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TECHNICAL REPORT

A Portfolio-Analysis Tool for Missile Defense (PAT–MD)

Methodology and User's Manual

Paul Dreyer, Paul K. Davis

Prepared for the Missile Defense Agency

Approved for public release; distribution unlimited

NATIONAL DEFENSE RESEARCH INSTITUTE

The research described in this report was prepared for the Missile Defense Agency. The research was conducted in the RAND National Defense Research Institute, a federally funded research and development center supported by the Office of the Secretary of Defense, the Joint Staff, the unified commands, and the defense agencies under Contract DASW01-01-C-0004.

Library of Congress Cataloging-in-Publication Data

Dreyer, Paul, 1973-
A portfolio-analysis tool for missile defense (PAT–MD) : methodology and user's manual / Paul Dreyer, Paul K. Davis.
p. cm.
"TR-262."
Includes bibliographical references.
ISBN 0-8330-3801-X (pbk. : alk. paper)
1. Ballistic missile defenses—United States—Costs. 2. Investment analysis. I. Davis, Paul K., 1943– II.Title.

UG743.D7435 2005
358.1'746'0973—dc22

2005009139

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Published 2005 by the RAND Corporation
1776 Main Street, P.O. Box 2138, Santa Monica, CA 90407-2138
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Preface

This report documents the underlying methodology of a portfolio-analysis tool developed by the RAND Corporation for the Missile Defense Agency's Director of Business Management Office (MDA/DM). It also serves as a user's guide.

The report will be of interest primarily to MDA officials and analysts who develop and assess the agency's programs of research, development, testing and evaluation, and deployment for their ability to generate real-world ballistic-missile defense capabilities. It should also be useful to some of MDA's contractors, as well as to officials and analysts throughout the Department of Defense, because portfolio-analysis methods and tools are sorely needed for implementation of capabilities-based planning.

This is the first version of a new tool, so questions and comments are especially welcome and should be addressed to the project leader (pdavis@rand.org) or the principal developer (dreyer@rand.org) at RAND's Santa Monica, CA, office.

This research was performed in the Acquisition and Technology Policy Center of the RAND National Defense Research Institute (NDRI). NDRI is a federally funded research and development center sponsored by the U.S. Department of Defense. It conducts research for the Office of the Secretary of Defense (OSD), the Joint Staff, the Unified Combatant Commands, the defense agencies, the U.S. Marine Corps, and the U.S. Navy. For more information on the center, contact its director, Philip Antón (by e-mail, Philip_Anton@rand.org, or by mail at RAND, 1776 Main Street, Santa Monica, CA, 90407-2138, telephone (310) 393-0411).

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Summary

RAND's Portfolio-Analysis Tool for Missile Defense (PAT-MD) was built to support high-level discussion and decisionmaking in the Missile Defense Agency (MDA) by providing summary portfolio-style characterizations of alternative investment options. These characterizations may involve projected capabilities in different missions, such as defense of the homeland from long-range missile attacks; the balance of emphasis across missions; the managing of risks; and economic considerations such as relative cost-effectiveness. The portfolio-style depiction attempts to provide a holistic, top-level view across all of these considerations and is intended to facilitate discussion of program tradeoffs and adjustments. Equally important, PAT-MD and a companion tool, RAND's Capabilities Analysis Model for Missile Defense (CAMMD), make it possible to "zoom" to higher levels of detail in order to understand the basis of high-level characterizations and how they would change if assumptions or priorities were changed.

Characterizing Investment Options with PAT-MD

PAT-MD is a tool that can accommodate many different choices made by the user. For example, a typical measure of ballistic-missile defense system (BMDS) capability is the fraction of an attack that would be intercepted. With PAT-MD, this can be generated separately for cases with different numbers of attackers and different countermeasure capabilities. Such capabilities can also be characterized separately for the missions of homeland defense (HD), defense of friends and allies (DOFA), and defense of deployed forces (DODF). And, of course, a given investment option generates capabilities over time, so potential capability can be assessed at different nominal slices of time, such as 5, 10, or 15 years into the future.

In characterizing risk, a typical application of PAT-MD may distinguish between strategic and technical/programmatic risks. An investment program might mitigate the former by assuring strategic adaptiveness—i.e., the ability to adapt to changes of mission emphasis, the emergence of new threats, the pace at which particular threats emerge, or positive opportunities. Technical and programmatic risks may be mitigated, for example, by competing approaches, competing contractors, and special risk-reduction investments.

PAT-MD can highlight a variety of budget considerations, including an investment option's cost in the next fiscal year, over the future years defense program (FYDP), or over 20 years. The costs might be expressed in nominal dollars, constant dollars, or present-value terms.

A classic issue in portfolio-style thinking is *balance*. Will a given investment program provide an appropriate balance of capabilities across missions, one consistent with strategic

priorities? Does the program balance the need to achieve effectiveness with the desire to reduce technical and programmatic risks? This issue is particularly troublesome for MDA because the capabilities needed for effective defense are especially demanding.

Finally, an important element of portfolio-style summary assessments is the providing of measures of relative cost-effectiveness. Analysts may use PAT-MD for marginal or chunky marginal analysis and may even use a composite measure of an option's effectiveness that considers the various missions and classes of risk. However, the philosophy underlying PAT-MD is that decisionmakers can best reason about the various issues of balance by seeing information presented simultaneously in various categories (e.g., implications of an investment option for mid-term and longer-term capability for homeland defense, defense of forces abroad and allies, and various types of risk). Rolling such information up into a measure of composite effectiveness and relative cost-effectiveness should be done, if at all, only as part of summarizing and tidying up once issues are well understood.

Consistent with this philosophy, PAT-MD can support a limited exploratory analysis of how robust composite-effectiveness and cost-effectiveness comparisons turn out to be. In practice, this is important, because, unless care is taken, such comparisons can be unduly sensitive to deeply buried mathematical assumptions.

Understanding the Origins of High-Level Assessments

Although it is difficult to quarrel with the need for high-level summary assessments across multiple considerations, such summaries necessarily are the result of many assumptions, some of which are subtle or even insidious. A core feature of PAT-MD is its ability to zoom to higher levels of detail as necessary to understand and second-guess summary judgments. A user observing a top-level scorecard may, for example, ask why an option is characterized as bad in providing capability for homeland defense. PAT-MD can zoom to a level of detail that shows the factors and assumptions that led to that characterization, allowing the user to change many of those interactively, as in "Oh, that 'requirement' wasn't intended to be quite so rigid. What happens if it is relaxed slightly?"

Sometimes, a second or third level of zoom is necessary—even in discussions with high-level decisionmakers—to achieve an adequately deep understanding of the issues. The information needed typically is different in character from that in a portfolio-style display. In particular, it must reflect broad, parametric capabilities analysis such as is provided by the capabilities-analysis tool, CAMMD. Because PAT-MD and CAMMD have been designed to work together, it is easy to zoom from one to the other, either in real time or by providing the relevant CAMMD displays as backups in a briefing.

Underlying Methodology

Tools for decision support provide summary information abstracted from more-detailed considerations. The methods used to abstract the information can materially affect results and impressions about those results, again sometimes in subtle or even insidious ways. It is therefore important for analysts to choose and tune the methods appropriately, and for decisionmakers receiving related analyses to ask related questions. PAT-MD provides five alternative

methods which correspond mathematically to alternative aggregation functions. Which method is appropriate depends on the analysis and context. In some cases, simple linear weighted sums, which are used extensively in utility-based decision-analysis methods, are adequate. In other cases, nonlinear methods are needed to enforce the concept that a system with several critical components will fail if *any* of its critical components fail, a situation that arises frequently in capabilities-based planning. Thus, doing even better than required on one component does not substitute for doing poorly on another, critical component. This has important implications for resource allocation. PAT-MD provides several ways to reflect such system effects. Significantly, PAT-MD also provides a straightforward way to test sensitivity to goals and thresholds in order to ensure that results are not unduly sensitive to arbitrary assumptions.

Acknowledgments

The authors appreciate the careful and constructive reviews of the draft manuscript provided by colleagues Manuel Carrillo and Barry Wilson, as well as many suggestions during the development of PAT-MD from Richard Hillestad, James Bonomo, and Henry Willis.

Acronyms

BMD	ballistic-missile defense
BMDS	ballistic-missile defense system
CAMMD	Capabilities Analysis Model for Missile Defense
DoD	Department of Defense
DODF	defense of deployed forces
DOFA	defense of friends and allies
ESG	engagement sequence group
FYDP	future years defense program
HD	homeland defense
IOC	initial operating capability
MCP	mission-capability package
MDA	Missile Defense Agency
PAT	portfolio-analysis tool
PAT-MD	Portfolio-Analysis Tool for Missile Defense
POM	program-objective memorandum
R&D	research and development
RDT&E	research, development, testing, and evaluation
SDI	Strategic Defense Initiative

1. Introduction

Background

Portfolio-Analysis Tools

A portfolio-analysis tool enables a user to compare and contrast investment options according to a number of quantitative and qualitative criteria, including various types of risk and cost. For strategic planning, such a tool can generate holistic, top-down depictions of alternatives and their implications, perhaps over many years into the future. For investment planning, such a tool can assist in "balancing" programs and in marginal analysis, i.e., assessing where to add or subtract the marginal dollar. Such actions are essential in capabilities-based planning.[1]

The Portfolio-Analysis Tool for Missile Defense (PAT-MD)

PAT-MD is a specialized version of an application-independent portfolio-analysis tool (PAT) tuned for the particular needs of the Missile Defense Agency (MDA). For example, it includes special input tables for building-block concepts that MDA refers to as engagement sequence groups (ESGs). Also, investment options input to PAT-MD are structured to be consistent with MDA's budget data, and PAT-MD's output displays have been designed with the director of MDA and his senior staff in mind. Finally, PAT-MD was designed to work seamlessly with RAND's Capabilities Analysis Model for Missile Defense (CAMMD), a capabilities-analysis model developed in parallel with it (Willis, Bonomo, Davis, and Hillestad, 2005).

PAT-MD has been implemented in Microsoft EXCEL®, an application that is ubiquitous in the analytical world. We have used it in a cross-platform, networked environment comprising both Windows and Macintosh computers.[2] Although an on-the-shelf version of the generic PAT has not yet been created, doing so should be straightforward.

---

[1] Our portfolio-management approach to defense planning was first suggested in an issue paper that discusses how the approach compares to portfolio analysis in the financial world (Davis, Gompert, and Kugler, 1996). We initially applied our approach using the DynaRank portfolio tool (Hillestad and Davis, 1998) to assess alternative defense-planning options, including those embracing what has come to be called transformation (Davis, Kugler, and Hillestad, 1997). Such portfolio methods should play a key role in analysis for capabilities-based planning (Davis, 2002).

[2] Our experience is limited to reasonably modern versions of software: Windows 2000, Macintosh OS 10.3, and Microsoft Office versions 2000 and 2004.

Functionality

PAT-MD is not a model; rather, it is a tool that facilitates capabilities-based planning by presenting information in a way that is useful to senior leaders. It is an empty vessel, but one with many useful features:

1. *Summary scorecards:* PAT-MD generates stoplight charts, simple color-scorecard summaries of how options rate on a number of juxtaposed criteria, including measures of capabilities, risks, and costs. These criteria may be quantitative or qualitative, objective or subjective.
2. *Zooming:* PAT-MD generates its summaries from more-detailed considerations, which can be viewed by zooming in to a level that provides a terse logic and a measure of rigor, even for qualitative assessments. Assumptions may or may not be valid, of course, which implies the need to vary them.
3. *Sensitivity analysis and exploratory analysis:* PAT-MD allows the analyst to recognize key assumptions quickly and to change them interactively. This may be done parameter-by-parameter (e.g., by changing the assumed performance of a particular interceptor), or it may be done more broadly, by invoking a different *set* of criteria and assumptions that represents a different *perspective*, such as greater concern about a future stressful threat than about a mid-term modest threat.
4. *Alternative aggregation methods:* PAT-MD allows the analyst to quickly change the character of the method by which summary depictions are generated from details (i.e., aggregated from the details or rolled up). The method may involve simple linear weighted sums, or it may be nonlinear, assessing an investment option harshly if *any* critical component of capability fails to achieve required performance. PAT-MD provides five different, useful aggregation methods (discussed in Chapter 2).
5. *Qinks to capability analysis and other sources of data:* PAT-MD links to even more-detailed information, such as that of a capabilities model, empirical data, or structured judgments. In practice, PAT-MD is intended to be used together with CAMMD (Willis et al., 2005), so that a user can shift interactively between them while working or while in a group discussion.
6. *V arginal analysis:* Although PAT-MD emphasizes multi-objective scorecards, it can also generate aggregate scores of effectiveness or cost-effectiveness. These can be used for marginal or chunky marginal analysis of how to spend (or cut) the next increment of funds. Such work should always include variation of both assumptions and aggregation methods. The premium is on finding robustly sound choices rather than allegedly optimal strategies that are sensitively dependent on assumptions.
7. *Facilitated operations:* At a more mechanical level, PAT-MD automates a great many tedious spreadsheet operations, enabling users to generate and manipulate portfolio-style scorecards and underlying detailed material quickly. It also provides a variety of graphics to assist in visualizing the capabilities of the investment options.

Chapters 2 through 5 describe PAT-MD, using notional examples and data for the missile-defense problem in the context of MDA.

Organization of the Report

Chapter 2 introduces the principal concepts and terms in PAT-MD and presents a schematic overview. Chapters 3 and 4 describe PAT-MD's input and outputs in user-manual detail. Chapter 5 discusses selected methodological issues, especially aggregation methods, in more detail, along with methods for marginal and chunky marginal analysis. Chapter 6 presents some concluding observations, including suggestions and cautions for users and some challenges for future work. Appendix A summarizes features of PAT-MD and compares them with those of DynaRank (Hillestad and Davis, 1998). Appendix B shows how to develop a portfolio view from the PAT-MD template. Users may wish to use the template and Appendix B early, especially if they prefer to learn by doing.

2. Overview of PAT-MD

The Black-Box Perspective

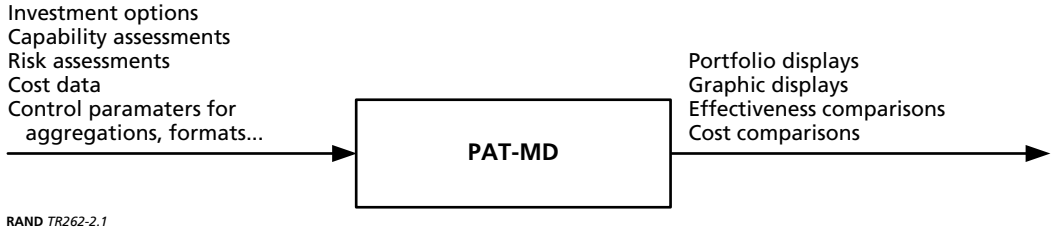
From a black-box perspective, PAT-MD takes a series of inputs and generates outputs in the form of portfolio-style tables and various charts and graphics (Figure 2.1).

