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Portfolio-Analysis Methods for Assessing Capability Options

Paul K. Davis, Russell D. Shaver, Justin Beck

Prepared for the Office of the Secretary of Defense
Approved for public release; distribution unlimited

RAND NATIONAL DEFENSE RESEARCH INSTITUTE

The research described in this report was prepared for the Office of the Secretary of Defense (OSD). The research was conducted in the RAND National Defense Research Institute, a federally funded research and development center sponsored by the OSD, the Joint Staff, the Unified Combatant Commands, the Department of the Navy, the Marine Corps, the defense agencies, and the defense Intelligence Community under Contract W74V8H-06-0002.

Library of Congress Cataloging-in-Publication Data is available for this publication.

ISBN 978-0-8330-4214-9

Cover Illustration by Stockbyte, courtesy of Media Bakery

Published 2008 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
RAND URL: http://www.rand.org
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Preface

This monograph presents a framework, methods, and tools to support capabilities analysis and related tradeoff work within the Department of Defense and the military Services. The monograph deals with choice and risk.

Some parts of the monograph are written for decisionmakers. These sections recommend and illustrate principles on which to base terms of reference for major capability reviews and organization of summary presentations. Other parts are more technical and are intended for readers who oversee or conduct capability evaluations in depth. The monograph in its entirety should also be of interest to researchers interested in theory, practice, and technology for supporting high-level decisionmaking.

The research reported here was sponsored primarily by Kenneth Krieg, Under Secretary of Defense for Acquisition, Technology, and Logistics (USD (AT&L)), and by James Raleigh Durham, Director of Joint Advanced Concepts in the Office of the Secretary of Defense (OSD (AT&L)). Most of the study was completed in 2006 and early 2007. The research began late in 2005 in response to an earlier request by Michael Wynne, then acting USD (AT&L), for a generic analytic framework to be used in capability-area reviews. The monograph also reflects earlier research, tool-development, and analysis done for the Missile Defense Agency (MDA) under the sponsorship of David Altwegg, MDA's Deputy for Agency Operations.

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This research was conducted within the Acquisition and Technology Policy Center of 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 Department of the Navy, the Marine Corps, the defense agencies, and the defense Intelligence Community. For more information, please contact the Center Director, Philip Antón, at RAND in Santa Monica (telephone: 310-393-0411, ext. 7798; email: atpc-director@rand.org).

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Summary

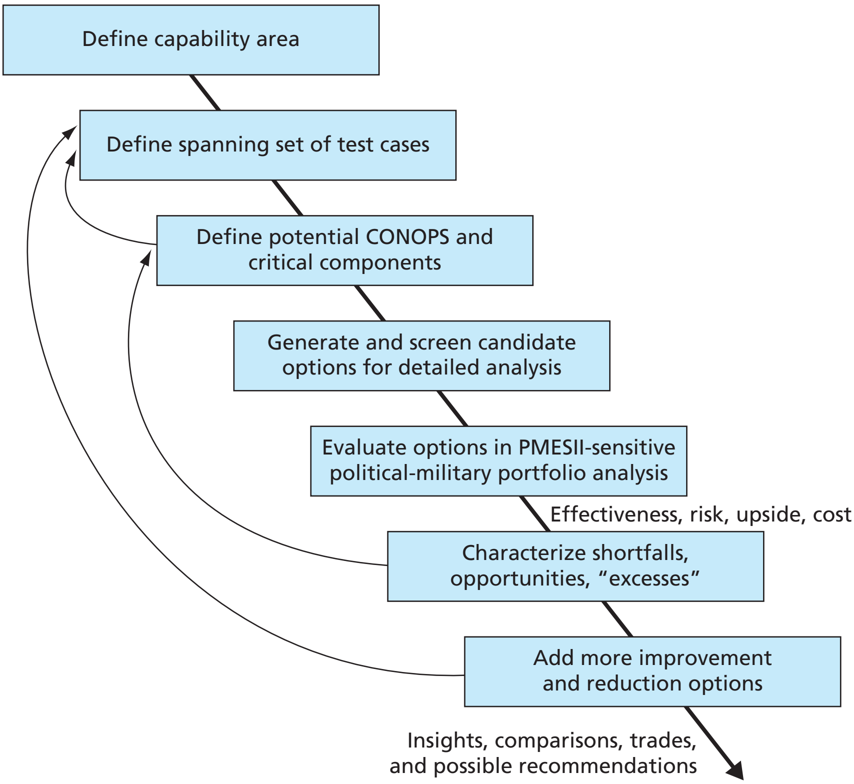
Objectives

The research reported in this monograph is part of RAND's continuing work on practical theory and methods for capabilities-based planning in the Department of Defense (DoD) and other organizations. Its particular contribution is to describe and illustrate in some detail an analytic framework and methodology for defensewide capability-area reviews—including DoD's experimental Concept Decision Reviews and related evaluations of alternatives (Krieg, 2007). The monograph also describes newly developed enabling tools—one for generating and screening preliminary options and one for evaluating in a portfolio-analysis structure those options that pass screening. Variants of the methods can be applied for analysis *across* capability areas or for strategic-level defense planning, i.e., force planning to establish the overall mix and balance of capabilities. Finally, the monograph illustrates concepts with applications to the capability areas of Global Strike and Ballistic Missile Defense (BMD).

A Generic Terms of Reference for Capability Reviews

Our analytic framework is summarized by Figure S.1, which sketches a generic terms of reference for a capability review. Although straightforward and seemingly familiar (just another process diagram), it posits the following important activities that are defined more fully below:

Figure S.1
Generic Analytic Process for Capability Reviews



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1. Define what the capability area "should be" to best support the intentions of decisionmakers and to address problems arising at the seams between capability areas.
2. Construct an analytically motivated *spanning set of test cases* to use in evaluating the options—not for optimum effectiveness in some nominal case, but for flexibility, adaptiveness, and robustness (FARness) across the range of possible situations.
3. Define concepts of operations (CONOPS) and identify critical components of those CONOPS to use in evaluating the options.

4. Generate diverse options and screen for those meriting fuller analysis.
5. Identify and evaluate options in a portfolio-analysis structure. With our apologies for using the current alphabet soup of terminology, the structure should include political, military, economic, social, infrastructure, and information (PMESII) factors. The options should draw upon diplomatic, information, military, and economic (DIME) instruments of power.
6. Characterize each option by its expected contributions, its limitations and associated risks, and its upside potential. Where relevant, point out where the option arguably creates an excess of capability, which might suggest potential bill-payers in subsequent tradeoff work.
7. Iterate by adding or modifying options and analytic structure based on initial experience. Continue until convergence occurs or time runs out.

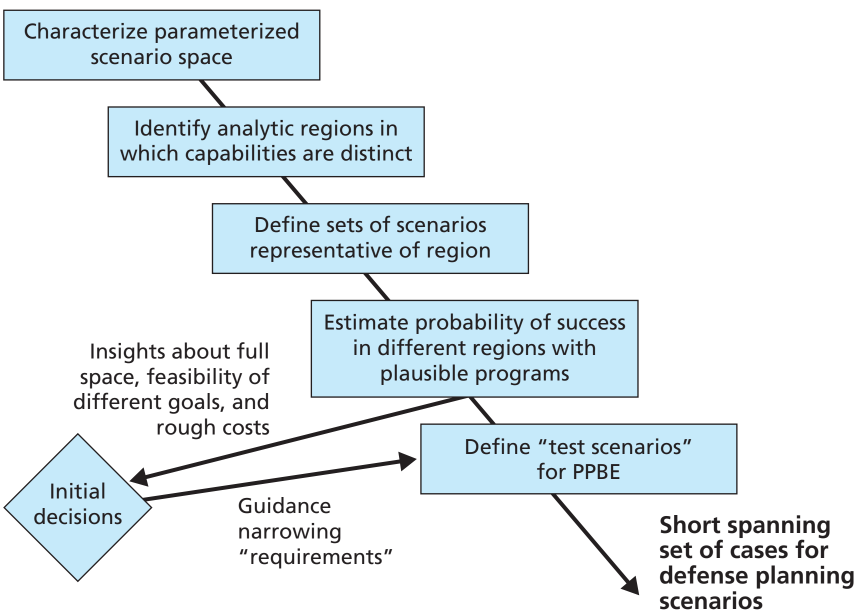
We see this process as modernization of classic activities with which good analysts are familiar. As in classic analysis, its purpose is to inform difficult choices in the presence of multiple objectives and economic constraints. We believe it goes well beyond classic methods, however, in its effective confrontation of multiple objectives, uncertainty, judgment, risk, and PMESII factors, all of which have a significant impact on choice. It also systematically considers a broader range of options than is the norm.

Establishing a Spanning Set of Defense Planning Scenarios

The next step of the process involves developing a *spanning set* of test cases. By definition, a spanning set is such that if a prospective system tests well against all of its cases, it is very likely that the system will provide appropriate capability in any of the diverse situations that may arise in the real world. That is, given a set of options to be compared, the spanning set stresses the various options in all of the key dimensions. As indicated by Figure S.2, we find an approximate spanning set by beginning with a broadly conceived and parameterized scenario space.[1] We then identify analytically distinguishable regions within that space and define a particular representative case for each region. Such a case is defined by a name-level scenario and the values of key parameters within it (e.g., "war with Country X, assuming 14 days of actionable warning before war begins and an enemy force level no greater than 5 divisions"). A coarse-grained spanning set would need relatively few parameters; a higher-resolution spanning set would require many more. Developing such a spanning set is not straightforward, and the quality of a proposed set depends on the quality of the analytic thinking that underlies it.[2]

Given a spanning set, initial analysis should then inform decisionmakers about the relative value, feasibility, and cost of improving

Figure S.2
Deciding on a Spanning Set of Cases



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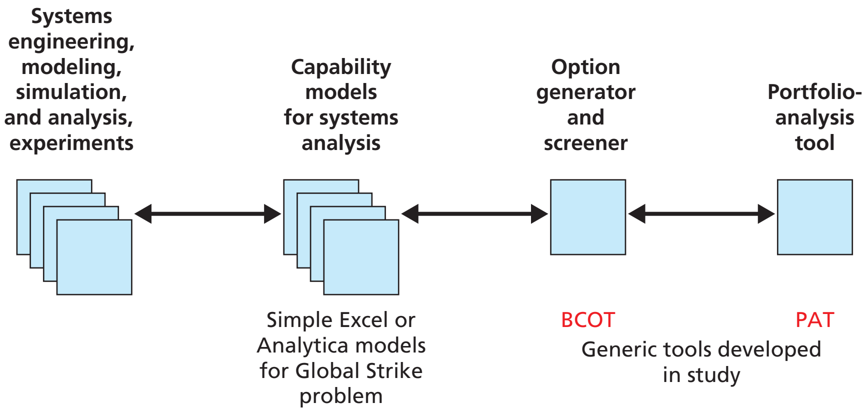
capabilities for the different regions. Decisionmakers can then make reasoned judgments about what capabilities to seek actively. These might include clearly achievable near-term goals and some optional "stretch goals" that would be appropriate for later in an evolutionary acquisition but that are not technically or economically implausible. Thus, decisionmakers should carefully express "requirements" (the initial-decisions node in Figure S.2) in light of the initial insights. This results in a smaller spanning set of cases, one that spans the domain in which improvements are to be sought. The set of cases can be embellished to become defense planning scenarios used throughout the Department of Defense and within the planning, programming, budgeting, and execution (PPBE) process in particular. In today's DoD, decisions on planning scenarios are made by the Deputies Advisory Working Group (DAWG). Our approach seeks to provide better analytical support for those decisions, so that the planning scenarios represent de facto requirements rather than mere expressions of diverse challenges.

Tools to Support Analysis

Several types of tools are needed for the analysis of Figures S.1 and S.2. Figure S.3 suggests this need schematically. Each capability area needs analytic support from a broad range of systems-engineering models, diverse models and simulations, experiments, and other forms of analytical information. Together, these represent foundational knowledge. "Capability models" are needed at a somewhat higher level, overlapping with aspects of systems engineering. These are typically parametric models suitable for systems analysis under uncertainty. They may be implemented in such analyst-friendly tools as Microsoft Excel® and Analytica.® Another class of tools generates options and then screens for the candidates that merit more-careful assessment. Finally, there is need for tools to assist in portfolio analysis, analysis in which options are evaluated by how—and with what economic efficiency—they contribute to a number of different objectives and to a balancing of ambitions and risk-reduction. As discussed in the main text, we have devel-

Figure S.3
Tools Enabling the Portfolio-Analysis Methodology



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oped and applied prototype versions of a special option generator and screener (Building Blocks to Composite Options Tool (BCOT)) and a generic portfolio-analysis tool (PAT).

The arrows in Figure S.3 are two-way because information flows in both directions, sometimes bottom-up and sometimes top-down. Moreover, crucial information or judgments may be introduced at different levels of detail. Detailed analysis is sometimes less sound and much less useful than higher-level analysis; at other times, it is only with detailed analysis and precise data that crucial factors can be understood adequately and effectiveness assessed. The need for such a multiresolution family-of-tools approach should be seen as part of a best-practices approach to capability development.[3]

Illustrative Application: A Notional Treatment of Global Strike

Most people learn from examples, working through particulars first and then abstracting to more-general principles. In this monograph, we describe two applications of our methodology, one to Global Strike (or, more precisely, to what DoD refers to as Global Strike Raid) and one to Ballistic Missile Defense (BMD). Some readers may wish to move directly from Chapter One to Chapters Five and Six for these applications, after which they may find Chapters Two through Four more meaningful. We discuss only the Global Strike example in this summary. The application to BMD, however, is also of interest because the technical challenges are so difficult.

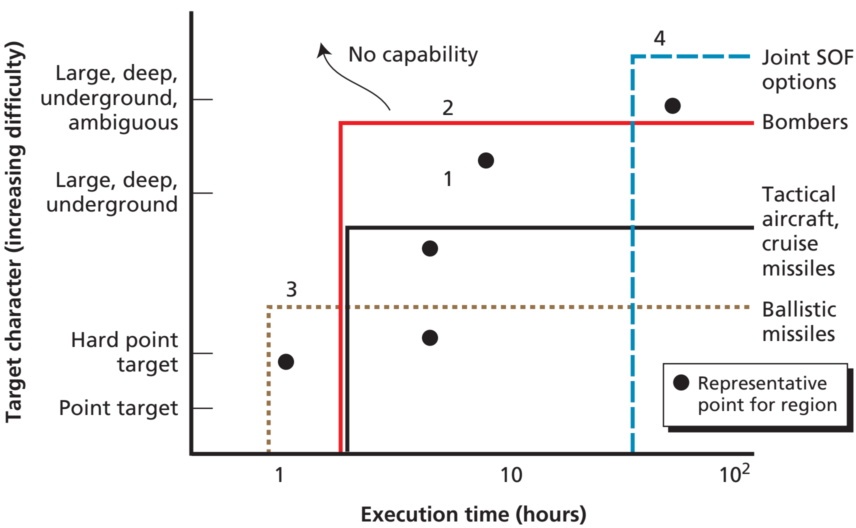
Structuring the Global Strike Problem

For the notional Global Strike application, we addressed what DoD calls Global Strike Raid: small, discrete, conventional-weapon strikes authorized by the president in a strategic context. We concluded—after various simplifications (e.g., ignoring cyberspace options) to permit unclassified analysis—that a reasonable spanning set of scenarios and cases would comprise fewer and more-challenging versions of scenarios nominally involving attacks on mobile targets, such as mobile intercontinental ballistic missiles (ICBMs); prompt strikes on terrorist leaders; and attacks on facilities for weapons of mass destruction (WMD).

Our approximate spanning set has a distinct analytical basis. It is akin to what a design engineer would identify as the *set* of design points and performance requirements that together stress all the key factors. Figure S.4 shows a simplified example. The (horizontal) x-axis measures the execution time required for a given system to perform the Global Strike mission after an order to do so. The (vertical) y-axis is a notional composite measure of the target's character, ranging from a simple point target at the bottom to an entire complex of hard and deeply buried targets at the top. Each of the numbered boundaries indicates the region of applicability for a given system. Thus, tactical aircraft and cruise missiles are associated with the region to the right of and below boundary 1 (black). Similarly, boundaries 2, 3, and 4 indicate the regions applicable to bombers (red), ballistic missiles (brown dashed), and joint Special Operations Forces (SOF) options (blue dashed), respectively. The solid dots indicate representative points to which test scenarios might correspond. That is, analysts need not consider every point within a given region, but only such a set of representative points.*

Figure S.4 suggests that tactical aircraft and cruise missiles (as well as bombers) can cover much of the space, but that ballistic missiles are uniquely capable among kinetic options for responses in one or a few hours. Bombers have special capability against underground targets; even bombers, however, may be insufficient against the more ambiguous hard and deeply buried targets. In those cases, we postulated for the sake of this example that there might be special weak points that might be discovered by classic intelligence work, cyberspace methods, or SOF. For the sake of the diagram, we postulate a region requiring some unspecified joint operation involving a combination of, e.g., bombers, missiles, and SOF.

Figure S.4
Distinct Regions of the Global Strike Scenario Space



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*The full analysis of options considers the times required for alerting and maneuvering of forces, command and control, targeting, mission planning, and decisionmaking. Figure S.4 defines analytical regions, showing essentially irreducible distinctions among options.

Figure S.4 provides one view of how the scenario space decomposes, but there are other dimensions. After considering a number of those dimensions, we concluded that our spanning set needed the three classes of scenarios mentioned earlier, associated nominally with attacking (1) mobile targets, (2) terrorist leaders, and (3) WMD facilities. We say "nominally" because diverse target types could fall into these classes.

As Table S.1 indicates, the major factors that we wanted to stress in our analysis (left column) could be accommodated by particular cases within these classes of scenario. For example, we used scenario class 2 (attacking terrorist leaders in a meeting of limited duration) to stress timeliness aspects of capability, to include dependence on warning. We addressed all of the factors in the left column in at least one scenario class, and sometimes in more than one. Some of these factors are more political-strategic in nature than military-technical. In our example, we did *not* treat several important dimensions that we most certainly would have treated in a real application. These were (1) size of attack needed, (2) target mobility at the time the strike reaches the

Table S.1
Degree to Which Scenario Classes Stress Selected Factors

Factor	Scenario Class 1 (mobile missiles)	Scenario Class 2 (terrorist meeting)	Scenario Class 3 (WMD facilities)
Timeliness and dependence on warning	●	●●●●	
Bases and permissions	●●	●	●●●
Penetration of defenses	●●●●	●	●●●
Target detection and characterization	●●●●	●	●●●●
Target destruction	●	●	●●●●
Collateral damage	●	●●	●●●●
Perceptions, escalation risk	●●	●●	●●●●

NOTE: The numberof bullets indicates the degree to which each factor is stressed. The number of bullets shown reflects our particular analysis. A given scenario could be chosen to be more stressful in other ways. For example, the mobile-missile and terrorist-meeting scenarios could readily stress timeliness and collateral damage, respectively.

target area, and (3) the value of the various options as the leading edge of a larger attack.

Methodologically, merely specifying a single concrete scenario of a given class is not very useful because of stark differences in challenge, depending on parameter values within the scenario. How many such cases need to be considered depends on the problem and the level of resolution needed, which in turn depends on the type of decision being made. For our example, we concluded that much could be accomplished with six cases, as described below—relatively favorable and unfavorable versions of the three scenario classes.

Outputs of Illustrative Analysis

The outputs of this analysis are illustrated by Figures S.5, which is based on notional and somewhat contrived data. The figure shows a top-level portfolio-analysis summary of effectiveness. It assesses options (rows) by each of seven measures (columns), which correspond to the approximate spanning set of three scenarios with two cases each, as well as a measure of overall risk across the scenarios. As usual in such scorecards, red, orange, yellow, light green, and green refer to very poor, poor, marginal, good, and very good, respectively. Letters within the cells indicate colors for the benefit of those using gray-scale prints or for color-blind readers.

Where Do the Colors Come From? Why Should We Believe Them? Although effective cognitively, color scorecards can be off-putting because even busy decisionmakers may want to know the *basis* for the evaluations and may want to have a reason to believe that the underlying staff work was rigorous. As discussed in Chapter Five, an important feature of our methodology and portfolio-analysis tool is that it allows for zooms or “drill-downs.” Someone viewing Figure S.5, for example, could ask about the basis for the colors in the first mobile-missile case. Successive drill-downs show color scorecards displaying underlying factors, calculations, or judgments. If even more detail is needed, it is best presented in parametric charts characteristic of classic systems analysis. By insisting on such drill-down capability, decisionmakers can create a powerful incentive for staff-level rigor. An additional reason for interactive drill-down is that portfolio analysis

Figure S.5
A Summary-Level Portfolio-Analysis Display of Effectiveness

Options	Measures of Option Goodness: Effectiveness (Color) by Scenario Class and Overall Risk						
Measures	Mobile Missiles (2020)	Mobile Missiles (2020) Reactive Threat	Terrorist Site (2020)	Terrorist Site (2020) Fleeting Target	WMD Facilities (2020)	WMD Facilities (2020) Hard Case	Overall Risk (2020)
Investment Options	Detail	Detail	Detail	Detail	Detail	Detail	Detail
Base Case	R	R	LG	R	R	R	R
Penaids	R	R	LG	R	Y	Y	Y
SLBM + Penaids	R	R	G	G	Y	Y	Y
SLBM + Penaids + SOF Vehicle	R	R	G	G	G	Y	Y
SLBM + Penaids + Sensors	O	R	G	G	Y	Y	Y
SLBM + Penaids + Sensors + SOF Vehicle	O	R	G	G	G	Y	Y
Adv. Bomber + Sensors + SOF Vehicle	G	R	LG	R	G	Y	Y

NOTE: Effectiveness colors: red, orange, yellow, light green, and green indicate very poor, poor, marginal, good, and very good.
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should be conceived not as a way to show cut-and-dried results, but rather as a format for revealing, discussing, *and changing assumptions* as the result of conversations with decisionmakers. Although some aspects of portfolio analysis are relatively fact-based and "objective," many others involve strategic judgments about relative priorities and concerns, potential constraints, and performance levels to be required—the very items for which decisionmakers are uniquely responsible. Thus, analysis should include serious "straw-man" assumptions but should be carried forward with the hope for and expectation of substantive interaction and iteration.

Scorecards Should Tell a Correct Story. With this background in the philosophy of our methodology, let us proceed. Although the results are only notional, Figure S.5 tells a story. As shown in the left column, the options considered (a subset of those discussed in the main text) include procuring certain combinations of penetration aids (penaids) for aircraft, a conventionally armed sea-launched ballistic missile (SLBM), advanced sensors such as a constellation of space-based synthetic-aperture radars (SARs) and automated-target-recognition (ATR) capability for aircraft, an advanced bomber, and a hypothetical advanced insertion vehicle for SOF.

The base case (reflecting currently programmed systems) asserts that projected ability to accomplish the various missions addressed in the three scenarios is mostly poor for the year 2020. A realistic assessment might differ, but the methodology is well served by a story with a poor baseline.

Results for the first mobile-missile column improve somewhat (to orange) with a combination of penetration aids *and* advanced sensors; they improve further with an advanced bomber as well as the advanced sensors, because we assumed that bombers could remain in the target area for a much longer period of time (the SOF vehicle is actually irrelevant to effectiveness in this scenario). The second column shows that against a reactive adversary with a range of technical and tactical countermeasures, results would not be improved from the baseline. In a real analysis, of course, there might be an additional and more cheerful column for results assuming U.S. responses to the adversary's responses.

In the terrorist scenarios, base-case capability is projected as fairly good (light green) for terrorist sites generally (third column), but very poor for the most fleeting targets (fourth column). That problem could be solved with a suitable ballistic missile, in this case an SLBM. A first version of such a capability may be the Conventional Trident Modification (CTM), which is proposed in the president's budget for FY08.

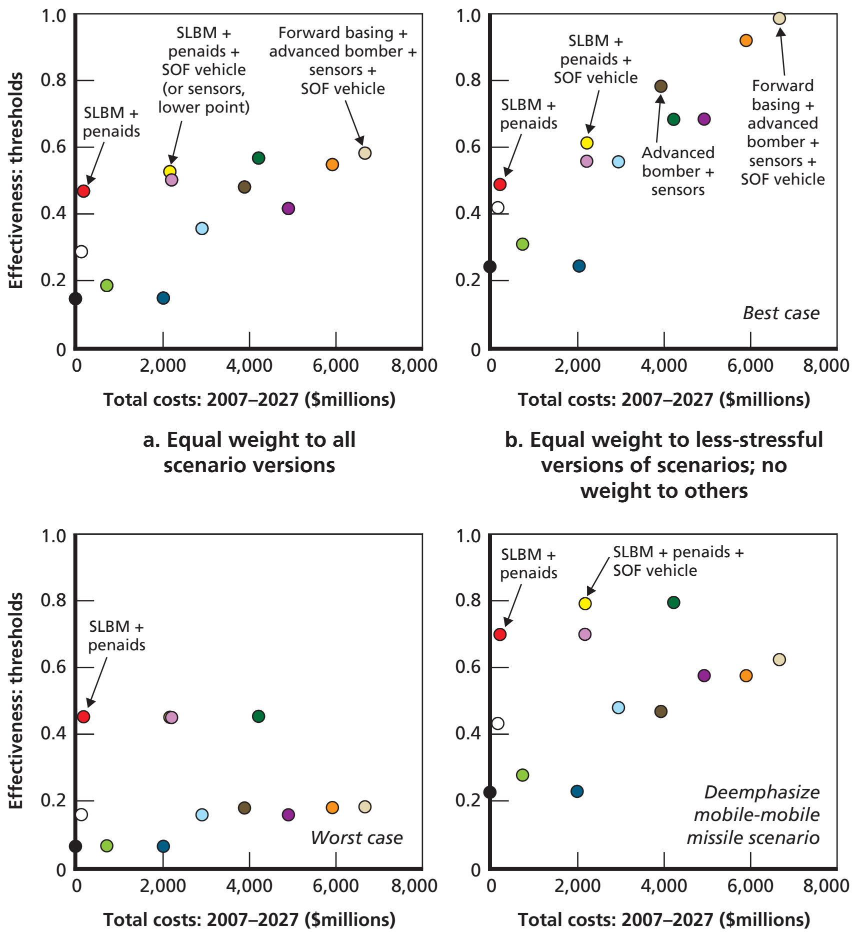
The results for the WMD-facilities scenarios indicate that penaids help because of the projected quality of enemy air defenses, but in our contrived example, they are not sufficient (effectiveness is shown as yellow, i.e., marginal). If we zoomed to a higher level of detail (as we do in Chapter Five), we would see that the reason for the assessment is that some WMD facilities are likely to be hard and deeply buried, so a sizable attack causing collateral damage might be required if accomplished with aircraft alone. The notional evaluations in the first WMD column, however, assume that intelligence information would make it possible to attack those successfully with a hypothetical joint operation involving a combination of missiles, bombers, and SOF—if penetration of defenses by SOF were enabled by procuring the specialized insertion vehicle. Such an attack might have more precision and might be able to avoid collateral damage caused by unintended release of materials. Thus, in the first of the two WMD-facilities columns, results are favorable for the options that provide all of these capabilities. In contrast, if intelligence were inadequate or if a sizable number of facilities were essentially invulnerable to a modest attack of any sort (second WMD column), results would remain mixed (yellow), reflecting the presence of good and bad cases.

Finally, Figure S.5 includes a column for a kind of "overall" risk associated with the different options. This summarizes the net effect of several types of risk. For example, the other columns of the scorecard reflect assessments based on assumptions. How risky are the assessments themselves? Another type of risk arises when there are importantly different subcases within a scenario case. The high-level evaluation is an aggregation, which may not take some of the subcases seriously enough. The risk column, then, can remind us of fragile assumptions. By zooming (or drilling down) on that column, we would see (as in Chapter Five) that the risks vary considerably among the three scenario classes.

Chapter Five's discussion of this material also covers a much larger set of options. This is important because in some cases substantial gains could be achieved less expensively with operational changes, such as forward basing of bombers or different choices of advanced sensors or advanced aircraft (manned or unmanned). Indeed, one part of the methodology (the fourth step in Figure S.1) is to generate potential options that may not have been suggested by proponents of the various programs and to screen for those that seem potentially attractive.

Figure S.6 presents cost-effectiveness charts for all of the options that we considered after screening out the less-attractive ones. Each point represents one option, and there are thirteen points in each chart rather than just six for the subset of options represented in Figure S.5. The colors of the points distinguish options; they have no other

Figure S.6
Cost-Effectiveness of Scenarios with Different Assumptions and Priorities



a. Equal weight to all scenario versions

b. Equal weight to less-stressful versions of scenarios; no weight to others

c. Equal weight to more-stressful scenarios; none to others

d. Equal weight to all versions of terrorist and WMD-facility scenarios; no weight to mobile-missile scenario

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significance. The effectiveness being measured is some kind of aggregation over the effectiveness of the seven scorecard columns in Figure S.5.

The top-left panel, if viewed by itself, would suggest a very high cost-effectiveness for the option with the SLBM and penaids, after which we see diminishing returns (i.e., more-expensive options are not substantially more effective). The real point of Figure S.6, however, is to demonstrate the extreme degree to which results depend on what we call "perspective." A perspective is a way of looking at the choices. Decisionmakers may, for example, have long-term rather than medium-term priorities; they may be more concerned about fielding useful capability than about whether there would be eventual countermeasures, or they might be very reluctant to go down a path for which countermeasures can already be identified. They might be much more concerned about some classes of future scenario than others. Some decisionmakers may be interested in a capability only if its expected performance is quite high, while others might settle for the earlier deterrent value of something with poorer performance.

Mathematically, we represent alternative perspectives with a combination of different weighting functions and performance requirements used in the computation of effectiveness. The top-left panel treats all cases as equally important. The panel at the top right is a "best case" for the options, giving weight to only the favorable case of each scenario. It might represent the perspective of a decisionmaker who believes—in this domain—that achieving capability is the prime consideration and that the United States would be able to develop counters to any adversary countermeasure. From this perspective, it is clear that effectiveness continues to rise substantially with investment. The bottom-left panel reflects a pessimistic perspective in that it considers only the less-favorable versions of the scenarios, the versions in which the adversary employs successful countermeasures. Finally, the panel at the bottom right shows results when the first scenario class (attacking mobile missiles) is ignored altogether—perhaps because decisionmakers conclude that it is an implausible scenario for a very limited global strike. In this case, the best option might be a combination of an SLBM, penaids, and SOF vehicles, which attend to issues in scenario classes 2 and 3. Further expenditure on items such as a satellite constellation of advanced sensors or an advanced bomber would obviously not be cost-effective—at least for the purposes of Global Strike Raid.

The relative goodness of the options varies a great deal among the four perspectives, illustrating that making choices is highly dependent upon assumptions, but in ways that can be summarized compactly—a necessary condition for the kind of interactive discussion and iteration mentioned earlier.

Much of the value of our methodology resides in the multiple levels of explanation and the ability to see crucial assumptions easily and to vary them systematically. What is needed here is not standard sensitivity analysis, but a version of exploratory analysis generalized to portfolio work. Exploratory analysis samples across the entire range of assumption combinations, not just excursions from a baseline varying one or two assumptions at a time. This can be crucial in finding the "corners" of the assumption space where capabilities would be most stressed. Adversaries in conflict routinely look for such corners.

Cross-Capability-Area Analysis

Our analysis demonstrates the limitations of a managerial approach that attempts to do resource-allocation decisionmaking one capability area at a time. For our Global Strike example, we found that the attractiveness—from a parochial Global Strike perspective—of options such as the advanced manned bomber or space-based SARs depends sensitively on the fraction of the actual acquisition cost that is charged to the Global Strike capability area. Knowing what that fraction should be and whether those systems are even likely to be acquired at all requires separate cross-cutting analyses in which the attractiveness of the big-ticket acquisitions is assessed simultaneously for each of the capability areas to which they would potentially contribute. If the overall attractiveness is deemed high by the Secretary of Defense, then the issue becomes one of allocating costs. Doing so may be straightforward (e.g., charge Global Strike for only the marginal cost of building some extra platforms for it) or somewhat arbitrary—with top DoD officials deciding on whether to acquire the system, how capability portfolios should be thought of as sharing its costs, and allocating funds appropriately (in some cases providing "new money" to one or more capability areas). None of these decisions can be made within a single capability area.

Next Steps for Research

Looking ahead, we recommend further research in four areas that we believe would have a high payoff for defense planning.

Analysis Cutting Across Capability Areas

Extending the analysis methodology to cut *across* capability areas is crucial for the reasons mentioned above. DoD leaders intend to have those responsible for capability areas do "portfolio balancing" within their respective domains, finding bill-payers as well as additions. However, as noted above, in many cases, it is necessary to do cross-area analysis to properly assess the value of a new system or activity, the implications of cutting back on another system or activity, or the way to think about tradeoffs. This work should be targeted at DoD's "tri-chair" leaders of capability development: the USD (AT&L), the Vice Chairman of the Joint Chiefs of Staff (VCJS), and the Director of Program Analysis and Evaluation (DPA&E).

Strategic-Level Portfolio Analysis

Although the work reported here was performed for the USD (AT&L) and his staff, with others in mind such as the DPA&E and VCJS, the same methods can be applied at the strategic level—both within DoD and across cabinet departments. Such work may be of particular importance in the near future as the activity in Iraq winds down and policymakers contemplate alternative relative emphases in defense and national security for the years ahead—e.g., the relative emphasis on the "long war," various regional instabilities, and the long-term competition in East Asia. What implications should there be for relative investment in recapitalizing the armed forces after some years of intense activity that has worn them down, for modernizing forces (even beyond what was envisioned by late-1990s transformation), for restructuring for low-intensity conflicts and operations, or for shifting the pattern of military environment-shaping worldwide?

Advancing the Science of Exploratory Analysis

As noted throughout this monograph, exploratory analysis is essential for pursuing investment strategies that exhibit FARness, i.e., strategies that are flexible, adaptive, and robust, rather than optimized for a particular image of the future. Such exploration goes far beyond the limited sensitivity analysis that has long been part of strategic studies. Great progress has been made over the past decade in developing methods for exploratory analysis and applying them to actual problems (Davis, 2002). A wave of new challenges, however, is posed by portfolio analysis. In portfolio work, the uncertainties have a different character, both substantively and technically. Significant research will be needed to extend the current theory and methods and to make them practically available to DoD. Some of these methods can call upon tools from economic theory and corporate planning, such as "real-option theory," but many are more nearly unique to national-security analysis. We have high expectations for what can be accomplished here.

Tool Refinement

In the course of the work described in this monograph, we developed prototype versions of RAND's Portfolio-Analysis Tool (PAT) and an option-generation-and-screening tool (BCOT). We then demonstrated how they can be used effectively, even in their current form. Further improvements, however, are highly desirable. One purpose should be to make them easier to use, understand, modify, and maintain by people other than their original developers. Another purpose should be to enrich their utility for exploratory analysis as discussed above and to incorporate new techniques for portfolio analysis, such as advances in real-options planning, which have been made in the fields of economics and business planning.

Acknowledgments

We appreciate collaboration with a number of colleagues: James Bonomo, Paul Dreyer, and Henry Willis in a related project for the Missile Defense Agency; Irv Blickstein in the early phases of our work on this project; and Gaga Gvineria (a doctoral candidate at the Pardee RAND Graduate School) in the development of the BCOT program used in this study. RAND consultant Robert Moore and Carl Rhodes of RAND provided thorough and constructive reviews. MG Jasper Welch (USAF, retired) was kind enough to review Chapter Two.

