 2007). Stephen De Spiegeleire reviewed security-relevant lessons from this and other trends in planning methods (De Spiegeleire, 2011).

Of particular importance to model-based analysis under uncertainty are the pioneering works of MIT's Jay Forrester on system dynamics (Forrester, 1963; Forrester, 1971; Forrester, 1994) and a related text (Sterman, 2000). Somewhat similar ideas and methods have also been developed in Germany by Dietrich Dörner (Dörner, 1997) and are often mentioned by European authors.

For those interested in the special difficulties and challenges associated with "wicked problems" and with other aspects of "soft" analysis of policy problems, a British-edited volume by Jonathan Rosenhead and John Mingers may be of considerable interest (Rosenhead and Mingers, 2004) as well as a book by Horst Rittel and Douglas Noble (Rittel and Noble, 1989).

The subject of real-options theory has been well studied in the economics literature and has implications for policy analysis, as noted in the literature-review section of a dissertation by Mahnovski (2007).

Mathematical methods that generalize methods of optimization have also been developed. Some of the terms used in the relevant literature are "robust optimization" (Bertisimas, Borwn, and Caramanis, 2011; Ben-Tal, El Ghaouli, and Nemirovski, 2009) and "post-optimization analysis."

Two new DoD publications deal with uncertainty. One is a book on "agility" by David Alberts (Alberts, 2011) arising from work of a NATO panel on command and control. The other is a report by Richard Danzig titled, aptly, "Driving in the Dark" (Danzig, 2011). As a past secretary of the Navy, Danzig is well accustomed to dealing with uncertainty issues from a policymaker's seat.

Finally, it would be remiss not to mention the many materials available, in one form or another, from major consulting companies such as McKinsey & Company (Rasiel, 1999), which has a regular publication with business-oriented tips and debates (McKinsey Quarterly).

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