Many of the inputs, such as the investment options to be compared, are what one might expect. For our purposes, an investment option specifies the investment in each budget category for each year covered by the analysis. It will include investments in the development and deployment of the many components of the ballistic-missile defense system (BMDS), e.g., particular interceptors, radars, and battle-management systems. An investment option will also include year-by-year investments in basic research and development (R&D) and in the general infrastructure associated with MDA's efforts. Investment options may differ, for example, in the components developed and the speed with which they are developed, in what will be deployed operationally, and so on. Investment options may differ simply because of cost considerations, or they may reflect alternative technical architectures or differences in mission priority, such as defending the U.S. homeland rather than defending allies or U.S. forces deployed abroad.

As shown in Figure 2.1, inputs to PAT-MD also include capabilities, risks, and costs for each investment option, as well as control parameters. These determine the form of the outputs, the assumptions and methods used for evaluation and aggregation, and so forth. Because they can strongly affect how the various options stack up in summary displays, it is important to understand them and to vary them systematically before drawing conclusions. This is discussed further below.

At this point, we shall introduce a number of terms and illustrate some basic concepts. A more complete and rigorous treatment is presented in Chapter 5.

Figure 2.1
PAT-MD as a Black Box



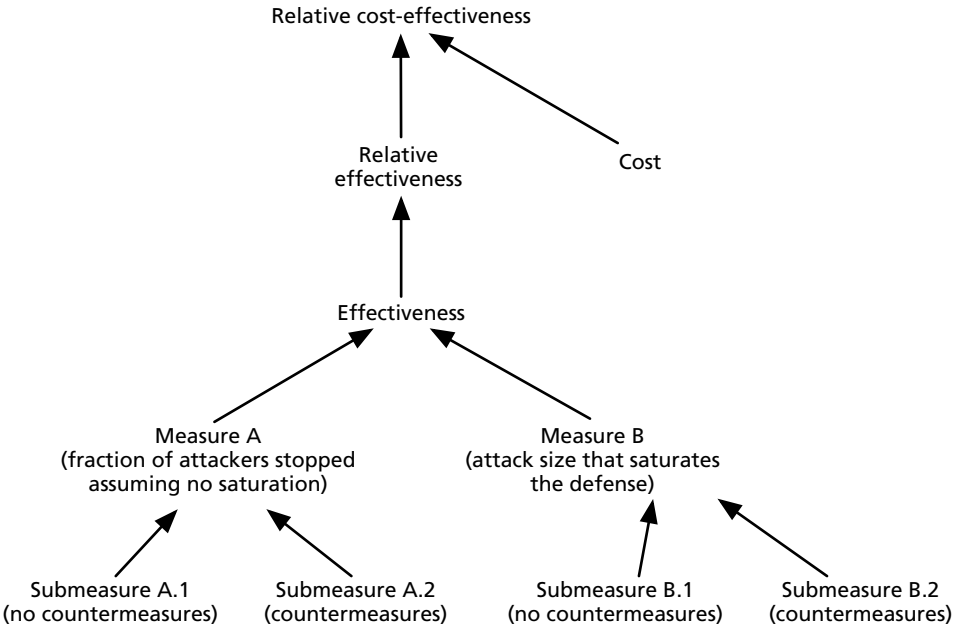
Fundamental Terms and Concepts in PAT-MD

The Baseline

Each investment option is evaluated in PAT-MD on a number of criteria called *measures*, each of which may be determined by multiple *submeasures*. Submeasures have *raw values* specified in the input data for each investment option. Usually, PAT-MD maps these raw values into *scores* by comparing them with goals.[1] These scores indicate "goodness," or utility. Submeasure scores are combined to generate the scores of measures, which are then combined to generate a composite score called *effectiveness*. Each of these steps is mere mathematics, but each involves important assumptions. We can illustrate the basics with a simple, contrived example, shown in Figure 2.2.

In this example, each investment option is evaluated in PAT-MD by only two measures relating to capability and also to cost (e.g., nominal dollars over a six-year future years defense program (FYDP) period or over 20 years). The option's goodness is measured by how well its defenses could stop a small attack (Measure A) and how large an attack could be engaged before the defense was saturated (Measure B). Goodness also depends on cost. Both measures are assessed for two cases, a simple attacker and one with substantial countermeasures. Success in these two cases is represented as submeasure data. As indicated at the bottom of Figure 2.2, as one moves upward, the aggregations are assumed to be simple averages.

Figure 2.2
An Example Illustrating Measures, Submeasures, and Combining Rules



Assumptions:
Each measure's score is the simple average of its submeasure scores.
Effectiveness is the simple average of Measure A and Measure B scores.

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[1] PAT-MD allows the user to adopt any of five different methods for characterizing options. One method, the Rankings method, generates rankings rather than scores (see Chapter 5).

To continue with the example, assume that the data of Table 2.1 apply for a particular investment option, Option 1. The goal scores are user input (an example of control settings). The assumed goal is for a defense that can stop 95 percent of a small attack that has no countermeasures (A.1) or 80 percent of a similar attack that does involve countermeasures (A.2). Another goal is for the defense to be able to handle attacks of 30 missiles without saturation effects, whether or not the attack includes countermeasures (Submeasures B.1 and B.2). With this background, the assumed data for Option 1 (i.e., the raw submeasure values) are 95 percent, 76 percent, 30 missiles, and 13 missiles. These data might have come from the capabilities model (CAMMD) or from a source inside MDA. The bottom row of Table 2.1 shows the *scores* of Option 1 as calculated by PAT-MD. The score for Submeasures A.1 and A.2 are 1.0 (i.e., 95/95) and 0.95 (76/80), respectively. The scores for Submeasures B.1 and B.2 are 1.0 (30/30) and 0.43 (13/30), respectively. Given those submeasure scores, the measure-level scores—assumed in the example to be simple averages—are 0.98 for A and 0.72 for B. Composite effectiveness, E, is simply the average of these, or 0.84. Table 2.2 shows how cost-effectiveness is calculated. This example assumes two options, the second of which is superior. Option 2's effectiveness, calculated in the same way as that for Option 1 in Table 2.1, is 0.95. Options 1 and 2 cost $10 billion/year and $8 billion/year, respectively. In this case, the relative effectiveness for Options 1 and 2 is 0.88 and 1.0, respectively, because Option 2 is better and Option 1 is compared to it (0.84/0.95 = 0.88). Cost-effectiveness is defined as effectiveness divided by cost (i.e., 0.84/10 = 0.084 and 0.95/8 = 0.12). The relative cost-effectiveness of an option is its cost-effectiveness divided by that of the option with the greatest cost-effectiveness. In this case, the relative cost-effectiveness of Option 1 is 0.70.

Table 2.1
Data for One Investment Option

	Submeasure A.1	Submeasure A.2	Measure A	Submeasure B.1	Submeasure B.2	Measure B	Effectiveness
Goal	Stop 95% of attack	Stop 80% of attack		30	30		
Raw values for Option 1	95%	76%		30	13		
Scores for Option 1	**1.0**	**0.95**	**0.98**	**1.0**	**0.43**	**0.72**	**0.84**

Table 2.2
Cost-Effectiveness Calculations

Option	Effectiveness	Cost ($ billions)	Relative Effectiveness	Cost-Effectiveness	Relative Cost-Effectiveness
1	0.84	10	0.88	0.084	0.70
2	0.95	8	1.0	0.12	1.0

The Need to Generalize

The example conveys the basic ideas, but we must now consider how many generalizations might be needed.

1. *Threshold effects*. It is often desirable to reflect thresholds, where a given score is zero unless a threshold is reached. That would correspond to the standard practice of "failing" an activity if it doesn't reach some requirement or acceptable level of performance. Mathematically, reflecting thresholds introduces another simple nonlinearity.
2. *Different importances or priorities.* Since submeasures often represent low-level objectives with different priorities, a measure-level score might be calculated as a weighted linear sum of the measure's submeasure scores, rather than a simple average. Similarly, effectiveness might be a weighted linear sum of the measure-level scores.
3. *System effects.* Since linear sums imply substitutability, scores for systems with individual critical components—i.e., components that must separately meet performance requirements—should be calculated with nonlinear combining rules, such as those discussed in Chapter 5.
4. *Other measures of cost for cost-effectiveness*. What is cost? The cost denominator used in cost-effectiveness might, for example, be a one-year cost, a six-year FYDP cost, or a 20-year (life-cycle) cost. It might be expressed in nominal or real dollars. It might or might not be in discounted dollars (i.e., in present-value terms). It might consist of R&D costs, deployment costs, or both. Various combinations could also be used, such as a weighted average of one-year costs for the next fiscal year, for the next six years, or for 20 years.

The primary point is that what may at first seem straightforward—providing a calculation engine for making multi-criteria assessments and cost-effectiveness comparisons—turns out to be complex in practice.

Scoring and Aggregation Methods

To provide flexibility in dealing with the issues noted above (possible generalizations), PAT-MD has five built-in methods for establishing scores and aggregating upward. Ideally, only one such method would be needed, thus simplifying the analysis. However, theory and experience tell us that alternative methods are needed—perhaps even more than those we have included in this version of PAT-MD.

Three of the five are our core methods, which we recommend for most MDA applications. Outlined briefly in Figure 2.3 and Table 2.3, they all include the concepts of thresholds, goals, and nonlinearity. Chapter 5 provides details on all five methods.

PAT-MD Core Methods Using Thresholds, Goals, and Nonlinearity

Table 2.3 shows how submeasure and measure scores are calculated for the three core methods (*Thresholds, Weakest Link,* and *Weak Thresholds*) and how the composite score (*effectiveness*) is calculated from measure scores (the scores of the various measures). First, raw submeasure values are mapped into submeasure scores, as shown graphically in Figure 2.3. The mapping is linear except that the score is zero for raw values below a threshold and constant for raw values above the goal. This is a simple approximation of an S-curve function, as used in earlier RAND work (Hillestad and Davis, 1998). Note that the curve can be reversed if the submeasure represents a parameter for which less is better (e.g., cost, expected number of leakers).

Figure 2.3
Mapping of Raw Submeasure Values into Scores

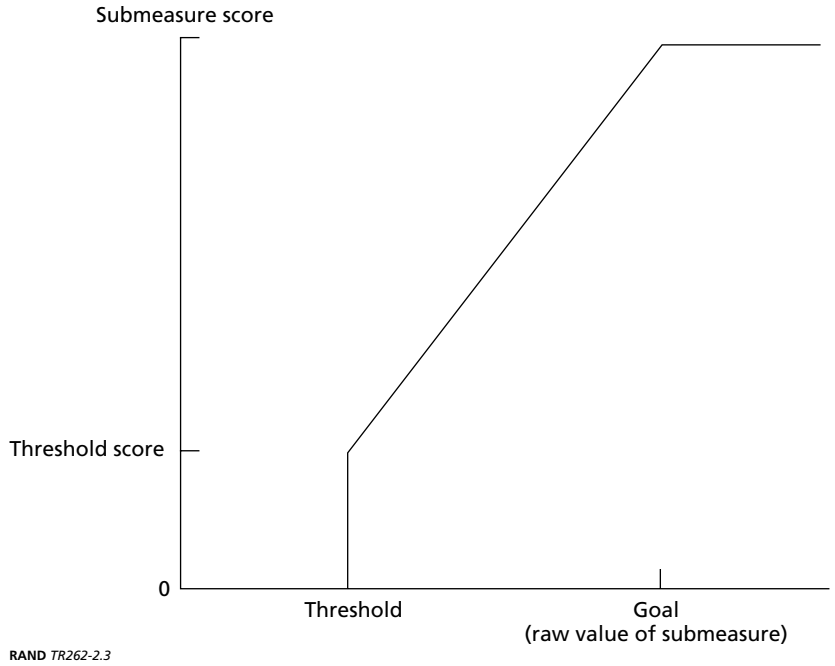


Table 2.3
Core Aggregation Methods in PAT-MD

Method	Submeasure Scores	Measure Scores	Composite Effectiveness	Comment
Thresholds	See Figure 2.3	0 if any raw value does not reach threshold; otherwise, a weighted sum of submeasure scores	Weighted sum of measures' scores	Appropriate if submeasures represent critical components of capability
Weakest Link[a]	See Figure 2.3	Minimum of submeasure scores	Minimum of measure scores	Appropriate if both submeasures and measures are individually critical
Weak Thresholds	See Figure 2.3	Weighted sum of submeasure scores	Weighted sum of measures' scores	Appropriate if submeasures are not all critical and measures are not all critical

[a]This method was introduced in DynaRank (Hillestad and Davis, 1998).

Next, measure-level scores are calculated from submeasure scores. Here the methods differ (Table 2.3). The default method (Thresholds) characterizes the measure-level score as zero if *any* of the raw values do not reach the threshold value defined for each submeasure. This is intended to enforce the concept that a system fails if any of its critical components fail; doing better on one component does not substitute for failing on another.[2] This method

[2] This emphasis on mission-system analysis (Davis, 2002) is consistent with thinking in terms of what the Department of Defense (DoD) sometimes calls mission-capability packages (MCPs) (Alberts, Garstka, and Stein, 1999). Operational commanders routinely try to identify all of the critical enablers of their proposed operation. In contrast, standard decision-analysis methods typically employ linear-weighted-sum techniques, which implicitly evaluate systems as though further improving one component of a system can substitute for improving another.

is appropriate if the submeasures do happen to be individually critical. The Weakest Link method is similar but even more stringent in some respects. It assesses measure-level score to be the lowest of the measure's submeasure scores and it assesses composite effectiveness as the lowest of the measure scores. The third method, Weak Thresholds, is less draconian than the others. Both measure-level scores and composite effectiveness are simply weighted sums. A submeasure that does not reach the threshold value will contribute zero to its parent measure score, but the measure score will not be zero (unless all submeasure scores are zero). This method is suitable if the submeasures or the measures are not individually critical.

These methods are essentially heuristic techniques, and no claims are made about achieving "optimal" decisions (see also Chapter 5). Evaluating something with rigid thresholds or saying that a system with several components has zero value if even one of its components is inadequate simplifies reality. In practice, these are effective heuristics, well understood by decisionmakers. As an example, a tough military commander may consider that one of his units "failed inspection," even though the unit did rather well in many respects. An operational commander in charge of a ballistic-missile defense system (BMDS) would regard the system as operationally useless if its kill vehicles did not work, even if the system's radars, infrared sensors, missiles, and battle-management capabilities were superb.