Abbreviations and Acronyms

ABP	assumption-based planning
ACDT	Advanced Concept Development Test
ALCM	air-launched cruise missile
AoA	analysis of alternatives
AT&L	Acquisition, Technology, and Logistics
ATR	automated target recognition
BCOT	Building Blocks to Composite Options Tool
BMD	Ballistic Missile Defense
BMDS	ballistic-missile defense system
C4ISR	command, control, communications, computer, intelligence, surveillance, reconnaissance
CAMMD	capabilities analysis model for missile defense
CAR	Capability Area Review
CAS	complex adaptive systems
CBP	capabilities-based planning
COA	course of action
COCOM	combatant commander
CONOPS	concept of operations
CTM	Conventional Trident Modification
CVBG	combat vehicle battle group

DAWG	Deputies Advisory Working Group
DCAR	Defense Capability Area Review
DDR&E	Director, Defense Research and Engineering
DIME	diplomatic, information, military, and economic
DoD	Department of Defense
DOFA	defense of friends and allies
DOTMLPF	doctrine, organization, training, materiel, leadership and education, personnel, and facilities
DPA&E	Director, Program Analysis and Evaluation
DSB	Defense Science Board
ECM	electronic countermeasures
EoA	evaluation of alternatives
ESG	Engagement Sequence Group
FAR	flexible, adaptive, and robust
FARness	an attribute of strategy: generating flexible, adaptive, and robust capabilities
FCB	Functional Capability Board
FCS	Future Combat System
FFRDC	federally funded research and development center
GPS	Global Positioning System
HDBT	hard and deeply buried target
IAMD	Integrated Air and Missile Defense
ICBM	intercontinental ballistic missile
IED	improvised explosive device
ISR	intelligence, surveillance, and reconnaissance
JCA	Joint Capability Area
JCAV	joint common aerospace vehicle
JCIDS	Joint Capabilities Integration Development System

JDAM	joint direct attack munition
JFACC	Joint Forces Air Combat Commander
JROC	Joint Requirements Oversight Council
JSTPS	Joint Strategic Targeting Planning Staff
JWCA	Joint Warfare Capability Area
LGB	laser-guided bomb
M&S	modeling and simulation
MCP	mission-capability package
MDA	Missile Defense Agency
MRM	multiresolution modeling
MTI	moving-target indicator
NGLRS	next-generation long-range strike
OSD	Office of the Secretary of Defense
OUSD	Office of the Under Secretary of Defense
PA&E	Program Analysis and Evaluation
PAT	Portfolio-Analysis Tool
PGM	precision-guided munition
PMESII	political, military, economic, social, infrastructure, and information
PPBE	planning, programming, budgeting, and execution
S&T	science and technology
SAM	surface-to-air missile
SAR	synthetic-aperture radar
SecDef	Secretary of Defense
SIOP	single integrated operations plan
SIV	special insertion vehicle (a hypothesized advanced vehicle for Special Operations Forces)
SLBM	sea-launched ballistic missile

SLGSM	sea-launched global-strike missile
SOF	Special Operations Forces
SoS	systems of systems
SSBN	nuclear-armed ballistic-missile submarine
TCM	Trident Conventional Missile
UAV	unmanned aerial vehicle
USD (AT&L)	Under Secretary of Defense for Acquisition, Technology, and Logistics
VJCS	Vice Chairman of the Joint Chiefs of Staff
WMD	weapons of mass destruction
WSEG	Weapons Systems Evaluation Group

Glossary of Terminology

building-block option. An element of military capability that may be acquired (e.g., an advanced radar or an advanced bomber). Most composite options involve multiple building blocks.

capabilities-based planning (CBP). A framework for planning under uncertainty that provides capabilities suitable for a wide range of modern-day challenges and circumstances within an economic framework that necessitates choice.

capability area. A category of military capabilities that can usefully be assessed to some extent independently of other areas. Examples include Ballistic Missile Defense, Strategic Mobility, and Air-to-Air Combat.

composite option. An investment option that involves acquiring one or more building-block options.

exploratory analysis. Analysis that systematically examines results as a function of different plausible values of key input parameters, varying those parameters simultaneously rather than individually as is done in normal sensitivity analysis. In exploratory analysis, where uncertainty is sometimes ubiquitous and deep, there may be no meaningful "best estimate" or baseline, other than for comparison purposes.

flexible, adaptive, and robust (FAR) strategies. Strategies that allow for diverse and perhaps unintended missions (flexibility); effective operations in diverse circumstances (adaptiveness); and ability to withstand and recover from adverse events or shocks (robustness).

perspective. A way of looking at the problem when assessing the "balance" within a portfolio of investments. A perspective is specified mathematically by the weighting functions and performance requirements used in the calculation of overall effectiveness of options.

portfolio. A collection, as in investments in a number of categories. A strategic portfolio might have categories for different functional classes of capability or categories for different theaters of interest; a portfolio within a capability area would have categories for different contributors to that area's overall capability.

portfolio analysis. Analysis that assesses alternative investment options by diverse quantitative or qualitative objectives, including risk mitigation. The analysis aids in "balancing" investments within a portfolio, i.e., in a mix of instruments. The intent is to address all objectives and mitigate all risks, but to different degrees, depending on priorities, budgets, and feasibilities.

spanning set. A small set of scenarios chosen to stress a design or investment plan in all critical dimensions. An option that does well across the spanning set of cases should do well in real-world situations (assuming good use of resources at the time), even though those situations will usually differ from the test cases.

CHAPTER ONE

Introduction

Objectives

This monograph describes an analytical structure and related methods for conducting defensewide capability-area reviews for the Department of Defense (DoD). Such reviews should define and prioritize needs, assess alternative ways to improve capabilities, illuminate tradeoffs among options within a given capability area, and identify decisions and trades cutting across capability areas. In some respects, such reviews are comparable to what were once called mission-area reviews.[*]

Our perspective is top-down and defensewide, intended to be comfortable to the Under Secretary of Defense for Acquisition, Technology, and Logistics (USD (AT&L)), the Vice Chairman of the Joint Chiefs of Staff (VJCS), the Director of Program Analysis and Evaluation (DPA&E), and other decisionmakers in DoD and the Services as they review current and projected capabilities and recommend difficult choices to the Secretary of Defense. Such choices reflect tradeoffs among objectives and risks, usually within the reality of economic constraints.

Decisionmaker styles vary a great deal, of course, as do the contexts of top-level meetings, including decision meetings such as those for go-or-no-go decisions on capability concepts. Our analytic frame-

[*] Capability areas are identified at different times for different purposes. As discussed in Appendix A, the Joint Staff has a comprehensive taxonomy of Joint Capability Areas (JCAs), but these are not always convenient for programming or acquisition work. We use Global Strike Raid and Ballistic Missile Defense as illustrative capability areas.

work can be used for in-depth analyses, and it also anticipates the need for condensed, meaty, but understandable summary discussions.

Except for the context-setting discussion in Chapter Two, the monograph is not about process issues but rather focuses on analytic frameworks and methods. The monograph is one element in RAND's continuing contributions to capabilities-based planning (CBP) (Davis, Gompert, and Kugler, 1996; Davis, 2002). Most of the research reported here was completed in 2006 and early 2007.

Structure of This Monograph

The remainder of the monograph is structured as follows. Chapter Two provides background on DoD's capability-development process, problems with that process, and the improvements expected from the new concept-development process. It establishes context for the rest of the monograph, although the methods we describe could be used in a variety of capability-development processes. Chapter Three presents our recommendations for a generic analytic framework and process. Chapter Four discusses tools and methods needed to accomplish the terms of reference. Chapter Five walks through a notional application to the problem of Global Strike. Chapter Six sketches a similar application to Ballistic Missile Defense. Chapters Five and Six, then, provide the reader with a rather concrete understanding of what we are suggesting and what is required. Chapter Seven briefly summarizes our conclusions and suggests desirable next steps for research. Appendix A summarizes the Joint Capability Areas used by the Joint Staff. Appendix B points out implications of this work for systems engineering and modeling and simulation. Appendix C describes features of RAND's Portfolio-Analysis Tool (PAT).

CHAPTER TWO

Background: The Capabilities-Development Process

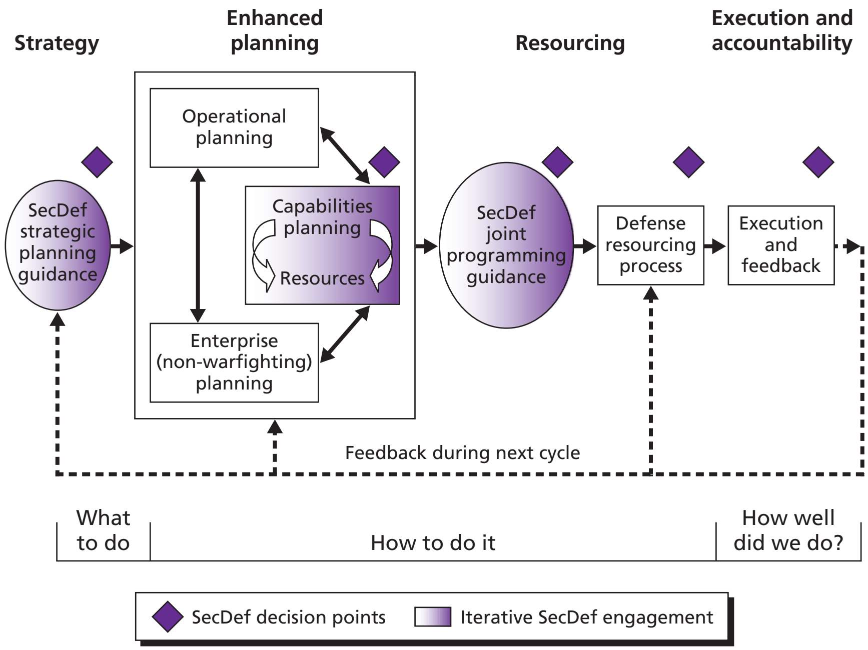
Context: DoD's Capabilities-Development Process

In recent years, the Department of Defense has sought to create a process suitable for the capabilities-based planning (CBP) mandated in 2001 and reinforced in the most recent Quadrennial Defense Reviews (Rumsfeld, 2001, 2006). The Aldridge Report (Joint Defense Capabilities Study Team, 2004) reviewed problems with the preexisting planning system and laid out objectives and schematics for an improved process. The Joint Staff has identified both operational and functional capability areas (see Appendix A) and has organized to address them systematically and comprehensively. The military Services have reorganized their planning systems accordingly. To a significant degree, commonalities of vocabulary and categorizations have been achieved. The Joint Staff has issued a draft instruction that summarizes the overall current process, including the primary activities, their relationships, and the inputs and outputs for the various activities (Chairman of the Joint Chiefs of Staff, 2007).

Problems with the Current Process

The overall process is described in the Aldridge Report. Figure 2.1, taken from that report, shows an overview. In this idealized concept,

Figure 2.1
End-State Planning Process



SOURCE: Joint Defense Capabilities Study Team, 2004.
RAND *MG662-2.1*

strategy poses challenges to planners, who develop requirements and capability options. Choices must then be made, programs and budgets developed, and capabilities acquired. Iteration occurs (see bottom of figure) as the result of time, experience, and changes in the environment. The authors of the Aldridge Report acknowledged that the boxed segment, enhanced planning, was where miracles must happen. When viewed in detail, that component turns out to be complex, burdensome, and bureaucratic—a problem recognized by senior officials and officers. DoD leaders have been trying to improve that process, and such efforts are continuing. In the meantime, success depends on high-level good will and collaborative efforts transcending organizational structure.

A sense of the problems is given by Figure 2.2, a widely used official depiction in 2005. Putting aside the busy nature of the diagram, a striking feature is the sequentiality of the process, with separate steps for defining operational concepts, conducting functional-area analyses, conducting functional-needs analyses, and conducting functional-solutions analyses, creating an initial capability document, followed by another sequence that includes analysis of refined alternatives, system engineering, and so on. This sequentiality is represented organizationally by a myriad of committees, boards, working groups, and studies. Less evident but even more troublesome is an underlying concept of the military developing "requirements" and potential solutions and then passing those potential solutions over the transom to the acquisition world of planning, programming, budgeting, and execution (PPBE), where decisions must be made on resource allocation. The separation was described rather starkly in classroom lectures on DoD's acquisition system until quite recently. Figure 2.3 was used in an internal Pentagon course on the JROC/JWCA* processes as of 2001. The vertical line separating the requirements side of the figure from the acquisition side was referred to as a "firewall."

This separation of supposedly military and civilian functions dates back to an unfortunate consequence of the Goldwater-Nichols Act (U.S. Congress, 1986). Superficially, it may seem logical for the military operators to establish requirements and the civilians to figure out how to meet those requirements and pay the bill. Upon reflection, however, that concept breaks down. In the real world, strategy, requirements, technological issues, economics, and other factors need to be addressed simultaneously—at least at the front end of the process. "Requirements" are not handed down on tablets of stone but should instead be seen as *outputs* of decisions reached after consideration of challenges, desired capabilities, technical feasibility, economics, organizational realities, and other factors.[4]

A historical problem with the linear construct has been that requirement-setters, when working in isolation, have often been either too conservative (not adequately appreciating future needs, technologi-

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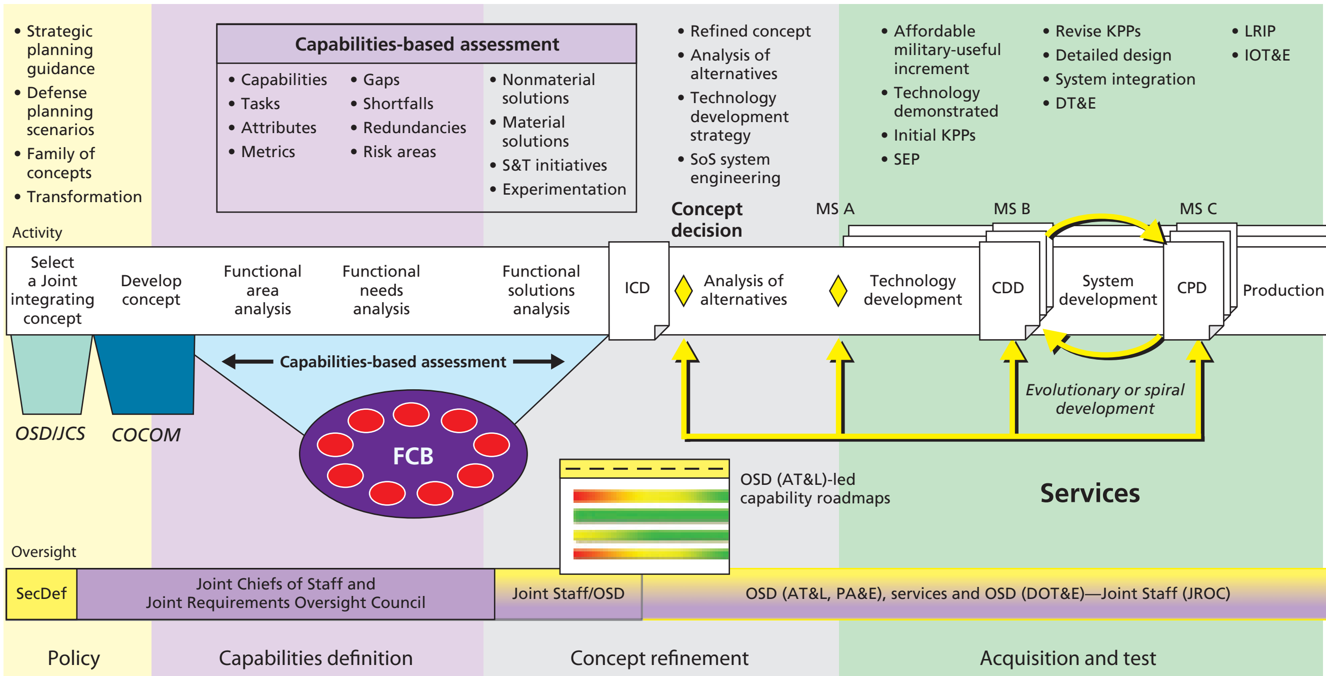
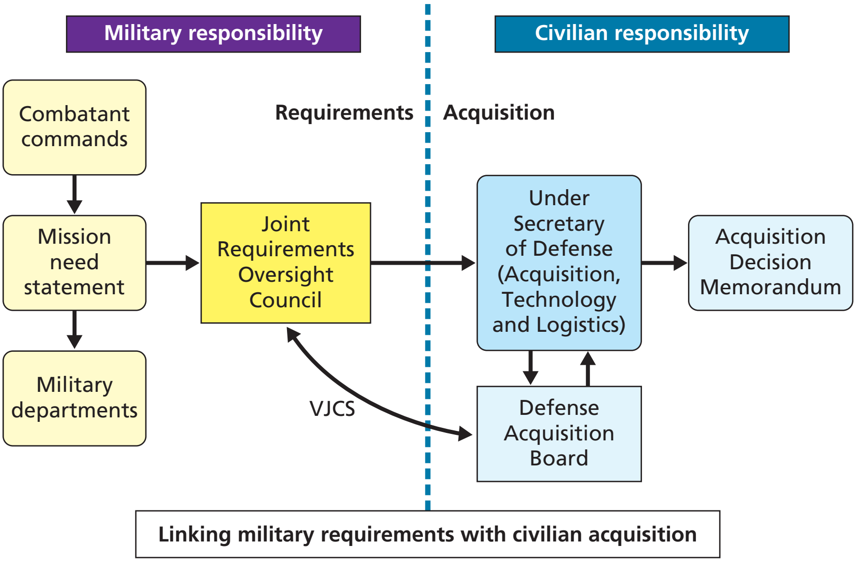
*Joint Requirements Oversight Council/Joint Warfare Capability Area.

Figure 2.2
A More Complex View of the Process



RAND *MG662-2.2*

Figure 2.3
Stark View of Requirements Versus Acquisition



SOURCE: From a Joint Staff course on the JROC/JWCA process in 2001.
RAND *MG662-2.3*

cal opportunities, and the likelihood of different concepts of operations) or naively optimistic (postulating the successful rapid development of capabilities beyond what industry could realistically generate on the timescale imagined).[5] Another problem has been that the linear construct defers serious thinking about economic considerations until—rather late in the process—the favored concept is finally recognized as unaffordable. In such cases, valuable time has been lost, time that might have been spent on developing more appropriate concepts or even modifying existing capabilities in lieu of developing something new.

Historical Successes in Capability Development

It is useful in thinking about the way ahead for DoD's capability-development efforts to also look backward. This is particularly so because the department has been spectacularly successful over the decades in many of its developments. What factors contributed to these successes?

Table 2.1 lists some of those spectacular developments. An overarching observation is that almost all of them were the result of far-sighted and technologically savvy people championing developments outside the mainstream bureaucratic processes of the time, often achieving their successes because they evaded or finessed the more tidy, deliberate, and sequential processes of their time.[6]

Another observation is that *most of the great developments included early systems analysis and systems engineering that integrated considerations of strategy, technological promise and feasibility, operational effectiveness, risk, and economic considerations.* There was also a good deal of creative tension, because participants had different perspectives and experiences. Recognition of such matters underlies part of DoD leadership's interest in the Concept Decision Reviews discussed below, which focus on the "big-A" issues rather than, say, those of how best to purchase equipment from industry (the "small-a" issues) (Krieg, 2007).

Although numerous examples could be given, we shall mention only a few:

- The 1967 STRAT-X study examined a broad range of options and greatly influenced development of U.S. strategic nuclear forces over subsequent decades.[7]
- Top Secret studies on strategic nuclear command and control, conducted by the Joint Chiefs' Weapons Systems Evaluation Group (WSEG), worked through the complex challenge of assuring the ability to command and control the nuclear retaliatory forces after even a bolt-from-the-blue attack that *destroyed many communication mechanisms.*
- The multi-decade development of the Global Positioning System (GPS) and its many applications to navigation and precision fires were strongly supported by studies conducted by federally funded research and development centers (FFRDCs) and industry, including very early studies envisioning with remarkable

Table 2.1
Some Spectacularly Successful Capability Developments

Capability	System	Comment
Sea-based airpower for fleet defense, strike, surveillance, etc.	Aircraft carriers	Developed despite lack of interest by and opposition of the "Battleship Navy"
Projection of ground forces from ships into defended land areas	Amphibious operations	Conceived and developed by visionary Marine colonel
Precision fires	Laser-guided bomb (LGB) and joint direct attack munition (JDAM)	Resisted consistently by Service PPBE processes and those adhering to a peculiarly strict interpretation of acquisition regulations
Maritime operations in littoral areas	Littoral combat ship	Scorned initially but championed by Chief of Naval Operations
Detection and tracking of moving ground targets	J-STARS	Moved directly into field from R&D during first Gulf War
Unmanned surveillance and targeting	Global Hawk and Predator	Resisted by Air Force
Tactical mobility	Stryker	Championed by Army Chief of Staff amid controversy
Strike, penetration	F-117, B-2	Championed by Air Force Chief of Staff and DDR&E
Precision navigation, precision fires	Global Positioning System (GPS)	Championed by DDR&E and Secretary of Defense and a few Air Force and Navy leaders
Early warning of ballistic-missile attack	DSP (early warning satellites)	Resisted by most, due to legacy programs, but supported by Air Force Chief of Staff
Submarine-based nuclear retaliatory forces	SSBNs (nuclear-armed ballistic-missile submarines)	Imposed on Navy by president
Assured dissemination of emergency action messages, even in surprise attack	Strategic nuclear command and control during Cold War	Involved largely separate system, thereby avoiding many sources of friction

NOTE: PPBE = planning, programming, budgeting, and execution; DDR&E = Director, Defense Research and Engineering. In the period referred to, DDR&E had power comparable to that of the current USD (AT&L).

prescience many of the radical changes that would occur in both military and civilian operations.[8]

It is the history of broadly based, cross-cutting, front-end analytic and decision efforts that we primarily wish to emphasize, because it bears on what we suggest in subsequent chapters. However, it is also appropriate to list some of the other characteristics common to the great developments.

People. The great developments have been conceived, envisioned, and managed by remarkable individuals. The consistent emphasis in interviews with "old-timers" who were involved in those developments is on people, not process. This is in contrast to the prevailing Pentagon culture, which emphasizes consensus and process. Indeed, this culture has now existed for so long that the very intuition of many people in the system revolves around consensus and process, with resulting "requirements" for bloated, exhausting activities and no one having the freedom to act.

A Sense of Mission. Many of the great developments were strongly motivated by a sense of mission, such as defending NATO in the event of a massive armored invasion by the Warsaw Pact or deterring major war generally through a combination of assured nuclear retaliation and the credible ability to use limited nuclear options to "reestablish deterrence" if conventional war began in Europe.

The Role of Vision. The great developments have often had an accompanying vision that provided coherence and direction over time, a vision with both substance and legs. These coherent visions identified "thrusts," examples of which we shall show later. These were developed and honed by small groups of top-notch mid-level "up-and-comers." A number of these young officers later became well-known flag officers.

Champions. The concepts that led to the great developments, however, would have gone nowhere except for another "people issue," the championing of ideas by, e.g., the Service chief and senior officials such as the DDR&E, who in earlier years had power comparable to that of today's USD (AT&L).[9] Typically, the concepts were disruptive and were therefore resisted by the existing organizations. Leaders had to override this organizational tendency to resist. That they often did so is perhaps remarkable to those familiar with the "innovator's dilemma" in industry (Christensen, 1997), but defense planning has objectives very different from profit-making.

Strategic Thinking. Top leaders associated with the great developments thought about the near, mid-, and long term and across development categories. They were not particularly focused on science and technology (S&T); they did, however, value it greatly and pushed innovation in diverse ways (e.g., Advanced Concept Development Tests (ACDTs) and continuing DARPA activities). They thought in terms of phased, evolutionary developments.

Mainstream Service Opposition. The great developments (e.g., the Global Positioning System, Global Hawk, Predator, the Non-Lethal Capability Set (NLCS), F-16s) usually had to overcome a lack of interest or even strong opposition within the eventually sponsoring Service. Often, Service chiefs played a critical role by "reaching down" and championing innovators who would otherwise have lost out in the competition for funding and priority. Similarly, Service chiefs were often the ones who faced reality about the need for tradeoffs. Sometimes they did so in behind-closed-doors cooperation with the DDR&E and the Secretary of Defense (SecDef), without consensus within the Service. Such was the case when the Air Force agreed to cooperate in a high-low-mix approach that included procurement of F-16s.

SecDef Intervention. Upon occasion, the SecDef had to intervene, overriding the preferences of the Services and even the Service chiefs. Sometimes it was as part of introducing new missions; sometimes it was to protect "national" programs such as SSBNs; sometimes it was to reflect conclusions of economic analysis (e.g., increasing the rate of procurement of precision weapons or unmanned aerial vehicles (UAVs)).

Finessing or Evading Processes. Especially relevant is the observation that *the great developments often succeeded despite, rather than because of, normal processes.* Nothing as complex as the Joint Capabilities Integration Development System (JCIDS) process (see Figure 2.2) existed until recent years, but at any given time, the then-normal process was often regarded as too burdensome and too perilous. The champions of the new ideas found ways to avoid that process (e.g., by black programs). In more-recent times, senior officials have again noted that many important developments are dealt with outside the normal process (e.g., the current task force on improvised explosive devices

(IEDs)). This should be a sobering cautionary for those who seek to solve current problems by perfecting established processes.

Past Recommendations and Recent Changes

Past Recommendations for Change

Against this background, a number of prominent public studies have called for major changes in the DoD acquisition system. These include reports of the Defense Science Board (Defense Science Board, 2005, 2007a, 2007b), the Kadish Study (Kadish, 2006), and a Center for Strategic and International Studies (CSIS) report, *Beyond Goldwater-Nichols* (Murdock, Flournoy, Campbell, Chao, Smith, Witkowsky, and Wormuth, 2005).

In 2004–2005, RAND provided a highly critical independent review of DoD's capabilities-development process, characterizing it as bureaucratic and dysfunctional.[10] It recommended major changes, particularly in the front end:

- *Integration and iteration*, rather than lengthy and sequential processes (of policy-setting, assessment, requirement-setting, solution specification, and handover to acquisition).
- *Having a single group approach each problem area early*, a group comprising strategic worriers, operators, technologists, and program analysts, although perhaps headed, in an individual case, by an ecumenical "operator" working for the SecDef and the Chairman of the Joint Chiefs of Staff.
- *More extensive early use of systems analysis and systems engineering* to filter by feasibility, define threshold capabilities and stretch goals, provide a framework for assessment and tradeoffs, and provide information with which to monitor and adjust.

An overarching recommendation was that *capability assessments should be accomplished on a DoD-wide basis, with close collaboration of the USD (AT&L) and the VJCS* .

This was in contrast to redundant and sometimes antagonistic Joint Staff and OSD processes. We suggested the name Defense Capability Area Reviews (DCARs) and anticipated a strong role for AT&L, particularly in technology-informed concept development, initial systems engineering, and systems analysis.

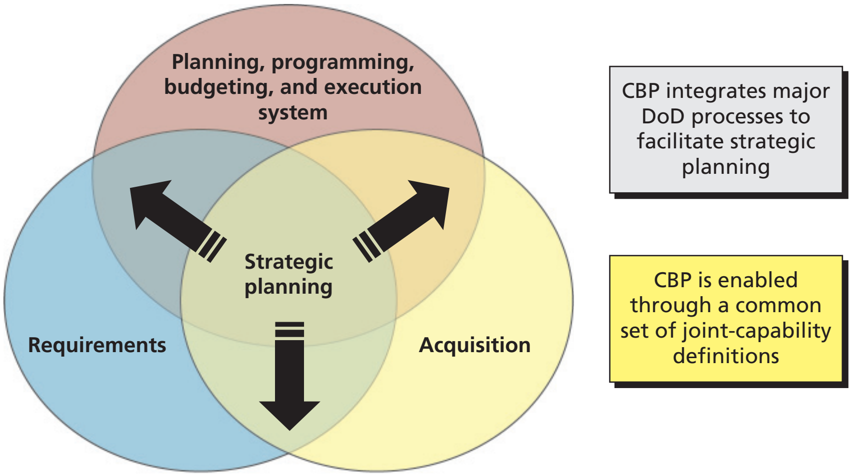
In its 2006 summer study, the Defense Science Board had a number of recommendations consistent with this move toward more-integrated planning. They included recommendations on assuring early-in-the-process influence of technological expertise, more-creative search for ways in which to exploit technological opportunities arising in the civilian sector, and the creation of mission-oriented portfolio managers (Defense Science Board, 2007b).

A Recent Change: Concept Decision Reviews

A consensus has emerged among DoD decisionmakers on many of the items described above, including the need for integrated work in which requirements, acquisition, and resourcing are all considered at the same time (Figure 2.3) and the special need for rejuvenated efforts of this type early in the development process. It is hoped that early top-level decisions will both avoid the start of inappropriate programs and build the intellectual and organizational consensus needed for rapid development of those programs that are approved.

A potentially important aspect of the new thinking is having DoD potentially move toward a new approach currently called the Concept Decision Review, illustrated schematically in Figure 2.4 (Krieg, 2007). In this new approach, important potential capability developments will be reviewed and the concepts will be accepted or rejected by a tri-chair group of decisionmakers, nominally the DepSecDef or USD (AT&L), the VJCS, and the Director of OSD (PA&E). Their decision will be based on substantial analysis prior to milestone A (a new concept), and following an evaluation of alternatives (EoA), which in turn will build upon products of the JCIDS process. The EoAs that are envisioned would be significantly different from the analyses of alternatives (AoAs) of past years. They would be broader and more creative in identifying options and would involve the integration of

Figure 2.4
The Capability-Development Process

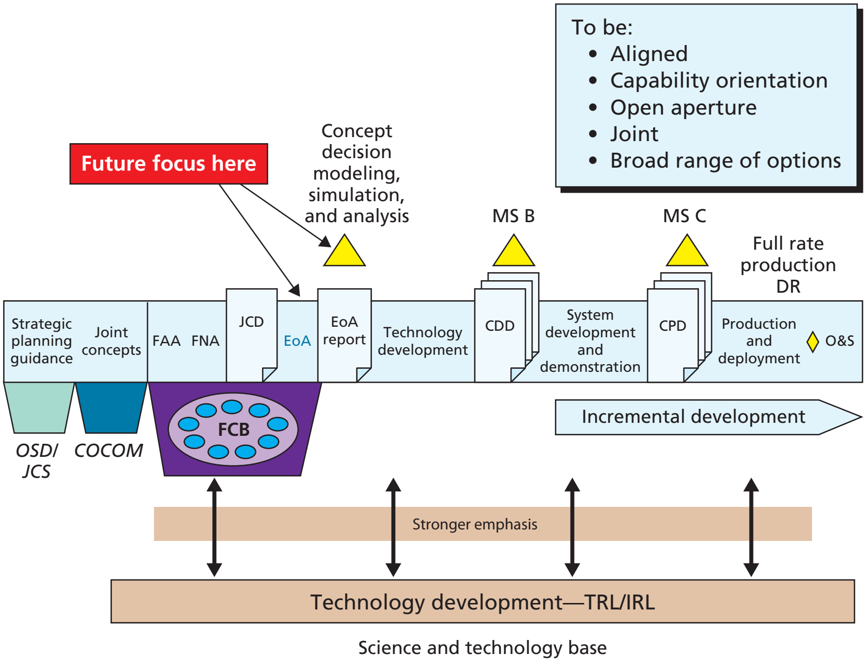


SOURCE: Adapted from a briefing by James Durham, OSD (AT&L), August 2006.
RAND *MG662-2.4*

need, technology, concepts, and economics, discussed earlier. Because decisions would also occur earlier, they would likely favor planning for sensible evolutionary development, with planned times for subsequent decisions at branch points.

The intent is then to have intensive technology development of an approved concept prior to a milestone B, which could be reached more rapidly and with less Office of the Secretary of Defense (OSD) management oversight than has typically been involved in going from milestone 1 to milestone 2 of the current process. As indicated at the bottom of Figure 2.5, the intention is to strongly inform early concept development by technology and analysis.

Figure 2.5
The Envisioned Concept Decision Process



SOURCE: Adapted from a briefing by James Durham, OSD (AT&L), August 2006.
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CHAPTER THREE

A Framework and a Generic Terms of Reference

Given the larger context described in Chapter Two, we next develop an analytic framework and methodology to support defensewide capability-area reviews, such as those in the new, experimental Concept Decision Reviews.* Some readers may wish to move forward to Chapters Five and Six to see concrete examples before reading the more-generic discussions in this chapter.

What Should a Capability-Area Review Accomplish?

The capability-area reviews that we have in mind are specifically for top DoD officials, such as the USD (AT&L), VJCS, and DPA&E. It is not the duty of such officials to manage programs. Rather, their responsibilities are at a higher level. The USD (AT&L), for example, should:†

- Influence initial concept decisions to approve only feasible and economically reasonable concepts with good threshold- and stretch-capability levels.
- Champion bottom-up innovation from the Services.
- Strongly influence design competitions, tradeoffs, and choices.

*The methods could be used within other processes, such as the Joint Staff's JCIDS, what OSD (AT&L) has in the past referred to as capability-area reviews (CARs), etc. However, the intent is to have a defensewide view.

†AT&L also has responsibilities for assuring efficiency of acquisition (what is sometimes referred to as "small-a acquisition").

- Assure a "systems approach," both in the design of individual systems and systems of systems and in planning for, e.g., a coherent logistics component.
- Influence priorities among systems and across missions.
- Influence science and technology (S&T) and developmental experimentation.

Perhaps needless to say, the capability-area reviews should also assure that jointness is taken seriously from as early a point in time as possible: Future concepts should typically be "born joint," in the sense of being defined with full appreciation of joint operations and the value of planning for cross-Service cooperation, coordination, and integration where that is effective.

With this in mind, we describe components of a generic terms of reference to guide a capability review. We developed these by reviewing what we had done in actual application projects, by generalizing, and by then following the generic terms of reference for a new application area as described in Chapter Four.

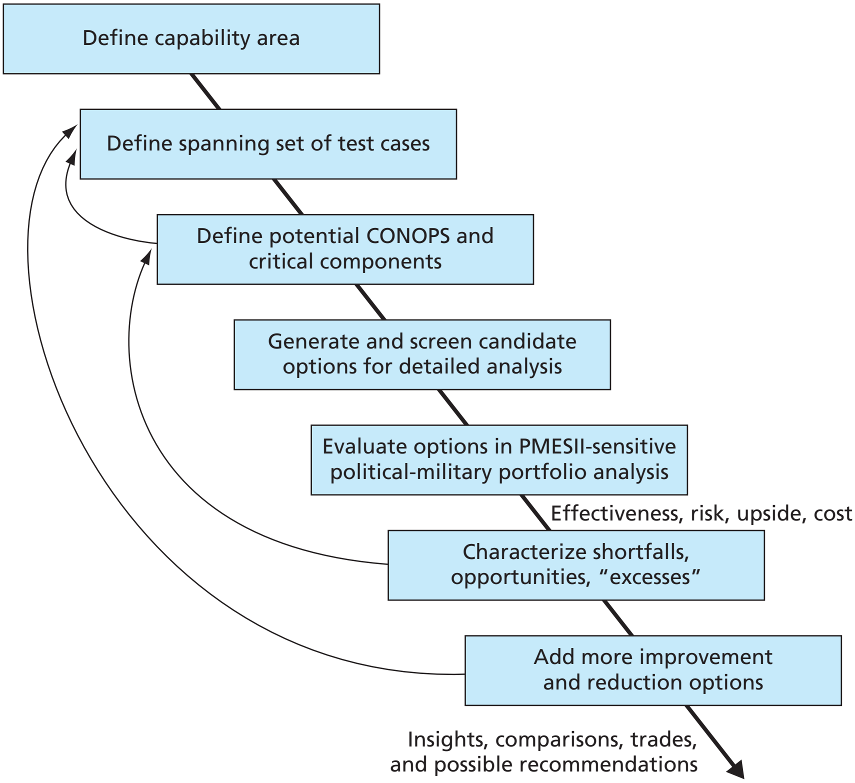
Figure 3.1 shows the key elements of a generic terms of reference as part of an assessment and monitoring process. It may appear at first to be just another flow diagram of the sort that populates so many studies, but it is importantly different from current practice in several respects. The following sections discuss each of these in turn.

Elements of the Generic Analytic Process

Define the Capability Area and Related Missions

What Needs to Be Done. The first purpose of a capability-area review should be to sharpen the definition of the capability area. A set of official joint capability areas (JCAs) has been developed by the Joint Staff (see Appendix A), but these may not be apt for a specific review. A review might need to consider an area that is more limited in some respects and more cross-cutting in others. How should a given capability area, in this sense, be defined? This issue may be nontrivial, because of pressures to narrow and simplify, leaving "seam issues" unaddressed

Figure 3.1
A Generic Analytic Process for Defense Capability-Area Reviews



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and the mission's range too limited ("We'd never do that." "We'd never be in that situation." "That's so-and-so's job, isn't it?"). Defining a cross-cutting area is often troublesome because it implies participation of several organizations.

The other part of this first component is identifying the operational missions associated with the capability areas so as to characterize what capabilities exist and what are needed.

Semantic issues intrude. The word "capability" has dual meanings in DoD planning. The Joint Staff's recent draft instruction defines it as follows:

> *Capability (1)*: The ability to achieve a desired effect under specified standards and conditions through combinations of means and ways to perform a set of tasks. It is defined by an operational user and expressed in broad operational terms in the format of a joint or initial capabilities document or a joint doctrine, organization, training, materiel, leadership and education, personnel, and facilities (DOTMLPF) change recommendation.

This definition is useful in one context, but it is not what a Secretary of Defense typically has in mind when he uses the term. Often, he would have in mind something like

> *Capability (2):* The ability to achieve a type of desired effect (e.g., accuracy or speed of action), perhaps through a number of different operational mechanisms over time.

Thus, he might refer to stealth or precision fires as "capabilities." To avoid confusion in this monograph, we use "broad capability" to refer to the second meaning above.

The relationship between these usages can be understood by attempting to give substance to the second definition. Precisely what would someone mean when talking about stealth or precision? How much, in what context, and as measured by what? Those questions are answered by considering possible operational missions, decomposing them into the tasks to be accomplished, and looking for natural metrics.[11] The risk exists, however, that the missions and tasks will be so narrowly and traditionally defined that they miss the point of the new broad capability. The difficulties can be illustrated by some historical examples.

Past Examples of Defining and Scoping. The case of strategic nuclear offensive forces was an early example of thinking through what constitutes a capability area and what the range of contributors to it should be. The choices made were not inevitable. Early on, the United States might have given the entire task of strategic offense to the Air Force, perhaps using a combination of bombers and ballistic missiles. In the 1960s or 1970s, it might have decided to rely entirely on sea-launched ballistic missiles (SLBMs). Instead, the nation chose to go with a triad concept of independently survivable ground-based intercontinental ballistic missiles (ICBMs), SLBMs, and manned bombers—later expanded to include air-launched cruise missiles (ALCMs) and SLBMs.[12]

The missions and priorities chosen for the forces were also not inevitable. From the era of President Eisenhower onward, the core concepts were deterrence through assured second-strike capability and then extended deterrence. Counterforce capability was always important as well.

From early on, strategic nuclear offensive forces were seen from what would today be called a joint perspective. Conceived in the late 1950s and created in 1960, the Joint Strategic Targeting Planning Staff (JSTPS) generated a single integrated operations plan (SIOP) in which synergies were considered and increasingly exploited. For example, early strikes by SLBMs on major Soviet radars would make subsequent bomber penetration much easier.

As a second historical example of the importance of defining a capability area, consider the missions of achieving and maintaining air superiority and conducting strike operations. As the result of an evolutionary process, today's military has a Joint Forces Air Combat Commander (JFACC) who coordinates *all* air operations—something very different from the situation decades ago. The change did not come about easily. However, the "seam" problems have been addressed and are more nearly solved than they were in past years.[13]

The examples, then, illustrate why the definitional stage of defensewide capability reviews is significant. The next stage is developing an analytic framework.

Characterize Operational Needs in a Scenario Space

The next component of our generic terms of reference (Figure 3.1) is identifying current and future operational needs within an analytic framework suitable for broad, creative, and rigorous thinking. Such a framework—fundamental to strong versions of capabilities-based planning (Davis, 2002)—involves parameterizing a broad scenario space. However, it is also valuable and perhaps even essential to refer to concrete, specific scenarios. In this section, we discuss how the broad, parametric, and concrete-scenario aspects relate to each other. We start with the broader discussion and then become more concrete.

There are two primary challenges in conceiving the parametric scenario space: effectively confronting massive uncertainty and considering *all* dimensions of a "scenario"—not just those convenient for quantitative calculations.

Planning Under Uncertainty. The Department of Defense has come a long way in improving its analytical methods for planning under uncertainty. Today's DoD planners consider a broad range of challenges represented most prominently by a substantial set of defense planning scenarios developed as part of what is called the "Analytic Agenda." The scenarios are used to coordinate planning across the entire department, as well as to encourage appropriate capability developments (Bexfield, 2004). Treatment of uncertainty still falls well short of what we consider desirable, but great strides have been made since the early 1990s, when the enrichment of scenarios began. That progress includes an increasingly healthy degree of consistency between programming analysis and operational analysis.

Motivation for taking the uncertainty aspects of planning seriously can be provided by a few examples.

Who Would Have Expected? Defense planners were as serious in the 1980s as they are today, and some considered numerous possible scenarios for the future. To our knowledge, however, none predicted or paid much attention to the possibility of, e.g., (1) a campaign of attempted coercion through strategic bombing of Serbia (1998); (2) a U.S. invasion of Afghanistan that would include projection of joint forces for vast distances and Special Operations Forces (SOF) fighting alongside tribesmen and calling in precision fires; or (3) a U.S. invasion of Iraq for the purpose of regime change, which would become a manpower-intensive operation of intended stabilization.[14]

How "Details" About Assumptions Matter. Historical examples illustrate the importance of parameterizing a scenario space when analyzing potential needs and solutions. Such "details" as the assumed warning time matter enormously, and different assumptions lead to different conclusions about the capabilities needed. When Saddam Hussein invaded Kuwait in 1990, the United States began deployment of forces a week *after* D-Day, rather than one to three weeks *before* D-Day, as is assumed in standard planning scenarios. One consequence was that airmen arriving in Saudi Arabia found themselves with a severe shortage of air-to-ground weapons because logistics had been based on the official planning scenario.

During the 1990s, U.S. planning scenarios included prominently the possibility of a new war with Saddam Hussein's Iraq. However, planning emphasized defense or quick reaction, followed by a restoration of boundaries or a subsequent counteroffensive. It did not consider the regime-change, nation-building, or lengthy stabilization operations that were subsequently launched. As is now well known, U.S. force structure and Army ground-force doctrine—although well suited to the earlier planning scenario—were not well suited to the stabilization phase.

Ultimately, the lesson is that a name-level scenario, such as a "war with Country X," with a single set of assumptions is a poor basis for planning, even about a possible new war with Country X (Davis, 1994, 2002)! Hence the need for parameterization of scenarios and what we call "exploratory analysis."

Let us now turn to the issue of taking a broad view of what the factors and uncertainties involve.

Including All Relevant Dimensions. It is common for today's DoD leaders to emphasize the need to consider DIME and PMESII aspects of scenarios.* Interestingly, it is something with which at least some defense analysts have long been acquainted. Some tangible examples may illustrate how important emphasizing these aspects has been.

Forward Defense and Flexible Response. During the Cold War, NATO's military strategy was dominated by political and economic considerations.[15] This was manifested by (1) dependence on U.S. strategic nuclear forces as an overarching deterrent; (2) a forward-defense posture that was militarily risky but essential politically; (3) the intro-

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*Diplomatic, information, military, and economic (DIME); and political, military, economic, social, infrastructure, and information (PMESII). The usual syntax is to refer to PMESII factors and DIME instruments. It is unclear that much value has been added by using so many capital letters.

duction of limited nuclear options to enhance flexible response, which in turn improved the credibility of NATO's defense generally; and (4) later improvement of conventional defenses without building a credible offensive threat. To narrow military analysts, the political factors may have been seen as mere constraints, but to defense planners, they were central. Influences also worked in the other direction. In particular, during the latter days of the Cold War, military analysis led the United States to conclude—and to convince its NATO allies—that conventional arms control should proceed toward equal limits, rather than a scaling down of existing forces.[16] Although diplomats expected this to be difficult to negotiate, there was an iron logic militarily: Proportional cuts would disproportionately endanger NATO's security. Even later, analyses of nonstandard scenarios demonstrated that the treatment of conventional forces in Europe should focus on a kind of *operational arms control* constraining real-world feasibility of a Soviet/Pact short-mobilization attack, rather than on such alleged confidence-building measures as withdrawal from borders.[17] The NATO Cold War experience, then, was a constant exercise in PMESII factors and DIME instruments.

The Messy Nature of Modern War. The web of relationships connecting political, economic, and military factors in modern warfare is well described by General Wesley Clark, based on his experiences as Combatant Commander during the Balkan crises of the late 1990s (Clark, 2001). In the Kosovo crisis, for example, NATO sought to use strategic bombing to coerce President Milosevic into capitulating. This bombing was constrained by alliance disagreements, complex command and control, and other factors. Political considerations (and differences of opinion within the military community) seemed to rule out a ground-force option for many weeks, even though such an option could scarcely have failed to alleviate coercive pressures. Then, after a surprisingly long time, but before the ground option had been resurrected and planned, Milosevic did indeed quit.[18] Sorting out how the various factors contribute is difficult in "messy" modern war.

The Concept of a Spanning Set in Capabilities-Based Planning. Capabilities-based planning (CBP) was mandated by the 2001 Quadrennial Defense Review, which urged planners to focus more on the attributes of capability that may be needed than on particular threat scenarios. Background analysis should consider a wide range of both name-level scenarios and key factors within them (what we refer to in this monograph as "parameters").[19] This has been the intention in the work of DoD's Analytic Agenda, something emphasized in guidance from OSD (Policy).[20]

The Value of Concrete Scenarios. Despite the need to think broadly about the entire scenario space of possibilities, there is great value in considering *particular* scenarios of crisis and war in which a great deal of context is specified. The reasons include

- Helping the analysts and the military operators who work with them "get into" the problem. Concreteness is both motivational and informative.
- Helping to make assumptions explicit and meaningful.
- Helping decisionmakers assess whether the capability at issue would merely be nice to have logically or would make a difference in *plausible* cases of concern (capabilities-based planning was never intended to be a blank check).
- Reducing the burden on analysts and analytic organizations: In the current-day Pentagon, much effort goes into imposing common scenarios and working them through in detail. That is not possible if the number of scenarios is large, because the specially capable officers who must work through force-employment concepts become overburdened.
- Facilitating communication: It is easier to compare options in a strategic-level framework if everyone has a fairly concrete mental image of what the evaluation cases are all about.

The Search for a Spanning Set. Accepting that it is valuable to have specific scenarios at some point, the question then arises as to how many and what type of scenarios are considered and how one knows that enough scenarios have been considered. That is, *which scenarios, with what characteristics? And why are those chosen?* Such matters are seldom discussed with any rigor. Therefore, we use the concept of a *spanning set:*

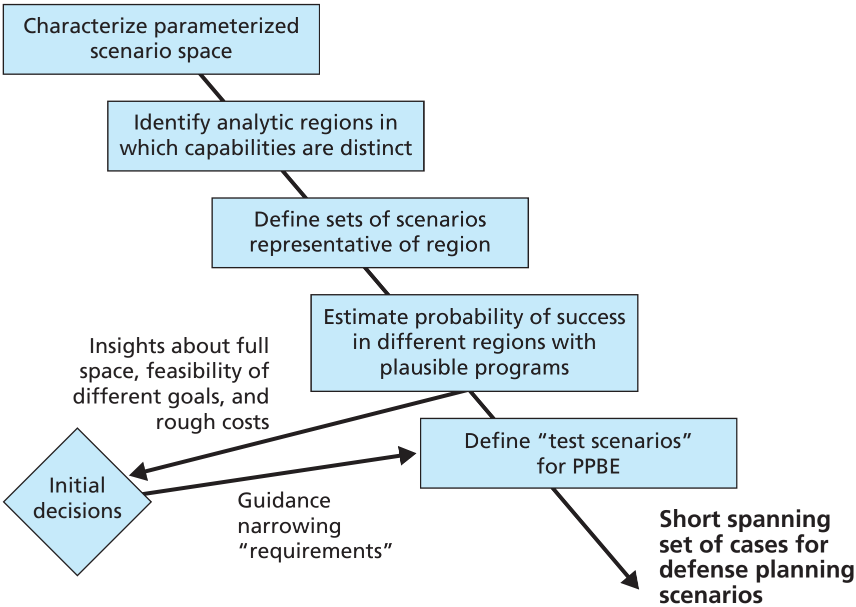
> A spanning set is a set of test scenarios chosen so that if alternative proposed systems are tested against them, the systems will be "stressed" in all the appropriate ways. Systems that do well across these test cases should do well in the situations that arise in the real world.

As mentioned earlier, "requirements" for capability are best seen as the *outputs* of a decision process informed by first-order analysis. To the extent that planning scenarios are used to assess the adequacy of programs, they serve as something like requirements and should reflect analysis concluding that the scenarios are appropriate for the purpose being considered. That is, the set of planning scenarios should be a spanning set.

Design engineers understand such concepts. They conceive their design space analytically and parameterize the principal variables—setting up models in which those key variables can be readily varied. They then identify distinguishable regions of the design space, such as a region requiring supersonic aircraft speeds or a region of low temperatures for a laptop computer. Ultimately, choices must be made, and some of the possibilities will be forgone. Once major decisions are made by the client, engineers can narrow the envelope within which the system will perform. This is still very different from designing for "point capability." For example, an aircraft may be required to operate with a high degree of stability and performance *anywhere* within a specified envelope of altitude versus speed. All bets are off, however, for aircraft flying outside the envelope.

Applying the same logic to defense planning leads to a process suggested by Figure 3.2. The first task is to think broadly about the design space (the space of possible operational contexts), characterizing analytical regions that are distinct. Policymakers must then decide which regions of capability are to be pursued, a decision informed by importance, costs, and feasibility. Given such a decision (perhaps recommended to the SecDef by DoD's Deputies Advisory Working Group), the next step is to identify scenarios representative of each of the regions for which capability is to be pursued. These become de facto requirements. As a classic example, a series of defense secretaries since

Figure 3.2
Establishing Priorities in a Design Space of Capability



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the 1960s have required strategic mobility capabilities adequate for two major "concurrent" conflicts, but not two fully simultaneous conflicts. Why? The secretaries were presumably convinced that the price tag would be high, that such situations were unlikely, and that—even if a situation of simultaneous wars arose—the United States would probably proceed more or less sequentially.

To reinforce the point, note that in Figure 3.2, analysis occurs early, to inform initial decisions about what test scenarios (and the performance demanded in those test cases) to insist upon. Such judgments should not be based on intuition alone.

Define CONOPS and Critical Components for Options

Concepts of Operations. Evaluation of options depends upon having a suitable concept of operations (CONOPS). If a new weapon capability is evaluated using only preexisting CONOPS, predicted effectiveness may be only marginally better than what existed previously. The issue of CONOPS becomes particularly important when assessing options that are significantly different from predecessors[21] or when joint CONOPS offer important synergies. The analyst must be wary of two different types of potential bias. First, scientists and engineers are sometimes prone to *assume* synergies that may not be realized in practice (e.g., that the vision of the Global Information Grid will be realized, with everyone getting the information he needs when he needs it). Second, Service-oriented operators may be chary of assuming efficient jointness because of conservatism based on history and their own experiences.[22]

Critical Components of Capability. An operational capability exists only if *all* the critical components for actually executing the mission in question are present. Although this is mere tautology (absence of a critical capability means failure), it is a problem in the real world, where programs often do not include some necessary components—perhaps to avoid price "sticker shock" and with the rationalization that other components can be obtained later. The missing components may include, e.g., a communication link to other C4ISR (command, control, communications, computer, intelligence, surveillance, and reconnaissance) systems, adequate weapon stocks, logistical equipment, doctrine, or trained personnel. DoD recognizes this to some extent by referring frequently to DOTMLPF, i.e., to the necessity of dealing with doctrine, organization, training, materiel, leadership and education, personnel, and facilities. One of the strengths of U.S. military staff operations is that officers are trained to worry about all such issues, often with strategies-to-tasks breakdowns. Although it does not extend into the full range of DOTMLPF issues, DoD's concept of mission-capability packages (MCPs) is similar in spirit and very important in systems-engineering work.[23]

Assuring the presence of all critical components is nontrivial for capabilities analysis, because many modeling and analysis methods either *assume* uncritically that "other" parts of the system exist or employ methods such as linear weighted sums to characterize net capabilities arising from a mixture of strong and weak components.[24] As we demonstrate in Chapter Five, it is possible to do much better.

Generate and Screen Candidate Options

Although options are typically already on the table when something like a capability-area review begins, those options are often insufficiently comprehensive or somehow parochial. One task for analysis, then, is to generate a more complete set of options that might be considered and to then conduct a preliminary screening to identify the candidate options worthy of fuller study within a portfolio-analysis framework. We shall discuss mechanisms for doing so more fully in Chapters Four and Five.

Evaluate the Options in DIME-Sensitive Portfolio Analysis

The Value of Portfolio Analysis. It is one thing for potential capabilities to appear very useful for ideal cases defined technically; it is quite another for those concepts to make sense operationally, economically, and strategically. Therefore, the analytic framework should give all of the dimensions visibility. Consistent with the need to plan under deep uncertainty, the framework should help decisionmakers understand both where the proposed capability would work and where it would not. It should address risks and also upside opportunities that would be bonuses. More generally, analysis should give decisionmakers a sense of the degree to which their investments are balanced across a wide range of considerations. This is precisely what portfolio analysis is good for, and we recommend that it be used routinely. We shall describe what we have in mind in more detail in Chapter Four and then illustrate it in Chapters Five and Six.

The Issue of Metrics. One aspect of evaluation is finding appropriate metrics by which to assess effectiveness, efficiency, and progress. A subtle problem here is that the framework and metrics need to fit the problem area at a technical and operational level, rather than merely seeming reasonable to strategic thinkers distant from the technical and operational issues. Even well-chosen top-level objectives, such as those relating to agility, must be translated into more-concrete and measurable factors.[25]

Historically, discussions of evaluation have emphasized the alleged necessity of defining quantitative metrics. That can be counterproductive. When carried to the extreme, it results in defining metrics that are conveniently quantitative and measurable but off point. For example, a combat unit may have equipment that makes it physically agile, but it may lack the doctrine, cultural awareness, and specialized training enabling it to be effectively agile in a difficult environment such as today's Iraq. Once this is acknowledged, of course, metrics can be introduced that measure time spent in relevant operations or training. Even then, however, a commander's soft judgments may be necessary to assess agility realistically. The commander might know, for example, that the unit's past experience or training taught the wrong lessons.

Characterize Shortfalls, Opportunities, and Surpluses

Shortfalls. Assuming that capabilities in a particular area can be characterized analytically, the next task is to characterize shortfalls of projected capability. It is already common throughout DoD and the Services to have presentations that do so. These may be the result of off-site meetings in which military officers take a hard look at their current and projected operational capabilities and make subjective assessments about areas of relative strength and weakness.

It is less common to develop such assessments with much rigor. Some of the shortfalls identified may be spurious if, for example, they are based on analysis that ignores qualitative considerations such as the fighting quality of an army or the disparity in command and control between two air forces. Other shortfalls may be underestimated because of excessive optimism regarding warning, allies, and the like.

As discussed in the previous section, capabilities-based planning considers a wide range of plausible scenarios and operational circumstances. This is not really straightforward, because an infinite number of possibilities exist and because subjective judgments—especially unaided ones—are often poor at characterizing results across the possibility space.

Opportunities. Identifying shortfalls is common and expected, but it is also important to identify opportunities and surpluses. For example, the United States recognized in the early 1970s that it had the opportunity to render Soviet air defenses obsolete with stealth technology. Doing so would not only be militarily effective, it would also be a U.S.-style asymmetric strategy, one using technology to undercut the value of something on which the adversary (the Soviet Union) had spent the equivalent of hundreds of billions of dollars.[26] Although penetrating defenses with traditional means would probably have remained possible, albeit with increasing dependence on electronic countermeasures, stealth provided a leapfrog opportunity.

Another well-known example was the opportunity provided by precision-guided munitions (PGMs). Again, the military value of weapon accuracy was appreciated, but the true significance was greater: Soviet military leaders were extremely concerned about the prospect of these weapons as of the early 1980s, because they recognized that the Soviet industrial base was unable to counter such development. Soviet concerns on this score were not well recognized for some time in the West, so while most Western commentators on the conventional military balance were full of gloom and doom because of Soviet quantitative advantages, the Soviets themselves saw dark days ahead.[27]

Surplus Capability. If identifying opportunities is somewhat unusual in capability assessments, identifying excesses is extremely so. It is simply unnatural for organizations to find their resources to be more than adequate for the tasks assigned. It is notoriously difficult for the Secretary of Defense to find a Service, or even a branch within a Service, willing to say, "Oh, we could tolerate a 10 percent cut in our budget; it would not significantly affect our capability to do our job."

Efforts have been made in modern times to identify excesses in order to pay for other initiatives, such as the transformation initiatives of Secretary Rumsfeld. Some of those efforts have been controversial, or even misguided. In the late 1990s, it was fairly common for observers to claim that the U.S. Army could be cut back by another 20 percent because of the changing nature of warfare, which was putting a premium on air power and precision weapons. The Army's alleged "excess" depended sensitively on the implicit assumption that actual demands would be comparable to those of planning scenarios in which the United States was defeating invading armies that conveniently poured down narrow highways, making themselves easy targets for the emerging precision fires. Only a few years later, with the benefit of experience in Afghanistan and Iraq, it is obvious that there are too few U.S. ground forces for what is needed in manpower-intensive operations.[28]

Implications. The moral of the story is that the methodology used to identify shortfalls, opportunities, and excesses needs to be rigorous, broadly based, and imaginative. One way to report the results of such work is to address both upside opportunities and downside risks explicitly. Indeed, doing so is arguably an example of best practices in decision support, one with roots in modern decision science.[29] As simple as that concept may be, it is notably absent from most current-day support of DoD decisionmaking (although the decisionmakers often add considerations of opportunities and risks in their heads). We shall discuss mechanisms for implementing such an approach in later chapters.

Add Options: Remedies and Possible Reductions

Identifying potential remedies is a routine undertaking, but DoD leaders sometimes worry about whether the remedies considered are sufficiently creative and farsighted. In some cases, the issue is having future operational concepts be born joint; in other cases, the issues relate more to using technology well or to being sufficiently realistic about how proposed remedies would fare in a range of circumstances, as mentioned above.

To illustrate the issues that can arise, consider ballistic-missile defense of the U.S. homeland, allies, and forward-deployed forces (see Chapter Six). The straightforward remedies that are most comfortable for existing organizations involve long-range ground-based interceptors and ship-based interceptors for medium- and intermediate-range attackers. In considering remedies, however, the Missile Defense Agency must consider a diversity of conflicts, potential attack modes (to include attacks from ships relatively close to the United States), countermeasures, and geographies. Questions arise about the possible long-term role of space-based weapons or midterm interceptors launched from bombers or even fighter aircraft. These types of remedy would be rather unconventional and organizationally disruptive; they might also have complex international ramifications. Another issue is how to assure that the future ballistic-missile defense system (BMDS) exploits the possibilities of networking, including the Global Information Grid and subsystems with more-stressful technical requirements. Will it be possible to do effective and efficient battle management drawing upon whatever BMDS components happen to be deployed in relevant but geographically separated ground bases, ships, and aircraft, and to do so using both U.S. and allied systems? And, taking a broader view yet, what about aspects of the "total system," such as defending U.S. installations or attacking or disrupting those of the adversary, perhaps preemptively and perhaps with means ranging from special forces to cyber attack?

Iterate

As indicated in Figure 3.1, the analytical process for capability reviews should be iterative: Analysis will generate ideas for alternative approaches, which will then need to be analyzed anew; doing so will point out the need to improve the analytic framework itself to make it include additional considerations. Iteration should continue until stable conclusions emerge or the time available is exhausted. Such iterations are important in practice and a major reason for high-quality analyses taking months rather than weeks.

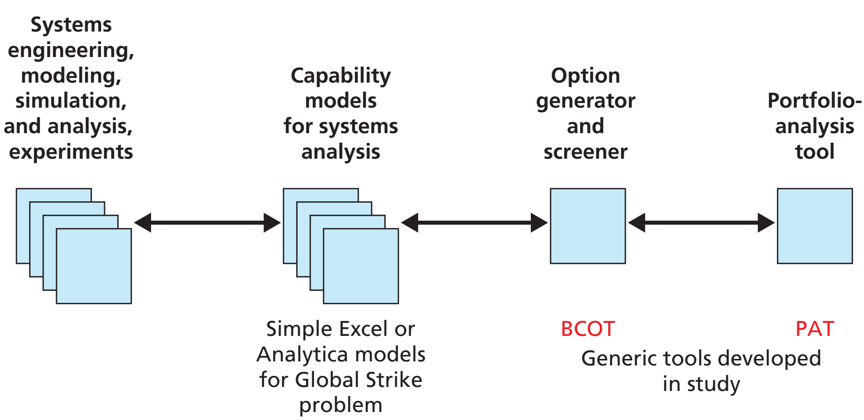
Having provided an overview of the analytic framework that we suggest, we next discuss some of the tools needed, after which we shall present some examples.

CHAPTER FOUR

Tools to Enable the Framework

A number of types of models and tools are needed to accomplish the goals described in previous chapters. Figure 4.1 indicates this schematically. The arrows are deliberately two-way. It would be folly to construct a bottom-up system for decision support, because so much of the reasoning and analysis needs to be top-down in character. Nevertheless, the quality of the framework used at higher levels and the validity of the information presented there sometimes depend on deep knowledge, such as that residing in the world of systems engineering, detailed modeling and simulation, and experimentation.

Figure 4.1
The Role of Models and Portfolio Tools in Investment Analysis



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Although this chapter discusses such cross-level issues in terms of tools, the most important aspects of cross-level work are typically organizational and social. It is all too easy for those who do the relatively higher-level work and those who do the relatively lower-level work to be in distinct organizations with little cross-boundary communication. That can be a serious problem. Ironically, despite the natural resistance to cross-boundary communication (the specter of meetings and bureaucracy and of dealing with unfamiliar people), such collaborations can be very interesting and rewarding.[30]

Let us briefly describe the elements of Figure 4.1, one by one.

Systems Engineering, Modeling, Simulation, and Analysis, and Experiments

Although merely touched upon in this monograph (see also Appendix B), the technical foundations for capability development are typically located at the levels of systems engineering and underlying technology, including experiments to motivate and test concepts. The tools used at that level include relatively detailed models and simulations. These are sometimes just tools used in analysis and sometimes the repository of the most accurate and precise knowledge available. Some of the detailed simulations are used directly in experimentation and merge to a greater or lesser degree with components of real-world command and control systems.[31] As a practical matter, experimentation programs are often more useful for testing the simulations than for establishing a firm body of empirical data; many decisions about design, development, and production are primarily dependent on information from those simulations.

Virtually all acquisition projects have associated systems-engineering models, although many of them reside only in industry.

Capability Models

By "capability model" we mean a model that characterizes the effectiveness of a current or prospective system or collection of forces in situations of interest. Although there is overlap among levels, these models are typically somewhat higher-level (and more aggregated) than those for systems engineering. Many examples exist throughout the defense community.[32] For example, EADSIM describes effectiveness of air-defense systems in diverse scenarios of enemy attack. RAND's CAMMD (Capabilities Analysis Model for Missile Defense) is a high-level model developed for the Missile Defense Agency that describes the effectiveness of a Ballistic-Missile Defense System (BMDS) as a function of the characteristics of the system and the attack. Two earlier RAND models (EXHALT and EXHALT-CF) describe effectiveness in interdiction campaigns as a function of forward presence, warning, access problems, the time required for suppression of air defenses, and other factors. Such models are typically math- and physics-based and parametric. For example, the model used in Chapter Four to estimate effectiveness of tactical air forces or long-range bombers has as a key input the class of air defenses the aircraft would encounter. A data table translates that class into probability of penetration. Campaign models (e.g., JICM, Thunder, and ITEM) are special, rather highly aggregated capability models. The "capabilities" treated by such models relate more to integrated, aggregate-level force capabilities than to the capabilities crucial in given missions. Campaign models are discussed in a recent master-plan study for DoD's Modeling and Simulation Coordination Office.[33]

Capability models exist for almost all subjects of interest in defense-oriented capabilities-based planning. The current models, however, may not be especially suitable for higher-level tradeoffs. For these, lower-resolution models tend to be more valuable than high-fidelity models because (1) they have fewer parameters about which to reason, (2) setup time is shorter, and (3) decisionmakers need explanations of important conclusions and often prefer them to be simple and understandable, rather than dependent on a myriad of unstated assumptions. Ideally, each capability area will have a family of capability models on which to draw, each with different strengths (e.g., greater or lesser resolution in various respects, different perspectives), but all informed by the others. Although somewhat unusual at present, such model families are feasible and highly desirable.[34]

Generating and Screening Candidate Options

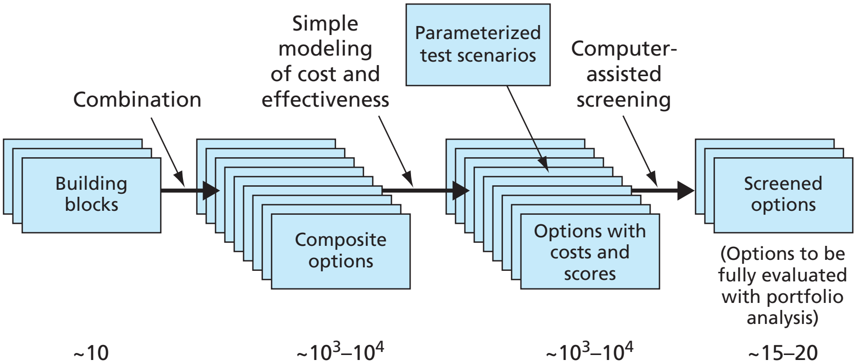
It is often assumed in discussions of methodology that the options to be evaluated have already been identified. However, the options that arise for consideration in a given capability area will often come from people and organizations who developed them based on their organizations' past efforts, knowledge, and interests. The suggested options will thus reflect diverse assumptions about what capabilities are needed. The individuals involved, in many cases, will not have thought much about opportunities for synergy, either across Services or across capability areas, except where synergy is natural for their particular interests (e.g., an airplane builder will see multiple missions). Further, only sometimes will the individuals have offered up variants that cost and deliver more or less than what they recommend. As a result, those who must allocate limited resources often lack information they need for tradeoff analyses, for combined strategies exploiting synergies and hedging against risks, and for making program adjustments wisely (e.g., increasing or decreasing allotments to various programs, relative to what is requested). Thus, there is need for a more comprehensive and systematic approach to option-generation, rather then merely the evaluation of options being proposed in the usual manner.

As described in a companion RAND report (Davis, Shaver, Gvineria, and Beck, 2007), we have developed the Building Blocks to Composite Options Tool (BCOT) to help in developing candidate options worthy of more-detailed analysis in a full portfolio structure. BCOT is discussed further below and is described schematically in Figure 4.2.

In the experiments that we have conducted, we began with 10 to 15 building blocks, generated thousands of composite options, and then used the screening methods to reduce the list to about five to 20 options.

Analysis begins by constructing a list of building-block investment options, such as buying a new radar, kill vehicle, or upgrade to a missile. Composite options are then constructed for all combinations of those building blocks. The composite options are next analyzed with a screening tool to eliminate those that don't meet thresholds of effec-

Figure 4.2
Schematic of BCOT



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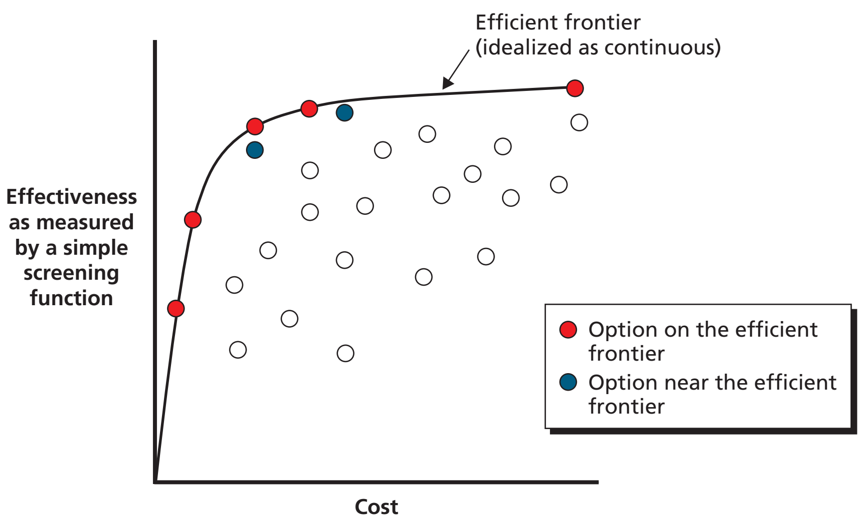
tiveness, that exceed a threshold of cost, or that are clearly inferior to other options from a cost-effectiveness perspective. The methodology expands significantly upon mathematical techniques developed years ago. That earlier work found options *on* the so-called *efficient frontier*.[*35] Ours finds non-redundant options that are on or close to the efficient frontier (see Figure 4.3). Redundancy here refers to an option having building blocks that add nothing to effectiveness but that do add costs. Retaining options that are *close to* the efficient frontier is important, because screening could otherwise discard some that appear in a first-order analysis to be inferior but that would be superior when viewed in a fuller portfolio analysis.

Portfolio-Analysis Tools

While the capability model produces raw effectiveness information as a function of many factors, it is the job of the portfolio-analysis tool to help make sense of the alternatives for investment. The user of such a

[*] The efficient frontier connects Pareto-optimal points (Winston, 1994). In a plot of effectiveness versus cost, a Pareto-optimal point is at least as effective as any other point with the same cost.

Figure 4.3
Schematic Depiction of Finding Points Near the Efficient Frontier



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tool must decide on, e.g., the investment options to be compared, the multifaceted measures of effectiveness to be applied, and measures of risk.

Once these are decided, the *structure* of the analysis is determined, but it is then necessary to populate that structure, i.e., to provide data on how the various options fare under the different measures of effectiveness, risk, and so on, and how much the options cost. The terminology of portfolio analysis comes from the use of somewhat analogous methods in economic theory. An investor, for example, should maintain a suitable portfolio of investments of different types (e.g., stocks, bonds, real estate, gold), in order to be well hedged against various types of risk. The investor should review and adjust that portfolio from time to time to assure that objectives and risks are properly balanced.

The portfolio-analysis tool should generate tables, graphics, and text—output that will help decisionmakers assess the relative strengths and weaknesses of the options and make judgments such as what to buy first, and so on. These outputs may take the form of colorful "scorecards," cost-effectiveness graphics, pairwise-comparison tables or charts, or other displays.