As discussed in Chapter 5, other threshold-related possibilities exist for aggregations. Nevertheless, we believe that the set of threshold-related alternatives provided is adequate; however, this will be reassessed after more experience is gained with PAT-MD.

Alternative Methods That Do Not Involve Thresholds

PAT-MD includes two other aggregation methods that can be useful in certain cases. Both are defined more fully in Chapter 5. The Goals method calculates a measure's score as simply the weighted fraction of the submeasure goals achieved by the option. Here, composite effectiveness is a weighted linear sum of measure effectiveness. The Rankings method focuses on a relative ranking of investment options, rather than on a comparison of scores. It uses a Borda count method that may be familiar to readers from other domains, such as voting or sports polls.

Navigation, Inputs, and Outputs in PAT-MD

This section provides an overview of how one navigates within PAT-MD, the inputs that must be provided, and the outputs it generates. Subsequent chapters will describe inputs and outputs in much more detail.

Architecture and Navigation

As mentioned earlier, PAT-MD is a spreadsheet tool built in EXCEL, which provides a spreadsheet-paradigm means of entering data and generates many of the graphs and charts needed for the portfolio tool. Underlying the visible aspects of PAT-MD is a great deal of Visual Basic code, which enables many operations that would not be available in an ordinary EXCEL spreadsheet. For example, the user can modify some of the names in output displays, and the changes will be automatically recorded in the underlying data so that the next viewing of the tool will show the new names. Or the user can modify the range of years to be in-

cluded in a display by modifying that range on the output sheet. PAT-MD then can extract the relevant data from that label change and correct the underlying control variable.

EXCEL uses multiple *worksheets* as input and output. The user navigates among sheets by clicking *tabs* or *buttons* in the currently visible sheet. Figure 2.4 is a screenshot showing the bottom of a PAT-MD display and some of its tabs (there are other tabs to the right, reached by clicking on the appropriate arrows). In this figure, the *Summary* worksheet is selected.

Table 2.4 itemizes PAT-MD's sheets, each of which has a tab. They are listed as output sheets or input sheets, although there is some cross-functionality. That is, one can make some changes to input by changing what is basically an output sheet.

Outputs

With this background, we now review schematically the key outputs from PAT-MD to provide a general sense of what PAT-MD does. Figure 2.5 shows our topmost display, the *Summary* sheet. This schematic suppresses many details that will be discussed in Chapter 4.

Rows in the *Summary* sheet contain investment options. Each option is scored in a variety of ways represented by the different columns. As shown in Figure 2.5, the first block of assessments is the color-coded *measure-level summary* table. Blocks to the right contain numeric values, such as selected submeasures that the analyst wishes to highlight, cost data, or effectiveness and cost-effectiveness values.

The essential challenge in working with such high-level depictions is to assure that they use the right representation of issues (i.e., they highlight the right considerations) and that they reflect assessments based on solid, reproducible analysis. The analysis may be based on information from sources such as capability models or on structured estimates of subjective considerations such as program risk. Or it may reflect higher-level subjective judgments.

Figure 2.4
Some PAT-MD Worksheet Tabs

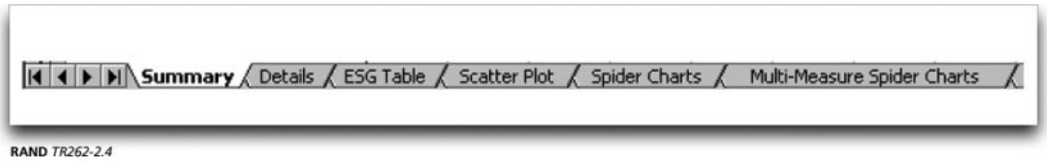
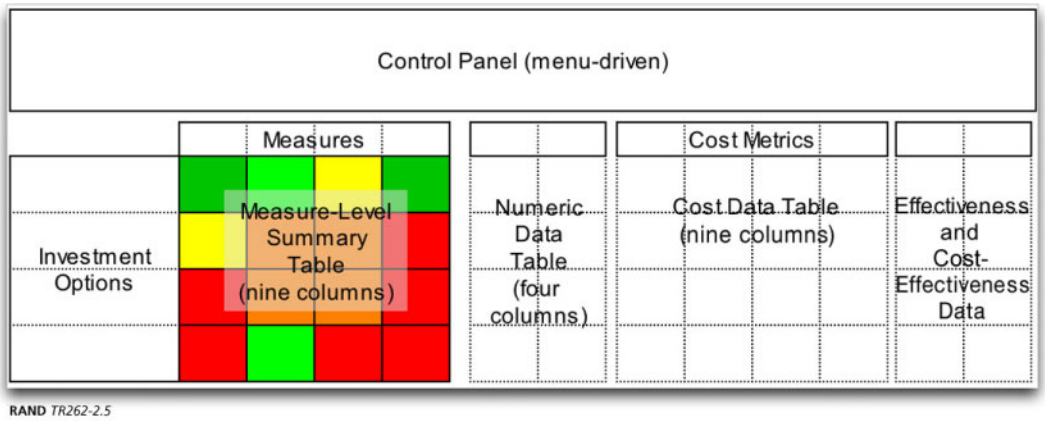


Table 2.4
PAT-MD Output and Input Sheets

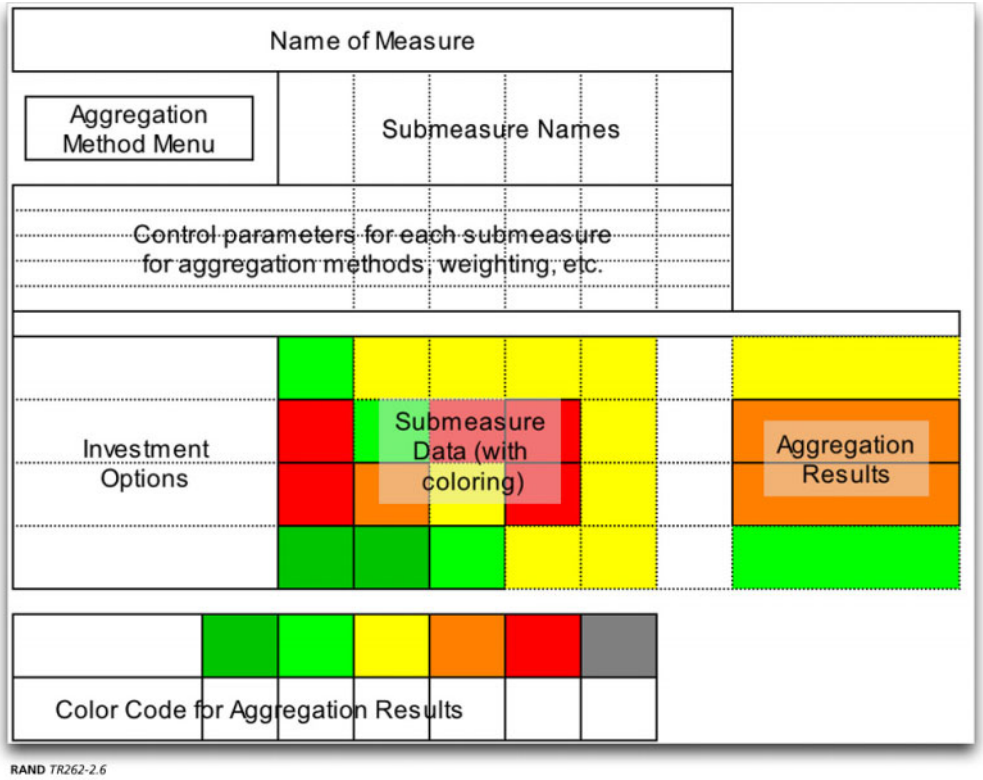
Output Sheets	Input Sheets
Summary	*Data Entry*
Details	*Cost Data*
ESG Table	*ESG Data*
Scatter Plot	*Perspective Cases*
Spider Charts	*Measure Comments and Weights*
Multi-Measure Spider Charts	*Dropdown*
Selected Details	*IOC to Cost Data*
Rankings Table	*Template Builder*
IOC to Cost Output (out of sequence)	

Figure 2.5
Schematic of *Summary* Sheet



PAT-MD users should have the ability to understand why a given cell of the measure-summary display is red rather than green (bad rather than good) or where various numbers came from. This can be done to a significant extent by moving—for a particular measure—to the *Details* sheet, which is a detailed view explaining how the top-level assessment has been generated from subordinate considerations. Figure 2.6 shows this schematically. Like the *Summary* sheet rows, those of the *Details* sheet contain different investment

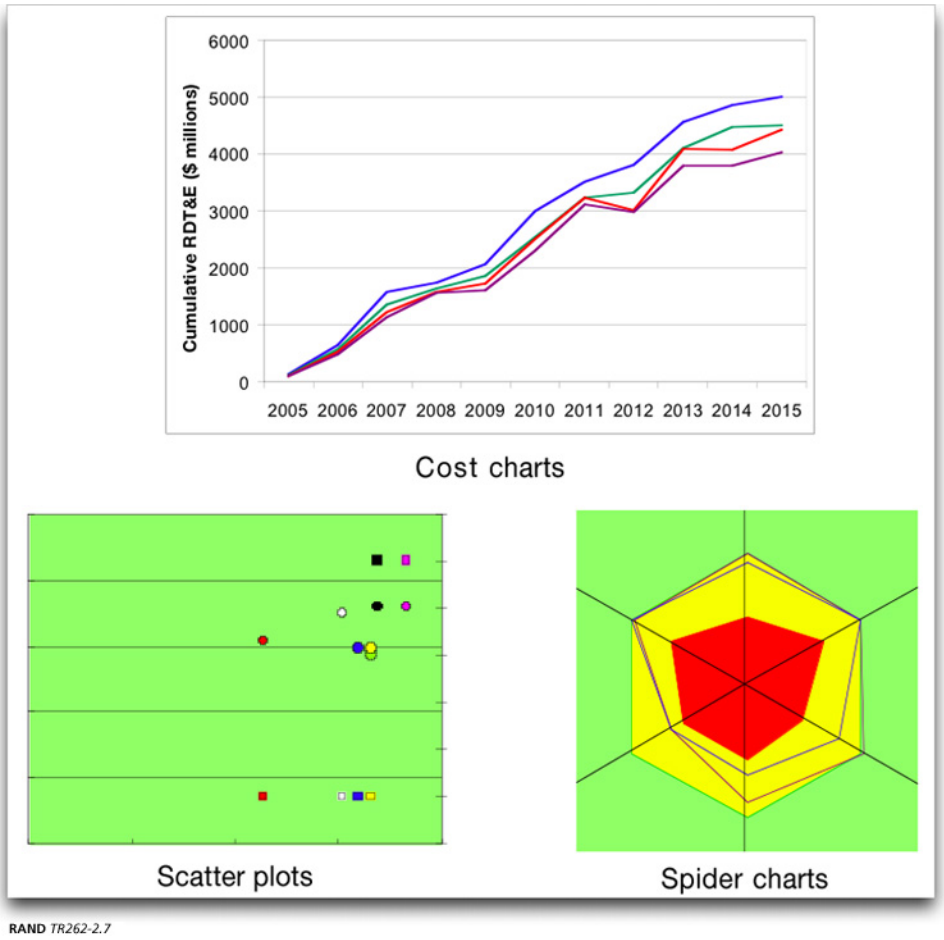
Figure 2.6
Schematic of *Details* Sheet



options, and the columns contain data on the submeasures that constitute a top-level measure. Truly understanding the assessments will sometimes require going into even more detail. This may involve, for example, studying results of exploratory analyses with CAMMD.

PAT-MD also generates numerous graphics, which can be quite useful in the course of analysis and the presentation of results. Figure 2.7 illustrates the range of such graphics, and examples will be discussed more fully in later chapters.

Figure 2.7
Sample Output Displays from PAT-MD



3. PAT-MD Input Sheets

This chapter describes each PAT-MD worksheet and shows either a screen capture or a schematic of each. The figures have letters overlaid indicating particular items that we refer to in the discussion. Names of the worksheets are in italics throughout the chapter.

Data Entry Sheet

PAT-MD data are categorized by measures and submeasures, which usually pertain to the anticipated capability or risk associated with an investment option. Measures are entered as headers of columns (A in Figure 3.1), and the names of the investment options (B) are the headers of the rows. Names of measures, submeasures, and investment options must be consistent across all sheets; if they are not, errors will arise during the generation of the output sheets. The error messages highlight the measure or investment option name that is at fault, enabling the user to fix the problem. Appendix B describes a *Template Builder* sheet that populates the input sheets with a consistent set of measure and investment-option names, thereby reducing or eliminating errors due to label inconsistencies.

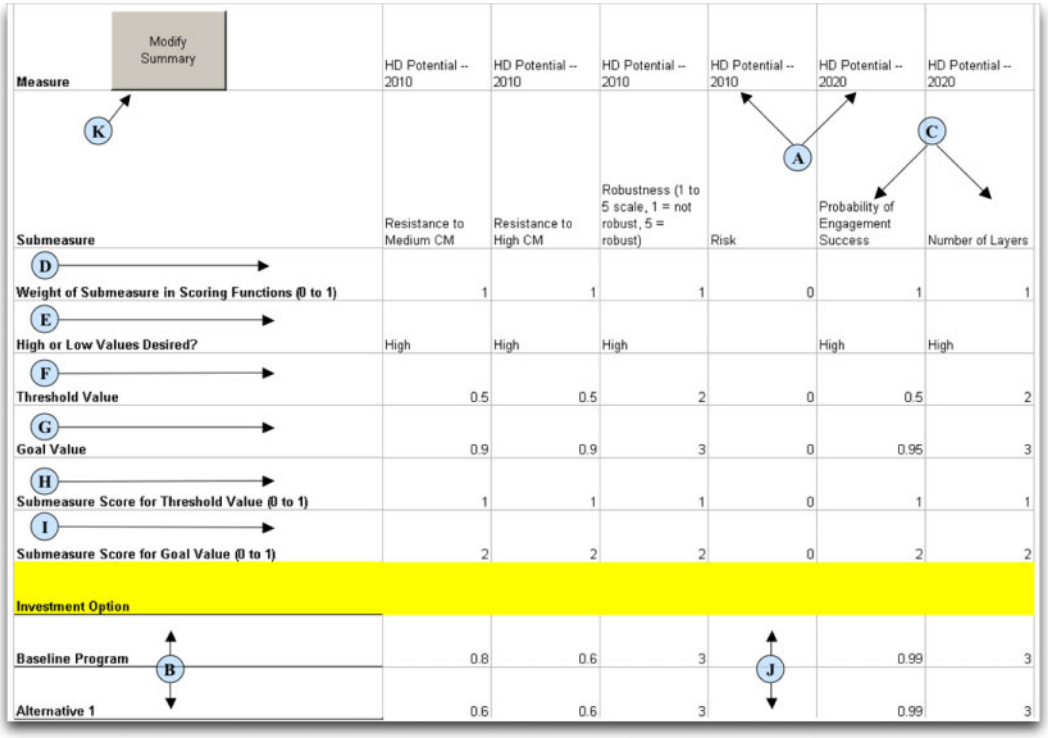
Figure 3.1 presents a subset of the columns; the full *Data Entry* sheet extends rightward as far as necessary. Submeasures are shown for HD Potential–2010 and HD Potential–2020, the homeland defense potential in 2010 and 2020. Measures are aggregations of one or more submeasures (C), such as the probability of engagement success (more properly, the probability that a missile fired at the United States would be intercepted), the number of layers (boost, midcourse, and terminal) in which the incoming missile is engaged, and resistance to countermeasures. The submeasures can be different for different measures.