Portfolio-analysis tools have existed for many years; some are custom-built by the users, and some have been developed commercially for routinized analyses such as arise in the commercial world. The relatively simple Balanced Scorecard method has been much discussed in recent years (Kaplan and Norton, 1996). A number of tools draw on the theoretical business literature, such as the work of Peter Weill on information technology portfolios. Providing such tools is a large business in itself. The tools needed for DoD's purposes, however, tend to be more complicated and sophisticated in some respects, multifaceted (there is no single measure of goodness, such as expected profit, in military applications), and useful for characterizing diverse types of risk and opportunity. Thus, portfolio analysis in defense work should be quite different from that in the financial world (Davis, Gompert, and Kugler, 1996).

Two related tools have been developed at RAND over the past decade, both of which are in use currently. Development of these tools was strongly motivated by our research in modern decision science (Davis, Kulick, and Egner, 2005), as well as many years of experience with studies in support of DoD and Service decisionmakers.

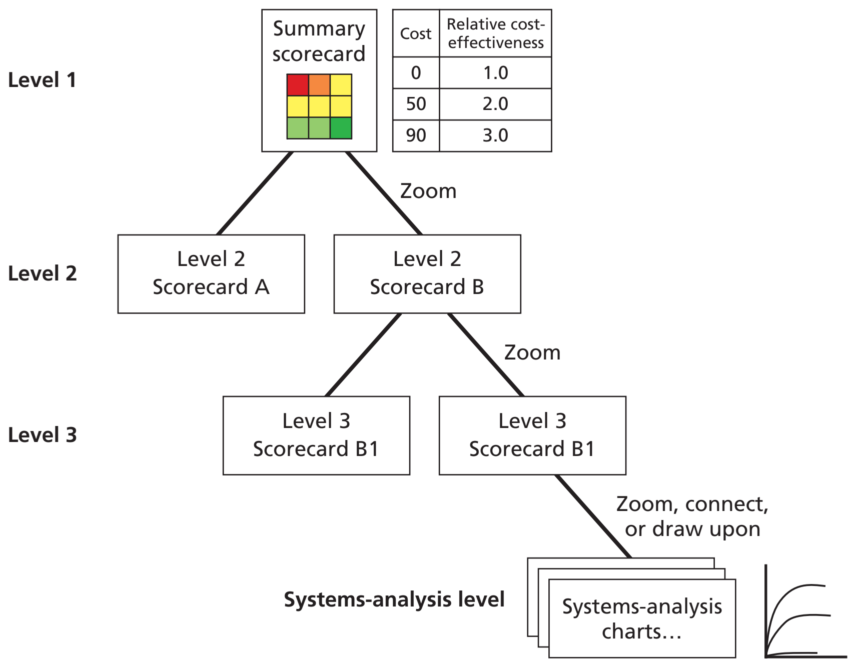
The first tool is DynaRank, developed primarily to rank options to assist in deciding what to fund (or cut) first, second, and so on when trying to work within a budget (Hillestad and Davis, 1998).[36] The most recent tool is PAT (Portfolio-Analysis Tool), a generic version of an earlier tool developed for the specialized purposes of the Missile Defense Agency (Dreyer and Davis, 2005). Use of PAT is illustrated in the next two chapters. At a technical level, some of PAT's more important features are

1. Scorecard methods that support making evaluations across numerous dimensions of effectiveness, risk, and cost
2. Zoom (drill-down) for visual explanation
3. Nonlinear assessment methods
4. Alternative "perspectives" (assumption sets used in the assessments) by which to perform cost-benefit calculations

5. Multiple resolution, enabling one to enter assumptions at different levels of detail.

Figure 4.4 indicates schematically the way PAT operates from a top-down perspective. Discussion begins by looking at a summary scorecard. A request for explanation (e.g., "Why is option 1 so much better than option 2 as judged by effectiveness for scenario class B?") can be answered by zooming into a second level of detail for the evaluation of scenario class B. If that level of detail is insufficient, another level of zoom is possible. And, where appropriate, it is possible to zoom to an even deeper level, what we call the level of systems analysis, to see crucial charts or tables. This level might have charts with-families of curves showing how results vary with the assumed values of key parameters. Or one level might have a live model (embedded

Figure 4.4
Hierarchy of Detail in RAND's Portfolio-Analysis Tool



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within Excel or separate) that allows the users to "see" effects of changes. We do not anticipate that there will be many decision meetings with live tools or with much discussion of technical detail. However, organizing the information in this way makes it possible to tailor presentations easily and—in response to either careful staff review or a decisionmaker's spot-check questioning—to drop down to details quickly.

Tailoring Analysis for Different Contexts

Good tools allow tailoring of analytic material for different audiences and occasions. The key factors in such a tailoring are (1) the nature of the decisions or judgments to be made; (2) the decisionmakers' relative interest in strategic, technical, or process issues; (3) the decisionmakers' preexisting depth of knowledge; (4) time; (5) the psychological context resulting from other contemporary events; (6) the format of presentation (briefing, discussion, written monograph, or a combination of these); and (7) personal inclinations and styles.

Generalizations on these matters are often misleading. Over the years, we have reported results of studies to senior people in meetings that have lasted tens of minutes or hours. We have gone into meetings expecting a high level of interest only to find the official distracted, and into meetings expecting a perfunctory discussion only to have the official engage in in-depth questioning. Most commonly, senior clients have been briefed and have done little, if any, reading on the subject. However, in some cases they have done significant reading—usually of executive summaries, but sometimes even portions of the full text. Sometimes the reading was scheduled, and sometimes it was ad hoc, perhaps on an airplane.

Another issue on which generalization is inappropriate concerns discussions of risk and uncertainty. Some high officials are exceedingly interested in these matters, regarding them as at the core of their responsibilities. They wish to know not only about best estimates, but also about "What ifs?" Other officials are more interested in best estimates concerning the way ahead and have little patience for discussion of uncertainty, which they see as cluttering the landscape with equivocation and tail-covering. They may appreciate risk and uncertainty at one level but believe that the only sensible way to proceed is to go with the most likely option, adapting later as necessary. Or, in a variant, they may believe that it is better to just press ahead and do something sensible (and iterate later) than to agonize about imperfectly understood alternatives.

Both history and decisionmaking research tell us that both styles exist widely among even very good decisionmakers. Further, analytical decisionmakers sometimes are poor at strategy and miss common-sense points, whereas intuitive decisionmakers are sometimes prescient and effective and sometimes disastrously wrong. Both types (and the many hybrids) can benefit greatly from good staff processes and staff analysis, but how they can best be helped varies substantially. These and other issues are discussed in related RAND work on modern decision science (Davis, Kulick, and Egner, 2005; Davis and Kahan, 2007).

A basic question we addressed as we prepared this monograph was how to deal with the variations described above. As strategic analysts, we are naturally very interested in methodology and subtleties, but in our role as advisors on support for decisionmakers, we must be realistic about what is both needed and useful.

To the extent that we have a solution, we believe that it depends on adhering to the principles summarized in Table 4.1. That, in turn, means relying on first-rate analysts operating in circumstances that allow them to do the kind of work described.

Having provided an overview of both methodology and tools, we shall now provide two examples of how they apply to concrete problems. Chapter Five deals with the issue of Global Strike and Chapter Six deals with Ballistic Missile Defense.

Table 4.1
Principles for Tailorable Decision Support

Principle	Comment
Prepare material with structure and rigor.	Do so even if only highlights are likely to be presented to decisionmakers.
Bring to bear imagination, creativity, and cross-cutting thinking.	This is in contrast to “by the numbers” analysis and bean counting.
Create frameworks that deal with risk, uncertainty, and political-military content.	Tailoring to the context is essential.
Insist on candor and clarity about both upsides and downsides; reveal, rather than hide risks.	Do so even if the audience may react negatively to reminders of risk or bad news.
Develop layered versions of analyses and stories.	Each layer should be as self-contained and comprehensible as possible.
Develop different layerings for different contexts.	The decompositions appropriate for 20-year strategic planning, “right-now” budget decisions, and concept decision reviews are fundamentally different.
Whether supporting analytical or naturalistic decisionmakers, present material so as to encourage and assist planning for flexibility, adaptiveness, and robustness (FARness).	Single words, such as “adaptiveness” or “agility” are often used to convey the same intention as FARness.

CHAPTER FIVE

A Notional Example: Global Strike

In this chapter, we walk through a notional application of our methodology to the Global Strike problem. When we chose Global Strike for our application, it had not yet been defined as one of AT&L's capability areas, and no major studies, such as analysis of alternatives (AoA), had yet been conducted. We saw this as an advantage for what was intended to be an unclassified illustration of methodology. Later, we were asked by AT&L to develop the work further as preparation for an evaluation of alternatives (EoA) for Global Strike within the new Concept Decision Process (Krieg, 2007; Durham, 2006). We did so, but this chapter continues to draw only on unclassified materials and deliberately excludes some options and considerations that would be examined in a full study of Global Strike options.[37]

What follows is a streamlined version of what was outlined in Chapter Three. In successive sections we (1) define the Global Strike mission; (2) define a parameterized scenario space and a small spanning set; (3) define potential CONOPS and critical components of capability; (4) evaluate effectiveness of the baseline and options; and (5) assess relative cost-effectiveness. We also include a section on the knotty problem of how to discuss risks analytically and summarize results compactly.

Defining Global Strike

Key Attributes

Ample information was available about the intent of the Secretary of Defense and the President on the matter of Global Strike. There has also been a good deal of public discussion and review.[38] Although much of the public discussion is concerned with nuclear issues, we focused exclusively on conventional strikes. The key attributes, or defining features, are as follows:

> A global strike, as we define it, is a discrete strike, not an entire campaign or even a bombing campaign, and one that is explicitly responsive to needs and concerns of the President, Secretary of Defense, and other top leaders, rather than, say, a combatant commander.[39]

This conception is very similar to what DoD has come to call Global Strike Raid, a subset of the larger Global Strike.[40]

A broader definition of Global Strike would include a strike to set the stage and "open the door" for a large conventional campaign. It would also include a *series* of small, discrete strikes that might be used to disrupt an adversary's operations and buy time for a larger U.S. response. Such extensions would imply the need for sizable forces and weapon inventories.[41]

Form. Even more than for other missions, a Global Strike force package would be assembled by drawing assets from all major commands and might be unique to the strike rather than something more ordinarily part of an individual combatant commander's (COCOM's) operations plan. The Global Strike mission should be conceived broadly enough so that execution could consist of or include Special Operations Forces (SOF).* It could also include various non-kinetic mechanisms, such as information operations or cyber attacks.

The Executing Command. By its very nature, global-strike capability cannot reside in a single command. Where a strike would be needed, and how best to accomplish it, would depend on the situation. U.S. STRATCOM has a special role by virtue of its global perspective and control of strategic forces, but at the time of a strike operation, command might be, e.g., in U.S. CENTCOM operating in the

---

*The White House has long-stated interest in using SOF for strikes (Clarke, 2004, pp. 141–144). The 2006 strike into Damadola, a remote village in Pakistan, was reportedly accomplished by a Predator (Katzman, 2006, p. 28.)

Middle East or U.S. PACOM operating in East Asia. Such complexity implies the need for unusual peacetime planning and coordination.

Special Considerations. Global Strike's execution would have to be unusually sensitive to domestic and foreign-policy considerations such as sovereignty and indirect political effects. Further, since some of the circumstances for which Global Strike capabilities are intended would be WMD-related crises, there would be reason to worry about collateral damage[42] and about issues such as erroneous perceptions by the target or other countries about the nature of attack, conceivably triggering escalation or use-it-or-lose-it launches. The U.S. Senate has expressed concerns about such issues (Woolf, 2007), as will be discussed later.

Historical Examples

We drew on historical cases to sharpen our concept of Global Strike. Analogs to global strikes in the past include

1. The 1980 failed rescue mission in Iran
2. The 1986 U.S. strike on Libya
3. The 1981 Israeli attack on the Iraqi nuclear facility at Osirak
4. Various strikes against Iraq between 1995 and 2000 (e.g., the 1998 strike on an al Qaeda training camp, which narrowly missed Osama bin Laden)
5. A strike on terrorist camps in Afghanistan (1998), launched in hopes of killing bin Laden,[43] and a simultaneous strike of a suspected chemical-weapons facility in Sudan (1998)[44]
6. The bombing of Damadola, a village deep within Pakistan, in January 2006 in an attempt to kill al Qaeda's number-two figure, Ayman al Zawahari.[45]

Timeliness Requirements

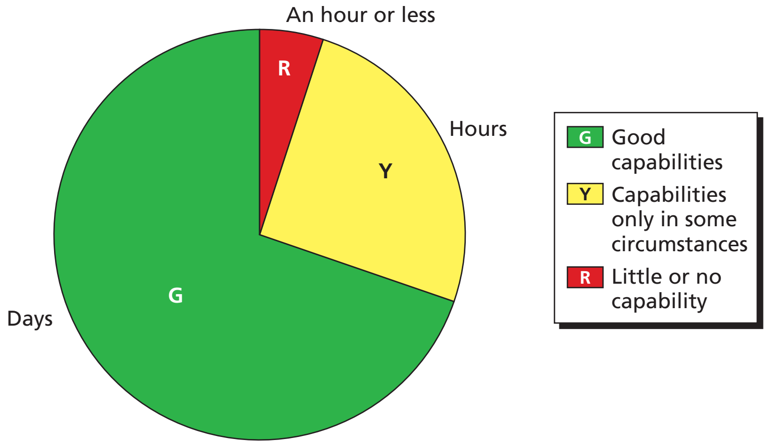
A global strike should be timely, but not necessarily "prompt," a term interpreted by STRATCOM's General Cartwright and others to mean within about an hour (Woolf, 2007, p. 12). In our view, timeliness does not ordinarily require such speed, while complex decision processes, checking of intelligence, and operational planning usually *are* needed.[46]

These can take tens of hours, or even days, in which case a wide range of forces could be used, and promptness might not be needed. Strategic strikes, even conventional strikes, are not undertaken lightly.

This said, *some* global strikes may need to be prompt, i.e., within an hour or so, and would also be feasible. The key factors are how long the target will be vulnerable, how much preparation and decisionmaking are necessary at the time (rather than earlier), and whether a slower attack (such as one with aircraft or cruise missiles) might be detected, with the target being warned and able to escape. We discuss this more extensively in a later section, along with various ways to improve timeliness.

The United States currently has little capability to accomplish a prompt global strike. Figure 5.1 illustrates this point schematically, indicating that qualitatively different timescales exist: one measured in tens of minutes up to about an hour, one measured in hours, and one measured in days. *Most* currently plausible Global Strike scenarios

Figure 5.1
A Notional Depiction of Current Capabilities for Global Strikes, by Timescale



NOTE: The three areas denote relative frequency of need for very short, short, and more-leisurely execution times. The perceived need for fast reactions might increase if the capability existed for strikes in tens of minutes or an hour. The figure is intended to be roughly accurate but is not based on actual calculations.
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involve many hours or days of warning and preparation, and the time to actually execute a mission is much less important than the ability to achieve surprise or avoid defenses. The United States already has a great deal of capability with which to execute strikes of this type, as indicated by the green region in Figure 5.1. Some Global Strike scenarios require strikes to be accomplished within hours, which is possible using forward-deployed tactical forces—*if* they are in the right location and alerted, *if* they can be employed safely without extensive preparations for penetration of air defenses, and *if* their forward posturing does not cause trouble in itself or give away warning.[47] We show such cases in yellow in Figure 5.1 because what is feasible depends on details. If strikes require execution times of only an hour or so, the United States currently has no non-nuclear options (except perhaps in cases where Tomahawk platforms happen to be forward-deployed close to the target area). It follows, as suggested by Figure 5.1, that a potentially serious shortfall exists. We might add that if the United States had prompt strike capability, many more opportunities needing that capability would be recognized.

Using these definitions and distinctions, we now move on to defining a parameterized scenario space.

Defining a Parameterized Scenario Space for Global Strike

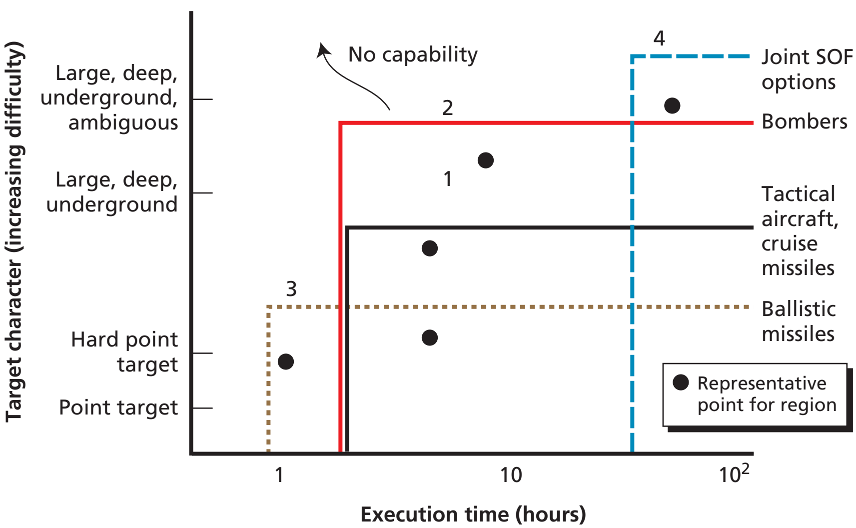
We discussed the concept of a spanning set of scenarios in Chapter Three. The first step in defining one is to conceive the broad scenario space. The most-abstract factors that should go into defining a scenario space are (1) political-military circumstances; (2) objectives, strategies, and tactics; (3) forces and weapons; (4) the capabilities of those resources; (5) environmental factors (terrain, weather, etc.); and (6) other model and data assumptions (Davis, 1994, 2002). For any given application, however, we need more concreteness about the specific context.

Our context was defense planning—i.e., developing plans and programs for future military capabilities. Furthermore, it was about "visible" military capabilities, rather than magic bullets that would—in some instances—be able to exploit special vulnerabilities of a particular adversary known from sensitive intelligence. That would include network attacks and other aspects of cyberwar. The pursuit of such capabilities is best discussed elsewhere.[48] We also excluded activities such as attempting to "strike" by specifically affecting the thinking of particular individuals with information or false information, or by physically apprehending them. Ultimately, for the purposes of this work, *we excluded discussion of both nuclear and non-kinetic instruments of strike.* We focused on finding a scenario space dictated largely by timeliness, target character, strike size, and strategic factors.

Timeliness, Target Character, and Number of Weapons

An Abstracted Design Space. A first task is characterizing the scenario space and its distinguishable regions. Figure 5.2 does this for two of the key dimensions (we shall discuss others later): execution time (x-axis), i.e., the time between the order to execute a strike and the time it achieves its effect, and the nature of the target (y-axis). The

Figure 5.2
Regions in Design Space



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target-character dimension is an abstraction: It ranges from single point targets at the "easy" end (bottom); to buried targets, which are more difficult; and to large, deeply buried, and ambiguous targets, which are maximally difficult (top).* By "ambiguous" we mean that the character, size, and structure of the underground parts of the target are not clearly understood. The black points indicate notional scenarios used to represent the region in question and establish reasonably stressful "requirements."

Each of the numbered regions indicates the boundary of applicability for a given system. Thus, tactical aircraft and cruise missiles are associated with the region to the right of and below boundary 1 (black). Similarly, boundaries 2, 3, and 4 indicate the regions applicable to bombers (red), ballistic missiles (brown dashed), and joint SOF options (blue dashed), respectively.† The solid dots indicate representative points to which test scenarios might correspond. That is, analysts need not consider every point within a given region, but only such a set of representative points.

Figure 5.2 suggests that tactical aircraft, cruise missiles, and bombers can cover much of the space, but ballistic missiles are uniquely valuable kinetic mechanisms for times of less than a few hours. Bombers have special capability against underground targets; even bombers, however, may be insufficient against the more ambiguous HDBTs, against which numerous large weapons might be needed. In those cases, we postulated that the facilities might have special weak points, which might be discovered by classic intelligence work, cyberspace methods, or Special Operations Forces (SOF). For the sake of the illustration, we postulated a region requiring some unspecified joint operation involving a combination of, e.g., bombers, missiles, and SOF.

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*DoD has long described hard and deeply buried targets (HDBTs) as particularly difficult challenges (Department of Defense, 2000).

†The boundaries are fuzzy. In some circumstances, for example, aircraft and missiles could have shorter execution times than those indicated by their boundaries. In other circumstances, times would be longer because of the need, e.g., for a carrier battle group to withdraw from another operation and reposition itself for a strike and to conduct final mission planning.

Although the United States currently has no capability for very short execution times, it could obtain that capability without violating laws of physics or mining Unobtanium. Indeed, the Defense Science Board and others have suggested fitting some Trident II SLBMs with conventional warheads (Defense Science Board, 2006), and Secretary Rumsfeld decided to proceed with what is called the Conventional Trident Modification (CTM) (Rumsfeld, 2006). He and General Cartwright, Combatant Commander for U.S. STRATCOM, established a "requirement," one that is not arbitrary or a "nice-to-have," but the result of assessing what is needed, what is feasible, and at what cost. This said, Congress has not yet agreed with the requirement or the solution, and the issue is currently being debated.[49] We shall return to this matter later.

Target Character. For this narrowed but still broad scope of Global Strike Raid missions, it is possible to learn much about the appropriate scenario space by reviewing the range of possible targets. We developed a taxonomy of targets, as shown in Table 5.1. Target characteristics are discussed in technical terms such as "point" and "area," or "hard" versus "soft." The rightmost column refers cryptically to examples. The taxonomy of target types is rather comprehensive[50] and distinguishes reasonably well among the many target circumstances for which a global strike might be contemplated. We have already discussed the timeliness issue, but it appears in the taxonomy as well.

As discussed in a later section on execution, the requirement to attack these many classes of targets has important implications for the mix of capabilities needed.

Attack Size (or Weapon Volume). Another dimension that matters in defining a scenario space is the size of the strike needed. As Figure 5.3 indicates, we envisioned a range of attacks with as few as one weapon to perhaps tens of weapons. We concluded that our spanning set should include at least one case each for the low end and the high end of our range.

Strategic Issues. Of the many strategic issues that should be considered in developing a scenario space, we identified bases and permissions, collateral damage, perceptions, escalation risk, and overall "plausibility."

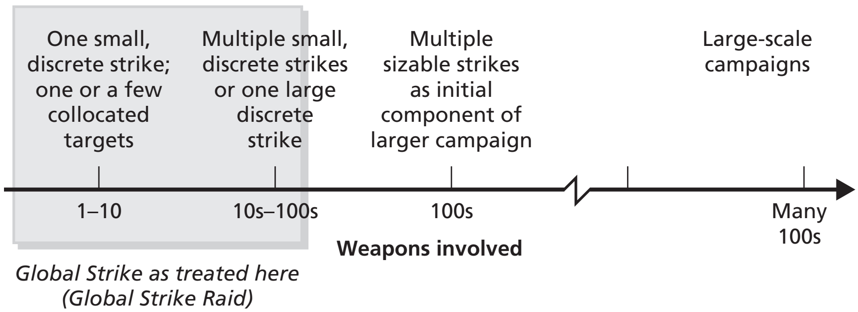
Table 5.1
Illustrative Taxonomy of Targets
(not including non-physical targets or targets attacked non-kinetically)

Point or Area?	Number?	Time Sensitivity?	Mobile?	Buried?	Hard?	Examples
Point	Small	No	No	No	No	Higher-level hq.
				Yes	Yes	WMD facilities
			Yes	No	No	Tactical command posts
		Yes	No	No	No	Mobile-missile sites
					Yes	Nuclear storage bunkers
				Yes	Yes	Leadership sites
	Large	No	No	No	No	Ports, airfields, bases
					Partially	Launch complex
			Yes	No	No	Exposed aircraft, depots
		Yes	No	No	No	Ground communication entry sites
					Yes	Missile silos
			Yes	No	No	Mobile missiles
Area	Small	Yes	NA	No	No	Garrisons
		?		Yes	Yes	Caves, unidentified facilities
	Large	?	NA	No	No	Urban areas
		Yes	NA	Yes	Yes	Large buried facilities

A Scenario Set That Stresses All Key Factors

After contemplating the various issues and dimensions, we concluded that a reasonable spanning set for purposes of demonstrating the methodology—and covering the principal issues—would need three classes of scenario, and that these classes could be represented by attacks on (1) mobile missiles, (2) terrorist leaders in an urban meeting, and (3) WMD facilities. Table 5.2 shows how each of the factors that we believe needed to be stressed would be stressed by suitable scenarios in the three classes. The point of Table 5.2 is to emphasize that the spanning set that we developed was the result not merely of creative

Figure 5.3
Possible Weapon Requirements for Strikes



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scenario-spinning, but rather of an analytical process: seeking as small a set of scenarios (and cases within them) as needed to stress developments in all of the appropriate ways.

In our illustration, we did *not* treat several important dimensions that we most certainly would have treated in a real application. These are (1) size of attack needed, (2) target mobility at the time the strike reaches the target area,* and (3) the value of the various options as the leading edge of a larger attack.

We have elaborated on the spanning-set concept because scenarios are often conceived poorly: They may be overly stressful in some respects, not stressful enough in others, and by no means adequate—even as a group—to define sound design requirements. This has been recognized for some years, but analytical practice has tended toward business as usual, with excessive emphasis on working through details of a few imperfectly chosen point scenarios.[51] In any case, the scenarios we suggest (black points in Figure 5.2) are based on a combination of need, technical feasibility, and operational feasibility.

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*The mobile missiles we considered move from their peacetime locations to operating areas in the field but are then usually in definite positions. Actually, moving targets are easier to deal with in some respects, because they are more easily distinguished from much background clutter.

Table 5.2
Degree to Which Illustrative Scenarios Stress Factors of Interest

Factor	Scenario Class 1 (mobile missiles)	Scenario Class 2 (terrorist meeting)	Scenario Class 3 (WMD facilities)
Timeliness and dependence on warning	●	●●●●	
Bases and permissions	●●	●	●●●
Penetration of defenses	●●●●	●	●●●
Target detection and characterization	●●●●	●	●●●●
Target destruction	●	●	●●●●
Collateral damage	●	●●	●●●●
Perceptions, escalation risk	●●	●●	●●●●

NOTE: The quantity of bullets indicates the degree to which the factor is stressed. The number of bullets reflects our particular analysis. A given scenario could be chosen to be more stressful in other ways. For example, the mobile-missile and terrorist-meeting scenarios could readily stress timeliness and collateral damage, respectively.

Description of the Scenario Classes. Table 5.3 provides more detail on the three scenario classes of our spanning set. There are many instances of each class; for example, the mobile targets might be trucks carrying smuggled WMD or related materials, and the hard, fixed installations might be command posts. Capability against one of our representative scenario classes should provide capability against other members of that class.

The first scenario class is represented by attacking mobile enemy missiles, such as those owned by either a rogue or a peer. The mobile missiles might be "generated" (i.e., deployed into the field for potential use) and might even be nuclear-armed. A response to a U.S. strike must be considered possible, and the nature of that response might be significantly affected by the success of the strike itself.

The second scenario class would have fleeting targets to be killed. Such a scenario might have high-ranking terrorists meeting in a house for some hours, with the United States knowing in advance that the meeting will take place in a particular city, but not knowing until late where or when it will occur. As discussed later, a real-world strike in 1998 had these characteristics.

Table 5.3
An Approximate Spanning Set of Scenario Classes and Cases

Scenario Class	Key Parameters to Test	Contributing Parameters
1. Attack mobile weapon systems	Penetration probability	Air-defense effectiveness Stealth levels Penetration-aid effectiveness levels
	Search capability	Search area Search rate Target-discrimination effectiveness Type of terrain
	Kill capability	Target hardness, location uncertainty, weapon type
2. Attack terrorist leaders in urban setting	Warning and decision times	Time for preparation and decision
	Required execution time	Target vulnerability time Minimum decision time
	Maximum collateral damage tolerable	Accuracy Fatalities (or other effects)
3. Attack WMD facilities	Penetration probability	Air-defense effectiveness Stealth levels Penetration-aid effectiveness levels
	Target hardness	Degree of size and hardness of target, mapping into whether small precision bombs are adequate
	Location (and distance from bases)	
	Target-location uncertainty	
	Special vulnerabilities	Existence of known exploitable special vulnerabilities

The third scenario class involves attacking a nuclear-weapons facility (or a facility generating or storing biological or chemical weapons). Such a facility might be underground, might not be well characterized (in which case, desired aimpoints would be unknown), and might or might not be well defended. An attack might need the assistance of on-the-ground intelligence agents or SOF.

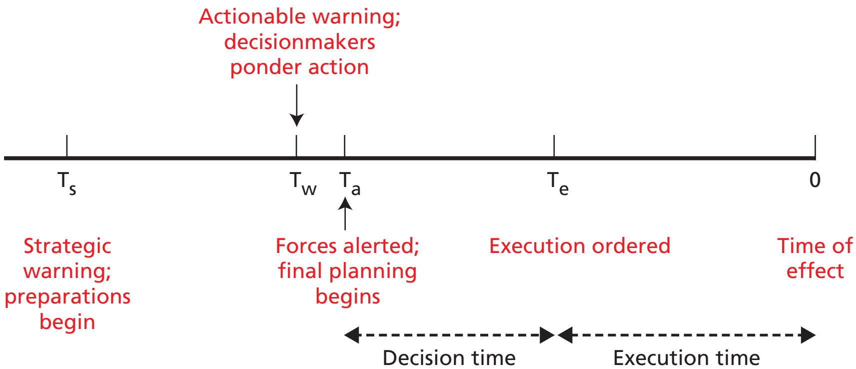
Parameterization. These descriptions are quick glosses. The next issue is parameterization. The primary purpose of the mobile-target class is to stress C4ISR and end-game weapon agility. The degree of stress, however, depends on a number of factors. Similarly, the point of the terrorist-meeting scenario is to stress capabilities for prompt precision attacks with minimum collateral damage. But how much warning would be given, and how long would the meeting last? How much uncertainty would there be? As for WMD facilities, some are above ground, some are below ground but well located, and still others are below ground and not well located. Imperfect targeting could cause the release of toxic materials, resulting in extensive collateral damage, extremely damaging international perceptions, or both. All such issues can be parameterized for exploratory analysis by varying assumptions.

The rightmost column of Table 5.3 shows the parameters we used to explore some of the questions. If we elaborated the table, we could assign values (e.g., low, medium, and high) to parameters. In our analysis, these were mapped into more-precise expressions. For example, an advanced air defense corresponded to "double-digit" surface-to-air missiles (SAMs) of the sort produced by Russia and available on the world market. Manned bombers can be characterized as having high, medium, or low levels of stealth, which can then be assumed to have high, medium, or low ability to penetrate the various classes of air defense. Going beyond this type of purely parametric work would require classified levels of analysis.

One other point should be made about the contributing parameters in Table 5.3. We defined them at different levels of resolution so that we could input something like a penetration probability directly or, with more effort and complexity, we could enter inputs for the air-defense level, the level of stealth, and the level of penaid effectiveness. That multiresolution approach is quite useful in practical analytical work.[52]

More on the Timeline Issue. Table 5.3 indicates that timeline parameters are important for scenario class 2. Figure 5.4 illustrates schematically the timeline issue for a nominal case in which the order of events is strategic warning, actionable warning and the beginning of top-level decisionmaking, alerting of forces, the order to execute, and, finally, the time that effects occur (e.g., a target is destroyed). Strategic warning might occur months in advance (the United States

Figure 5.4
An Illustrative "Normal" Timeline



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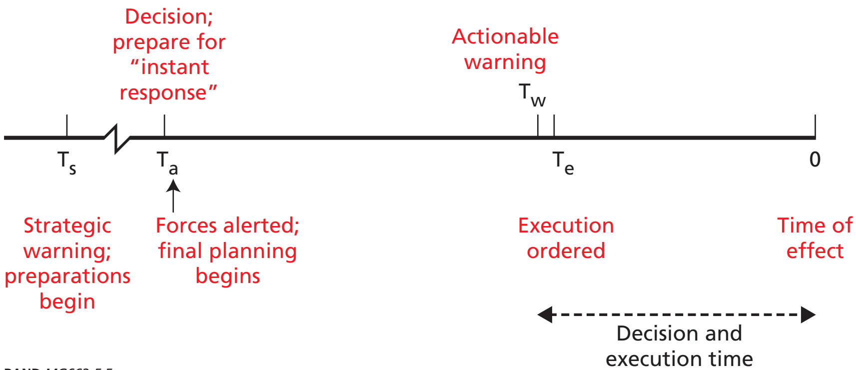
already has strategic warning about the need to attack al Qaeda leaders, for example), whereas actionable warning might come within a day or even hours of when a strike will be needed. The order to execute might come a day or so in advance, or perhaps only an hour or so before the effects of a strike are needed on the target. In one historical example, the U.S. strike on al Qaeda training camps in 1998 was motivated by intelligence that bin Laden would appear at one of the camps on a specific day a few days hence. Deliberations began and forces were alerted. When the order to execute was given, flight time for the cruise missiles was about two hours—after days of preparation (Clarke, 2004; Clinton, 2004). According to some accounts, the strikes were just a bit too slow.

The case illustrated in Figure 5.4 is only one of a number of possibilities, because even the order of events in the timelines is uncertain. Figure 5.5 shows one contrasting possibility. In this case, because of prior intelligence and decisionmaking, there is no gap between actionable warning, alerting, and the ordering of execution. Execution might be ordered immediately upon receiving actionable warning consistent with the strict criteria of a decision. Further, in this case, the execution time would be the limiting factor in determining the relative goodness of Global Strike options.

Figure 5.5
An Illustrative Timeline with Prior Preparations and Decision



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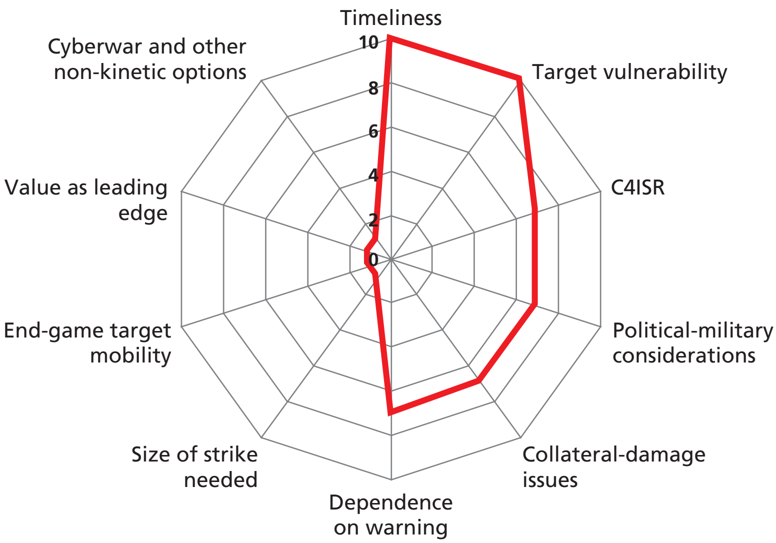
Yet another possibility is that a local commander could act immediately upon warning because of having been delegated to do so. In practice, it is very likely that U.S. strategic strikes, even if of a very limited nature, will be strongly and centrally controlled. Some opportunities may be lost, but the implications of actually conducting a strike are so great that extreme precautions are merited.