Much of the *Data Entry* sheet is filled in with submeasure values for the investment options and measures. These data may come from a capabilities model such as CAMMD or from other sources. The rows at the top of the sheet specify the control parameters needed to aggregate from submeasure scores to measure scores and from measure scores to composite scores (effectiveness). How and whether a given control parameter is actually used depends on the scoring and aggregation methods used.

Scoring and Aggregation-Function Control Parameters

The scoring and aggregation functions depend on parameters such as goal values. Four rows in the *Data Entry* sheet are used to set those parameters:

Figure 3.1
***Data Entry* Sheet**



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1. ***Weight of submeasure in scoring functions (0 to 1) (D).*** This row sets the relative weight of the submeasure when calculating the measure score given in the *Summary* sheet's measure-summary table. A weight of zero means that the submeasure is not considered.[1] Thus, a submeasure can be built in but then toggled on or off as appropriate for a particular analysis. This parameter should not be interpreted to specify relative weight across measures. It provides only the relative weights of submeasures within a given measure. The relative weights of different measures for further aggregation calculations are specified in the *Measure Comments and Weights* sheet described below.
2. ***High or low values desired? (E).*** Users may wish to input some measures or submeasures for which more is better and some for which more is worse. PAT-MD allows this, but the user must specify. This row of the *Data Entry* table takes two possible values: high and low. For example, if the submeasure is defended area, the appropriate value would be high, because defending more area is good. If the submeasure is the desired date of initial operating capability (IOC), low values would be good (the sooner the better).
3. ***Threshold value (F).*** This is the threshold value described earlier for the Thresholds, Weakest Link, and Weak Thresholds scoring methods.
4. ***Goal value (G).*** This is the goal value used in all of the non–rankings-based scoring functions. For submeasures where high values are desired, the goal value cannot be lower than the threshold value; for submeasures where low values are desired, it cannot be higher than the threshold value.

[1] In this case, under the Goals method, a measure will not fail merely because a zero-weight submeasure fails.

Control Parameters for Cost-Effectiveness

Effectiveness and cost-effectiveness calculations aggregate across measures and must operate on a common scale. Two control parameters specify how to accomplish this. Because the values of the submeasures are on different scales, the two remaining control parameters set up a common scale of effectiveness across submeasures:

1. ***Submeasure score for threshold value (0 to 1) (H).*** This is the score assigned to a given submeasure if its threshold is just reached (for scoring methods that incorporate thresholds).
2. ***Submeasure score for goal value (0 to 1) (I).*** This is the score assigned to a given submeasure if its goal value is reached or exceeded. For scoring methods that incorporate thresholds, the effectiveness score for a value that falls between the threshold value and the goal value is interpolated, depending on how close the value is to the goal. It is good practice to set this value to 1 for all submeasures and then weight the relative contributions of each submeasure using the submeasure-weights row above.

Risk

In addition to the submeasures discussed so far, each measure may include a special submeasure called *Risk* (J). When this submeasure is included and there is text in the cell describing the risk of an investment option with regard to that measure, a flag appears on the *Summary* sheet, highlighting the risk of that particular investment option for that measure. The user can view the text in the risk column on the *Summary* sheet by placing the mouse cursor over the cell containing the flag.

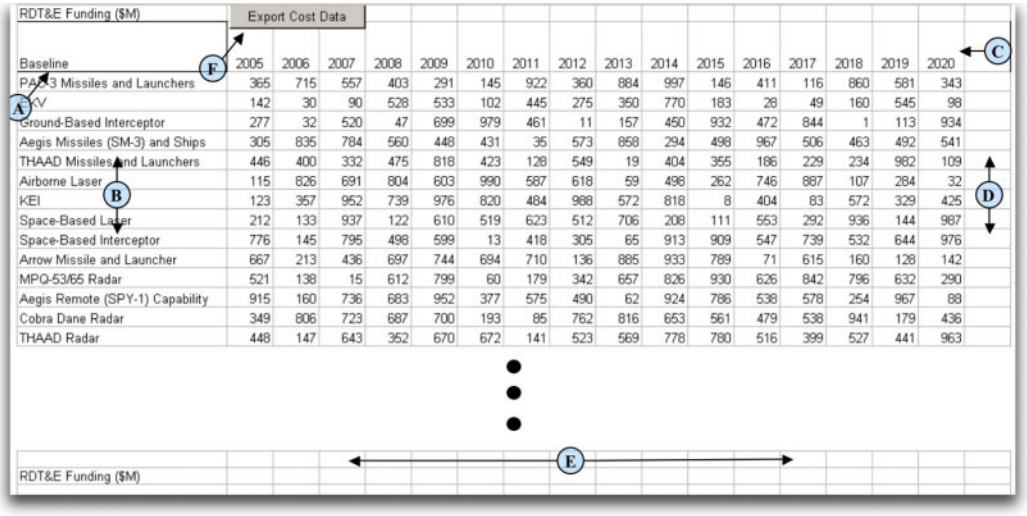
Other Controls

The *Data Entry* sheet is the principal input sheet. However, for convenience in interactive work, many of the items may be viewed and modified on the *Details* sheet, which is nominally an output sheet and is described in Chapter 4. If changes are made there, however, they will not take effect until the user clicks the Modify Summary button (K) on the *Data Entry* sheet or an equivalent button on the *Summary* or *Details* sheet.

Cost Data Sheet

To incorporate cost data into the analysis, the user first identifies the set of BMDS components that are under consideration. In addition, the user may include as "components" catch-all investment categories covering, for example, low-level R&D and continuing general systems engineering. Each investment option, e.g., Baseline (A in Figure 3.2), is defined by the amount of investment over time (which we call *investment streams*) for each BMDS component (B). Each row defines an investment stream for one component, and Figure 3.2 shows a partial list of components, along with fictitious budgets, to illustrate how this sheet functions. These investment streams are broken down by year (C) and by the amount of money allocated to research, development, testing, and evaluation (RDT&E) and the deployment of the BMDS. A single column separates the tables for RDT&E and deployment costs for each investment option (D), with a single row separating consecutive investment options (E).

Figure 3.2
***Cost Data* Sheet**



RAND *TR262-3.2*

Clicking the Export Cost Data button (F) produces two text files that can be exported into CAMMD: RDTECost.txt and DeplCost.txt.

These cost data are used in PAT-MD in cost-effectiveness calculations and for determining the initial operating capability (IOC) dates for both system components and ESGs. Each system component is considered available for deployment when the cumulative investment in it passes a user-defined cost threshold (these thresholds appear on the *ESG Data* sheet described next). An ESG is considered available for deployment when all of the components it comprises are available. Thus, the IOC of an ESG is the maximum of the IOCs of its components.

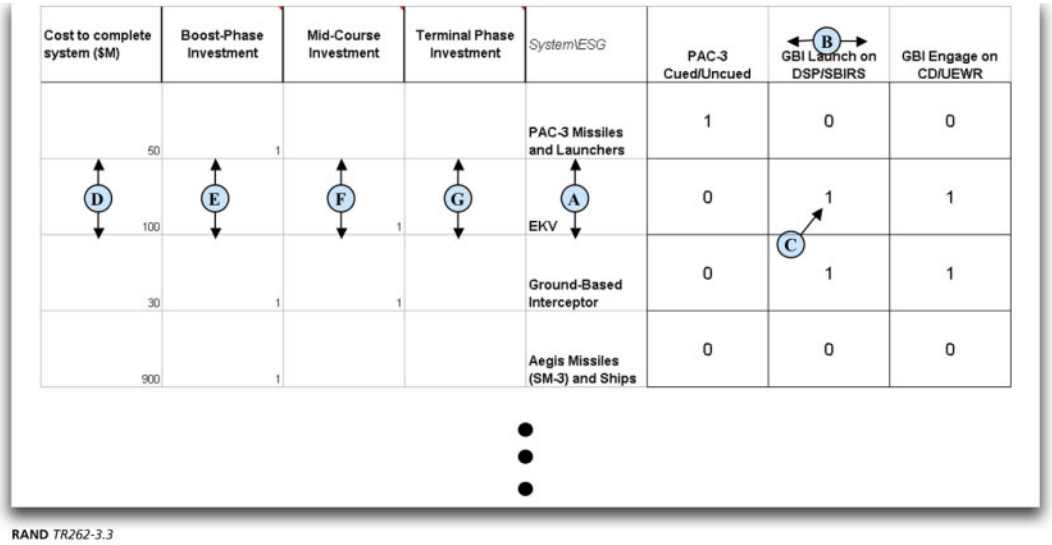
The cost data are presented in a variety of ways on the *Summary* and *ESG Table* output sheets. As explained in Chapter 4, users can present RDT&E, deployment, or total costs on the output sheets for any sequence of years.

ESG Data Sheet

The ESG concept is very important in current MDA thinking. ESGs, however, are not typically the basis for budget line items, nor are they acquired and deployed. Moreover, some components that are acquired and deployed, such as the Defense Support Program's early-warning satellites or Aegis-based radars, could be parts of several ESGs. The *ESG Data* sheet, shown in Figure 3.3, specifies which components constitute ESGs of interest.

For an ESG to be effective, all of the critical components it comprises must be fully developed. This is a core element of system planning. The main piece of the *ESG Data* sheet is a table with the system components as the rows (A) and the various ESGs under consideration as the columns (B). If a component is a critical part of an ESG, there is a 1 in the corresponding cell in the table (C). The column at the left of the table gives the amount of money that needs to be spent for a system to be fully developed (D), as well as a set of three classifi-

Figure 3.3
***ESG Data* Sheet**



cation categories to enable tracking on the *ESG Table* output sheet of the amount of moneyspent in each category for each investment option (E–G). The categorization in this example is by whether a system is involved in boost-phase, midcourse, or terminal intercept, but the user can change this. A system can appear in more than one category.

Perspective Cases Sheet

The results on the *Summary* and *Details* sheets are driven by a particular set of assumptions about the relative weights of the measures and submeasures, as well as the goal and threshold values set for each submeasure. These values can be set directly on the *Data Entry* sheet. However, one of the primary problems with scoring methods that depend on aggregation is that the results depend upon the rules used for aggregating (e.g., the scoring methods, the relative weights, thresholds). As first discussed some years ago (Hillestad and Davis, 1998), a better way to proceed is often to define a *set* of alternative perspectives that span the space of interesting disagreements. Each such perspective has its own assumptions about scoring methods, weights, and so on. Given a set of perspectives, one can do exploratory analysis across that set. If a given investment option ranks highly across different perspectives, it can be considered an especially good candidate. Interestingly, this often occurs because the cold reality of costs dominates the calculations, and people with very different perspectives may find themselves agreeing, albeit grudgingly, on the merits of a particular alternative (Davis, 2002).

The *Perspective Cases* sheet (a portion of which is shown in Figure 3.4) contains the perspectives available for exploration. After it is filled out, the user may shift among perspectives when viewing the *Summary* sheet and may generate comparison displays. The user may specify alternative perspectives on the sheet or may change some of the parameters of an existing perspective in the *Data Entry* sheet, in which case he will have the opportunity to save

Figure 3.4
Portion of *Perspective Cases* Sheet

Emphasis on Measure 1	2			1		
Measure	Measure 1	Measure 1	Measure 1	Measure 2	Measure 2	Measure 2
Submeasure	Submeasure 1.1	Submeasure 1.2	Risk	Submeasure 2.1	Submeasure 2.2	Risk
Weight of Submeasure in Scoring Functions (0 to 1)	0.5	0.5		0.5	0.5	
High or Low Values Desired?	High	High		High	High	
Threshold Value	1	1		1	1	
Goal Value	2	2		2	2	
Submeasure Score for Threshold Value (0 to 1)	0.5	0.5		0.5	0.5	
Submeasure Score for Goal Value (0 to 1)	1	1		1	1	
Emphasis on Measure 2	1			2		
Measure	Measure 1	Measure 1	Measure 1	Measure 2	Measure 2	Measure 2
Submeasure	Submeasure 1.1	Submeasure 1.2	Risk	Submeasure 2.1	Submeasure 2.2	Risk
Weight of Submeasure in Scoring Functions (0 to 1)	0.5	0.5		0.5	0.5	
High or Low Values Desired?	High	High		High	High	
Threshold Value	1	1		1	1	
Goal Value	2	2		2	2	
Submeasure Score for Threshold Value (0 to 1)	0.5	0.5		0.5	0.5	
Submeasure Score for Goal Value (0 to 1)	1	1		1	1	

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the revised set of parameters as a new perspective, which will be entered into this sheet automatically.

To add a perspective directly onto the *Perspective Cases* sheet, one inserts a row with the name of the perspective case (for example, "Emphasis on Measure 1") in the first column below the top eight rows, which contain all of the measure and submeasure names, weights, goal values, and threshold values. This row must also have, for every measure, at least one column with a number representing the weight of the measure (defined on the *Measure Comments and Weights* sheet). (See Appendix B for a worked-out example.) In Figure 3.4, the weights on Measure 1 and Measure 2 are 2 and 1 for the "Emphasis on Measure 1" perspective, and they are reversed for the "Emphasis on Measure 2" perspective.

When a new perspective is selected on the *Summary* sheet, the first rows on the *Data Entry* sheet are automatically replaced by the corresponding rows associated with the perspective on the *Perspective Cases* sheet, and the weights of the measures are updated on the *Measure Comments and Weights* sheet. PAT-MD checks to make sure the measures and submeasures on the *Perspective Cases* sheet match up column-for-column with the corresponding columns on the *Data Entry* sheet.

Measure Comments and Weights Sheet

All the measures are listed in the first column of the *Measure Comments and Weights* sheet (shown in Figure 3.5). Their names must be typed precisely as in the other sheets on which

Figure 3.5
***Measure Comments and Weights* Sheet**

Measure	Comment	Weight
Homeland Defense - 2011	Capability to defend against an attack on the US in 2011	1
Homeland Defense - 2015	Capability to defend against an attack on the US in 2015	1
DOFA/DODF - 2011		1
DOFA/DODF - 2015		1
Technical / Program Schedule Risk		1
Strategic Risk		1
Cost and Risk for DOFA or Homeland		1

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they appear. The next column contains comments describing the measures that appear on the *Summary* sheet when the user passes the cursor over a measure's name. Finally, the third column is used to specify the relative weight of each measure for effectiveness calculations.[2]

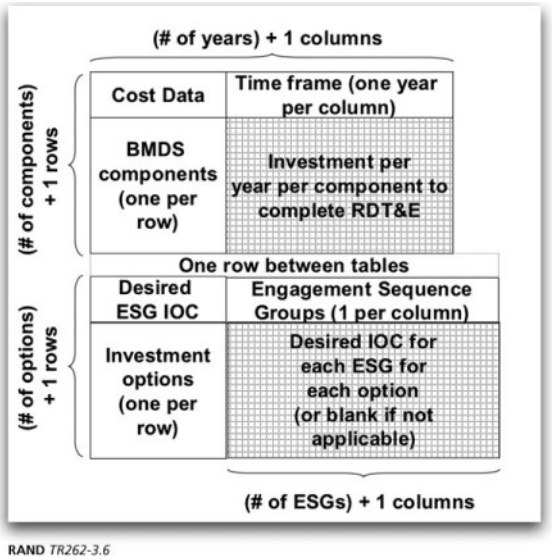
IOC to Cost Data Sheet

In standard use, investment options are the PAT-MD inputs, and those options specify yearly expenditures in each BMDS component over a time period. One of PAT-MD's outputs (informed by other sources, such as CAMMD) is potential capability versus time. Decisionmakers, however, may wish to invert this and specify the dates by which to have IOC of every ESG. In that case, the investment streams needed to achieve these goals is an output. PAT-MD can generate first-cut approximations to these investment streams, based on the current investment schedule for each system component. This is intended as an alternative means of generating investment options, but the output from the *IOC to Cost Data* sheet (sketched in Figure 3.6) is completely independent of the rest of the tool unless the investment options are entered in the *Cost Data* sheet and elsewhere. The raw values in the *Data Entry* sheet for these investment options would still have to be generated by some other means, as well.

The *IOC to Cost Data* sheet has the current investment schedule for each system component. If a component's schedule needs to be accelerated or decelerated, the investment schedule must be compressed or stretched accordingly. For example, assume a system was originally scheduled to be completed in six years, with investments of $150 million for each of the first four years and $200 million for each of the last two years. If the schedule were

[2] The weights can also be specified on the *Summary* sheet (nominally an output sheet) or changed when the perspective is changed. The changes are automatically entered on the *Measure Comments and Weights* sheet when the appropriate update button is clicked.

Figure 3.6
***IOC to Cost Data* Sheet**



accelerated to achieve completion in four years, each year in the new schedule would represent 1.5 years of investment from the old schedule. Thus, the new investment schedule would be $225 million for each of the first two years (Year 1 in the new schedule would have all of the investment from Year 1 in the old schedule plus half of the investment from Year 2 in the old schedule), $250 million for Year 3 (all of Year 4 and half of Year 5 from the old schedule), and $300 million for Year 4 (half of Year 5 and all of Year 6 from the old schedule). This is only a first approximation of how the money would be reallocated, but it is a good starting point. Finally, because stretching or accelerating programs creates instabilities that typically raise overall costs, we include a multiplier to estimate this effect roughly. It is set by using the Cost Multiplier dropdown menu on the *IOC to Cost Data* sheet. The multiplier may be set to 1, assuming that there is no effect, but effects of 5 to 30 percent would not be surprising. Thus, the multiplier should be informed by historical experience.

Below the cost streams on the *IOC to Cost Data* sheet is a table with the investment options as the rows and all of the ESGs as the columns. Each entry in the table corresponds to the desired ESG availability date for a particular investment option. When the Generate Cost Data button is selected, the RDT&E cost data for each investment option appear on the *IOC to Cost Output* sheet. Note that the deployment funds must be entered separately. That is, PAT-MD does not calculate a deployment schedule.

Dropdown Sheet

The entries of all of the dropdown menus are stored on the *Dropdown* sheet. These menus are generated on the fly by PAT-MD, so there is no reason for the user to ever modify this sheet. Indeed, doing so would cause problems, and PAT-MD has not yet been fully "gorilla-proofed."

4. PAT-MD Output Sheets

Summary Sheet

The *Summary* sheet is the main output for PAT-MD. Its overall structure was shown in Figure 2.5. It is shown here in Figures 4.1a and 4.1b, and its components are discussed below.

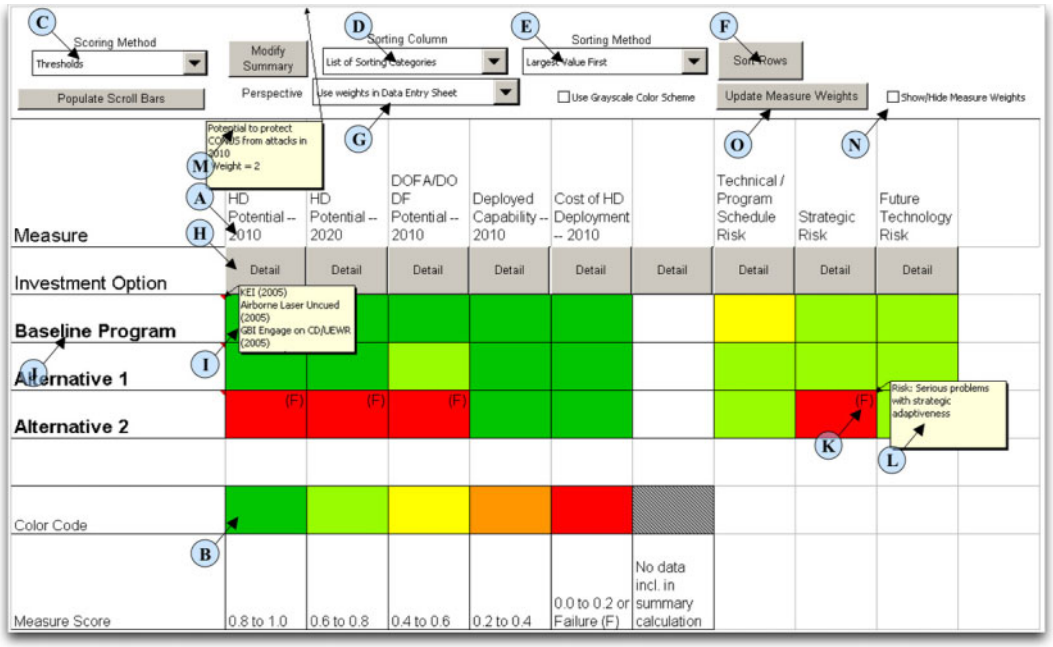
For each investment option, there are three sets or tables of results:

- Nine columns of color-coded measure-summary assessments (Figure 4.1a)
- Four columns displaying numeric data (e.g., cost data or the raw values of important submeasures) (three columns are shown in Figure 4.1b)
- Six columns of cost data (three of which are displayed), with two additional columns presenting the relative effectiveness and relative cost-effectiveness of the investment options (Figure 4.1b).

To include a measure in the measure-summary portion of the sheet (the stoplight chart), one can either use the template to generate the *Summary* sheet (Appendix B) or enter the name of the measure (A in Figure 4.1a) in any of the entries on the first row above the first table. This name must match the name of a measure listed on the *Data Entry* sheet. To include a submeasure in the numeric data table, one enters the name of the submeasure using the format *measure::submeasure* (A in Figure 4.1b). There are three types of cost metrics to be included in the cost-data columns: RDT&E costs only, deployment costs only, and total costs (RDT&E + deployment) (B in Figure 4.1b). The format for the titles of those columns is xxxx cost: yyyy – zzzz ($M), where xxxx = Total, RDT&E, or Deployment, and yyyy and zzzz are the beginning and ending years of the time period under consideration. Alternatively, the column may be titled xxxx Cost: yyyy ($M) if only one year of expenditures is under consideration.

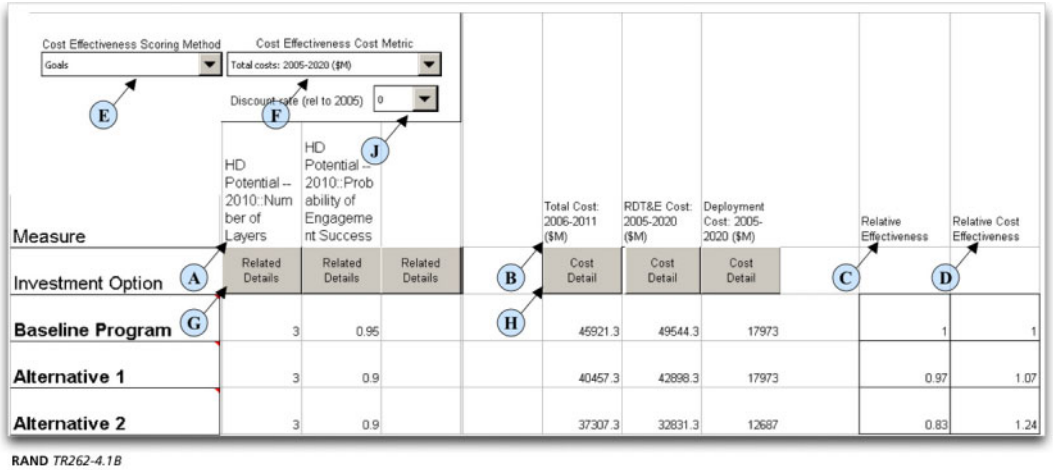
The two final columns are called Relative Effectiveness (C in Figure 4.1b) and Relative Cost-Effectiveness (D). The scoring method used for the effectiveness calculation is selected from the Cost-Effectiveness Scoring Method dropdown menu (E), and the cost metric used in the cost-effectiveness calculation is selected using the Cost-Effectiveness Cost Metric dropdown menu (F). The cost metric may be any of the six cost data columns on the *Summary* sheet, or RDT&E, deployment, or total costs over the entire time period under consideration. In addition, a discount rate can be applied to the cost numbers, using the Discount

Figure 4.1a
Left Side of *Summary* Sheet



RAND *TR262-4.1A*

Figure 4.1b
Right Side of *Summary* Sheet



RAND *TR262-4.1B*

Rate dropdown menu (J). The effectiveness and cost-effectiveness values are scaled so that the topmost investment option has a value of 1 and all other investment options are compared to it.[1]

The colors in the measure-summary table (the stoplight chart) depend on the scoring method chosen by using the Scoring Method dropdown menu (C in Figure 4.1a)—Goals,

[1] Another approach would be to compare to some baseline or some ideal, but that did not seem appropriate for missile-defense options.

Thresholds, Weak Thresholds, Weakest Link, or Rankings. The meaning of each color in the table appears below the table (B in Figure 4.1a). If the scoring method is changed, the sheet will be automatically regenerated under the new scoring method.

The rows of the table may be sorted by the values in any column, including Relative Effectiveness and Relative Cost-Effectiveness. To sort the rows, the user clicks on the Sorting Column (D in Figure 4.1a) or Sorting Method (E) dropdown menu to change the desired sorting column or method (that is, in increasing or decreasing order). The sheet will be automatically regenerated with the rows sorted. Alternatively, clicking on the Sort Rows button (F) will sort the rows and regenerate the sheet. In addition, the user can select a different perspective (see the *Perspective Cases* sheet in Chapter 3), using the Perspective dropdown menu (G).

Above each of the measure-summary columns is a button called Detail (H in Figure 4.1a). Clicking this button brings up the *Details* sheet for the particular measure (column). Similarly, clicking the Related Details button (G in Figure 4.1b) for any of the numeric data columns brings up the details of every submeasure that shares the same measure as the submeasure in that column. Clicking the Cost Detail button (H in Figure 4.1b) generates the tables and charts on the *ESG Table* worksheet, described below.

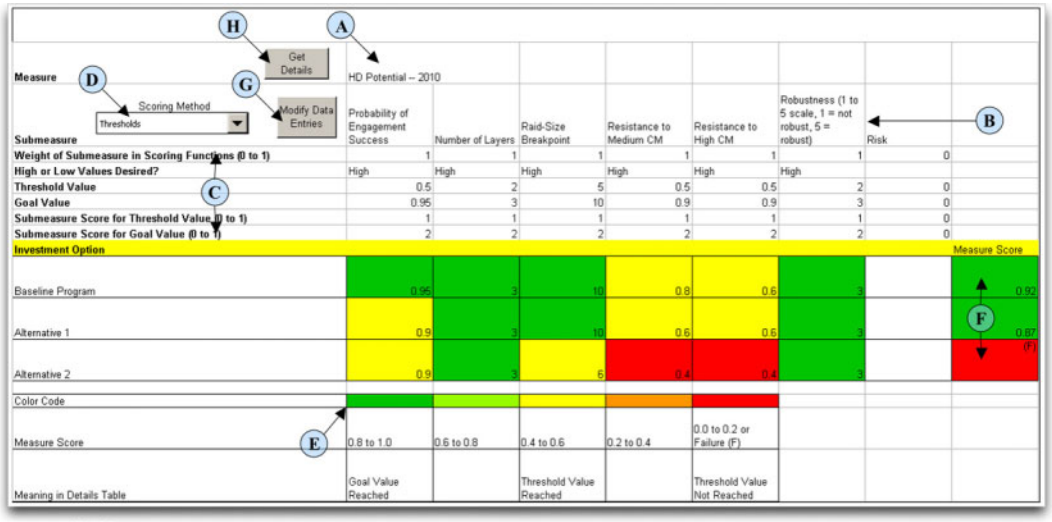
Every investment option has a comment (I in Figure 4.1a) in the cell containing its name (J) (indicated by a red triangle in the upper right-hand corner of the cell). Passing the mouse over that cell brings up a comment that has information on which ESGs are developed under that investment option, as well as when each ESG becomes available. Similarly, if a cell in the color-coded measure-summary table has a flag (K), passing the mouse over it reveals a comment (L) with a description of the option's risk for that particular measure. Finally, passing the mouse over the name of a measure brings up a comment (M) from the *Measure Comments and Weights* sheet describing the measure and giving its weight in effectiveness calculations. In addition, clicking on the Show/Hide Measure Weights checkbox (N) displays the weights of all of the measures under the Detail buttons. The measure weights can be directly modified on the *Summary* sheet, and the sheet can be recomputed by clicking on the Update Measure Weights button (O). This also modifies the weights of the measures on the *Measure Comments and Weights* sheet.