Within both Figures 5.4 and 5.5, the parameter of greatest importance analytically is the latest of T_w and T_e, the times of actionable warning and preparation, and decision and execution, respectively.[53]

Characterizing Comprehensiveness. The scope of our approximate spanning space is conveyed compactly in the "spider chart" shown in Figure 5.6.[54] It could be briefed at a review meeting as follows (if participants already understood spider charts):

> Before showing results of our comparison of options, remember that we have not considered *all* possible uses of Global Strike for various reasons relating to feasibility, plausibility, and the time available to us. We have sought to be quite demanding in looking at the timeline issue (including dependence on warning), degrees of vulnerability of the targets to our weapons systems, C4ISR issues related to detection and tracking, and the potential for a reactive threat. We have been less comprehensive in thinking through the different

Figure 5.6
Coverage in Assumptions Space



NOTE: The contour shows schematically the degree to which analysis stresses the various factors: High numbers (toward the outside) correspond to high stress. Our analysis stresses timeliness and target vulnerability heavily and C4ISR and political-military considerations significantly; it excludes cyberwar and other non-kinetic options.

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political and operational constraints that might apply. And, because we looked at small strikes for very limited purposes, our analysis did not address the size of attack needed, for example, as the leading edge of a large strike. Also, in this analysis, we do not treat anything related to cyberwar, such as network attacks, or to other non-kinetic mechanisms of attack. Those will be addressed separately.

Having developed our approximate spanning set of parameterized scenarios, let us now move on to concepts of operations and critical components.

Defining CONOPS and Critical Components for Global Strike

Critical Components of Capability

Successful global strikes could depend on many factors, but the catechism of our approach includes boiling these down and developing hierarchies. From a high-level perspective, we identified three aggregate-level critical components: (1) military-technical effectiveness, (2) political-military effectiveness, and (3) price of executing the mission (loss of personnel or equipment). For each, it is necessary to distinguish between "expected" results and what *might* happen, to appropriately address risks. We address the second and third components first and then discuss military-technical effectiveness in more detail.

Political-Military Effectiveness. Ultimately, a global strike may be intended to accomplish more than destroying one or a few targets. The likely intended effect may be more political-military than military-technical. It may sometimes be social. In addition, various effects will be very undesirable. Will the collateral damage be acceptable, given the circumstances? Will execution of the strike be tolerable in terms of, say, respect of sovereignty, coordination with allies, or even integration of allies in the operation? Will *perceptions* about the strike—locally and globally—be as desired?[55] Do the various options for Global Strike vary in their likely effects or related risks? If so, that information should be included in the assessment.

Price of Executing the Mission. What would be the likely or possible price in terms of, e.g., the loss of pilots, SOF personnel, and military equipment? This question might not seem very strategic at first blush, but the American military ethos calls for extraordinary efforts to protect and recover personnel. Moreover, there are dangers associated with captures, such as show trials, loss of leverage, and loss of sensitive equipment. Thus, such considerations should be evaluating options for a global strike.

Military-Technical Effectiveness. The primary measure, of course, is military-technical effectiveness, or what we shall call "execution effectiveness." We deal with that in the next section in connection with concepts of operations.

Concepts of Operations

Options cannot be evaluated for effectiveness without specifying concepts of operations (CONOPS). Not much detail is necessary for our purposes. We assumed, for each CONOPS used, that the United States would have adequate strategic warning and long lead-time preparation. We also assumed effective command and control. For Global Strike, this could mean substantial dependence on the Global Information Grid, with information flow among airborne, space-based, and ground-based sensors, command-and-control centers, supporting organizations, and tactical operations.

Given these circumstances, any CONOPS for our various options must deal with

1. *Penetration* of weapons to the target (and egress, for manned aircraft)
2. *Timeliness* of the strike
3. *Finding the target* (i.e., some combination of detecting, locating, characterizing, or tracking)
4. *Destroying* the target (or functionally disabling it).

As examples, manned bombers need to penetrate air defenses, find the target, destroy it, and return; ballistic missiles do not usually have to deal with defenses and would not need to return, but still need to find and destroy the target; SOF units would need to penetrate in-country defenses covertly (e.g., by coastal patrols, border guards, infantry protecting installations, and aircraft responding to alerts), conduct their mission (e.g., target-spotting or characterization, or even direct attack), and escape.

In what we call a "joint CONOPS" (a bit of a misnomer because all of the concepts of operations would be joint in one way or other), combination actions would be used. For example, aircraft and/or missiles could attack defenses, while SOF units could then attack the target; or SOF units could help with detection and tracking but leave target-killing to aircraft and/or missiles. In some cases, targeting might be provided by intelligence assets or friendly foreign nationals. All of these have precedents in the 1991 Iraq war and U.S. conflicts in Iraq and Afghanistan.

Each of the above items is a critical factor, as are the political-military effects and the price of execution mentioned earlier. It follows that our analytic framework and methods must deal with all of them.

Identifying, Evaluating, and Comparing Global Strike Options

The Options Themselves

We began with a set of building blocks (described below), experimented using our option-generation-and-screening tool, BCOT, as described in Chapter Four, and iterated. The result was a shorter set described in the second subsection below.

Initial Building Blocks. The baseline program is the natural first option to examine. It includes substantial capability in the form of B-2Bs, Air Force and Navy tactical aircraft, conventional cruise missiles, Special Operations Forces (SOF), precision weapons of various types, satellite communications, national intelligence systems, regional C4ISR systems such as J-STARS, and so on. If the purpose of the analysis is to find tradeoffs and bill-payers, the baseline might be the current program of record *minus* elements to be computed again, but in our application, there were no obvious elements of this type within the Global Strike Raid domain.

The building-block options *add* capability to the baseline. After early discussions, we decided to use the building-block options shown in Table 5.4. Many of these involve systems with multiple purposes, but here we consider only their value for Global Strike missions.

If expensive systems are procured specifically for Global Strike, we should also include "negative building blocks," i.e., building blocks calling for reductions of the baseline program in one way or another. That was not relevant for the Global Strike Raid problem, because the baseline program does not include sizable chunks specifically for Global Strike Raid. Instead, bill-payers must ultimately come from capabilities usually associated with other missions.[56]

Table 5.4
Building-Block Options

Building Blocks and Abbreviations	Motivation in Global Strike Context
Forward basing of B-2s (forw. basing)	To reduce timelines
Penetration aids (penaids) for Air Force tactical aircraft	To increase penetration capability against advanced SAMs
Penetration aids (penaids) for Navy tactical aircraft	To increase penetration capability against advanced SAMs
Space-based synthetic-aperture radar (SAR) and moving-target-indicator (MTI) radar	To enhance detection and tracking of mobile targets, among other capabilities
Automated target-recognition systems (ATRs)	To enhance detection and identification of targets by distinguishing them from ground clutter
Enhanced insertion vehicle for SOF (SOF vehicle)	To enhance deep, covert penetration into defended areas
Armed Predators for SOF (Predators)	Additional armed Predators specifically to allow SOF units to stand off from targets
Air Force conventional ICBM (ICBM)	To provide a conventional option for strategic forces
Navy submarine-launched conventional ballistic missile (SLBM), such as the Conventional Trident Modification (CTM)	To provide a conventional option for strategic forces
Advanced manned bomber (adv. bomber)	To increase penetration of even the most advanced SAMs and to avoid discovery
Joint common aerospace vehicle (JCAV)	To develop improved search, track, and kill for ballistic missiles and to operate on both Air Force and Navy missiles

NOTE: Building blocks are additive to the baseline program, which includes B-2s, tactical aircraft, cruise missiles, SOF, and C4ISR systems. Items in parentheses are short names used in subsequent tables and figures.

Our initial building-block options, listed in Table 5.4, were motivated by concerns raised in connection with the scenario set described in the previous section. They involved ability to penetrate advanced air defenses ("double-digit SAMs," potentially networked); ability to detect, find, and track mobile targets; timeliness; ability to deliver the payloads needed for attack of some targets; and ability of SOF forces to penetrate.

Our list includes nothing exotic. Forward basing of bombers would be a logical (even if sometimes impractical) way to shorten timelines for bombers. Penetration aids for tactical aircraft have long been planned as part of a natural evolution.

Space-based synthetic-aperture-radar (SAR) systems for combined defense and intelligence-community applications have been in development within the Space Radar program. According to the program manager in 2005 (Sheridan, 2005):

> The main capabilities we're talking about for Space Radar are to provide a day-night, all-weather, synthetic-aperture radar; surface moving-target indication collection capability; high-resolution, terrain-imaging capability; advanced-geospatial intelligence capability; and an open-ocean surveillance capability. We plan to be able to gather and collect information in all those types of formats and to process it and to provide it back to users as needed.

Automated-target-recognition (ATR) systems have been in research and development (R&D) for decades, and considerable progress has been made, albeit with continuing challenges and the need for dramatic increases in sensor capability. MIT's Lincoln Laboratory has been a leader in such work (Vasile and Marino, 2005).

The SOF insertion vehicle to which we refer is notional, but U.S. SOCOM is always looking into such advanced capabilities, which are offered up by industry in a variety of forms, are in different states of R&D, and involve different degrees of technological risk. In our analysis, the capabilities are merely treated as parameters with a range of possible values. Stealthy SOF penetration is achieved, of course, by a combination of factors, including the launch platform, the detectability of the insertion vehicle, and the tactics of choosing flight paths.

Armed Predators for SOF are an obvious possibility, given the general procurement of Predators and past examples of the use of Predators with weapons to attack Middle Eastern terrorist targets directly.

The Air Force Minotaur program is looking at a conventional ICBM option based significantly on preexisting missile components. This conceptual missile was compared with the nearer-term option for the Navy's Conventional Trident Modification (CTM) in a recent news article based on an interview with Air Force Col. Rick Patenaude

(Strak, 2006). A more extensive discussion has been published by the Congressional Research Service (Woolf, 2007). In addition, the U.S. Senate asked a National Academy panel to review some of the issues and options relating to prompt nuclear strike. The academy's interim letter report recommended going ahead with full R&D for the CTM (including testing) but recommended another year's delay before deciding on acquisition and fielding. It also recommended pursuing R&D on other missile options such as boost-glide systems, including the Minotaur and an Army system, but described them as being longer-term options with more technical risk (National Research Council, 2007).

One building block that we might have included is the sea-launched global-strike missile (SLGSM), which could be deployed on submarines, surface ships, or both. It is currently seen as a potential follow-on to the CTM and would benefit substantially from experience with the CTM.

As for advanced bombers, a next-generation long-range strike (NGLRS) platform has been under consideration with industry developing manned and unmanned alternative concepts for the Air Force and even a white paper (U.S. Air Force, 2001). Chief of Staff General Moseley and Air Force Secretary Wynne have discussed the NGLRS concept in interviews and in Congressional testimony. The NGLRS concept's purpose seems much broader than Global Strike Raid.

The JCAV that we postulated does not seem to exist as yet. Instead, it appears that the Navy and Air Force ICBM programs are developing separate front ends, at least in part because the missile diameters are different and because of additional design constraints for systems to be operated in a submarine.

An Iterated Set of Building Blocks. Based on extensive work with our screening tool, BCOT, we considered thousands of composite options (options to buy various combinations of one or more building blocks). Our intention was to take a broad view initially and then screen. We shall spare the reader the description of our discussions along the way and merely summarize our results, which led to an iteration of building blocks. The conclusions were the following:

- The armed Predator (or a functional equivalent) should be considered on its broad merits and, if found attractive, included in all of the composite options considered further. One reason for this is that the option has a relatively low price tag.
- If penetration aids are needed for current-generation fighter and bomber aircraft, they should logically be procured for both Air Force and Navy systems. Thus, we introduced a new building block called "joint penetration aids." In practice, they would have Service-specific differences, but those are matters for higher-resolution analysis.
- It would probably make sense—from a strictly Global Strike perspective—to procure a satellite constellation with synthetic-aperture radars (SARs) *and* capabilities for automated target recognition (ATR) on board penetrating aircraft. In operational analysis, both would probably be necessary in the scenarios for which either would potentially be most useful.* Thus, we substituted a combined option for both ATR and SARs, calling it "sensors" for short.
- Our notional analysis was to be indifferent to whether the advanced bomber should be a very stealthy, high-capacity, long-range bomber available perhaps by 2025, or a medium-range aircraft, perhaps available as early as 2018 as mandated by the Quadrennial Defense Review for less than compelling reasons. The cost of such platforms would differ significantly, of course, but we were not attempting to use accurate cost data in any case.
- We reluctantly dropped the concept of the JCAV because it appeared highly speculative and unsupported, and retaining the option would have added complexity of little interest for the notional analysis.

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*This conclusion is arguable, since ATRs are merely an efficient mechanism for identifying targets amid clutter, and such data analysis need not necessarily be accomplished on-board a penetrating aircraft.

Table 5.5 summarizes the iterated set of building blocks used in the next phase of our analysis.

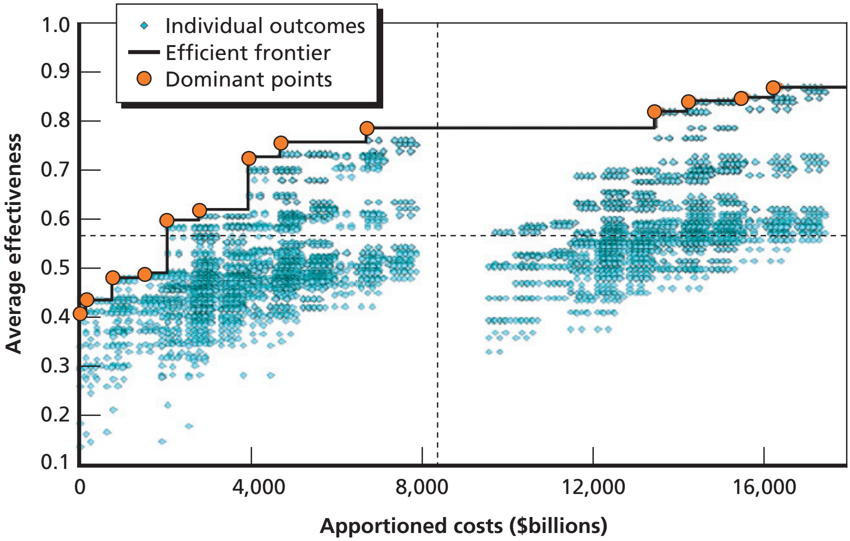
Finding Candidate Options for a Fuller Analysis

Analysis Based on Nominal Parameter Values. We continued to exercise BCOT, considering thousands of possible combinations of the building blocks in Table 5.5. We sought a screen for a small set of composite options that would make sense from an effectiveness perspective. For a given set of assumptions—akin to analysis based on a DoD-specified set of scenarios and a DoD-specified database of scenario data, including assumptions—we used BCOT to generate diagrams like Figure 5.7, which shows a simplified measure of effectiveness for each composite option, i.e., each point in the figure. The *dominant* points are those on the *efficient frontier*, which is the solid line. At a given program cost, the most effective option available is no more effective than the value shown on the efficient frontier, and the "best" option will be the point on that frontier at or below the cost level in question. The dominant points, then, are the best points identified in a first look.

Table 5.5
Iterated Set of Building Blocks

Building Block	Motivation in Global Strike Context
Forward basing of B-2s	To reduce timelines
Penetration aids (penaids) for Air Force and Navy aircraft	To increase penetration capability against advanced SAMs
Space-based synthetic-aperture-radar (SAR) and automated-target-recognition systems (ATR) for Air Force and Navy aircraft	To enhance detection and tracking of mobile targets; other.
Enhanced special insertion vehicle (SIV) for SOF	To enhance deep, covert penetration of defenses
Air Force conventional ICBM	To provide a conventional option for strategic forces
Conventional Trident Modification (CTM)	To provide a conventional option for strategic forces
Advanced manned bomber	To increase long-range penetration of even the most advanced SAMs

Figure 5.7
Finding the Dominant Options



NOTE: Each point is a composite option. The plot was generated before we had narrowed the range of building blocks deemed to be useful. As a result, it contains thousands of points.

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Exploratory Analysis Across Parameter Uncertainty. As discussed in a companion report on BCOT (Davis, Shaver, Gvineria, and Beck, 2007), a number of considerations temper the neatness of this mathematical analysis. First, we want to consider not only dominant-point options, but also some that are near the efficient frontier. Some of those may prove superior under more-extensive analysis with additional measures of effectiveness and risk. Second, the determination of which options are dominant (or near the efficient frontier) depends sensitively on many assumptions about the warfighting scenarios, component capabilities, force employment, costs, and so on. In particular, the dominance of the options depends on the relative emphasis placed on the different scenarios (something we call “focus”) and the different cases within them.*

Table 5.6 illustrates how the identity of the dominant points—the strongest candidates for a full portfolio analysis—varies depending on which scenario classes are considered and how their relative importance is weighted.

As expected, options involving advanced sensors (the SAR and ATR building blocks) show up only if the mobile-missile scenario is either emphasized or at least given weight equal to that of the other scenarios (the first and fourth columns, respectively). Which options appear as dominant points also depends on many parameter assumptions, so Table 5.6 is merely one of many possible displays. Still, it dramatizes the point that the attractiveness of options depends strongly on the criteria used.

After studying such results, we concluded the following:

- The options for more-extensive analysis should be the *combinations* of those that do well for the different “focuses,” i.e., options that are dominant for the mobile-missile scenario class *or* the terrorist-scenario class *or* the WMD-facility scenario class.
- Similarly, we should retain an option even if it is dominant only for special (but important) cases within a single scenario class.
- Finally, we should retain some options that are near the efficient frontier but not on it if they have special features making them potentially attractive in a fuller analysis.
- Iteration is necessary: After comparing options in the full portfolio structure (next section), we may find some options that were initially screened out to be more attractive. Redoing the BCOT analysis with a different effectiveness function would then be desirable.

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*Numerous options may have effectiveness as good as that of a dominant point and be only slightly more costly (see Figure 5.7). Thus, there may be too many options near the efficient frontier. BCOT includes an algorithm that uses set theory to eliminate the uninteresting points.

Table 5.6
Sensitivity of the List of Candidate Options to Focus

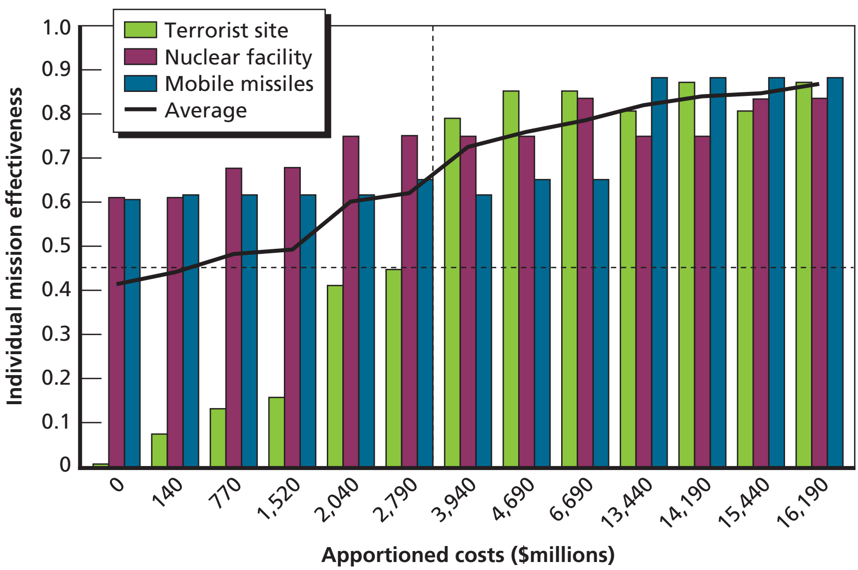
Scenario Class 1: Mobile Missiles	Scenario Class 2: Terrorists	Scenario Class 3: WMD Facilities	Average over All Scenarios	Average over Terrorist and WMD Scenarios
Sensors	Forw. basing	Penaids	Forw. basing	Forw. basing
Penaids + sensors	SLBM	Adv. bomber	Penaids	Penaids
Sensors + adv. bomber	Forw. basing + Penaids	Penaids + SOF vehicle	Forw. basing + penaids	Forw. basing + penaids
		Adv. bomber + SOF vehicle	Forw. basing + adv. bomber	Forw. basing + adv. bomber
			Forw. basing + SOF vehicle + penaids	Forw. basing + SOF vehicle + penaids
			Forw. basing + sensors + penaids	Forw. basing + sensors + adv. bomber
			Sensors + SOF vehicle + adv. bomber	
			Adv. bomber + sensors + SOF vehicle + adv. bomber	
			Sensors + SOF vehicle + adv. bomber	
			Forw. basing + sensors + SOF vehicle + adv. bomber	

NOTE: Options in each column are on or near the efficient frontier for the "focus" indicated by the column title. Different focuses imply different relative weighting of scenarios in calculating effectiveness. The first three columns consider only one scenario; the "all scenarios" column weighs the three scenarios equally; the rightmost column averages over the second and third scenario classes.

Mathematically, the first conclusion corresponds to using the union of option sets that are attractive in one or another interesting class of assumptions. The last conclusion means, in practice, that we examined options near the efficient frontier one by one before deciding whether to cull them. Thus, the methodology is computer-assisted, not fully automated. This is a strength, not a weakness, because analysts will almost always have knowledge not represented in the relatively simple effectiveness function used in an option-generating-and-screening tool. We have no particular interest in a clever automated tool that precludes the easy application of common sense. Besides, the time required for an analyst to read through a near-final list (perhaps a day?) is small compared with the time required for analysis (months). This said, in our experimental work, the purely mathematical use of BCOT did remarkably well.

Figure 5.8 illustrates the sensitivities mentioned above. Each group of bars corresponds to one of the dominant points in Figure 5.7.* However, Figure 5.8 shows the effectiveness of each such point (option) for the baseline versions of the three representative scenarios. In this case (i.e., with the particular assumptions used to generate the

Figure 5.8
Sensitivity of Dominant-Point Effectiveness to Scenario



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*This is not immediately obvious because of differences in scale, but the reader can at least verify that there are 13 dominant points in Figure 5.7 and 13 groups of bars in Figure 5.8.

chart), most of the dominant-point options are in fact quite ineffective for attacking mobile-missile targets (scenario class 1). With a different set of equally reasonable assumptions, the dominant points themselves would be different, and it might be that another scenario class would not be dealt with effectively.

Dealing properly with such large and complicated effects of uncertainty requires a new version of exploratory analysis that we are in the process of developing. In the meantime, we used more-classical methods of sensitivity analysis that provided insights, although they were not entirely satisfying. Table 5.7 lists the parameter variations that we used in our analysis.

A fuller exploratory analysis would examine results throughout the parameterized space. Among other things, it would include finding results for all combinations of the various excursions in Table 5.7, as well as varied assumptions about all the other factors mentioned earlier (focus, building-block costs, and so on). In some problems, that kind of extended exploratory analysis would reveal issues not previously appreciated; in others, it would not. A major characteristic of good analysts, of course, is that they are able to identify the key factors intuitively,

Table 5.7
Illustrative Broad-Ranging Sensitivity Analysis During Screening

Sensitivity	Values Used in Excursions
Performance of automated-target-recognition (ATR) systems	False-alarm rates higher and lower than baseline value by a factor of 10
Level of air defense	Penetration probabilities for advanced, double-digit SAMs, with and without networking
Vulnerability of buried targets	Effects of uncertainty in underground locations, hardness, and potential effectiveness of joint-attack mechanisms
Performance of advanced bomber	Degrees of stealth (as proxied by ability to defeat advanced air defenses)
Sensitivity to assumed suppression attacks	Consequences of not having initial defense-suppression attacks in mobile-missile and WMD-facilities scenario classes
Cost-sharing for advanced bomber	Substantial increase in Global Strike's share of cost (25% or 50%, rather than the baseline value of 10%)

without the benefit of the more-systematic exploration that is only now becoming possible through the use of advanced computers and computational methods.

Without further elaboration, the set of options that passed screening and seemed to us appropriate for a next phase of analysis in a fuller portfolio framework is shown in Table 5.8.

As suggested by our discussion above, some of the options were expected to look good only in some scenario classes, or even in particular cases within those scenario classes. Others were seen as more generally useful.

A basic issue in evaluating an option-generation-and-screening tool such as BCOT is whether the results highlight options that would have been missed otherwise. Our experience is that additional options *do* turn up as a consequence of using such a tool. Afterward, it may be "obvious" that those options should have been considered, but intuition is notoriously discontinuous (what is obvious afterward was not obvious before). The value of the approach is especially high when there are multiple objectives or, as in the Global Strike example, when there are multiple scenarios with which to deal.

Table 5.8
Screened Composite Options for Portfolio Analysis

Forw. basing
Penaids
SLBM + penaids
Sensors
SLBM + penaids + SOF vehicle
SLBM + penaids + sensors
SLBM + penaids + sensors + SOF vehicle
Forw. basing + sensors + SOF vehicle
Forw. basing + penaids + sensors + SOF vehicle
Adv. bomber + sensors
Adv. bomber + sensors + SOF vehicle
Forw. basing + adv. bomber + sensors + SOF vehicle
ICBM + SLBM + adv. bomber + penaids + SOF vehicle

Framework for Portfolio Analysis

As mentioned earlier, we have used a portfolio-analysis tool to organize information and generate displays appropriate for review meetings. Table 5.9 shows a schematic of the summary display at the beginning of our work. Options are in rows (Base, 1, 2, 3), with the baseline option (no changes in programs) as the first option to be evaluated. Columns provide different measures of the options' goodness. The scorecard region provides a quick overview. The area to the right includes columns with numbers rather than colors—e.g., the options' costs, a net effectiveness computed over the various evaluation cases in the scorecard, and a relative measure of benefit divided by cost. Often, we don't show these columns at the same time we show those of the effectiveness scorecard.

As discussed earlier, we concluded that for summary purposes, it was sufficient to show effectiveness in each of two cases for each of three scenario classes.

Summary (Notional) Results for Effectiveness

Figure 5.9 is a screenshot of the scorecard portion of the summary sheet for our illustrative analysis. The results shown here are notional and

Table 5.9
Schematic Representation of Displays to Follow

	Measures of Option Goodness							Cost	Net Effectiveness	RCE
	Effectiveness by Scenario Class									
	Mobile Missiles		Terrorists		WMD facilities					
Option	A	B	A	B	A	B	Risk			
Base										
1										
2										
3										

NOTE: Risk = a measure of net risk across the scenario classes; cost = dollar cost, as in present value of life-cycle cost; net effectiveness = net effectiveness across the measures of option goodness; RCE = relative cost-effectiveness.

Figure 5.9
Summary Scorecard

Options	Measures of Option Goodness: Effectiveness (Color) by Scenario Class and Overall Risk						
Measures	Mobile Missiles (2020)	Mobile Missiles (2020) Reactive Threat	Terrorist Site (2020)	Terrorist Site (2020) Fleeting Target	WMD Facilities (2020)	WMD Facilities (2020) Hard Case	Overall Risk (2020)
Investment Options	Detail	Detail	Detail	Detail	Detail	Detail	Detail
Base Case	R	R	LG	R	R	R	R
Sensors	R	R	LG	R	R	R	R
Forw. Basing	R	R	G	R	R	R	R
Penaids	R	R	LG	R	Y	Y	Y
Forw. Basing + Penaids + Sensors	O	R	G	R	Y	Y	Y
Penaids + Sensors + SOF Vehicle	O	R	G	R	G	Y	Y
SLBM + Penaids	R	R	G	G	Y	Y	Y
Adv. Bomber + Sensors	G	R	LG	R	Y	Y	Y
SLBM + Penaids + Sensors	O	R	G	G	Y	Y	Y
SLBM + Penaids + SOF Vehicle	R	R	G	G	G	Y	Y
Sensors + SOF Vehicle	G	R	LG	R	G	Y	Y
Sensors + SOF Vehicle	O	R	G	G	G	Y	Y
Bomber + Sensors + SOF Vehicle	G	R	G	R	G	Y	Y

NOTE: Effectiveness colors: red, orange, yellow, light green, and green indicate very poor, poor, marginal, good, and very good. Options are listed in increasing order of cost. An (F) indicates that the option failed a performance threshold.

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somewhat contrived—they do not reflect accurate data on the options. The options appearing in the rows are those identified by the screening as worthy of detailed analysis. PAT can order the options in a variety of ways, but in Figure 5.10, they are ordered by effectiveness, with the least-effective option (the baseline) on top.

Although it is not evident from Figure 5.9, the results shown for some of the options assume force employment based on naval aviation from carrier battle groups; other options employ the advanced bomber;

Figure 5.10
Zooming to Understand the Basis of Top-Level Assessments

Options	Factor Values			Net Evaluation
Level 2 Measure	Timeliness	Execution	Operational Effects	
Investment Option				Mobile Missiles (2020) Score
Base Case	G 24.00	R 0.00	G 1.00	R
Penaids	G 24.00	R 0.00	G 1.00	R
SLBM + Penaids	G 24.00	R 0.00	G 1.00	R
Forw. Basing	G 16.00	R 0.00	G 1.00	R
Sensors	G 24.00	R 0.00	G 1.00	R
SLBM + Penaids + SOF Vehicle	G 24.00	R 0.00	G 1.00	R
SLBM + Penaids + Sensors	G 16.00	O 0.60	G 1.00	O 0.22
Forw. Basing + Penaids + Sensors	G 16.00	O 0.60	G 1.00	O 0.22
Adv. Bomber + Sensors	G 24.00	G 1.00	G 1.00	G 1
SLBM + Penaids + Sensors + SOF Vehicle	G 16.00	O 0.60	G 1.00	O 0.22
Forw. Basing + Penaids + Sensors + SOF Vehicle	G 16.00	O 0.60	G 1.00	O 0.22
Adv. Bomber + Sensors + SOF Vehicle	G 24.00	G 1.00	G 1.00	G 1
Forw. Basing + Adv. Bomber + Sensors + SOF Vehicle	G 24.00	G 1.00	G 1.00	G 1

NOTE: Effectiveness colors: red, orange, yellow, light green, and green indicate very poor, poor, marginal, good, and very good. Timeliness is indicated in hours; execution and operational effects are measured in probabilities of success.

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still others employ ballistic missiles; and so on. For each row, the results shown are for the most effective force-employment mechanism available within the baseline program, supplemented by what the particular option procures. That is, *the analysis was based on optimized force employment* (within the possibilities specified as CONOPS). In some cases, the most effective force employment in an option is to use only baseline capabilities.

Zooming (Drilling Down) for Explanation

According to the notional analysis, projected baseline capability is rather poor, although the United States retains some capability against the terrorist-like class of targets. Successive rows in Figure 5.9 eventually show relatively good results for attacking terrorists and WMD facilities, but mediocre results for attacking mobile missiles, if the SLBM option, penaids for tactical aircraft, sensors, and a SOF vehicle are added. One noteworthy point is that some options—as expected—improve results for one class of scenarios, but not for another (as in Figure 5.9).

Suppose, now, that we ask for an explanation of results for the first scenario class, the class involving mobile missiles. Figure 5.10 shows the result of zooming on the second column of the scorecard in Figure 5.9 (the column for mobile missiles (2020)). That column is reproduced as the rightmost column in Figure 5.10, i.e., it is the *result* of combining the results on the left side of the table. We see that the evaluation in Figure 5.10 is an aggregation based on considering the timeliness of attack, the effectiveness of the attack's execution itself, and an assessment of likely operational effects (i.e., whether the attack would accomplish the larger military purpose). According to Figure 5.10, results for the first and third of these are very good (green), but the ability to execute the attack is very bad (red) in many cases—except in those that include procurement of the advanced sensors, as well as either an advanced bomber or penetration aids. That is, in this scenario, the United States has difficulty penetrating to the target area and loitering long enough to search for targets, and it lacks the sensor capabilities permitting that search.

In this and other zooms, the issue of how we aggregate upward arises. That is, given the component values in Figure 5.10, how do we calculate the net result? The question is not trivial, and a significant part of our effort went into thinking through the related theory.

The answer is that the aggregation rule depends on the particular problem addressed. It can be as simple as an average or a linear-weighted sum. Or it may be more complicated, as in evaluating the whole as the worst value of its components. In still other cases, as shown in what follows, we specified a combining rule corresponding to the mathematics of combining probabilities, e.g., the probability of A and B is the product of the probabilities for A and B separately. Specifying the combining rules is quite important and therefore not something to be hardwired into a tool (as is common in commercial decision-support tools, which assume aggregation by linear weighted sums, ignoring important effects of nonlinearity).

If we wish to find out why execution failed, we can zoom again, this time to the display shown in Figure 5.11. Because we assumed that the problem of killing the target was trivial if the target could be found, the calculation depends only on penetration and find-and-kill probabilities. The primary problem is in the find-and-kill column. The figure indicates that many of the options have extreme problems finding and killing the targets—even if they are able to penetrate air defenses successfully, as options with SLBMs or ICBMs could. This merely reflects the absence—in currently projected forces—of good capabilities for searching areas to find mobile targets. The combined effectiveness is then calculated as the *produc*t of two probabilities, and it is shown to be bad. Visually, this means that the result of a red and a green is not yellow, but red. The figure indicates that with a combination of advanced sensors, the finding-and-killing problem can be resolved, and with the addition of an advanced bomber or penaids, the mission can be accomplished rather well (subject to assumptions in the default set of parameter values for, e.g., the capabilities of advanced air defense, search capability with a combination of advanced sensors, and so on). The last column is necessary for explanation if the user has identified minimum levels of effectiveness that are to be given any credit—i.e., if the user has identified thresholds. In that case, the results in the

Figure 5.11
Zooming Further to Understand Assessment of Execution

Options	Factors		Net Evaluation		Rescaled Net Evaluation
Level 1 Measure	Mobile Missiles (2020)				
Level 2 Measure	Execution				
Level 3 Measure	Reach Target	Find and Kill	Comb. Effectiveness		
Investment Option				Execution Score	L2 Score (0.5, 0; 1, 1)*
Base Case	R 0.00	R 0.00	R 0.00	R	R 0
Penaids	G 0.80	R 0.00	R 0.00	R	R 0
SLBM + Penaids	G 0.80	R 0.00	R 0.00	R	R 0
Forw. Basing	R 0.00	R 0.00	R 0.00	R	R 0
Sensors	R 0.00	LG 0.75	R 0.00	R	R 0
SLBM + Penaids + SOF Vehicle	G 0.80	R 0.00	R 0.00	R	R 0
SLBM + Penaids + Sensors	G 0.80	LG 0.75	LG 0.60	LG 0.6	O 0.21
Forw. Basing + Penaids + Sensors	G 0.80	LG 0.75	LG 0.60	LG 0.6	O 0.21
Adv. Bomber + Sensors	G 1.00	G 1.00	G 1.00	G 1	G 1
SLBM + Penaids + Sensors + SOF Vehicle	G 0.80	LG 0.75	LG 0.60	LG 0.6	O 0.21
Forw. Basing + Penaids + Sensors + SOF Vehicle	G 0.80	LG 0.75	LG 0.60	LG 0.6	O 0.21
Adv. Bomber + Sensors + SOF Vehicle	G 1.00	G 1.00	G 1.00	G 1	G 1
Forw. Basing + Adv. Bomber + Sensors + SOF Vehicle	G 1.00	G 1.00	G 1.00	G 1	G 1

NOTE: Effectiveness colors: red, orange, yellow, light green, and green indicate very poor, poor, marginal, good, and very good. Numbers shown are probabilities.
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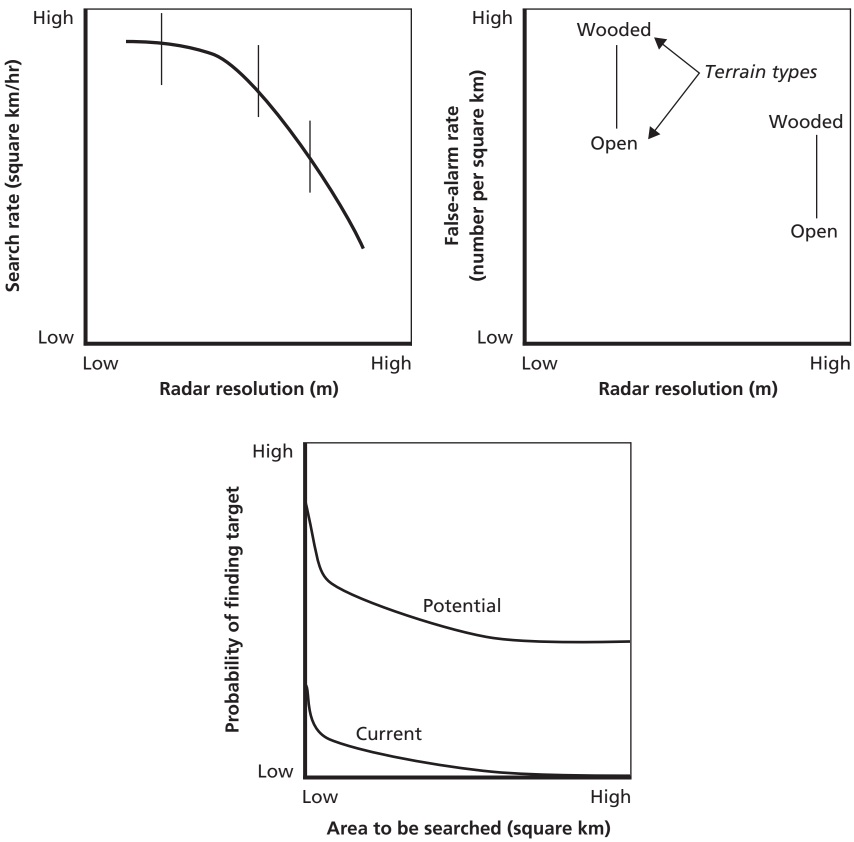
next-to-last column are rescaled before being shown at the higher level (in this discussion, Figure 5.10). For this example, we set a threshold of 0.5.

Zooming to a Level of Systems Analysis

Occasionally, it will be necessary to go even deeper to understand a high-level result. The next zoom in our methodology is different in kind from the previous zoom. Its intent is to summarize systems analysis. The appropriate zoom depends on the options we are looking at. Let us ask why locating and killing targets might be enhanced by automatic-target recognition, a satellite constellation for persistent surveillance, and defense suppression.

The displays in Figure 5.12 are in the natural language of systems analysis—charts, rather than top-level management spreadsheets. The three panels show what we might see at that level, representative parametric plots. The top left panel explains that search rate drops rapidly as the resolution of a search radar increases. The top right panel explains that the false-alarm rate is quite high for low-resolution radars but falls by orders of magnitude with increased radar resolution. Putting these two conflicting considerations together with simple mathematics, one can estimate the probability of finding (and killing) a mobile target such as a mobile ICBM. The calculation depends on the search area (which might be reduced with the existence of space-based synthetic-aperture radars), the search radar's resolution, and the presence on attack aircraft of advanced signal-processing technology such as automated target recognition for reducing the number of false targets. The bottom panel summarizes this calculation, indicating that whereas currently programmed capabilities would be poor, even if the search area were low, it is possible with advanced capabilities represented in some of the options to achieve better results if the search area is small enough—as it might be as the result of pre-attack intelligence and advanced surveillance. This assessment is sensitive to assumptions and requires engineering-level analysis.[57] As a sobering calibration point, in Operation Iraqi Freedom the search area was in the high range of Figure 5.12. It should not have been surprising that the famous "Scud Hunt" was a failure.

Figure 5.12
Zooming to the Level of Systems Analysis



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Another sobering observation is that the competition of measures and countermeasures is always an issue. If the United States deployed the advanced sensors and ATR capabilities allowing it to find mobile missiles, the adversary would employ countermeasures, and the United States would then have to improve its capabilities further to counter those countermeasures.

How, then, do we assess the capability of such advanced systems amid uncertainty? Assuming success of technology, effectiveness would be high in the absence of countermeasures and low or marginal if countermeasures were present. We don't want to "average" those cases, so instead we show results with and without the successful countermeasures.

A Final Example of Zooming

We present one more example to show how zooming can be important to understanding and using the portfolio-analysis tool. Looking back at the last column of Figure 5.10, we see that results for attacking WMD facilities are generally mediocre to poor. That may seem counterintuitive, because "surely" the United States will have the ability to penetrate air defenses and deliver precision munitions against such facilities. Figure 5.13, however, shows that at the next level of detail (not actually very much detail in this case), the collateral damage factor is poor (orange). The reason is that if intelligence were fairly poor and the facilities had to be attacked by massive bombing alone, even with precision weapons there would be (according to this notional analysis) a substantial chance of releasing toxic chemicals, biological materials, or even radioactive material. This problem did not arise in the first of the two WMD-facilities cases because it was assumed that the facilities could be appropriately destroyed, damaged, or put out of commission without such indiscriminate bombing—perhaps through joint operations involving bombers, missiles, intelligence, and SOF units. Had we considered cyberspace options, those might also have played a role here.

Figure 5.13 also illustrates another mechanism that we use to highlight fragile assumptions that might otherwise be hidden. Figure 5.9 contained small red triangles (warning indicators) in many of the cells. By mousing over these triangles, the PAT user will see a brief textual warning message. The warning column in Figure 5.13 shows the text itself.

Figure 5.13
Explanation of Poor Results Against WMD Facilities

Options	Factors		Net Assessment of Effectiveness		
Level 2 Measure	Execution	Collateral Damage	Timeliness	Warning	
Investment Option					WMD Facilities (2020) Hard
Base Case	R 0.00	O 500	24	intel, fallout	R 0.18
Penaids	Y 0.56	O 500	24	intel, fallout	Y 0.46
SLBM + Penaids	Y 0.56	O 500	16	intel, fallout	Y 0.46
Forw. Basing	R 0.00	O 500	16	intel, fallout	R 0.18
Sensors	R 0.00	O 500	24	intel, fallout	R 0.18
SLBM + Penaids + SOF Vehicle	Y 0.56	O 500	16	intel, fallout	Y 0.46
SLBM + Penaids + Sensors	Y 0.56	O 500	48	intel, fallout	Y 0.46
Forw. Basing + Penaids + Sensors	Y 0.56	O 500	16	intel, fallout	Y 0.46
Adv. Bomber + Sensors	LG 0.70	O 500	20	intel, fallout	Y 0.53
SLBM + Penaids + Sensors + SOF Vehicle	Y 0.56	O 500	16	intel, fallout	Y 0.46
Forw. Basing + Penaids + Sensors + SOF Vehicle	Y 0.56	O 500	16	intel, fallout	Y 0.46
Adv. Bomber + Sensors + SOF Vehicle	LG 0.70	O 500	20	intel, fallout	Y 0.53
Forw. Basing + Adv. Bomber + Sensors + SOF Vehicle	LG 0.70	O 500	16	intel, fallout	Y 0.53

NOTE: Timeliness and warning are not used in calculated net effectiveness. Collateral damage is measured in fatalities. The first and last columns have numbers corresponding to highly notional probabilities. Timeliness is measured in hours.

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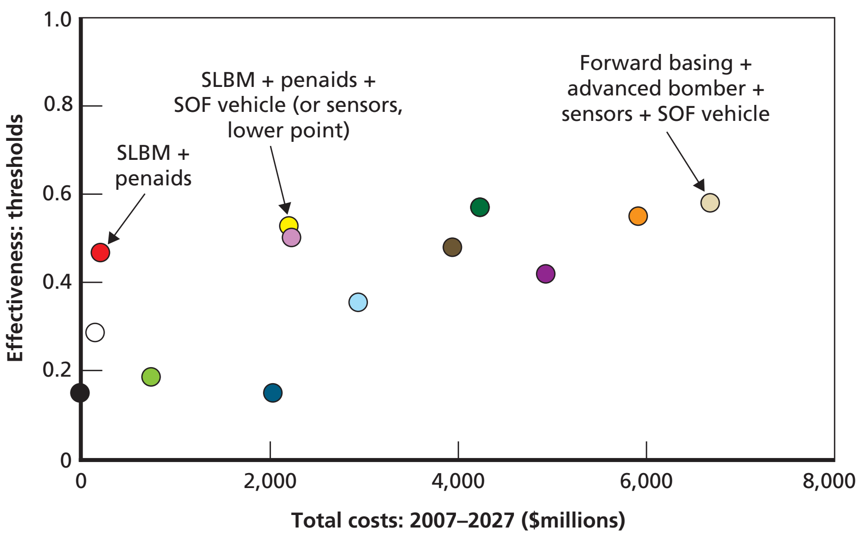
Summary Results for Cost-Effectiveness Comparisons

Traditionally, a key aspect of defense-planning analysis has been the economic analysis: How much payoff can be obtained as a function of expenditure?

Figure 5.14 shows an illustrative bottom-line display of effectiveness versus costs for the various options.* Such displays can be readily generated with PAT. Each dot on the chart represents a different investment option. The dots' colors have no meaning other than to distinguish among options. For the particular set of assumptions underlying Figure 5.14, an attractive point might be procuring the SLBM, penetration aids, sensors, and a SOF vehicle. Even more effectiveness can be

Figure 5.14
Cost-Effectiveness for a Baseline Analysis



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*The astute reader may be asking why this chart does not look more regular, with more-expensive options always being better. The reason is that the options plotted showed up as "good" (i.e., at or near an efficient frontier) in some of the cases used for screening, but not necessarily on average.

achieved with the buy-everything option, which includes an advanced bomber and a ground-based ICBM.* However, those additions cost a good deal more money for little additional benefit.

Unfortunately, but consistent with a continuing theme of this monograph, it is impossible to draw valid conclusions from any one such chart; the results depend far too sensitively on assumptions for such "mechanical" analysis to be useful. Notions of optimization are inappropriate.

Figure 5.15 compares similar plots but with different relative emphases on the six scenario cases that we have used. The first plot (top left) is the same plot shown in Figure 5.14 and corresponds to equal weighting of the six scenarios. The next plot (top right) corresponds to giving equal weight to the three less-stressful versions of the scenarios. It is, more or less, a best case for the options, because the various improvement options all have substantial effects, and the more one spends, the better the overall results turn out to be. In contrast, the bottom left figure corresponds to giving equal weight to the three most-stressful versions of the scenarios (those that include countermeasures—the second, fourth, and sixth cases). Here, the plot of effectiveness versus cost is more nearly flat—except for a significant payoff at very low cost. The "smart" option would be to buy just the Trident Conventional Missile and penetration aids.

Finally, the bottom right plot shows results if only the terrorist and WMD-facility scenarios are considered and the four corresponding cases are equally weighted. That is, we discount the mobile-missile scenario (perhaps because of a judgment that its success is too dubious and that type of global strike would be very risky). In this case, we see that a "smart" option might be to proceed with the SOF insertion vehicle, as well as the Trident Conventional Missile and penetration aids.

With our apologies for redundancy, we emphasize yet again that these results are all notional and would change in a more-complete analy-

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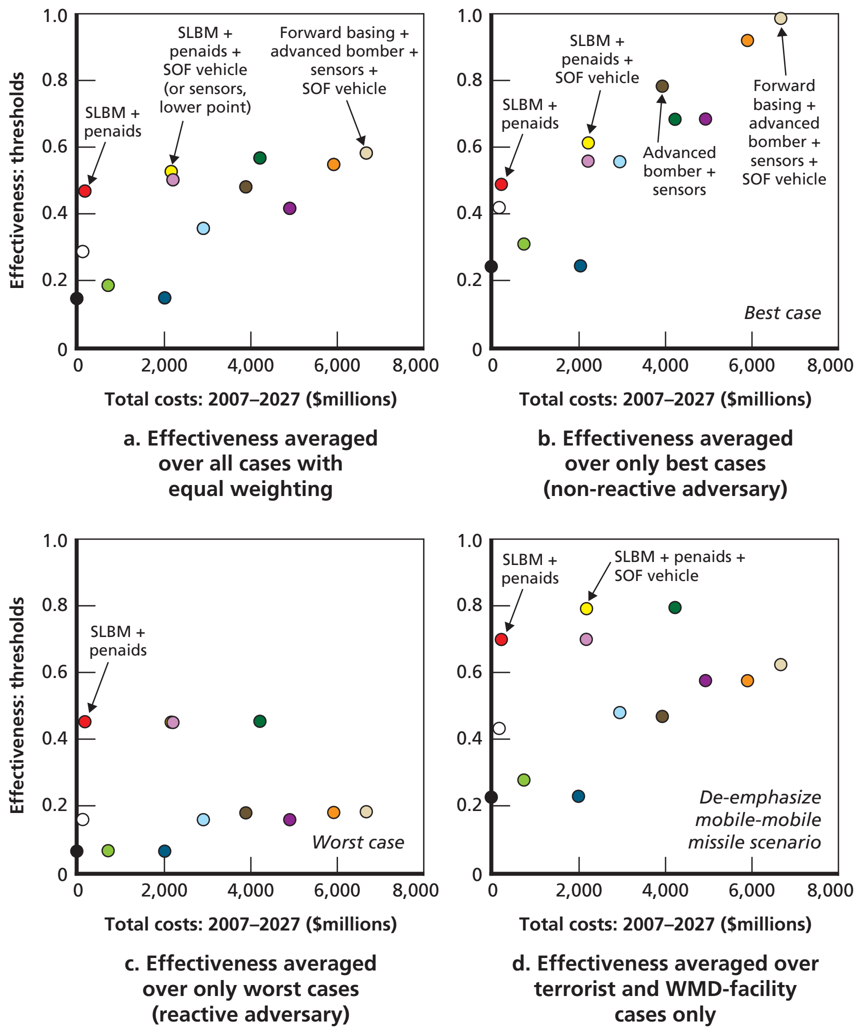
*In our illustrative analysis, the ICBM provided no more than the Trident Conventional Missile (TCM), but at a much higher cost. A more complete analysis would have included measures giving more value to the ICBM for its payload and growth potential and its ability to avoid overflying countries of concern. Such a boost-glide capability, however, would entail considerable development risks.

Figure 5.15
Cost-Effectiveness Plots for Different Assumptions



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sis or with more-accurate data. In particular, results would change if, for example, we (1) discounted the need for one-hour execution times because other factors were dominating, (2) discounted the feasibility of achieving adequate penetration probabilities by merely adding penetration aids to current aircraft, (3) assumed more- or less-effective intelligence, surveillance, and reconnaissance (ISR), and so on.

Despite our trepidation at doing so because of the notional character of our data, we will draw some tentative conclusions later in this chapter, but they will be conclusions that appear—without the benefit of more-detailed analysis—to be relatively robust. Before that, however, let us touch upon the problem of interactions across capability areas and assessments of risk.

Finding Tradeoffs and Bill-Payers Within a Capability Area

DoD policymakers routinely lament the difficulty they have in finding recommendations for cutting back on one investment to help pay for another. Such cutbacks may be referred to as "taking more risks in one area in order to reduce risks in another," or as "recognizing where we have an excess of capability." It is unnatural for organizations to volunteer recommendations about where cuts can be made in their own domains. It usually proves more productive to give them a budget and force them to work within it. They will then make their own tradeoffs, drawing on their in-depth knowledge.

This situation has led to the frequent suggestion that those responsible for capability areas should seek to balance their portfolios separately for those areas. That can sometimes be feasible and useful (putting aside issues of organizational structure and power). However, our work on Global Strike has demonstrated clearly why such a strategy is unworkable in many cases of interest.

The core problem is that capability areas interact: A given system, such as a potential constellation of space-based synthetic-aperture radars (SARs) or a new long-range bomber, would contribute substantially to multiple capability areas. This implies that to do cost-benefit analysis within a given area, one must use the fractional costs allocated to that area, as in assuming that Global Strike will pay for, say, 10 percent of a SAR constellation. But who does the allocation, and what if the number later changes? It is one thing to have uncertainty about a system largely associated with the area in question (e.g., a 20 percent uncertainty in the cost of a new conventional ICBM, all of which should be borne by the Global Strike capability area), but the uncertainty in the cost to Global Strike might be a factor of two or more for something like the space-based SARs. Why? Because the 10 percent figure would be substantially arbitrary, the result of negotiations and gamesmanship. Consequently, it might be doubled at some later date. Another aspect of this problem is that the real issue is cross-cutting: Is there enough cumulative demand for the system at issue, demand *across* capability areas, to justify its procurement? A given capability area's "manager" cannot by himself decide to buy or forgo the system unless his capability area will carry the burden of the expense.

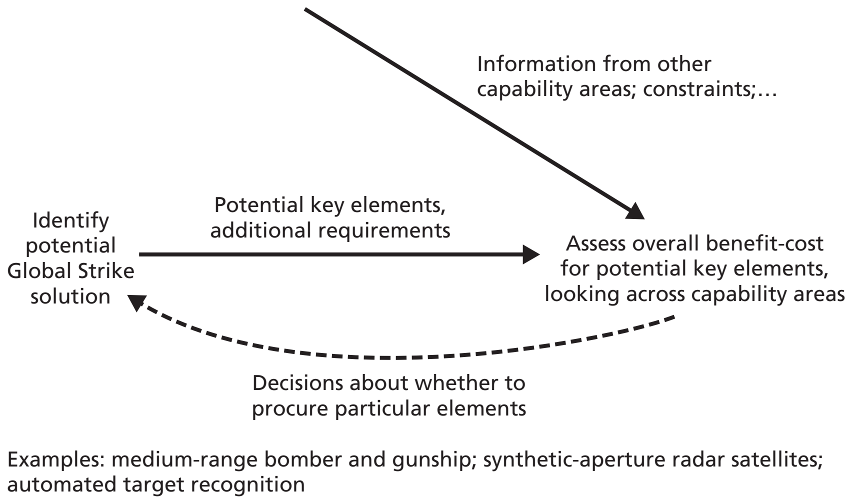
Another economic problem is that two capabilities may have comparable costs but may arrive years apart, even a decade or more apart. Comparisons are then difficult, even though using net present values is a well-established method in economics. Unlike in the business world, there is no clear-cut discount rate to be used for defense-system procurements. Further, it may be more important that one capability arrives later than the other than that it costs more or less.

These problems are by no means insurmountable. In a particular case, it will be necessary to step outside the individual capability area and have a cross-area decision process focused on the particular candidates of interest. Figure 5.16 illustrates the point schematically. Suppose, for example, the Global Strike analysis is uncertain because it is not known how much of the cost of some systems (e.g., a constellation of SARs) should be allocated to the Global Strike capability area. The issue cannot be resolved "inside" the Global Strike domain. Instead, a side assessment would be needed that would consider the other capability areas to which the system in question would contribute. Judgments would be needed as to how overall costs would be allocated across areas. Some pointed research is needed to clarify precisely what the process shown would require, analytically and otherwise.

Treatment of Risk

Although we did not discuss the risk issue earlier, it was folded into the portfolio analysis shown in Figures 5.10 onward. Here we discuss in more detail what we did to address risk, making points that are relatively generic.

Figure 5.16
Cross-Area Decisions



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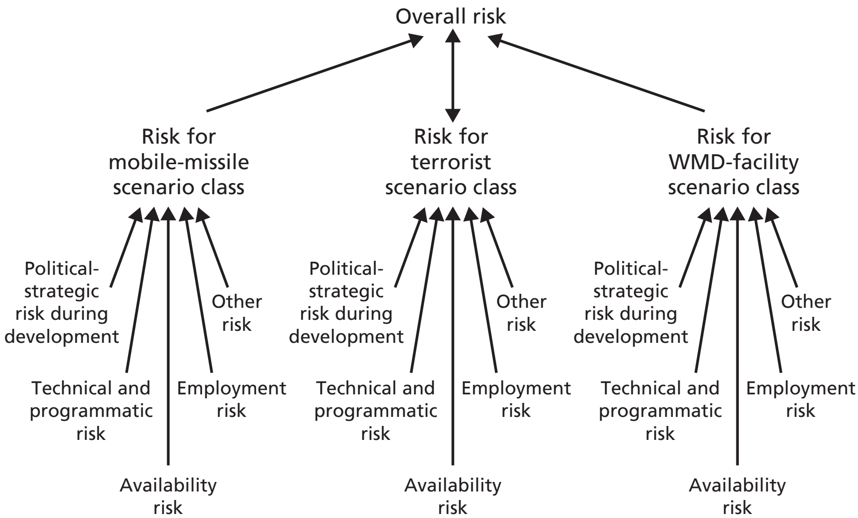
There are many different kinds of risk, some of which cannot be measured with accuracy and precision or even quantified in the usual sense. The most important of these should be represented in the analysis, even if their basis is subjective and qualitative. It is important, however, to define clearly what is being assessed and why the judgments expressed were used. This constitutes a form of rigor that should not be underestimated. No policymaker likes to be shown colored scorecards dominated by mysterious subjective judgments arrived at by voting schemes, especially when the voters are a miscellany of people who typically do not see the world the way the policymakers, whether general officers or civilians, do. The policymakers want to know *who* made the judgments (by name) and *why.* Thus, explanation is important.

Types of Risk

In our application to Global Strike, we created placeholders for the following types of risk, as indicated in Figure 5.17.

Figure 5.17
Risk Hierarchy Used in the Global Strike Application



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Political and Strategic Risk During Development. How likely is it that the program will be rejected by Congress or, if it depends on bases or other allied cooperation, by the relevant friendly governments? Even if there is initial assent, will it persist over the longer term? Such risks for Global Strike arise with respect to forward basing of aircraft and the staging of SOF operations. It might be argued that such "political" issues have no role in analysis, but we disagree to the extent that there is a sound basis for distinguishing among otherwise similar options with low, moderate, or high risks of this type. Within the realm of Global Strike, an example of political risk is that Congress will refuse to fund certain prompt Global Strike options (such as the Conventional Trident Modification) because of concerns about a launch being mistaken for a nuclear attack, resulting in a nuclear response being made against the United States.*

*The Senate Appropriations Committee has expressed concerns about this and other matters. A recent National Academy study describes the concerns and its own assessment. It recommends doing full research, development, and testing of the CTM but deferring deci-

Technical and Programmatic Risks. How likely is technical failure to achieve the posited capability, and how does that likelihood vary with time and expense? Some options are uncertain only in that times may slip and costs may go up; in other cases, it is not clear that the problems of physics and engineering can be solved; in still other cases (not so much with Global Strike options), it may be unclear whether the industrial base is able to accomplish what is needed.[58] For Global Strike, achieving adequately good automated target recognition involves considerable technical and programmatic risk, especially in areas with complex terrain or considerable clutter.[59]

Strategic Risks at the Time of Execution. How likely is it that the posited capability would be usable when needed? Again, there are issues about both internal political and strategic judgments and what allies would permit or tolerate. The flexible-response options of the 1970s and 1980s were highly controversial but were deemed relatively credible because NATO took extraordinary efforts to implement relevant strategic, operational, and tactical doctrines.

Another source of strategic risks at the time of execution could be a situation in which other military actions are tying up U.S. forces associated with the option in question. For example, many supporting resources would probably be deemed necessary to achieve penetration of air defenses, even if those resources—e.g., tactical aircraft of various types, tankers, aircraft carriers, national C4ISR assets—were fitted with penetration aids. "Maldeployment" and simply being otherwise occupied, then, are strategic risks affecting the various options differently.

Another class of strategic risks could arise if a strategic strike with conventional weapons were misperceived as involving nuclear weapons. This concern has been raised with respect to using Trident or Minuteman missiles for conventional strikes, although the issue is more generic.

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sions about deployment until test results are in and the issues are more fully analyzed. (See National Research Council, 2007.) The House Armed Services Committee supported the CTM option as of summer 2007.

A final example of this class of risks involves the Bush administration's intention to deploy ballistic-missile defenses in Eastern Europe. This issue has become highly controversial, antagonizing to the Russians and in conflict with current public opinion in most of Europe. Attitudes on the matter could shift and shift again in the years ahead, depending on political developments in Iran and elsewhere.

Availability. A risk common to all of the options but of more importance in some of the test cases than others, is the risk that the option's preferred instrument for a given mission (the mission of one of the test scenarios) will not be available when it is needed. Possible reasons for such unavailability include (1) not enough warning time, (2) maldeployment (e.g., a carrier battle group may be hundreds of miles from where it needs to be), and (3) an ongoing operation (e.g., a separate crisis or even a major exercise). Many other possibilities also exist.

Analyses of such issues are interesting and in some respects counterintuitive. Skeptics of "prompt global-strike options" such as the Conventional Trident Modification (CTM) or other ballistic-missile approaches tend to note that substantial times would be needed for alerting and maneuvering forces, conducting surveillance, targeting, mission planning, and especially decisionmaking. Therefore, they argue, there would be little value in an option that improved execution time a bit (e.g., reducing it from several hours to one hour). Execution time would be a small fraction of the total time. The argument, however, is flawed. First, as discussed earlier in this chapter, historical and prospective cases exist in which execution time is indeed the limiting factor because of prior intelligence and decisionmaking. Second, even if some hours are available and needed for decisionmaking and other preparations, it may very well be that platforms such as an aircraft carrier are in the midst of operations hours away from where they need to be. The operation may also depend on tanker aircraft positioning themselves appropriately. Thus, the timelines shown early in this chapter for tactical aircraft are optimistic. Considering such risks increases the relative attractiveness of ballistic-missile options (because of their speed and readiness) and perhaps cruise-missile options (because the launch platforms may be less likely to be maldeployed). It also makes the long-range-bomber option less unattractive—that is, it competes well if something on the order of 10 or 12 hours is needed for all the preparations.

We did not analyze availability issues in any depth. However, in a real-world study, we would have done so. We might, for example, have evaluated an option in part on how well the mission could be performed by the second-best choice of employment mechanism (e.g., a long-range bomber from CONUS, rather than tactical aircraft on a combat vehicle battle group (CVBG) in the region itself). In principle, one could attach "probabilities" based on historical experience or projections into the future.

Operational-Employment Risks. To some extent, operational risk in our example was measured as 1 minus the effectiveness score (which is something like a probability of success in such examples). However, there is a chance that we don't understand what the operation will entail and that something not considered in the nominal analysis will bite. For example, surface-to-air missiles (SAMs) might have capabilities that have never been observed because of strict operational security; U.S. military headquarters might be infiltrated by agents who could provide warning of operations and their nature; or U.S. military networks might be penetrated. Such risks apply to all options, but in different ways and to different degrees. Experience would tell us, for example, that many of our weapon-system platforms have reliabilities that are well understood. In contrast, major surprises have historically occurred with respect to the effectiveness of C4ISR and sometimes with respect to the ability to suppress air defenses. Further, deception practices can obfuscate which targets are real and lucrative and even where the correct aimpoints actually are.

Other Risks Associated with Operational and Strategic Effects. Assuming that kinetic effects are achieved as intended and that the targets are destroyed, how likely is it that the *consequences—effects* of operational-level and strategic-level effects, will be bad rather than good? This is significant for Global Strike options. A strike intended to deter or coerce might be misinterpreted as the beginning of a major strategic attack, precipitating unfortunate responses against the U.S. allies, U.S. forces, or even the United States itself. Even if it did not, the effect might be to firm up the adversary's resolve and hostility, rather than to favorably affect behavior. Strategic bombings in the course of history have frequently had such effects.[60] Yet another possibility is that a U.S. strike would be perceived unfavorably by the world generally, and even by important allies. This could be the result of misunderstanding or simply of the adversary being more successful than the United States in publicizing its narrative, even if that narrative were false. To this day, many people in the Middle East continue to believe that Israel was somehow responsible for the September 11 attack on the World Trade Center. During the 1990s, many people in Africa believed that the CIA was somehow responsible for starting the HIV epidemic. Many people in China, including officials, believe that the U.S. bombing of the Chinese embassy during the Balkans conflict was deliberate.

The overall class of risks related to *effects* should be a matter of great concern and careful analysis in so-called effects-based operations. Unfortunately, uncertainty and related risks are sometimes given short shrift. The analytic community itself is sometimes part of the problem here, because its emphasis on modern tools and visual displays conveys a false sense of certainty or, more subtly, provides misleadingly precise estimates of uncertainty.[61]

Aggregation of Risks

Given this lengthy list of risks, which we are sure is incomplete, how does one "roll them up" to summarize risk level succinctly? As with all aggregation challenges in portfolio analysis, there is no single answer. The use of linear weighted sums is often insufficient, because in such calculations the individual risks must *all* be kept modest. Therefore, we have typically aggregated by having the higher-level summary risk be evaluated as the worst of the subordinate risks.

With this background, Figure 5.17 shows the risk hierarchy we used in our Global Strike application. As a practical matter, the lowest-level inputs were entered subjectively for each investment option, e.g., assuming that the technical-programmatic risk for the advanced-sensors (ATR/SAR) option would be moderate for the mobile-missile scenario but small for the other scenarios. That is, the technical-programmatic risk would be the same, independent of scenario of employment, but these capabilities have little effect on the terrorist or WMD-facility scenarios and therefore contribute minimal risk.[62]

Illustrative Conclusions for Global Strike

Our summary conclusions for Global Strike fall into two categories: (1) conclusions reached from a cost-effectiveness perspective, and (2) conclusions reached from a perspective of maximizing flexibility, adaptiveness, and robustness.

Investment-Related Conclusions: Cost and Effectiveness

Despite our emphasis on the notional character of our applications, it is useful to draw some illustrative conclusions from the analysis. The only ones we shall mention, even as illustrations, are those that appear to hold up despite the manifold uncertainties in data—the ones that seem to fall out from even first-order analysis.

We present the conclusions in three tables: First, we observe insights about the challenges; second, we offer insights about solutions; and third, we offer insights about cost-effectiveness. In each table, we include a column for key assumptions. From a methodological perspective, this seems crucial: Decisionmakers don't want lengthy explanations about assumptions, but they do want and need succinct flags.

Table 5.10 presents three major observations about the challenges: First, the projected level of capability (with no investments beyond the baseline program) is bleak. Capability against mobile targets will be limited by ability to penetrate *and* ability to find targets; capability against fleeting targets, such as terrorist leaders, will be limited by general intelligence (not treated in this monograph) and, in some cases, by execution time; capability against WMD facilities will be limited by ability to penetrate to the targets, to characterize them in enough detail for precision attack, and to destroy them with conventional weapons.

Table 5.11 makes some observations about the potential solutions that have been considered. Of the options considered for attacking mobile targets, *none* can provide high-confidence future capability, because at-the-time capability will depend sensitively on counter-

Table 5.10
Insights

Assertion	Basis	Assumptions
Baseline projected capabilities are inadequate for the missions examined (e.g., for 5 to 10 years from today).	Advanced SAMs, deeply buried targets, targets with brief vulnerability times.	• No fixes are possible with the baseline program alone; new development is needed.
A niche problem is the occasional need for a very short execution time (e.g., one hour).	Such times may be representative of terrorist targets, an illegal WMD shipment, or preparation for a missile or ASAT (antisatellite weapon) attack.	• Execution time will sometimes be the limiting factor in a global strike.
A niche problem is the potential for deep underground targets with unknown character and structure.	WMD facilities, even Soviet-era leadership facilities.	• The U.S. might be willing to attack such targets conventionally.

measures, counter-countermeasures, and associated tactics. However, there is the potential for improved capabilities. Even so, decisionmakers should give considerable thought to whether the scenarios of use—very limited conventional strikes into countries that may possess weapons of mass destruction and the means by which to deliver them—are plausible. Arguments can be made for both sides of this issue, but merely having a modicum of military-technical capability may not be sufficient. At the same time, having *no* such capability might be deemed utterly unacceptable (as policymakers have concluded is the case for Ballistic Missile Defense).

Finally, Table 5.12 offers some insights on cost-effectiveness issues. These are, again, based on rough, unclassified data. The conclusions, however, are relatively robust because the cost differences among the options are huge. The principal caveats are shown in the assumptions column.

Note that *all* of the Global Strike options we considered are "affordable" by the United States. Their costs are small or moderate in

Table 5.11
Possible Solutions

Solution	Basis	Assumptions
Counter-mobile-target options would be low-confidence investments but would move in a good direction technologically.	Enemy tactics and countermeasures could be a problem; SAR and ATR provide capability; enhancements are possible.	• Intelligent adversary; no technical breakthroughs; no silver bullets.
Solutions for mobile-missile targets have large inherent risks.	Deep, limited attacks against states with substantial capabilities.	• Such attacks would not obviously be the "last move" and could trigger a large retaliation.
Trident II CTM in the near term is attractive.	Partially fills a capability gap; is technologically feasible and very inexpensive.	• Even low-volume prompt attack would be valuable. • Ambiguity problems will be resolved adequately. • Will not weaken strategic deterrent.
Joint operations with SOF, missiles, and aircraft may be important.	SOF has potential for special targets, given capability for insertion and extraction.	• Plausibility of kinetic attacks of this sort; operational feasibility.

comparison with, for example, the cost of the ballistic-missile defense system (BMDS), aircraft modernization, or adding additional ground-force units to the force structure. They are also small in comparison with the costs of the war in Iraq. The issue, then, is not affordability, but rather that of wise choices given the national budget for defense. This said, the defense budget is likely to come under great pressure over the next few years. At that point, attitudes about affordability will change.

Seeking Flexibility, Adaptiveness, and Robustness in a Global Strike

The last of our conclusions relate to the continuing theme that investments should be chosen so as to maximize flexibility, adaptiveness, and robustness (FARness). This has considerable application for the Global Strike problem. In particular, even our illustrative analysis was sufficient to identify the following ways to achieve FARness:

Table 5.12
Insights on Cost and Effectiveness

Conclusion	Observation	Assumptions
Even with a small investment budget for Global Strike, fund Predators for SOF, Trident II CTM, and penaids.	Cost to Global Strike (and overall) is low for each. Trident TCM option provides "niche" capability (low volume, but very prompt). Funding would be sensible even with more far-reaching investments (e.g., for a new bomber or conventional ICBM). Time scale could be short.	• Predators for SOF have many applications. • Even very small CTM capability would be useful. • Penaids would work.
With a larger investment budget, consider funding SAR satellite constellations, a next-generation bomber, and/or a new ballistic missile for conventional strike (e.g., boost-glide ICBM or SLBM).	SAR satellites and a next-generation long-range bomber would be largely paid for by other capability areas. A new ballistic missile would be expensive and more exclusively for Global Strike.	• Plausibility of related missions. • Successful R&D. • Global Strike would pay only very small share of SAR and NGLRS costs

NOTE: SAR = synthetic-aperture radar; TCM = Trident Conventional Missile; penaids = penetration aids; NGLRS = next-generation long-range strike.

- Assure multiple ways of performing potential missions to hedge against maldeployment, simultaneous crises, the inability to use bases, the need for sequential attacks, and so on.
- Do not *rely* upon "special" capabilities. Various types of counter-countermeasures and cyber-attack methods have important potential in some circumstances, but they may be fragile and uncertain. They are therefore best not counted upon to close shortfalls.
- Encourage competition among the military Services and branches; many ways exist to accomplish the various types of global strike that have been identified by defense officials. More than one approach should be pursued in R&D, perhaps through at least prototype testing.
- Prepare soberly for a continuing competition of measures and countermeasures. Since many Global Strike options can be countered, next-round capabilities will be needed. This is an eternal

struggle in warfare, but it is best conducted by anticipation and investment rather than an attitude of "Well, first let's develop a capability, and then—when we see problems arising—we will think about next steps." The problem with such an attitude for the Global Strike domain is that at least some countermeasures should be expected sooner rather than later. There may not be a lengthy period of one-sided advantage.

- Lay the base, with R&D, for capabilities that may in the future be crucial but are currently not recognized as such. A continuing tension between the Defense Department and Congress involves various special weapons, such as earth penetrators. There are arguments on both sides of this issue, but the world situation and intentions of nations change, sometimes quickly, whereas it takes many years to develop such specialized capabilities. The necessary technology development should be completed whether or not the weapons are expected to be acquired.