Details Sheet

When a Details button is clicked on the *Summary* sheet for a particular measure (A in Figure 4.2), all of the submeasures (B) for that particular measure are displayed on the *Details* sheet, along with all of the parameters used in the scoring functions (C) associated with the submeasures.

The color of each cell in the table will depend on the scoring method selected. The default scoring method was used to generate the *Summary* sheet, although this can also be changed using the Scoring Method dropdown menu on the *Details* sheet (D). The two-row color code at the bottom of the table (E) explains the coloring scheme used in the table as well as the one used to color the results of the summary calculation on the right-hand side of the table. The latter coloring scheme is identical to the one used in the measure-summary table on the *Summary* sheet for the same scoring method.

Figure 4.2
***Details* Sheet**



RAND *TR262-4.2*

If the Goals scoring method is selected, cells will be green or red depending on whether or not the raw value for the submeasure shown reaches the goal. The rightmost column (F) shows the weighted percentage of goals achieved over all of the submeasures for a given measure, and the color of the cell in the rightmost column is the same as that of the corresponding cell on the *Summary* sheet.

If the Thresholds, Weak Thresholds, or Weakest Link scoring method is selected, cells in the table will be colored red, yellow, or green, depending on whether the raw value does not reach the threshold value, reaches the threshold value but does not reach the goal value, or reaches the goal value, respectively. The color of the cell corresponds to the measure score, the maximum score being 1 (corresponding to green) and the minimum score being 0 (corresponding to red).

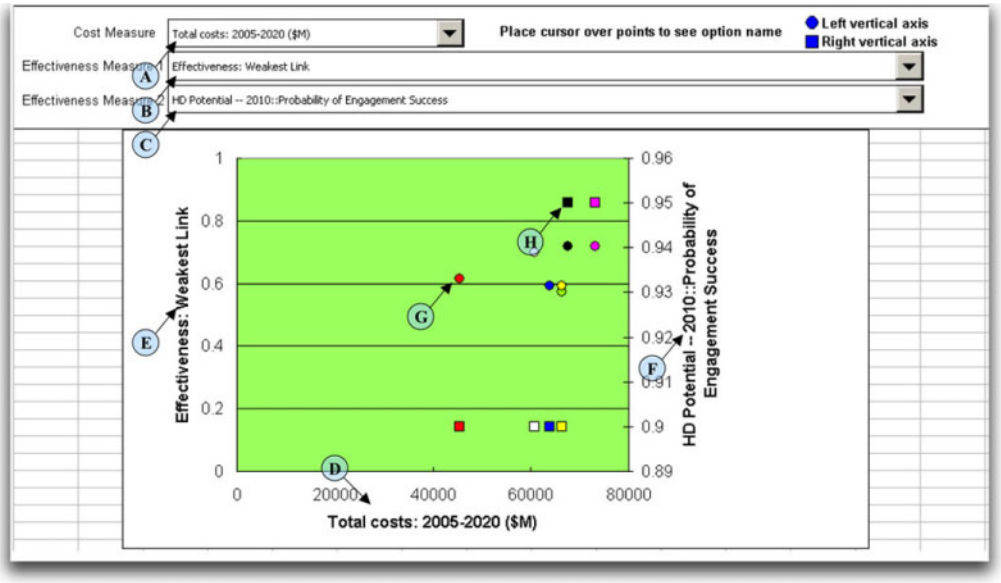
For the Rankings scoring method, each submeasure is ranked individually, with the colors of the cells (from light blue to dark blue) based on how well the investment options rank relative to one another. The rightmost column shows a weighted-average ranking of all of the submeasures, with the color of the cell identical to the color of the corresponding cell in the *Summary* sheet for that investment option and measure.

The raw values and the scoring-function parameters for each submeasure (except the submeasure names) may be edited in the *Details* sheet, even though it is nominally an output sheet. After the data and parameters have been changed, clicking on the Modify Data Entries button (G) will update the *Data Entry* table with the new raw values and will also recreate the *Summary* and *Details* sheets with the new information. In addition, to view the details of another measure, the user can replace the name of the current measure with that of the desired measure and click on the Get Details button (H).

Scatter Plot Sheet

In the *Scatter Plot* sheet, the user can choose a cost metric (A in Figure 4.3) and up to two evaluation metrics (B,C) to be plotted. The cost metrics may be the RDT&E, deployment, or total investment over the entire time period under consideration or one of the user-defined cost metrics on the *Summary* sheet. The evaluation metrics may be submeasures from the *Data Entry* sheet or an effectiveness score using any of the scoring methods. All investment options will be arrayed on a scatter plot with cost as the x-axis (D) and the evaluation metrics presented on one or two y-axes (E,F). Circular points (G) indicate the performance of investment options relative to the first evaluation metric, and square points (H) indicate the second evaluation metric. Passing the mouse over a point on the graph lets the user know which investment option is represented by that point. This output sheet is particularly useful for helping to determine which programs should be dropped because of reduced funding. Starting with a baseline investment option (developing a particular set of ESGs), one can produce investment options corresponding to all subsets of the set of ESGs associated with the baseline. Then, after results are generated from the capabilities model, the scatter plot can highlight (for a particular evaluation metric) which programs should be retained, based on the size of the funding reduction. One simply locates the collection of ESGs with the highest value of the evaluation metric to the left of the new funding limit. Changing the evaluation metric or any of the investment options will automatically regenerate the scatter plot, as will clicking on the Generate Scatter Plot button (not pictured), which should be used when the raw submeasure values or the parameters on the *Data Entry* sheet are changed (the scatter plot pulls values from the *Data Entry* sheet only when the chart is generated).

Figure 4.3
***Scatter Plot* Sheet Showing Two Evaluation Metrics Versus Cost**

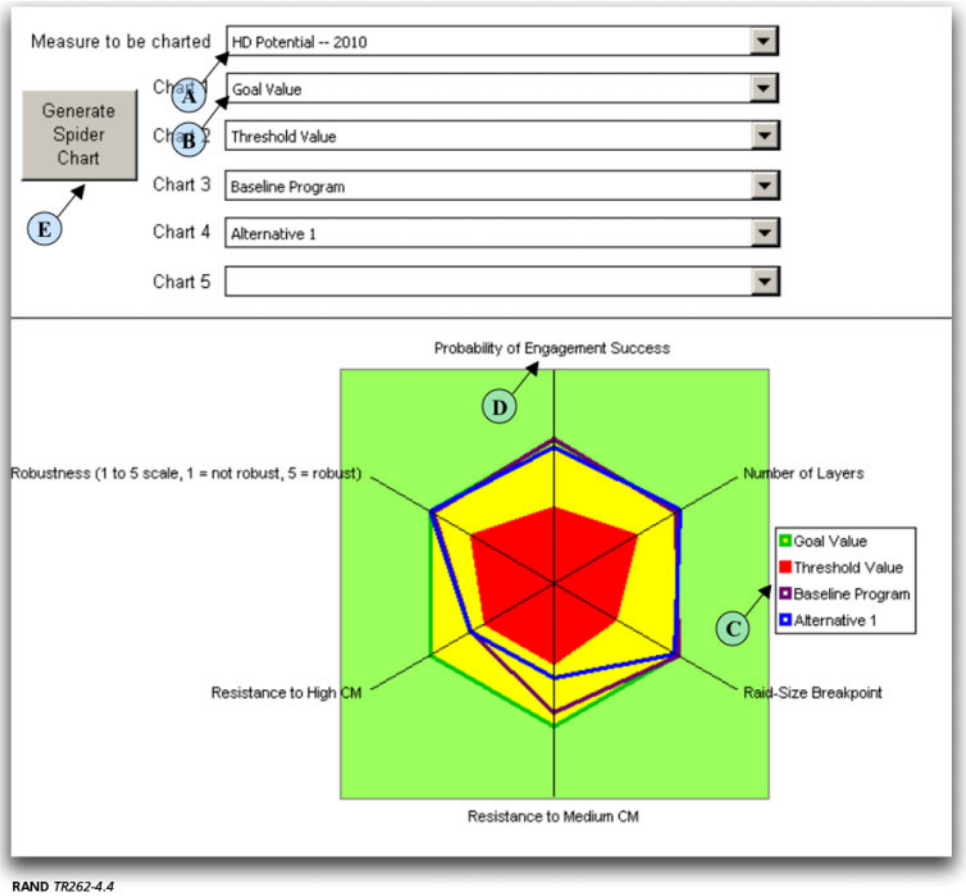


RAND *TR262-4.3*

Spider Charts Sheet

The *Spider Charts* sheet[2] allows the user to select a measure (A in Figure 4.4) and up to four investment options to be included in the spider chart (B,C). Two of the investment options may be replaced by the goal and threshold values for the submeasures in the chart. All of the submeasures (of non-zero weight) of the selected measure are shown as arms of the spider chart (D). The values in the chart are all scaled relative to the investment option (or goal or threshold value) selected as Chart 1. In addition, the raw values of submeasures for which small values are desirable are inverted so that the better the value, the further outward the corresponding point is on the spider chart. There are no values on the axes of the spider chart; the purpose of the chart is to show the relative capabilities of each investment option for a particular measure. Changing the measure to be charted or any of the investment options will automatically regenerate the spider chart, as will clicking on the Generate Spider Chart button (E), which should be used when the raw values or parameters on the *Data Entry* sheet are changed (the spider chart pulls values from the *Data Entry* sheet only when the chart is generated).

Figure 4.4
***Spider Charts* (Radar Charts) Sheet**

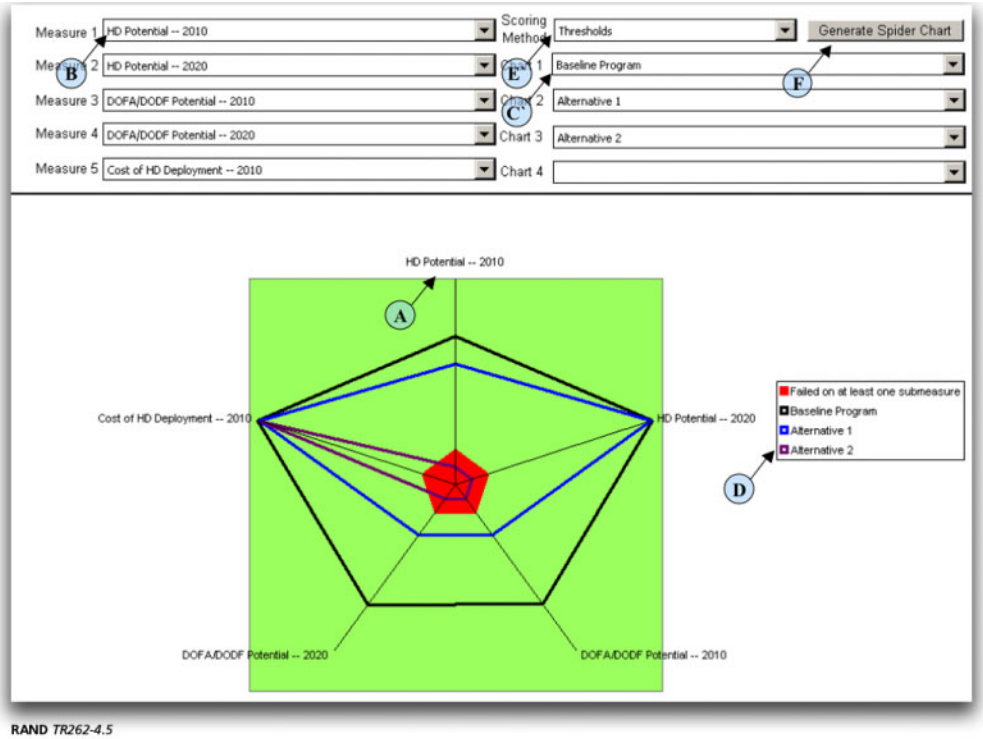


[2] Spider charts are called "radar charts" in some application areas.

Multi-Measure Spider Charts Sheet

Whereas the *Spider Charts* sheet provides a visual depiction of a given measure's submeasures, the *Multi-Measure Spider Charts* sheet (shown in Figure 4.5) provides a visual depiction across different measures. For this sheet, the arms of the spider chart (A) represent different measures (B). For each investment option displayed (C,D), the values along each arm correspond to the average rank for the Rankings scoring method or the measure score for the other scoring methods. With the Thresholds scoring method, if any investment option fails for a submeasure, the value for the corresponding measure falls inside a red polygon representing failed measures. The user can select the scoring method, using the Scoring Method dropdown menu (E), and up to four investment options. Changing the measure to be charted or any of the investment options will automatically regenerate the spider chart, as will clicking on the Generate Spider Chart button (F), which should be used when the raw values or parameters on the *Data Entry* sheet are changed (the spider chart pulls from the *Data Entry* sheet only when the chart is generated).

Figure 4.5
***Multi-Measure Spider Charts* Sheet**

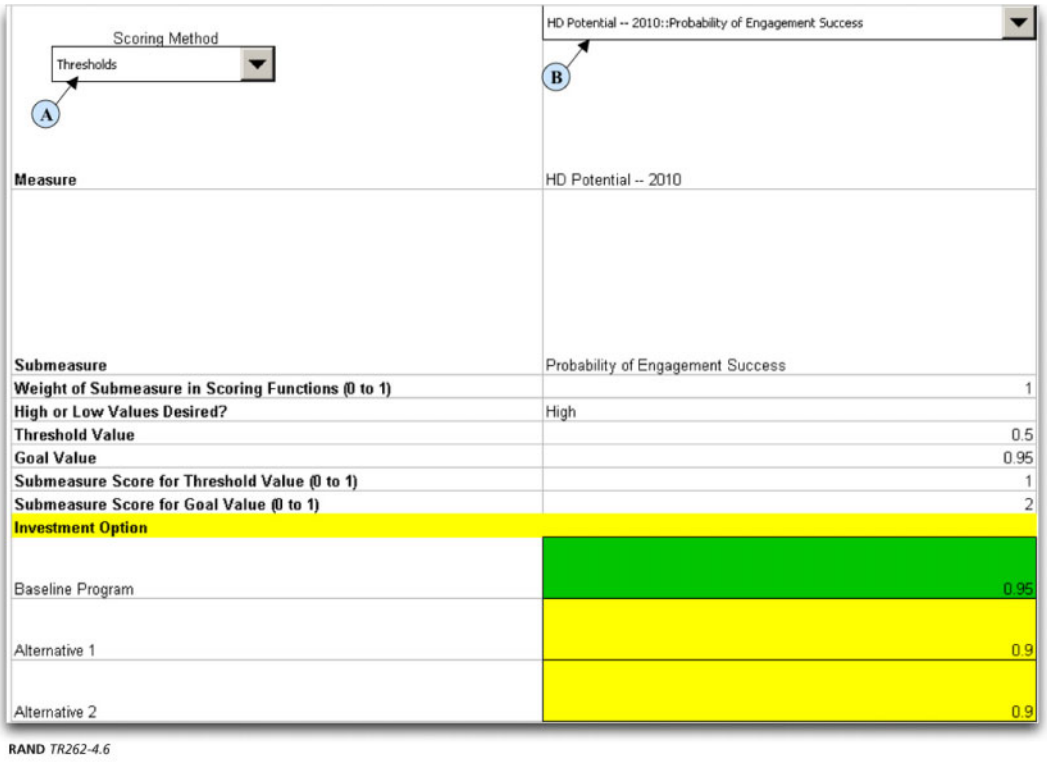


RAND *TR262-4.5*

Selected Details Sheet

The *Selected Details* sheet (shown in Figure 4.6) allows the production of a sheet similar to the *Details* sheet, except that the submeasures in the columns are specially chosen for the purposes of the particular discussion in which PAT-MD is being used, and they may come from different measures. This allows for a more customized display. That is, whereas the *Details* sheet provides a zoom of a particular measure (the basis for a particular column on the *Summary* sheet), this sheet allows the user to tailor a display with details selected from several measures. As with the *Details* sheet, all scoring methods (and the associated coloring schemes) may be displayed on the sheet by using the Scoring Method dropdown menu (A). To display a particular submeasure in a column, the dropdown menu (B) lists all of the submeasures, using the format *measure::submeasure*.

Figure 4.6
***Selected Details* Sheet**



RAND *TR262-4.6*

ESG Table Sheet

The *ESG Table* sheet (sketched in Figure 4.7) contains a collection of tables and charts associated with the cost data for each investment option. Seven tables provide the content for six charts of cost data, which are located to the right of the tables. For each investment option, the tables give, in order, ESGs available (by year), ESG availability date (by ESG), cumulative RDT&E cost (by year), annual RDT&E cost, and a breakdown of expenditures by the categories defined on the *ESG Data* sheet (by year). Only the ESG availability-date table does not have an associated chart. The charts on this sheet are regenerated each time the *Summary* sheet is generated or when the Cost Detail button over any of the cost-data columns on the *Summary* sheet is clicked. Note that the charts on this sheet are not automatically changed when the *Cost Data* or *ESG Data* input sheet is modified.

Rankings Table Sheet

The *Rankings Table* sheet (shown in Figure 4.8) ranks the investment options (E) by effectiveness (or cost-effectiveness, depending on whether the Rank on Cost-Effectiveness checkbox (A) is checked) for each perspective (B) defined on the *Perspective Cases* sheet. The scoring method used to compute effectiveness can be selected by the user from the Scoring Method dropdown menu (C), as can the cost metric to use when computing cost-

Figure 4.7
***ESG Table* Sheet**

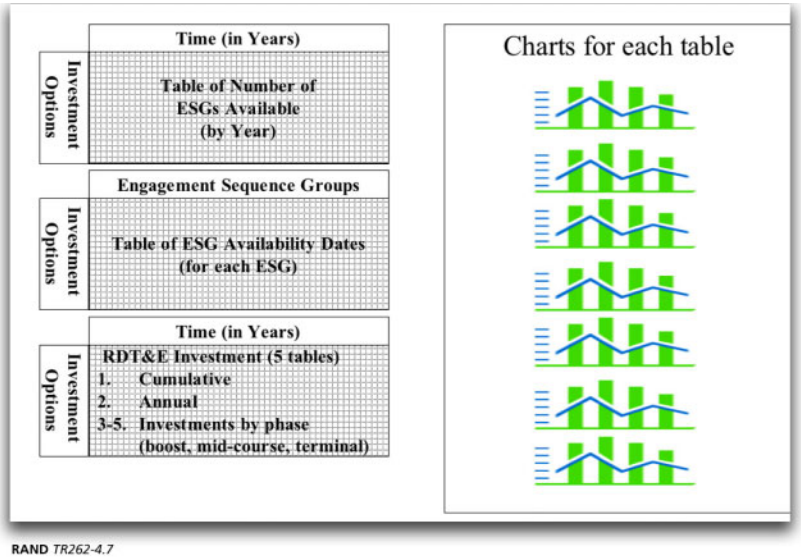
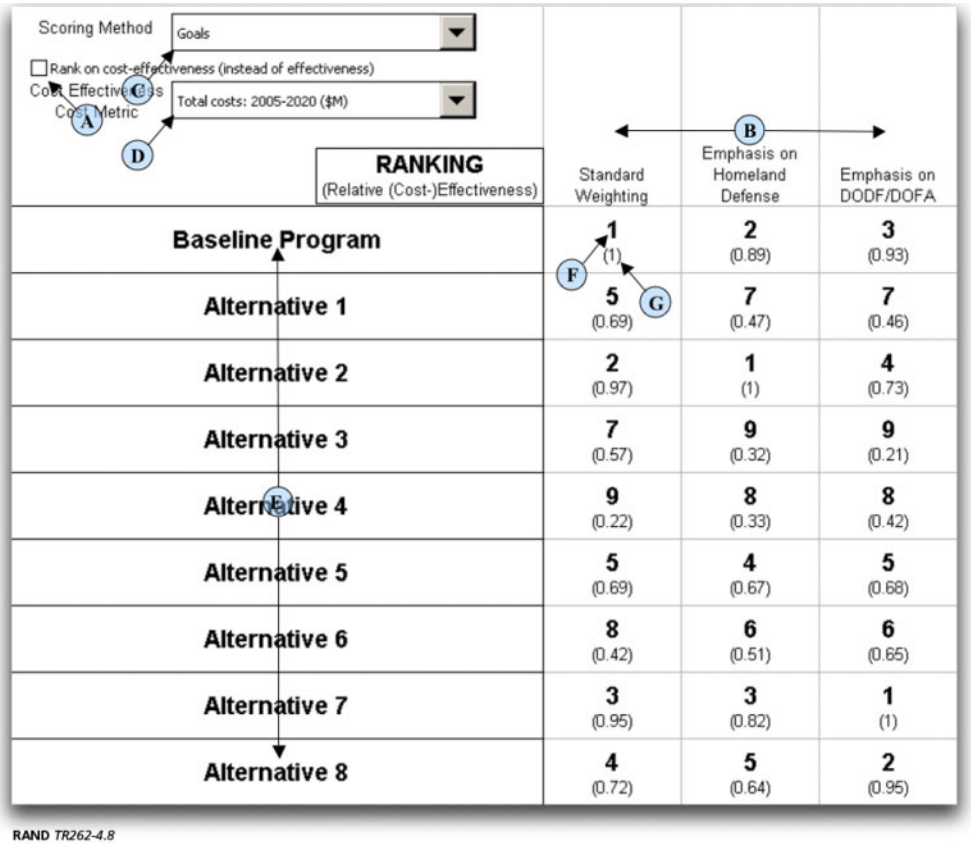


Figure 4.8
***Rankings Table* Sheet**

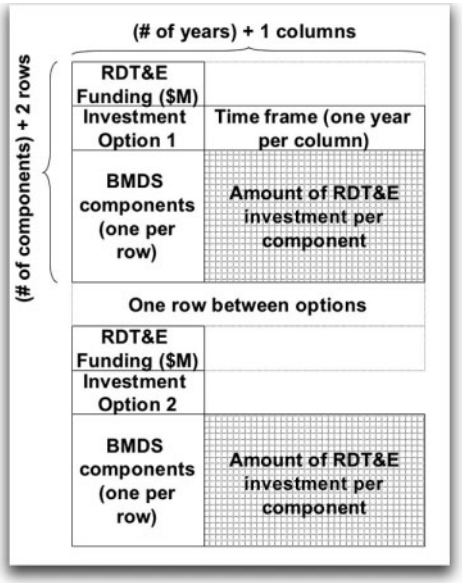


effectiveness (if applicable) (D). In each cell, the rank is in large bold text (F), with the relative (cost-) effectiveness in parentheses under the ranking (G). The investment option with the highest absolute (cost-) effectiveness for each perspective is given a relative (cost-) effectiveness of 1, and all other (cost-) effectiveness values are measured against it.

IOC to Cost Output Sheet

The *IOC to Cost Output* sheet (sketched in Figure 4.9) contains the output produced when the Generate Cost Data button is clicked. The output tables are identical in format to those used as inputs in the *Cost Data* sheet. The results can be copied and pasted into the RDT&E columns of the *Cost Data* sheet as the cost data for the investment cases in PAT-MD or can be exported to CAMMD.

Figure 4.9
***IOC to Cost Output* Sheet**



RAND *TR262-4.9*

5. Details of the Methodology

Chapter 2 introduced methodological issues in PAT-MD, using a very simple example. This chapter reviews those issues and provides additional generalizations, details, equations, and subtleties. It first presents definitions, then equations are given for the five different scoring and aggregation methods available in PAT-MD. Finally, worked-out examples are presented to illustrate how effectiveness and cost-effectiveness can be calculated for marginal and chunky marginal analysis.

Basic Concepts and Definitions

Figure 5.1 shows schematically how PAT-MD operates analytically.[1] For each investment option, PAT-MD takes a series of inputs (the shaded items in Figure 5.1) and generates characterizations of how well the option performs on different criteria, including cost-effectiveness. The concepts and terminology of Figure 5.1 are explained below.

Investment Options

Alternative investment options are alternative programs of investment over time. They are expressed as expenditures (projected costs) for each year treated and for each budget category of interest in the analysis. These options are inputs to PAT-MD. Most budget categories identify systems or components being developed or deployed (e.g., an Aegis radar upgrade, a midcourse-interceptor missile, or a kill vehicle). Other budget categories might cover certain continuing infrastructure expenses.[2]

Attributes of the Investment Options

Each investment option is characterized in a number of ways. Some of these characterizations are input, while others are calculated within PAT-MD.

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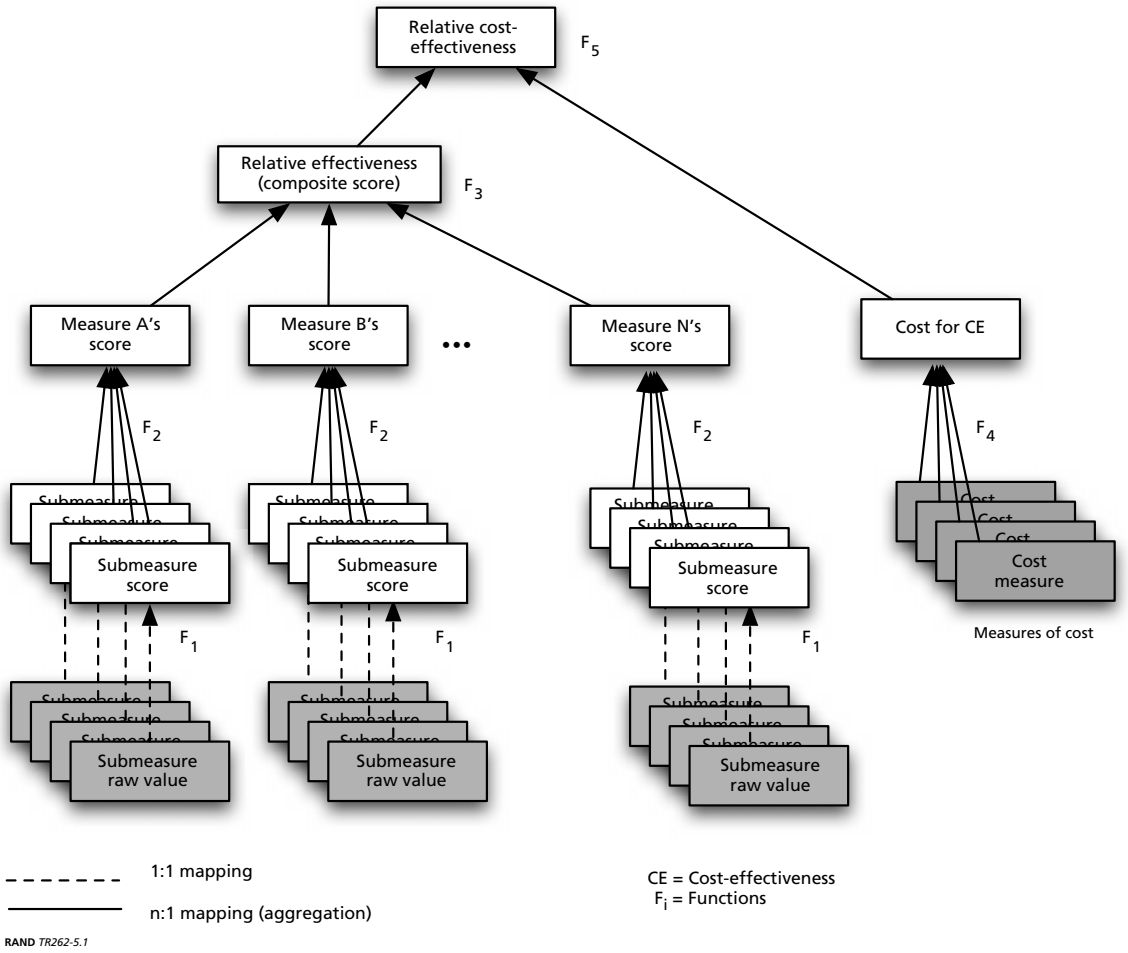
[1] Figure 5.1 is not precisely correct for use with the Rankings method, as discussed in the next section.

[2] Analytically, it would be preferable if alternative investment options were fairly narrow, e.g., "develop system X" versus "develop system Y." It would then be clear that in characterizing capabilities or risks, we were referring to system X or system Y. To date, however, the investment options for our MDA analysis have been total-program options, usually described as a baseline plus or minus some particular systems or activities. Such a total program must be characterized along a number of dimensions—hence, the multiple measures and submeasures discussed below.

Figure 5.1
Generation of Scores, Effectiveness, and Cost-Effectiveness in PAT-MD (shaded items are inputs)



Costs. Each option may have a number of types of cost, such as one-year, six-year, or 20-year costs, with the numbers expressed either in current dollars or in dollars corrected for inflation. It is also possible to use "discounted dollars." Although that information is seldom available to PAT-MD as an input, PAT-MD can transform the various types of input costs into discounted versions.[3]

Measures and Submeasures. The options are characterized by a number of criteria called *measures,* each of which has one or more *submeasures*. The measures and submeasures typically relate to types of capabilities or risk.[4] They are akin to what some call metrics.