Strengths and Weaknesses of the Approach

We believe this example has illustrated fairly well the nature of our methodology and related tools. Strengths of the approach include (1) widening the set of options considered, (2) reducing the number of such options to consider to manageable proportions, (3) comparing the options in a portfolio-analysis framework that allows one to see the strengths and weaknesses (including risks) of the options in a single summary scorecard, (4) being able to drill down to see why the options are evaluated as they are, and (5) a sophisticated version of cost-benefit analysis that highlights the extent to which the relative cost-benefit "goodness" of options depends on perspective, i.e., on the relative weight given to different classes of mission and scenario.

The methodology is not intended to substitute for in-depth systems analysis and systems engineering; instead, it draws upon such work in its effort to provide a high-level top-down summary of the options and their relative merits. We might also note that methodology is only methodology; it does not by itself have content. The methodology's virtues would be entirely undercut if it is used poorly—e.g., by not considering stressful scenarios, or by considering only options with prior organizational or political support. As always, quality depends on the analysts themselves (and the organizations in which they work).

CHAPTER SIX

A Second Example: Ballistic Missile Defense

In this chapter, we sketch a second application of the methodology, one for the Missile Defense Agency (MDA).[63] This application illustrates choosing among investments in diverse technologies and systems for a single mission, whereas the Global Strike example in Chapter Five involved investing with alternative missions in mind. Classification guidelines prohibit much discussion of even hypothetical systems and their potential shortcomings and vulnerabilities, but we can make a number of methodological points. Consistent with our general methodology (Figure 3.1), we discuss, in turn, defining the mission; developing an appropriate scenario space and a parameterized spanning set of scenarios; defining CONOPS and critical components; and identifying, evaluating, and comparing options in a portfolio framework that includes benefits, risks, and costs. The chapter ends by discussing some principles of the portfolio analysis, including the principle that the portfolio chosen provides overall flexibility, adaptiveness, and robustness.

Defining Ballistic Missile Defense Missions

MDA's capability area is Ballistic Missile Defense (BMD). It excludes air defense, including defense against cruise missiles. If a capability-area review were to approach the matter freshly, it might or might not conclude that the capability would be extended to include cruise missiles. The argument for doing so would include the desire to have a comprehensive view of missile-defense capabilities. The argument for not doing so would include the recognition that defending against air-breathing missiles is different technically and involves entirely different platforms and organizations. In business terms, one might ask whether it would be appropriate for MDA to go beyond its "core competence" by getting into defense against cruise missiles.

The most important part of MDA's mission statement* is that it explicitly identifies three missions:[64]

1. Homeland defense
2. Defense of U.S. friends and allies (DOFA)
3. Defense of U.S. military forces deployed abroad.

This is in contrast with focusing only on homeland defense and is consistent with national strategy, which recognizes the importance of assuring friends and allies in various ways, of dissuading adversaries from aggressive courses of action abroad, and of using U.S. projection forces in overseas theaters of operation where they might be threatened by missile attacks.

A Parameterized Scenario Space for BMD

Dimensions of the Problem

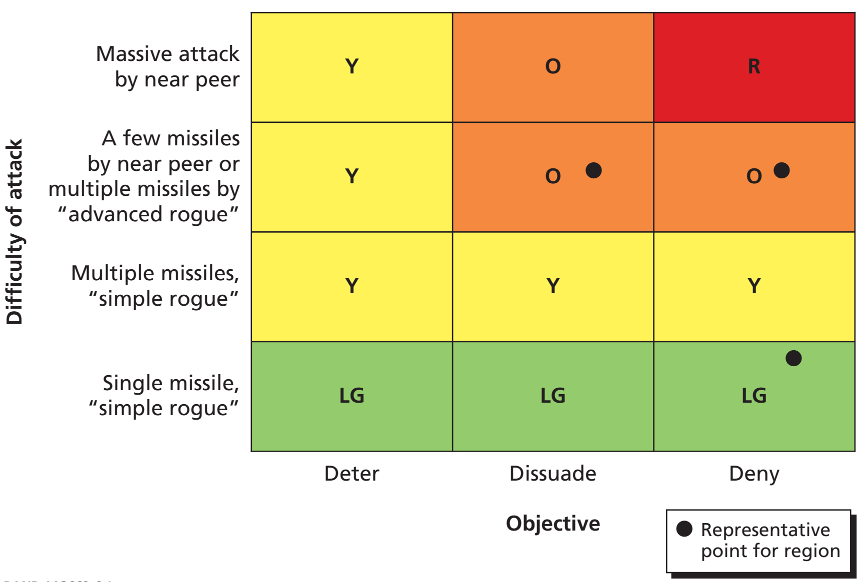
We discussed the generic issues involved in developing an appropriate scenario space and a simplified spanning set of parameterized scenarios in Chapter Three. The specific issues in doing so for BMD are unusual in several respects, primarily because the BMD mission for homeland defense is exceedingly challenging from a technical perspective—so much so that debates have gone on for years as to what level of national BMD, if any, the United States should seek. The United States currently has some deployed BMD capability, but robust levels of homeland-defense capability will take decades to achieve if they

*As of April 2007, the mission statement was online at http://www.mda.mil/mdalink/html/aboutus.html. The motivations for the director's strategic intent are rooted in Public Law 106-38, 1999, the National Defense Strategy of the United States, and other public documents.

can be achieved at all. In contrast, much has been accomplished with respect to theater defenses against shorter-range ballistic missiles, and those efforts have never been particularly controversial.

Figure 6.1 presents one view of how to think about the problem space. Reducing the many dimensions of the problem to just two, we show a region plot with U.S. objectives for the BMDS along the x-axis and the difficulty of the threat along the y-axis. The purpose is to indicate that the various areas of the region plot present very different challenges. The difficulty of an area's challenge is characterized by the area's color (with red indicating the highest level of difficulty and light green indicating the lowest). Thus, if the U.S. objective is merely to have a good enough BMDS that it is not "naked" and is able to intercept a small, simple attack, the challenge is well within what is possible. Against a small, simple attack, it should also be possible to have a high-quality defense that would in fact intercept attacking missiles. Thus, the bottom row of areas is shown as light green. Countermeasures and

Figure 6.1
One View of the Scenario Space



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other aspects of threat sophistication, however, make even the ability to deter somewhat uncertain, so the colors shown along the left column are yellow for more-advanced threats. As we move rightward in the figure, we see being able to substantially disrupt an attack and perhaps thereby dissuade a would-be attacker becomes difficult (orange) for more-advanced threats. The challenge of defending quite successfully and thereby denying the attacker any gain, however, appears to us to be beyond the pale for a large-scale attack by a near peer (i.e., a country with technical and military prowess akin to that of the former Soviet Union).

At this stage of history, U.S. BMD capability (deter or dissuade, for a simple rogue) is probably somewhere in the light green or yellow areas at the bottom left of Figure 6.1. As the United States plans improved capabilities, whether or not they are physically deployed, what cases should it write into its planning scenarios? Our own view is that, at present, the three points shown represent an adequate spanning set from the perspective of this simple representation. It is reasonable to measure future BMDS options by the criteria associated with those points. Presumably, U.S. objectives against a simple rogue, or even a relatively advanced rogue, should be stringent. At the same time, it would be wasted effort—for now—to focus analysis on the top right-hand corner. That is not currently an area of interest, and the systems currently programmed or under serious consideration would not deal with it.

So far, we have discussed only a very simple conception of the scenario space. Table 6.1 shows what we see as the principal dimensions of the more technically meaningful scenario space, along with what we regard as natural measures of effectiveness.

We can elaborate somewhat on the dimensions, as follows:

1. Planning for BMDS must consider the near to mid-term because problems exist in today's world, and more serious problems could arise quickly. However, advanced BMD capabilities will take decades to develop. When evaluating alternative programs, all of these timescales matter.

Table 6.1
Parameterizing Scenario Space and Characterizing Capability

Dimensions	Measures of Effectiveness
• Time frame: near to mid-, long, and very long term • Geography: target and launch locations • Size of attack • Attack tactics (e.g., sequential or salvo, one-time or continuing) • Countermeasure cases • Strategic warning needed • Size and configuration of the BMDS • Risk	• Probability of intercept (or its inverse, probability of target penetration) • Confidence in U.S. probability of intercept • Expected number of leakers • Nominal probability of zero leakers • Probability of systematic failure

2. The primary geographic issues are the range of the attack, which relates to whether defenses must cope with something like a short-range Scud missile or an ICBM, and whether the United States has forces in the right positions to intercept an attacking missile. Particularly important is whether the United States would be able to intercept a missile in its boost phase, during which it is potentially quite vulnerable and is a single target.[65]
3. Size of the attack is an important variable because some defense systems can handle larger attacks better than others can. Similarly, some defense systems are far more capable than others against tactically complex attacks.
4. Next, there is the matter of countermeasures. The voluminous public literature on countermeasures to BMD systems dates back to the 1950s (Carter and Schwartz, 1984; Office of Technology Assessment, 1986, 2002), although it would be a mistake to depend on that literature exclusively, because it tends to be written by BMD skeptics and because MDA is pursuing a variety of counter-countermeasures that are not discussed in the open literature. For our purposes, it is sufficient to assert that there are countermeasure classes and to denote them as, A, B, ... With this simplification, BMD analysis should separately characterize capability against threats, using the various classes of countermeasure.

5. Dependence on strategic warning is an issue because some components of the BMDS, such as ships and sea-based radars or airborne lasers, may or may not be deployed appropriately at the time of a crisis. Other components, such as long-range ground-based interceptors, are less sensitive to this issue.
6. Obviously, effectiveness will also depend on the size of the defense system, where its components are deployed, and so on.

As for measures of effectiveness, simplicity has considerable merit. From an analytical viewpoint, the best single measure is the fraction of an attacking force that would be intercepted. However, the consequences of failing to intercept an attacker would be quite severe, so it is also important to measure the confidence of the assessment. If the expected result would be interception of 90 percent of the attacking missiles, how likely is it that the result would instead be 50 percent or 100 percent? The methods of calculation involve some statistical uncertainties, but—far more important—there are complications such as might be encapsulated in the statement, "Well, Mr. President, we should intercept virtually all of the attackers if we understand the enemy's systems correctly. If we don't, and if he has a countermeasure for which we are unprepared, then we might not intercept anything. That's unlikely, however (perhaps one chance in ten), so let's report 90 percent confidence." Clearly, the meaning of "90 percent" here is different than it would be if one said, "Well, Mr. President, there are random failures here and there, so we should expect to intercept only 90 percent of the attack."

When dealing with small attacks involving nuclear weapons, many analysts have discovered over the years that policymakers want to know the probability that *all* of the attack can be stopped. That is what we mean by the nominal probability of zero leakers. It is a misnomer, however, and potentially very misleading, because of the problem mentioned above: It measures statistical confidence, but only for the case in which the attacking system and the defense system are adequately understood. Systematic errors are a special issue. A key issue in any systems-engineering analysis is assuring the absence of common-mode failures that obviate the benefits of firing multiple interceptors at a given target, or having what are intended to be independent defense layers for boost, midcourse, and terminal phases of flight. Some examples might be a critical flaw in the global command and control system or a critical flaw in the kill device used on several types of interceptors. Despite uncertainties about such matters, analysis can represent the implications of degrees of containment. Our colleague David Vaughan has done mathematical work on such issues in the past, and we have incorporated related algorithms in RAND's capabilities analysis model for missile defense (CAMMD) (Willis, Bonomo, Davis, and Hillestad, 2006).

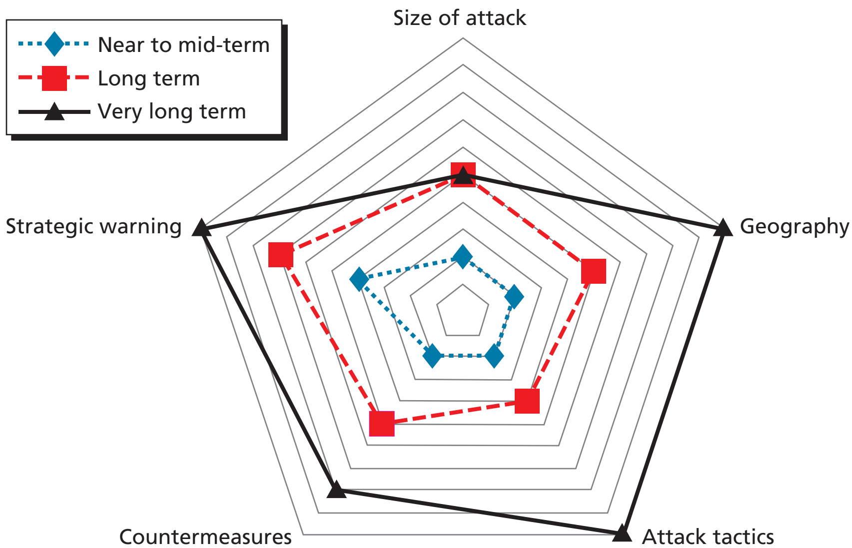
A Perspective on Capabilities-Based Planning

Because developing and fielding a BMDS is so challenging and the baseline as of a few years ago was so poor, commanders at MDA have made a clear distinction between what capabilities they will be able to deliver at a point in the future and whether those capabilities are sufficiently good to merit deployment.[66] As indicated in Figure 6.2, the expectation has been to develop systems with increasing degrees of capability over time. Figure 6.2 is merely a cartoon, but it suggests an image of starting with minimal capability and slowly moving outward, with emphasis on solving the problems posed by geography, countermeasures, the need for warning, and attack tactics, but not the problem of attack size. It further acknowledges that the problems of countermeasures are unlikely to be fully solved. The path the United States actually follows remains to be seen.

CONOPS and Critical Components

For Ballistic Missile Defense, a given concept of operations (CONOPS) is often described by reference to an Engagement Sequence Group (ESG). Successful intercept of an attacking ballistic missile requires detecting and tracking the attacker, launching and guiding an interceptor (or high-powered laser), engaging and destroying the attacker, and assessing results. This may be accomplished in a myriad of ways, drawing upon whatever component systems are available and appropriate

Figure 6.2
Capabilities Versus Time



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for the particular engagement. The components can include air-, sea-, or space-based sensors and interceptors. A centralized command and control system is involved, but so also are more-regional systems. Battle management may be quite complex because of the broad stretch of geography involved and also the need to cross command and control boundaries. That is, an attack may be launched in one combatant commander's (COCOM's) area of responsibility, pass through another's, and then approach the United States itself, which is NORTHCOM's responsibility. U.S. STRATCOM has the overall lead for strategic defense, but battle management must be globally integrated.

Defining a given CONOPS for even high-level systems engineering requires a finer level of detail because, for example, a sensor may be adequate for approximate tracking, but other sensors may be needed for fire control; multiple sensors may be needed for discrimination or traffic management; and interceptors and their kill vehicles need the capability to do final discrimination, maneuver, and kill of separate targets.

Analysis of BMD capability, then, requires paying attention to whether *all* of the necessary elements are present, both at the level of a viable ESG and at finer levels within it. We shall not discuss the BMD-specific matters further in this monograph, but the issue of identifying critical components and doing capability analysis with the hard-nosed view that *all* critical components must work is a fundamental part of the overall methodology, as discussed in Chapter Three.

Framework for Portfolio Analysis

Top-Level Structure

A basic problem in portfolio analysis, which we have encountered every time we have applied it, is that the number of dimensions exceeds what can reasonably be displayed to decisionmakers in a summary account. It comes down to the number of columns that can be shown without causing eyes to glaze. This is a problem familiar to analysts, and there is no ultimate solution. Table 6.2 shows a simplified depiction of a possible summary for the BMD problem, for a context in which decision-

Table 6.2
Notional Top-Level Portfolio Structure for BMD Analysis

Option	Defend homeland		Defend allies, friends, deployed forces		Strategic risk	Technical and schedule risk	Annualized 20-year cost (relative)
	Near term	Long term	Near term	Long term			
A	Y	R	Y	Y	R	LG	1.0
B	LY	R	LY	LG	O	LG	1.2
C	LY	LY	LY	LY	LY	LY	1.5
D	LY	LG	LY	LY	LG	O	2.0
E	LY	LG	LY	LG	G	R	2.2

NOTE: Wholly notional options, evaluations, and costs.

makers are considering alternative missile-defense programs and viewing effectiveness, cost, and risk simultaneously.

Table 6.2 condenses the top-level summary into a chunk for homeland defense and a combined chunk for defending both allies and friends and deployed U.S. forces. It then has a column for strategic risk, a column for technical and schedule risk, and a column for relative cost. The second through fourth columns show estimated effectiveness in defense. The estimates are an aggregation of results for various scenarios and cases. Strategic risk is a partially subjective assessment of the degree to which a given program would prepare the United States for anticipating or responding very quickly to serious threats involving ballistic missiles. Technical and schedule risk is a combined and partially subjective assessment of the degree of risk involved in achieving the level of effectiveness asserted for the option.

Although the options are unspecified and the evaluations and costs are purely notional, the story being told is that the baseline option (option A) will lead to substantial strategic risk. It will not be very troublesome technically or programmatically, and won't cost very much, but the results will be mediocre and the strategic risk high. Option B would spend more to shore up BMD capability in important theaters of operation such as East Asia or the Middle East. It would do little about homeland defense, however, so risks would remain high—a bit lower than in option A because of the theater defenses, but still worrisome.

Option C would invest more in systems for homeland defense, which would somewhat improve projected capability and would lay the base for greater effort if that should be necessary. Thus, it would reduce strategic risk but increase technical risk, because the systems at issue require the success of new programs. Option D is an even more ambitious investment in homeland defense, one that might deliver relatively substantial capability in ten years or so. The technical risk, however, would be even greater for the systems at issue. Finally, option E is something approaching a crash across-the-board effort. In this notional analysis, it would deliver substantial capabilities for both theater and homeland defense and would greatly reduce strategic risk (associated with ballistic missiles). The technical risks would remain high, as for option D, and in addition, the crash program would entail major cost-schedule risks.

The rightmost column suggests that the ratio of costs varies from a baseline value to something more than twice as great. Since the BMD program cost is roughly $10 billion/year, the most expensive program might assume the expenditure of another $12 billion/year over the next 20 years.

Note that the display is not the classic presentation of three options, the best of which is always the middle one. Instead, it conveys a sense of choice. If decisionmakers were convinced that theater BMD was a serious problem that could be greatly mitigated, whereas homeland defense was technically dubious, expensive, and apt to worsen international relations, they might choose option B. In contrast, if they concluded that homeland defense was an urgent priority and that the technology was within grasp (albeit risky), they might tilt toward option D or E.

Zooming for Explanation of Summary-Level Results

Although we do not describe the process further in this monograph, in our work for MDA, our summary-level results (in something analogous to Table 6.2) were undergirded by work with a capabilities model (CAMMD) and extensive interactions with MDA's systems engineers. These technical and personal interactions were crucial, because so much of what matters in BMD analysis can be understood only with a relatively deep understanding of the relevant physics, engineering, and even operations.*

Zooms to explain a summary chart such as the notional Table 6.2 would address capability against a variety of adversaries with a variety of countermeasures.

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*The RAND team, led by James Bonomo and Paul Davis, benefited from work with Dr. Edward Gerry and other members of MDA's National Team, which draws from industry, FFRDCs, and national laboratories. It was gratifying to learn that we could use our top-down portfolio-analysis tool and our high-level capability model to connect with and summarize from the results of systems-engineering work.

Shortfalls, Opportunities, and Surpluses for the BMD Program

It is not possible, for reasons of classification, to characterize the current or projected effectiveness of the BMDS in a meaningful way. However, MDA's Director, Lt. General Henry (Trey) Obering, has testified regularly before Congress and has sought to "underpromise and overdeliver." In a summary comment at a news conference, in response to questions about capability, he said*

> Well, it depends on . . . what type of countermeasures that the North Koreans or other nations could use. . . . I feel confident we can handle simple countermeasures, just like I said . . . I was confident in the overall performance of the system. We will prove that in the tests to come. But also, one of the reasons I say that is that, as I said, we have flown countermeasures against this system in the past. We had a prototype of the kill vehicle that we used today, and we used countermeasures against that prototype. And so the ability to discriminate between those countermeasures and the RV [reentry vehicle] has been demonstrated in the testing that we did in the 2001–2002 time frame.
>
> So that's why we test to where we have—we believe we have some capability, we put it in the field. We test some more systematically, one step at a time, put some more capability into the system. So we're trying to do this in an evolutionary fashion where we grow the capability, because we want to make sure that we're doing it the right way.

Identifying, Evaluating, and Comparing BMD Options

The building-block options that have been considered for the BMDS include those in Table 6.3 (and some others that we do not consider in

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*From *DoD News Transcript*, September 1, 2006 (http://www.defenselink.mil/Transcripts/Transcript.aspx?TranscriptID=3710).

Table 6.3
Building-Block Options for Ballistic Missile Defense

Component	Phase for Intercept of Target	Timescale	Comments
Aegis ships and SM-3 interceptors	Ascent, midcourse	Near term	
Patriot PAC-3	Terminal	Near term	
THAAD	Terminal	Mid-term	
Ground-Based Midcourse Defense (GMDS)	Midcourse	Near term	Based in Alaska and Vandenberg
Kinetic-energy interceptor (KEI)	Boost, midcourse	Long term	
Multiple-kill vehicle (MKV)	Midcourse	Long term	
Space-based surveillance and tracking system (STSS)	Boost, midcourse	Mid-term	
Sea-based X-band radar (SBX)	Boost, midcourse	Near to mid-term	
Forward-deployed radars			
Airborne laser (ABL)	Boost	Mid-term	
Advanced-Discrimination Initiative (ADI)	Midcourse	Mid-term	
Air-launched interceptor	Boost, midcourse		Not currently being funded
Space-based interceptors (SBIs)	Boost, midcourse	Long term	Not currently being funded
Space-based lasers (SBLs)	Boost, midcourse	Very long term	Not currently being funded

NOTE: Elements of the BMD program are described on the MDA web site; in particular, see http://www.mda.mil/mdalink/html/factsheet.html; http://www.mda.mil/mdalink/html/asptinitiative.html;http://www.mda.mil/mdalink/html/asptmkv.html; and http://www.mda.mil/mdalink/html/japan.html.

this discussion). All of these are noted on the MDA web site.* Importantly, however, many of the components in Table 6.3 are already in the baseline MDA program. The typical decision issues concern whether to increase or decrease funding for them. Thus, a given decision option might be about whether to add additional ground-based missile-defense batteries, to accelerate the Kill-Vehicle program, or to slow one or another development.

*For fact sheets on these items, see http://www.mda.mil/mdalink/html/factsheet.html.

We have not as yet applied our option-generation-and-screening methodology to Ballistic Missile Defense. In principle, however, doing so should be a useful exercise—especially if some of the building blocks involve a *reduced* level of effort in some initiatives. Some of the military-economic tradeoffs obtained might also be valuable.

In our work for MDA, we have emphasized some particular issues in evaluating options. With the encouragement of senior MDA officials, we have sought to

- Highlight shortcomings, rather than performance only, for standard threat cases. That is, decisionmakers should be able to see quickly what advances will be made by the option at issue and what shortcomings will remain.
- Clearly characterize expected performance against adversaries exhibiting a range of countermeasures.
- Characterize the program's *balance* across MDA's missions of homeland defense, defense of friends and allies, and defense of U.S. forward-deployed forces.
- Characterize the relative technical risk of options, thereby establishing values for hedging, as with overlapping technical approaches, competition among contractors or military Services, and so on.
- Characterize the degree to which an option establishes the R&D base for later developments that may be necessary even though they are not currently being emphasized in U.S. policy and congressional funding.

These actions may seem obvious to a reader not involved in BMD issues, but none of them are so obvious in practice. For example, it is natural for an organization to develop summary presentations that put its preferred options in a good light—highlighting the expected accomplishments but downplaying continued shortcomings that might be criticized by outside observers. This has been especially true in BMD work, because the technical problem is so difficult and the risks are high. Many critics are against all but a minimal BMD program, if that, believing that the challenge is impossible and that investments made in BMD are wasted. As reflected in public law in 1999, however, the United States decided that it must pursue a BMDS, even one with limited capability, because BMD capabilities are deemed useful and can be seen as deliberate movement toward something more substantial over time. Decisionmakers have also taken the view that having no defense system is unacceptable in an era of dangerous states with WMD and ballistic-missile programs.

The issue of balance is important because, over the decades (not so much in recent years), the national mood (along with congressional funding) has gyrated among objectives: In some years, the focus has been on homeland defense; in other years, it has been on theater defense (of both allies and forward-deployed forces). In some years, the emphasis has been on achieving minimal capability, while in other years, it has been on the pursuit of substantial defense capability. All of this is understandable in a complex world, but *major capability developments do not do well in the midst of such gyrations in policy and funding.* In recent times, the tension has been more between preparing a technical base for future deployment decisions and deploying currently available systems.

Another reason for our emphasis on portfolio balance is that, from a strategic perspective, *all* of MDA's three missions are and will continue to be important. It would arguably be irresponsible for the United States to pursue a BMD program that ignored some of the missions because of mood swings. To be sure, the relative balance of funding among the missions may very well change over time as the result of decisions by both national leaders and the voting public, but it is a responsibility of planners to think in terms of establishing the right balance, rather than of tilting drastically in one direction or another. It is quite possible that technical options forgone now will be demanded later, with expressions of incredulity when it is learned that they had not been pursued. Let us stress, however, that we are referring primarily to research and development, perhaps through prototyping, rather than to deployment. That is, our recommendations tend to be toward establishing a strong technical base of potential capability and distinguishing that sharply from deployed capability. As the world changes, national sentiments about the need for deployed BMD will and should change as well. DoD's technical and industrial base should be able to respond quickly.

From a decision-analytic perspective, the key points here are the following:

- Basic research is inexpensive; development is more expensive; development and testing is more expensive yet; but deployment with the associated operations and maintenance costs for an indefinite future is *very* expensive. The ratios here are something like 1:5:10:50.
- Investments in R&D provide future *options*, which may or may not succeed, and even if they do, they may or may not be pursued. Successful options, however, are potentially quite valuable.
- The *regrets* associated with not having laid the groundwork in R&D could be quite severe. Such R&D takes years, and even longer if it is begun without a warm industrial base, and the threats against which options might be deployed can emerge almost overnight.

The careful reader of this monograph will have noticed that the philosophy we have expressed is consistent with the overall theme of seeking investment strategies that maximize flexibility, adaptiveness, and robustness, rather than expected results for some allegedly best-estimate image of the future and conflicts within that future.

CHAPTER SEVEN

Conclusions and Next Steps

Conclusions

The primary conclusions of this monograph are the following:

- The relatively generic methodology we have described *and demonstrated* can be used to guide and report results of defensewide capability-area reviews such as those now under way in DoD, particularly the new integrative Concept Decision Reviews that are a highlight of USD (AT&L)'s strategy.
- The methodology can be depicted in a simple process diagram, but one that includes important new analytical features that are frequently not present in reviews.
- The enablers of the methodology include underlying capability models for the area under study, a tool for generating and screening options to identify good candidates for richer analysis and comparison, and a portfolio-analysis tool that organizes coherent discussions that simultaneously address effectiveness, risk, and cost.

The methodology has been applied, to various degrees, over the course of the past decade. In this monograph, we have summarized a notional application to Global Strike and an application to Ballistic Missile Defense.

Although the methodology and related tools are powerful, they are hardly panaceas. The limiting factors in analysis will continue to be the analysts themselves and the organizations in which they work.

Next Steps

A traditional part of a final chapter is discussion of what should come next. Several important topics that have been given short shrift so far in our work should have priority attention in subsequent work:

- Analysis cutting across capability areas
- Strategic-level portfolio analysis
- Advancing the science of exploratory analysis
- Tool refinement

Analysis Cutting Across Capability Areas

Extending the analysis methodology to cut across capability areas is crucial, since major decisions will often depend on whether an option would provide benefits in several capability areas. Also, the cost-sharing issue mentioned earlier can be addressed only this way. DoD leaders hope to have those responsible for capability areas do a great deal of "portfolio balancing" within their respective domains, finding bill-payers as well as new contributors. However, in many cases, it is necessary to do cross-area analysis in order to properly evaluate the value of a new system or activity, the implications of cutting back on another system or activity, or the way to think about tradeoffs. This work should again be targeted at DoD's tri-chair leaders of capability development, i.e., the USD (AT&L), VCJS, and DPA&E.

Strategic-Level Portfolio Analysis

Although the work we have reported here was accomplished for the USD (AT&L) and his office, with others in mind, such as the DPA&E and the VCJS, the same methods can and should be applied from a top level—both within DoD and across cabinet departments. Such work may be of particular importance in the near future as the activity in Iraq slowly winds down and policymakers contemplate alternative relative emphases in defense and national security for the years ahead—e.g., the relative emphasis on the "long war," various regional instabilities, and the long-term competition in and status of East Asia. What implications should there be for relative investment in recapitalizing the armed forces after some years of intense activity that has worn them down, modernization along the lines associated with late-1990s transformation, restructuring for low-intensity conflicts and operations, or shifts in the pattern of military presence worldwide? The first versions of the portfolio-analysis methods described in this monograph were actually developed for such strategic-level work in the mid-1990s and proved useful in casting the debates of that time in strategic terms.* It is arguably time for the strategic level of analysis to be revisited. Such work would best be done on a cross-cutting basis, with the Office of the Under Secretary of Defense for Policy as a major client.

Advancing the Science of Exploratory Analysis

As noted throughout this monograph, exploratory analysis in pursuit of investment strategies that are flexible, adaptive, and robust—rather than optimized for a particular image of the future—is essential. Great progress has been made over the past decade in developing methods for exploratory analysis and applying them to actual problems. A new wave of challenges, however, is posed by portfolio analysis. In portfolio work, the uncertainties have a different character, both substantively and technically. Significant research will be needed to extend the current theory and methods and to make them practically available to the Department of Defense.

Tool Refinement

In the course of the work described in this monograph, we made substantial enhancements to the Portfolio-Analysis Tool (PAT) and developed a new tool (BCOT). These tools are ready for use, as we have demonstrated in our own work, but further work is needed on both, especially efforts to refine them so that they can be more easily used, understood, modified, and maintained by people other than their original developers.

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*The work contributed significantly to development of the 1997 Quadrennial Defense Review and to subsequent work, over two administrations, on transformation (Davis et al., 1996; Davis, Kugler, and Hillestad, 1997; Davis, Gompert, Hillestad, and Johnson, 1998; Hillestad and Davis, 1998; Davis, 2002).

APPENDIX A

Joint Capability Areas

The current Joint Capability Areas (JCAs) are listed in Table A.1. However, the list is subject to change from time to time.*

Table A.1
Joint Capability Areas

Battlespace Awareness
Command and Control
Network Operations
Interagency Coordination
Public Affairs Operations
Information Operations
Protection
Logistics
Force Generation
Force Management
Homeland Defense
Strategic Deterrence
Shaping & Security Cooperation
Stability Operations
Civil Support
Non-Traditional Operations
Access & Access Denial Operations
Land Control Operations
Maritime/Littoral Control Operations
Air Control Operations
Space Control Operations

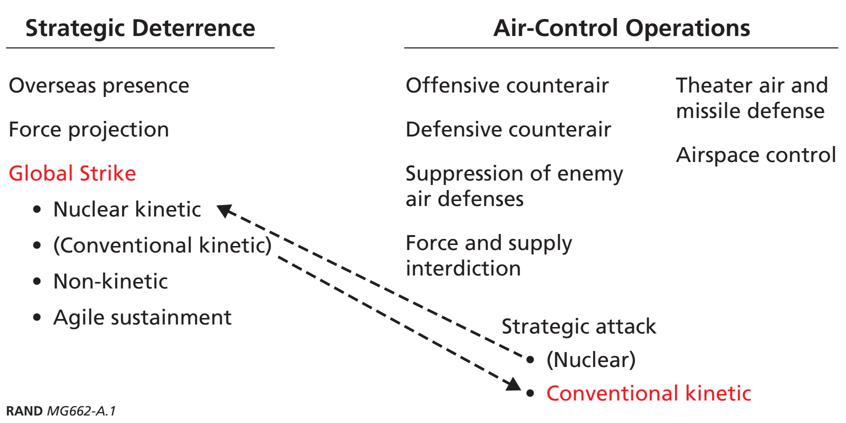
*As we completed this monograph, it appeared likely that the number of JCAs would be reduced substantially and that the new ones would align better with the Joint Staff's Functional Capability Boards than has been the case in the past. If this occurs, it would be a useful development.

Because the JCAs are so broad, it is often necessary to look to their components for something meaty. Secretary of Defense Rumsfeld approved a list of Tier 1 JCAs and their Tier 2 components in a memorandum on May 6, 2005.

The decomposition used for the JCAs is both arguable and complicated, since there is a great deal of overlap among areas, and components are relevant to multiple areas. Figure A.1 illustrates this for the Global Strike problem.* The salient points are as follows:

- Global Strike is categorized as a Tier 2 component of Strategic Deterrence.
- Global Strike has a Tier 3 nuclear component, a conventional kinetic component, a non-kinetic component, and a logistics component.
- The conventional kinetic component is seen as "belonging to" a Tier 2 component of a different JCA, the Strategic Attack com-

Figure A.1
Global Strike in the JCA Analysis Framework



*The taxonomy continues to evolve. This material is based on Secretary Rumsfeld's memorandum and a briefing by LTC Bryan Luke, Chief of the Joint Experimentation Branch, Joint Staff (J-7), dated August 2006.

ponent of Joint Air Operations. Joint Air Operations, in turn, has a conventional kinetic component, which "belongs to" Strategic Deterrence/Global Strike.

Although this may appear a bit confusing at first, it is an inevitable result of efforts to develop taxonomies: The real world is not neatly hierarchical; rather, it has various interactions across "branches" of a hierarchical tree. In any case, the focus in this monograph is on the conventional-kinetic component of Global Strike.

Other DoD offices have found it necessary to use different categories and to construct complex mappings to the JCAs. OSD (AT&L), for example, has noted that because of the very high degree of overlap among JCAs, it has been difficult to use them effectively for work in programming or acquisition. OSD (AT&L) has over the past several years called for Capability Area Reviews (CARs) on such topics as integrated air and missile defense (IAMD), joint battlefield management command and control (JBMC2), and unmanned aerial vehicles (UAVs), among others.

One suggestion has been to lump the JCAs in different categories as shown in Table A.2.

In this construct, the enabling JCAs enable warfighting in different kinds of engagement. The effects category refers to operational effects in different warfighting domains (land, air, etc.). Composite JCAs achieve an objective by drawing on both enabling and effects-oriented JCAs. Institutional JCAs are those requiring institutional support for battlespace operations.

Another attempt to map the JCAs to what are seen as "practical" categories has been made by OSD (PA&E). The key dimensions in PA&E's breakdown are summarized in Table A.3. The three major categories listed in the table can be seen as the axes of a three-dimensional cube.

Table A.2
A Suggested Categorization of Joint Capability Areas

Category	Joint Capability Area
Enabling	Joint Battlespace Awareness Joint Command & Control Joint Logistics Joint Net-Centric Operations
Effects	Joint Air Operations Joint Land Operations Joint Maritime/Littoral Operations Joint Protection Joint Space Operations Joint Special Operations
Institutional	Force Generation Force Management Joint Interagency/IGO/NGO Coordination Public Affairs
Composite	Joint Access & Access Denial Operations Joint Global Deterrence Joint Homeland Defense Joint Stability Operations Defense Support of Civil Authorities Shaping

SOURCE: Adapted from Kristen Baldwin and Judith Dahmann, "JCA Implementation OUSD (AT&L) Update," unpublished briefing, March 2006.

Table A.3
An Alternative Breakdown by Category

Major Category	Capability Areas Relating Loosely and Imperfectly to JCAs
Role	Shaping Global Deterrence Land Operations Maritime/Littoral Operations Air Operations Space Operations Homeland Defense Stability Operations
Function	Battlespace Awareness Lethal Force/Effects Application Net-Centric Operations Command and Control Logistics Protection Information Operations Interagency/IFO/NGO Coordination
Effects and Targets	Military Adversaries Non-Military Adversaries Emerging Threats and Technologies WMD and WMD Capabilities General Populations

SOURCE: Adapted from Porter, Bracken, and Kneece (2007). That study, in turn, drew upon Office of the Secretary of Defense/DPA&E (2006).

APPENDIX B

Implications for Systems Engineering and Modeling and Simulation

One task in our original research project for OSD (AT&L) was to examine family-of-models issues, because, as discussed in Chapters Three, Five, and Six, a portfolio-analysis approach to capability assessment depends on knowledge at different levels of detail, sometimes in very different forms. As it happened, much of that research became part of our efforts for OSD (PA&E) and a National Academy panel (Davis and Henninger, 2007; National Research Council, 2006). We shall merely touch upon that research here. First, we discuss systems of systems (SoS), which are increasingly relevant to DoD programs. The Army's Future Combat System (FCS), for example, is an SoS. Alternative SoS could be evaluated in the kind of portfolio-analysis framework we describe in this monograph.

A New Paradigm for Systems Engineering?

OUSD (AT&L) has in recent times reemphasized the importance of systems engineering to its work (Lamartin, 2004; Wynne and Schaeffer, 2005; Krieg, 2007). Others have also commented, sometimes in reviews of DoD's or Services' approaches to modeling, simulation, and analysis, and sometimes in reviews of DoD's capability-development process (National Research Council, 2004, 2005).

A new wrinkle in systems engineering is the special problem of SoS. Although no single definition has been agreed upon, we consider an SoS to be a system many components of which are also full systems in their own right, perhaps developed independently for relatively narrow applications. The special features of SoS tend to arise when these component systems relate to very different subject areas, in which case the SoS may be referred to as having heterogeneous components and interdisciplinary character.

Although it can be argued that the original principles of system engineering carry over well to SoS work, some of us are skeptical about that perspective (even if it is logically correct), because—in practice—designing, acquiring, and operating an SoS is quite different from doing so for normal systems. A number of conferences and workshops have now been held on the matter, with different conclusions being reached, depending on those in attendance. Table B.1 summarizes what we see as distinctions between old-style and new-style approaches in system design. Older readers may note reference to the changed conception of "integration." For many years, an "integrated" system was a clever

Table B.1
Contrasting Styles in System Engineering

Issue	Old Style (Stereotyped)	New Style?
Design	Top-down with detailed specs; hierarchical and horizontal decomposition, but not modularity	Top-down for architecture, but with more open competition of potential components; modularity
"Integration"	Components that optimize performance for known task (e.g., 1970s compact stereos)	Interfaces with open standards to maximize flexibility and adaptiveness
Organization	Tight internal control; hierarchical; teams of like-minded engineers	Networking; control of architecture; black-box testing; teams cutting across disciplinary, social, and organizational boundaries
Origin of interface specs	Top-down; design requirements	Top-down, bottom-up, and sideways, with satisficing choices
Components	Mix of new and on-the-shelf; long component lifetimes	Mix of new and on-the-shelf; fast turnover of IT components

SOURCE: Paul K. Davis, CSER 06, panel on Complex Systems Engineering, April 7–8, 2006, Los Angeles, CA.

assembly of components developed to work together extremely well—i.e., optimized for that particular system. In today's world, designers are much less concerned about perfecting the interactions than they are about open interfaces allowing for great flexibility over time. Those involved in system development for network-centric operations emphasize agility (akin to what we mean by flexibility and adaptiveness) and see the promise of networking as very dependent upon being able to use many component systems in larger systems of systems and to vary which components are used and how they interact, depending on the circumstances.

Modeling and Simulation

The concepts discussed in this monograph have major implications for analysis practices and for the models and simulations on which they depend. In particular, if a defense program and individual programs are to be assessed for their flexibility, adaptiveness, and robustness (their FARness), then it follows that analysis must be restructured accordingly. Moreover, analysis will need to draw on M&S toolkits that are suitable for this challenge, rather than just estimating effectiveness in particular, detailed cases. To be sure, baseline cases will still be very useful, and even essential, for both integration and comparison. However, whereas the vast majority of work time by practitioners of M&S is currently spent on standard cases, future efforts will need to be much broader. The work most badly needed for DoD's capability-development efforts is more like good high-level design than working through details. Such design, of course, may be erroneous unless it is rooted in deeper knowledge and is supplemented by more-detailed work, where such work is useful. Thus, what is needed to support analysis is a family-of-tools approach to M&S.

These issues have been discussed elsewhere, both by the senior author (Davis, 2003; Davis and Henninger, 2007) and by various national panels such as the Defense Science Board (Welch, 1996) and the National Academy of Sciences (National Research Council, 1997, 2004, 2006). DoD's forthcoming master plan for modeling and simulation will probably embrace the need for a family-of-tools approach (Allen, 2006).

Relationships to Complex Adaptive Systems

Another recent development has been the bottom-up emergence, within the systems engineering community, of what is being called Complex Systems Engineering because of the need to draw upon the paradigms of complex-adaptive-systems (CAS) theory to better address the modern issues of systems of systems. At a recent conference on the topic sponsored by Aerospace, MITRE, and RAND,[67] one of the authors (Davis) summarized his views on what is special about systems of systems and how they relate to CAS.

The relevance of all this to the current monograph is that our approach presupposes an underlying basis for evaluation of portfolio options, a basis rooted in good system engineering and modeling. The quality of that base, however, will increasingly depend upon the analytical communities embracing the lessons from CAS research and reflecting the insights in the variables and processes contained within the models and analyses, the components that are recognized, and the criteria by which evaluations are made. In this monograph, we have emphasized the need to evaluate options for whether they contribute to FARness of capability. This is precisely what is emphasized in the first column of Table B.2. It is very different from what would be emphasized in a traditional acquisition contract with industry, one with highly detailed specifications and an emphasis on performance within the narrow specifications rather than on FARness.

Table B.2
Systems of Systems and Complex Adaptive Systems

Systems Engineering and SoS	Relationships to CAS Theory
Although most systems engineering principles carry over to SoS, many SoS have unusual features: • Some SoS are "capability kits" allowing quick, at-time, unique configuring of situation-specific systems • Networking for tomorrow's operations • Premium on flexibility, adaptiveness, and robustness • The right building-block components • Superb assembly capability • Graceful degradation • Special SoS are ideal for true evolutionary acquisition • Valuable capabilities at each spiral • Rethinking of requirements at each new spiral • Certainty of capability expansion, not mere refinement, over time • Certainty of need to exploit newly proven technology components Result: different conception of how to assess programs, with unusual categories and metrics and unusual testing	CAS theory is key to distinguishing SoS from traditional complicated systems. Characteristics include: • Hierarchical vertical and horizontal components; networks • People and organizations that learn, innovate, behave semi-randomly, and adapt in competitive environments • Diverse, changing contexts, which promote change • "Emergence" of patterns and operations not explicitly designed-in • Patterns of cooperation (or non-cooperation) not originally intended Military examples: • SOF officers working with bomber pilots and horseback tribal chieftains for tactical precision strikes on enemy forces • Air-mobile/air-assault Army forces launched and supported from aircraft carriers after de-loading of some usual Navy aircraft • Future ad hoc creation of tailored maneuver units for ground operations; excellent real-time networking with local police and military, with SOF and intelligence; exploitation of fresh-from-laboratory sensors and weapons

SOURCE: Paul K. Davis, CSER 06, panel on Complex Systems Engineering, April 7–8, 2006, Los Angeles, CA.

APPENDIX C

RAND's Portfolio-Analysis Tools

In the mid- to late 1980s, RAND developed a portfolio-analysis tool called DynaRank (Hillestad and Davis, 1998), which has been used in a number of projects for both defense and social-policy applications. It continues to be improved by colleague Richard Hillestad. The Portfolio-Analysis Tool (PAT) was developed as an offshoot with some significantly different characteristics. The first version was the Portfolio-Analysis Tool for Missile Defense (PAT-MD), which was developed in 2004–2005 for the specific needs of the Missile Defense Agency (Dreyer and Davis, 2005). Partly as product improvement for MDA and partly for the more generic purposes of the research reported here, Dreyer and Davis have extended the latter significantly, creating PAT. Since only the older PAT-MD has published documentation (cited above), we note the changes in this appendix, after some general comments.

Applicability of PAT

PAT, as illustrated in Chapter Five in particular, is intended to assist in top-down portfolio analysis and support of decisionmaking. Many types of portfolio exist, and PAT is designed to be rather generic. The common feature in all applications of PAT is the ability to characterize the relative goodness and shortcomings, cost, and cost-effectiveness of alternative investments intended to contribute value in a number of different categories, such as geographic theaters, warfare domains, capability areas, and strategic categories such as warfighting, environment-shaping, and laying the basis for future large-scale adaptations. The contributions may be ambiguous because of uncertainty, so it may be necessary to address different cases, such as warfighting scenarios. PAT is merely a spreadsheet tool that assists in laying out information accordingly. Options appear in rows, various measures of goodness appear in columns, and the categories in the portfolio are represented by groups of columns.

For capability-area analysis, the options that might be compared in PAT could range from singular systems, such as a new missile for Global Strike capability, to alternative approaches to systems of systems, e.g., alternative approaches to complex command-and-control systems extending across Services, nations, and even non-national groups. PAT is an "empty vessel," so each application requires thinking through the problem area and developing appropriate structures for use in the analysis. We have used PAT so far in projects for the Missile Defense Agency, OSD (AT&L), and the Joint Staff. Earlier related work used DynaRank in a study for OSD (Policy) on high-level alternative strategies of a sort to be considered in a Quadrennial Defense Review.

Major Improvements in Functionality

The principal improvements in functionality relative to PAT-MD have been the addition of (1) multiresolution capabilities, (2) a second level of zoom (drill-down), (3) alternative formats for scorecards, including some suitable for users who are color-blind, and (4) improved mechanisms for adding or editing "perspectives."

Multiresolution Data Entry

Using PAT requires inputting a great deal of data, whether generated empirically, from models, or subjectively. PAT also includes several levels of detail, so that the user can observe results in the summary scorecard and then zoom down into detail for explanations of why the summary values are assessed to be as shown. Although it may seem ideal to have higher-level assessments determined by detailed calculations, the reality is that there are often major uncertainties about the data for the detailed calculations, and even the calculations themselves. In other cases, the detail is spurious because it reflects speculation about underlying factors but not a complete treatment. Thus, the detail may be useful conceptually, but not reliable numerically. Indeed, detailed data may often be much less reliable than more aggregate-level information. This is particularly so when the aggregate-level information is pessimistic. It may be that the detailed calculations correspond to a particular assumed mechanism of effectiveness, whereas the more-aggregate input (often a judgment) would be based on knowing from experience that many detailed factors are at work, are difficult to control, and often cause trouble. So, for example, crude experience-based estimates of how long developments will take may be more reliable than the result of detailed and honestly intended proposal estimates. This suggests the need to be able to input higher-level data directly, if desired, rather than always proceeding bottom-up.

Another compelling reason for preferring such flexibility in data entry is pragmatic: Inputting large amounts of data is tedious, and the potential for error is high. It is often more expeditious, especially in early parts of an analysis or in response to rapidly changing assumptions, to take the shortcut of entering higher-level data directly.

Finally, it should be noted that when experts review assumptions in tools such as PAT, they look at relatively aggregated assumptions and compare them with their experience and intuition. If they urge using different assumptions, it is far easier—and may be much more sound—to use those directly rather than developing some particular way of disaggregating them into the terms of detailed calculations.

To be less abstract, suppose that we were evaluating the probability of mission success for deep strikes, with non-stealthy F-16 aircraft being used to penetrate advanced air defenses. Is there any value in entering all the detailed performance data for SAMs and radars, the observability characteristics of the F-16s, and so on? Or would it be more sensible to simply input low probabilities directly, so as to spend precious time on other parts of the analysis, such as estimating the need for various degrees of stealth in current and next-generation aircraft? If a typical number calculated from detail were 0.6, and an expert review panel insisted on using an even lower number, say 0.3, one could perhaps do no better than just inputting the 0.3 directly—unless there were a sound basis in detail for disputing the experts' judgments.

Another argument with the same conclusion is that missions change, the world changes, assumptions change, and it becomes very difficult, if not impossible, to keep up if one's decision-support tool requires excessively detailed data. Further, even if changes can be made quickly, checking them out carefully may take time.

To use another example, an experienced program manager assessing odds of success in several parallel developments will be drawing upon judgments about the particular companies involved, their management teams, and their recent records of success or failure. His net judgment may be either more optimistic or more pessimistic than that coming from a straight engineering-level assessment. If the senior manager's judgment is regarded as the best available input, then it may be best to let it be a high-level input rather than to pretend that it is the result of a more-detailed calculation.

PAT now allows users to input options' effectiveness data at levels 1, 2, or 3 of detail. Costs may also be introduced in diverse ways. For example, one might enter the annualized 20-year steady-state cost of alternative systems directly, or one might instead have separate inputs for R&D, acquisition and deployment, and operations and maintenance. The latter might be totals for the 20-year period or specified on a year-by-year basis, as in any detailed budget.

Alternative Formats for Scorecards

The default PAT approach is the ubiquitous and intuitive color scorecard, with red, orange, yellow, light green, and pure green denoting assessments of very poor to very good. A significant minority of people in any given audience, however, may be partially color-blind, rendering the "intuitive" displays useless. Further, hardcopy prints are sometimes in grayscale. Finally, some organizations prefer other color schemes for one reason or another. PAT now allows the user to choose from among four formats. The recommended format is the usual color scheme, but with the letter corresponding to the color also appearing in the cell (as in Figure 5.11).

Alternative Perspectives

A core concept in using PAT is acknowledging uncertainties and searching for strategies that are flexible, adaptive, and robust. One way to go about such exploratory analysis is to have alternative perspectives, each of which is a collection of key assumptions in PAT's calculations. The word "perspective" is apt, because frequently, resource-allocation decisions are complicated by differences of opinion among principals, differences that trace to their differing perspectives on the world, the future, and priorities.[68] If the alternative perspectives are defined appropriately, having the relative goodness of options hold up across the perspectives is often a measure of FARness.

It is now rather easy to construct alternative perspectives in PAT and to compare portfolio-level assessments made with different perspectives. Much more progress can be made in this area, but the current version of PAT is already quite useful.

Comparison Scorecards

One problem with color-scorecard displays is that they show results for one set of assumptions, whereas comparison across assumption sets is usually desired. PAT permits side-by-side comparison of scorecards for different assumption sets. The mechanism is simply defining a duplicate set of effectiveness columns but specifying that the values in those columns are those for the alternative assumption set.

Alternative Aggregation Formulas

We discovered in the course of the Global Strike application that PAT's alternative mechanisms for aggregating upward were insufficient. Although working around this problem required no changes in PAT itself, the technique for doing so had not been recognized or documented previously. The method is simply as follows: If the intention is to aggregate from level 3 to level 2 using a different combining rule than is allowed by PAT, the user can simply add an additional level 3 component called, e.g., net effect. The user can enter the relevant formula in the cells of that column, using standard Excel functionality. The formula can refer to the component column values. If the component columns involve variables X, Y, and Z, the formula might, for example, be X*Y*Z or 1 – MIN(X,Y,Z). The next step is to set the values of the weights for the contributing columns to something very small but nonzero, such as 0.01, with only the net-effect column having a weight of 1. The result at level 2 will then be as specified by the formula, but drilling down from level 2 to "understand" the result will show the component values. This technique is a workaround for a problem that only some users would encounter, but it is useful to know. We do not anticipate changing PAT in the near term to make the workaround unnecessary.

Additional Columns

PAT now allows users to have more top-level measures of options' strengths and weaknesses.

Notes Sheet

PAT now includes a Notes sheet in which users are encouraged to record assumptions, musings, and hints. Although trivial from a technical perspective, this mechanism can be quite useful in collaborative work.

Simplified Data Entry

PAT now includes a much improved version of the "template-builder" tool described in the original documentation. It is now possible to make substantial changes, such as adding or subtracting measures of effectiveness, and to generate the new scorecards while retaining all of the previous data that are still applicable. It is necessary only to enter new data.

Interface Improvements

Improving interfaces is a continuing effort over time. Hands-on experience with tools reveals interface problems that were not appreciated originally, and as more people use a given tool, more ideas arise about ways to make working with the tool easier, more transparent, and less error-prone. The improvements reflected in PAT include

- More intuitive naming of PAT objects, such as levels
- A top-menu option for navigating to other sheets (an alternative to using the bottom-of-sheet tab mechanism)
- Better defaults for fonts and font sizes in sheets and graphics
- Improved methods for making changes while preserving some or all previous data.

Performance Improvements

The natural history of software tools often includes a lengthy period of early development and experience, followed by an intensive period of reprogramming to maximize efficiency. PAT is still in the developmental phase, but it has benefited from several rounds of partial reprogramming, which have substantially improved performance. Calculations are now much faster (e.g., seconds instead of tens of seconds), refreshing graphics or changing displays or formats is much faster, and the effects of many calculations ripple through the program automatically without requiring the user to do anything. In addition, a few bugs have been identified and fixed.

Endnotes

1. Methods for characterizing and parameterizing a broad space are described in earlier work (Davis, 1994, 2002).

2. The rigorous sufficiency of an intended spanning set depends on many assumptions, e.g., that resources will be used well in any situation that arises, that the low-resolution depiction has not omitted any key dimension, and that the low-resolution depiction of a given dimension is a conservative representation of more-detailed matters. For example, a test scenario characterized by a week's warning time would not represent a real-world scenario in which the warning exists but is not disseminated to field units.

3. See, e.g., National Research Council (2006) and Davis and Henninger (2007).

4. Secretary of Defense James Schlesinger expressed this point more than three decades ago. It has been raised more recently by the Vice Chairman of the Joint Chiefs of Staff, Admiral Edmund Giambastiani, and the USD (AT&L), Kenneth Krieg.

5. As an example of conservatism, in the late 1990s, DoD conducted a strategic-mobility requirements study that did not consider operational concepts and revised military units akin to what were "in the air" and soon emerged as part of military transformation. As an example of naive optimism, the Army's *initial* approach to the Future Combat System (FCS) depended on technologically unrealistic estimates of light-armored-vehicle weights and operationally unrealistic assumptions about what could be accomplished with modern information technology that was more suitable for warfare in the open than for warfare in forests or urban settings.

6. This material draws on Chapter 4 and Appendix G of a lengthier Defense Science Board discussion for which one of the authors of this monograph (Davis) was responsible (Defense Science Board, 2007b). We benefited from discussions with current and past senior officials, including General Larry Welch (USAF, retired), John Foster, Major General Jasper Welch (USAF, retired), Larry Lynn, Admiral Dennis Blair (US Navy, retired), and Lt. General Glenn Kent (USAF, retired). Some of Kent's insights are also reflected in a RAND monograph on what might be called leader-centric strategic planning (Kent and Ochmanek, 2003).

7. Chaired by General Maxwell Taylor, President of the Institute for Defense Analyses, the study drew on top scientists, engineers, and analysts from across the defense industry. It anticipated greatly improved Soviet strategic systems and evaluated alternatives to counter and trump those systems within the paradigm of assured retaliation.

8. One of the authors (Shaver) commissioned RAND's first GPS study in 1968.

9. The DDR&Es of the earlier era included Herbert York, Harold Brown, John Foster, and William Perry, all of whom had deep scientific credentials and authority just below that of the Deputy Secretary.

10. Paul K. Davis, James Bonomo, Irv Blickstein, and Robert Moore, "Toward a Systematic Approach to Capability Area Reviews (CARs)," unpublished material prepared for Acting USD (AT&L) Michael Wynne (December 2004) and USD (AT&L) Kenneth Krieg (January 2005).

11. Developing metrics tied to operational missions is discussed in a study on implementing the 2001 Quadrennial Defense Review (Kelley, Davis, Bennett, Harris, Hundley, Larson, Mesic, and Miller, 2003).

12. A cynic might claim that the result was simply the consequence of organizational competition and log-rolling. The decisions, however, were top-down national choices that did *not* neatly correspond to organizational preferences. The Air Force preferred manned aircraft, and the Navy saw the SSBN program as a national burden that it was willing to accept but not something to be sought enthusiastically.

13. For an early discussion using case histories to draw lessons about why a joint approach is needed, see Winnefeld and Johnson (1991).

14. We exclude reference to the 1990–1991 war with Iraq because that scenario had been considered since the late 1970s and was a significant factor in defense planning that led to the creation of U.S. Central Command and its capabilities (Department of Defense, 1991).

15. See Kugler (1993) for an excellent history of the NATO alliance.

16. See Thomson and Gantz (1987), an influential paper of its time.

17. These RAND analyses were done for OSD (Policy) (Ben-Horin, Darilek, Jas, Lawrence, and Platt, 1986; Davis, 1998; Darilek and Setear, 1990). Instead of fixating on standard scenarios, the 1998 study argued that a short-mobilization attack was the largest military risk borne by NATO, that Soviet planners might reasonably conclude that their best chance for rapid victory would be with such an attack—coupled with political deception—to achieve a degree of operational surprise, and that the feasibility of such an attack could be undercut by verifiable constraints on the readiness of Soviet operational reserves.

18. The reasons for Milosevic's eventual capitulation may never be known. Some historians make a case that the cumulative and increasingly pointed effects of strategic bombing were decisive, with other factors contributing (Hosmer, 2001). Others are more equivocal (Daalder and O'Hanlon, 2000; Lambeth, 2001), discussing how strategic bombing, diplomacy such as Russian recommendations to Milosevic, and the threat of an eventual ground-force invasion interacted and jointly resulted in the decision.

19. See Davis (2002) for discussion of capabilities-based planning and scenario-space methods for going about it.

20. See Bexfield (2004) on the Analytic Agenda. See Swett (2003) for a discussion of how OSD (Policy) approached issues of uncertainty in scenario planning.

21. The new generation of precision weapons not only further improved the target-kill potential of bombers using older precision weapons, but also allowed them to strike multiple targets per sortie, thereby going far beyond what had been possible previously.

22. Enthusiasts of long-range fires and airpower may argue that the Army can forgo heavy artillery, but ground-force officers know of historical cases where air forces, which might have protected them in principle, were temporarily not available. Also, there can be a critical need for significant levels of indirect fire—in part, to cope with enemy infantry approaching through complex terrain (Matsumura, Steeb, Herbert, Lees, Eisenhard, and Stitch, 1997; Matsumura, Steeb, Gordon, Herbert, Glenn, and Steinberg, 2000; Defense Science Board, 1998).

23. See, e.g., Alberts and Hayes (2003) for a discussion of mission-capability packages.

24. The latter problem is sometimes egregious in methods eliciting subjective judgments about the adequacy of a system's parts from various people within the organization and then using standard decision-analysis software to tote up the results using linear-weighted sums. Not surprisingly, these judgments are often looked upon unfavorably by top officers or officials, who want to know *who* made them and the *logic* behind them.

25. See Kelley et al. (2003) for a discussion of finding metrics to correspond to guidance in the Quadrennial Defense Review.

26. In terms of 2007 dollars, the Soviets had spent on the order of $600 billion on their air-defense system as of 1989 (Lepingwell, 1989).

27. Some of the best early research on this matter was accomplished for the OSD's Office of Net Assessment in the mid-1980s (Hines, Petersen, and Trulock, 1986).

28. A significant literature exists on these matters (Quinlivan, 1995; Dobbins, McGinn, Crane, Jones, Lal, Rathmell, Swanger, and Timilsina, 2003). The Army War College and other organizations also have extensive related databases.

29. See Davis, Kulick, and Egner (2005) for a survey of modern decision science and its implications for high-level decision support. Davis and Kahan (2007) discuss applications to effects-based operations.

30. After a RAND review of its processes, the Missile Defense Agency (MDA) established a mechanism encouraging such communication across the boundary of investment-planning and systems-engineering domains. This proved valuable during 2005 and 2006 in assuring that top-level assessment and development of programs was consistent with the best technical knowledge from systems engineering.

31. This point can be appreciated from a discussion in an AIAA volume on modeling and simulation for space systems prepared by the Aerospace Corporation (Rainey, 2006).

32. For a broad discussion of classic models, see Hughes (1989). EADSIM's web site states that EADSIM is the most heavily used force-on-force model in existence. See http://www.eadsim.com/EADSIMExecSum.pdf.

33. See Allen (2006) for community input coordinated by the Institute for Defense Analyses describing the several campaign models. For CAMMD, see Willis, Bonomo, Davis, and Hillestad (2006). For EXHALT, see McEver, Davis, and Bigelow (2000). For EXHALT-CF, a closed-form version of EXHALT, see Davis, McEver, and Wilson (2002).

34. See National Research Council (2006), Davis and Henninger (2007), and Davis and Bigelow (1998).

35. The efficient-frontier method in financial analysis is a special application; it was pioneered in the 1950s (Markowitz, 1952) and was subsequently improved by Sharpe and others (Sharpe, 2006). In financial applications, the efficient frontier usually refers to a curve on a plot of expected profit from a stock portfolio versus some measure of risk, such as the variance to be expected in the value of the portfolio over time. A better measure of risk looks only at the probability of negative fluctuations from the expectation.

36. DynaRank does not generate a simple "priority list" of the sort often used. Instead, it evaluates options across multiple criteria and uses potential contributions to net effectiveness and cost to suggest the order of investments to meet the constraints of a budget. The result can be seen as a kind of priority list but is informed by cost-effectiveness considerations.

37. The Joint Staff has also used a simplified version of Global Strike to describe aspects of analytic methodology at an unclassified level (Joint Staff (J-8), Force Application Assessment Division, 2006).

38. See Rumsfeld (2006); Cartwright (2006); International Institute for Strategic Studies (2006); Arkin (2001).

39. A combatant commander might recommend a particular global strike or might be asked to plan and conduct one, but deciding on the strike itself would be a presidential issue.

40. For discussion, see unpublished work by MITRE and Joint Staff (J-8) (Yost, 2006). See also a Joint Staff doctrine study (Joint Chiefs of Staff, 2005, p. III.3), which says that global strikes are rapidly planned, limited-duration, extended-range precision attacks that are conducted to achieve strategic objectives. Global strikes may be executed against highly valued adversary assets, using both kinetic and non-kinetic methods. Global-strike targets include adversary centers of gravity, WMD and their delivery systems, production facilities and storage sites, key leadership, and critical infrastructure. Other examples of homeland-defense offensive actions include (special operations) direct action, space-negation denial, and computer-network attacks.

41. For broad conceptions of Global Strike, see early comments by the Air Force Chief of Staff (Jumper, 2001) and a Joint Staff integrating concept (Joint Staff (J-8), 2004).

42. Some related discussion can be found in a recent paper speculating about the feasibility of Israel attacking Iranian nuclear facilities (Raas and Long, 2006). Such an attack could release radioactive materials. Worries about release of toxic chemicals after bombing arose in U.S. deliberations before the Desert Storm operation in 1991, and some public literature exists about toxic-release issues as a result of Gulf War Syndrome investigations. See, e.g., CIA Director Robert Walpole's testimony in 2000 (on DoD's web site at http://www.gulflink.osd.mil/oversight/xcript_hearing_13jul99.html#cia).

43. The August 20, 1998, strike against Afghan camps illustrated the potential value of promptness in Global Strike. It was hoped that the attacks would kill bin Laden, who was expected to be present at one camp (Clarke, 2004, p. 184). Although bin Laden was not killed, some reports indicated that he had left only shortly before the strike; if this was in fact the case, a shorter execution time might have made a difference. The facts remain murky, and according to President Clinton's account, "we never knew for sure" (Clinton, 2004, p. 803). The strike had been planned for days as the result of intelligence that bin Laden would be present in the camp, and execution time may have mattered. Other efforts to hit bin Laden were stood down for reasons of uncertainty and likely collateral damage, but if conducted, they might well have been execution-time-limited. This can be inferred from accounts of the period (Benjamin and Simon, 2002, pp. 280ff).

44. The 1998 strike into Sudan was based on what many saw as marginal data and inference; it was severely criticized both within the administration and by outsiders. See "To Bomb Sudan Plant, or Not: A Year Later, Debates Rankle," *New York Times*

on the Web, October 27, 1999 (http://query.nytimes.com/gst/fullpage.html?res=9A04E7D71238F934A15753C1A96F958260). As of 2004, President Clinton stated that he "still believed we did the right thing there" (Clinton, 2004, p. 805). This judgment reflected an after-action review that he requested when he himself became doubtful. An account by NSC staffers of the original evidence, criticism, and subsequent review makes clear how difficult choosing strike targets can be and how difficult it can be to persuade critics that attacks were made in good faith, let alone with correct judgment (Benjamin and Simon, 2002, pp. 352–362).

45. About 20 people were killed in Damadola, according to news reports from Pakistan. Of those, some may have been members of al Qaeda. The strike was accomplished with a Predator drone, according to a Congressional Research Service report to Congress (Katzman, 2006).

46. As an example, President Clinton sought opportunities to strike against bin Laden after the 1998 embassy bombing in Kenya. When opportunities arose, lengthy evaluation processes were needed, because of risks such as the potential for one strike to kill members of the royal family of the United Arab Emirates. See testimony of CIA director George Tenet to the 9/11 Commission (National Commission on Terrorist Attacks, 2004).

47. At one point in the bin Laden hunt, the Navy was directed to hover off the coast of the Arabian Sea in hopes that an opportunity to strike would arise. Pakistani patrol boats motored out to the fleet and reported, with the information presumably being relayed to the Taliban. Subsequent "hovering" relied on submarines (Benjamin and Simon, 2002, p. 280).

48. An analogy can be drawn to planning for nuclear strikes by manned bombers during the Cold War. Electronic countermeasures (ECM) can be extremely effective in defeating air defenses. Through the 1970s, however, it was customary for related studies to be done separately and for capability assessments related to bomber penetration to be conducted without assuming such countermeasures. The reasoning was simple: ECM are often fragile capabilities, dependent on good intelligence and on the adversary not knowing their capability; ECM's effectiveness can sometimes be undercut quickly (on the timescale of development) and possibly without the side possessing the ECM knowing about it. The B-1B was eventually procured with more explicit dependence on ECM than earlier planners had recommended, but the wisdom of that course of action is still debatable.

49. In 2007, the Senate Appropriations Committee expressed concerns about the CTM and other prompt Global Strike options and asked for a National Academy Study on the subject. The committee members expressed particular worry about what they saw as ambiguities, i.e., whether launches from a Trident submarine would be perceived as nuclear. They also expressed skepticism about the availability of adequate intelligence to justify prompt attack.

50. Some logically possible cases are excluded as unnecessary. For example, a small point target might be buried but not hard.

51. For a related discussion, see recent NRC reports (National Research Council, 2005, 2006) and a white paper developed for DoD's master plan for modeling and simulation (Davis and Henninger, 2007).

52. Multiresolution modeling has been discussed at some length elsewhere (Davis and Bigelow, 1998).

53. During the Clinton administration, serious efforts were made to strike bin Laden. The combination of shortcomings in information and high degrees of risk caused the president, in each case, to forgo the attack. Critics who claim that the information justifying a strike was adequate might ponder the miserable record of intelligence during Operation Iraqi Freedom, when numerous strikes were made, starting with the dramatic effort to kill Saddam Hussein himself. Repeatedly, the intelligence information—including that from human sources—proved faulty, and the strikes failed to accomplish their goal. Moreover, they caused numerous unintended fatalities.

54. The intention is to minimize the time spent, while conveying the essence of the subject. Multiple viewgraphs of assumptions take time to present and explain and therefore have a high opportunity cost and the potential for "turning off" recipients.

55. As an example, early in the campaign in Afghanistan, air strikes were perceived as being too indiscriminate to justify their modest accomplishments, and the United States was being criticized harshly, despite the perceived legitimacy of the attack into Afghanistan following September 11. The criticism dissolved as airpower began supporting effective ground operations by allied tribesmen working with U.S. SOF units or intelligence operatives. It became clear that world opinion would "tolerate" collateral damage if it were seen as unavoidable in accomplishing something legitimate. Empirical information on such matters is discussed in a recent RAND study prepared for the U.S. Air Force (Larson and Savych, 2006).

56. Despite the oft-heard claim that the Services never offer up tradeoffs, the Navy's conventional Trident Missile Concept (TCM) would reduce marginally the number of strategic nuclear ballistic missiles on alert in deployed Trident boats. That is, some TCMs would replace nuclear missiles, rather than requiring an additional submarine or new launch tubes. A partial bill-payer would be on-alert nuclear capability. The Air Force, in proposing a new long-range bomber (or a medium-range bomber, or both) suggests, e.g., a substantial reduction in the number of legacy bombers (B-52s and B-1Bs). Congress is reluctant to retire the older aircraft (Tirpak, 2006).

57. RAND analyses for the U.S. Air Force by colleagues Bill Stanley, Carl Rhodes, and Richard Mesic have generated plots of this general character, but the plots shown here are purely notional.

58. An example from another domain is relevant: We have seen the abject failure of extremely expensive private-sector and government efforts to develop high-functioning, reliable information-technology systems. This has been a problem for the Internal Revenue Service, the FBI, and major commercial banks, among other oganizations.

59. A number of the possible programs for Global Strike five to 15 years from now have considerable technical risks. The Air Force and the Army, for example, are both considering programs to build sophisticated missiles with boost-glide capability. Such missiles are quite plausible, but some of the enabling technologies are at an early stage of development.

60. The controversial history of strategic bombing is analyzed in a book by Robert Pape (Pape, 1996). The most successful example of strategic bombing is probably that in the conflict over Kosovo, although assessments differ on the relative effects of the bombing, the threat of ground-force invasion, and intervention by Russia (Hosmer, 2001; Lambeth, 2001).

61. Some of the difficulties are described in recent work done as part of a Ph.D. dissertation by Zoltan Jobbagy (Jobbagy, 2006). That reference also contains an extensive bibliography. For a discussion of analytical issues, see also Davis (2001) and Davis and Kahan (2007). For an official description of effects-based operations, which is notable in part for its failure to address uncertainty, see a recent monograph by US JFCOM (Joint Warfighting Center, 2006).

62. Some care must be taken in estimating these risks, because even if the new capability provided by an option fails in practice, the ability to accomplish the mission may not be too severely affected when alternative concepts of operations are available that would not need those capabilities.

63. MDA requested that RAND review its approach to investment planning, relating it to capabilities-based planning, as discussed in earlier RAND work (Davis, 2002). An unpublished report on that review led to a project on investment-planning methods and tools.

64. The mission statement specifies a layered defense and capability for defense in all phases of flight. Such specificity belongs in a solution rather than a mission statement, but it reflects the drafters' desire to require flexibility and depth of capability.

65. Such issues are discussed in a recent academic study (American Physical Society Study Group, 2003).

66. This reflects discussions with Lt. General Ronald Kadish (USAF, retired) and Lt. General Trey Obering (USAF), the current and past commanders of MDA.

67. The Symposium on Complex System Engineering was organized by Russ Abbott of Aerospace and California State University, Los Angeles and supported by Aerospace, MITRE, and RAND. It was held at RAND's Santa Monica, Calif., head-

quarters in January 2007. A very brief discussion of conference themes is given in a briefing by Abbott posted on his web site, http://cs.calstatela.edu/wiki/images/b/b1/Abbott.ppt.

68. Multiresolution data entry is closely related to multiresolution modeling (Bigelow and Davis, 2003; Davis and Henninger, 2007; National Research Council, 2006).

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