[3] We refer here to making "present-value calculations," in which current expenditures are treated as effectively more costly because they use funds that could otherwise be invested in other ways (i.e., agreeing to pay someone $1,000 in ten years is much less painful than paying him $1,000 now, because, in principle, one could invest the $1,000 for ten years, pay the debt at that point, and keep the returns). The adjustment uses compounding with the so-called discount rate. The economic calculations are well understood (Hitch and McKean, 1960), although economists continue to differ about what discount rate should be assumed, especially for government expenditures. For tutorial information on present-value calculations in defense acquisition, see Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics, n.d.

[4] Other possibilities exist. If, for example, space-based defenses were somehow more psychologically impressive and therefore more valuable for deterrence or coercive diplomacy, one measure could be "psychological value." During the Cold War,

Submeasure information is input to PAT-MD. As is the case throughout mathematics and computer science, the same label (e.g., "a missile's single-shot kill probability") is used to refer to both the abstract concept that a measure or submeasure represents and the value of that measure.

Raw Values of Submeasures. A submeasure's raw value is data input to PAT-MD. These data might come from system specifications (with the assumption that the specifications will be met), from test data, from models, or from expert judgment. The raw values may be expressed in different units and on different scales, and a larger raw value may be good or bad, depending on the submeasure.

Submeasures do not necessarily convey directly any sense of sufficiency. For example, if an option generates a defense system that could be saturated by 12 attackers (12 would be the raw value of a submeasure), this does not indicate whether 12 is good or bad, sufficient or insufficient.

Goals and Thresholds. Most of the methods used in PAT-MD involve goals or both goals and thresholds (again, the Rankings method is the exception). Inputs to PAT-MD then include, for each submeasure, a raw value corresponding to the goal and possibly a raw value corresponding to a threshold (a minimum level for perceived utility).

Submeasure Scores. PAT-MD calculates the score of a submeasure from its raw value, other inputs regarding goals and thresholds, and the raw values of the submeasure for other options. In PAT-MD, for all methods except the Rankings method, the score is between 0 and 1, with 1 being good.

Measure Scores. The score of a measure is calculated from the scores of its submeasures; that is, a measure's score is an aggregation of its submeasure scores.[5] Except under the Rankings method, measure-level scores (or, simply, measure scores) are also between 0 and 1.

Composite Score (Effectiveness). Once PAT-MD has calculated scores for the measures characterizing the investment options, it can generate composite scores of effectiveness, or simply effectiveness. And it can use the highest such score as a base and compute the relative effectiveness of the investment options.

Relative Cost-Effectiveness

Cost-effectiveness is calculated using the ratio of effectiveness and cost. With PAT-MD, an analyst can use any of the input cost categories (e.g., six-year costs in real dollars) as the basis for the cost-effectiveness calculation. PAT-MD calculates an intermediate cost-effectiveness for each option (not shown in Figure 5.1) and then uses the largest value as the base, to which it compares all the options' cost-effectiveness. The result, then, is the relative cost-effectiveness for each option.

---

the Soviets probably earned far more perception points for their large-throw-weight ICBMs than they deserved, from a technical standpoint. So also, the American Strategic Defense Initiative (SDI) had a greater impact on Soviet thinking than was merited by its technical success at the time.

[5] A more rigorous term is "abstraction." That is, a measure is an abstraction from its subordinate submeasures. It abstracts from, or captures the relevant essence of, the submeasures. It may be a simple average, or it may be a more context-sensitive projection. Historically, "aggregation" meant the result of collecting, as one might aggregate the strengths of nine battalions to estimate the strength of a division. Perhaps unfortunately, "aggregation" is coming to have a more general meaning akin to "abstraction." In software, for example, aggregation is sometimes seen as a composition technique for creating a new object, in part, by using component objects. For a more careful discussion, see Zeigler, Zeigler, and Praehofer, 2000.

Methods and Functions

The progression summarized in Figure 5.1 requires numerous functions (F_1,F_2,..,F_5), as indicated. These accomplish the following transformations:

- Submeasure raw values to submeasure scores
- Submeasure scores to measure-level scores
- Costs of various types to a single cost used in cost-effectiveness calculations [6]
- Measure-level scores to a composite score (effectiveness)
- Effectiveness scores and cost to cost-effectiveness

The different methods in PAT-MD to which we have alluded use different functions, as discussed below.

Table 5.1 summarizes the terms used in PAT-MD and their meanings and includes an example of each.

Table 5.1
PAT-MD Terminology

Term	Meaning in PAT-MD	Example
Abstraction	A generalization derived from specific more-detailed or more-concrete cases, perhaps with a particular context of use in mind.[a] Measures are abstractions of submeasures.	Engagement effectiveness is an abstraction derived from radar, missile, and kill-vehicle effectiveness.
Aggregation	Abstraction.	Ten-year cost is a simple aggregation of one-year costs. Overall risk of an option might be a more-complex aggregation of technical, strategic, and political risks.
Cost-effectiveness	The ratio of an effectiveness score to a measure of cost.	
Effectiveness	A composite score formed by abstracting from the scores of one or more measures.	A given investment option might have a score of 7, reflecting high technical effectiveness in some, but not all, missions and situations.
Measure	A way of evaluating something; a dimension of an assessment. An investment option is assessed by different measures. Measure is similar to metric.	The size of attack that saturates a defensive system.
Method	A procedure used to map raw scores into scores or to calculate higher-level scores from lower-level scores.	A measure's score might be the simple average of its submeasure scores.
Raw value of a submeasure	An unscaled value of a submeasure, which may not itself convey a sense of goodness or utility.	The size of attack that saturates a defensive system in the absence of offensive countermeasures might be 12. Is that good or bad?
Relative effectiveness	The ratio of an effectiveness score to the highest such score among options.	
Relative cost-effectiveness	The ratio of an option's cost-effectiveness to that of the option with the highest cost-effectiveness.	
Score	A value derived from raw values and goals to convey a sense of goodness.	A score of 0.6 might be calculated as the ratio of a raw score of 12 and a goal value of 20, scaled to be between 0 and 1.
Submeasure	One of the factors determining a parent measure.	The size of attack that saturates a defensive system in a particular case (e.g., with attacker countermeasures).

[a] The average depth in the deep-water area of a swimming pool might be an example. It is not the pool's overall average depth but, rather, an average relevant to safety calculations concerning diving boards. In physics, "projection operators" generate such pointed abstractions.

[6] Currently, this is implemented in PAT-MD as a selection rather than an aggregation. That is, a user who enters costs in various forms can select which form to use in cost-effectiveness calculations.

Alternative Methods Used in PAT-MD

The Need for Alternative Methods

As discussed above, each of the steps in Figure 5.1 requires specifying the appropriate mathematical function (e.g., for mapping raw values into scores or for calculating cost-effectiveness). In a given application of PAT-MD, the analyst chooses a scoring method. Each such method must specify the five functions indicated in Figure 5.1 (F_1,...,F_5). No single "right" method exists, even though the bulk of work in mathematical decision analysis uses a single method based on linear weighted sums contributing to a single measure of "utility." That standard method is taught in many schools and is embedded without comment in much decision-support software.[7] It is often quite useful, just as assuming that the probabilities of various factors affecting a problem are independent is often quite useful.

Nonetheless, in capabilities-based planning (and in much of systems analysis and policy analysis more generally), the standard approach is insufficient for several reasons:

- Decisionmakers need to know separately about some of the "apples and oranges," and total aggregation into a single utility suppresses too much information and depends too heavily on underlying assumptions and preferences that are the decisionmaker's province rather than the analyst's.[8]
- Similarly, decisionmakers need to know how a given option addresses each of their separate high-level objectives.[9]
- Aggregation rules sometimes need to be nonlinear because of system effects.

To elaborate for the MDA context, it is important that decisionmakers be able to see information about BMDS capabilities against small and large attacks and attacks with and without countermeasures separately. No single measure of BMDS performance is adequate. Similarly, MDA has different missions and different objectives for each mission. At a more technical level, MDA's capabilities-based planning is concerned with systems and with systems of systems (e.g., the overall BMDS). The result is a need to highlight the importance of individual critical components and to be concerned with interdependencies rather than suppressing them. This implies a need to allow for nonlinearities in the mathematics used (Davis, 2002).

Suppose, for example, that a system has three critical components: a radar, an interceptor, and a kill vehicle. Since they are all critical, a valuation scheme might weight them equally in a linear sum: system quality = (radar quality) + (interceptor quality) + (kill-vehicle quality).

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[7] The classic introductory book on decision analysis (Raiffa, 1968) is quite readable. A later text (Keeney and Raiffa, 1976) treats multi-objective decision analysis. Although it emphasizes combining into a single utility, Keeney and Raiffa (1976) also discusses alternatives to simple linear weighted sums.

[8] This consideration has led to the current emphasis on scorecards in policy analysis. Such analytic summaries emerged independently in a number of places, but an early in-depth application with considerable methodological discussion was the analysis of a Netherlands water-management problem (Goeller, 1983). PAT-MD is a modern manifestation.

[9] A form of multi-objective decision analysis that organizes around the user's objectives is value-focused thinking (Keeney, 1992). It is currently popular for many applications, including work in military organizations (Parnell, Burk, Westphal, et al., 2004).

Or suppose that improving the radar is very inexpensive because it is a simple modification of an existing radar, whereas improving the kill vehicle is extremely expensive. If the above equation were correct, then, even with weighting factors, a seemingly cost-effective investment strategy would be to put all of the funds into the radar—the mathematical implication of the assumed linearity. But that investment would be absurd.

To reflect such common system-related issues, something other than simple linear sums is needed. A number of possibilities exist, ranging from using a multiplicative relationship instead of an additive one to methods that involve enforcing threshold requirements for each of the critical components. In PAT-MD terminology, this corresponds to enforcing threshold requirements for each of the submeasures that characterize an investment option.

Therefore, we have built five distinct methods into PAT-MD. This has the great advantage of increasing flexibility but the disadvantage of causing potential confusion and undercutting the goal of providing relatively simple, logical, and intuitive results for decisionmakers. Thus, in what follows, we describe the five methods; the analyst, however, should decide which method or methods to use and should then present only those. The five methods are (1) goal-based (Goals, for short), (2) goal-based with weak thresholds (Weak Thresholds), (3) goal-based with thresholds (Thresholds), (4) goal-based with weakest link (Weakest Link), and (5) rankings-based (Rankings).

These are described separately in what follows and are then summarized in a table. For each method, the description specifies how scores are generated from the raw values of submeasures and how higher-level scores and effectiveness are calculated by aggregation.

We use a common notation, as defined in Table 5.2.

Goals Method

The Goals method is the simplest method to describe and is often appropriate. Every measure consists of a collection of submeasures, each of which has a goal value that each investment option is trying to achieve for it. For example, a kill device might have two kill mechanisms, A and B, either of which would be sufficient. In designing the device, an engineer would have a goal for the capability of each mechanism.

Submeasure Scores for the Goals Method. The score of a submeasure is 0 or $G_{j,k}$, depending on whether the submeasure's raw value has reached the submeasure's goal. That is, for any investment option i and any measure j, if the scale is increasing so that goals correspond to high values, then the k^{th} submeasure's score is given by

$$\begin{aligned} S_{i,j,k} &= 0 \text{ if } V_{i,j,k} < V^G_{j,k} \\ S_{i,j,k} &= G_{j,k} \text{ if } V_{i,j,k} \geq V^G_{j,k} \end{aligned} \tag{5.1}$$

If goodness increases with decreasing raw values, then the equations change accordingly.

Table 5.2
Notation for Defining Scoring Methods

Symbol	Meaning	Source
Parameters		
i, j, k	Indexes for investment option, measure, and submeasure, respectively	n/a
m	Number of measures	n/a
n_j	Number of submeasures of measure *j*	n/a
$\{V_{i,j,1}, V_{i,j,2}, ..., V_{i,j,n}\}$	Raw values of the submeasures for investment option *i* and measure *j*	Input (*Data Entry* sheet)
$\{S_{i,j,1}, S_{i,j,2}, ..., S_{i,j,n}\}$	Scores of the n_j submeasures (submeasure scores) for investment option *i* and measure *j*	Calculated
$\{M_{i,1}, M_{i,2}, ..., M_{i,m}\}$	Scores of the *m* measures (measure scores) for investment option *i*	Calculated
E_i	Composite score (effectiveness) for investment option *i*	Calculated
Parameter values used in calculations		
$\{V^T_{j,1}, V^T_{j,2}, ..., V^T_{j,n}\}$	Threshold raw values for each submeasure of measure *j*	Input (*Data Entry* sheet)
$\{V^G_{j,1}, V^G_{j,2}, ..., V^G_{j,n}\}$	Goal raw values corresponding to each submeasure of measure *j*	Input (*Data Entry* sheet)
$\{T_{j,1}, T_{j,2}, ..., T_{j,n}\}$	Submeasure scores when submeasure raw values have reached thresholds, under measure *j*	Input (*Data Entry* sheet)
$\{G_{j,1}, G_{j,2}, ..., G_{j,n}\}$	Scores of submeasures that have reached their goals under measure *j*	Input (*Data Entry* sheet)
$\{W_{j,1}, W_{j,2}, ..., W_{j,n}\}$	Weights of the submeasures in computing measure scores	Input (*Data Entry* sheet)
$\{C_1, C_2, ..., C_m\}$	Weights of the measures in computing effectiveness	Input (*Measure Comments and Weights* sheet, or *Summary* sheet)

Aggregation to Measure Scores for the Goals Method. The function used to calculate the score of a measure is simply a weighted sum of the submeasure scores.

$$M_{i,j} = \frac{\sum_{k=1}^{n_j} W_{j,k} S_{i,j,k}}{\sum_{k=1}^{n_j} W_{j,k} G_{j,k}} \tag{5.2}$$

If all submeasures were equally weighted, the measure score would be the fraction of the measure's submeasures that reached their goals. The resulting measure scores are between 0 and 1 because of the normalization accomplished by the denominator. In practice, the values of $G_{j,k}$ will all be equal to 1, with the $W_{j,k}$ values establishing the relative weights of the submeasures, but for the sake of completeness, we include $G_{j,k}$ in our equations.

Aggregation to Composite Score (Effectiveness) for the Goals Method. The function used to set the composite score or effectiveness under investment option i is also a weighted sum over measures:

$$E_i = \frac{\sum_{i=1}^{m} C_i M_{i,j}}{\sum_{i=1}^{m} C_i} \tag{5.3}$$

The measure and effectiveness scores all have values between 0 and 1. The weights need not be between 0 and 1, since PAT-MD performs normalizations, but it is arguably good practice to enter weights in that range that add up to 1. This requires some additional work on the part of the analyst entering data, but in our experience, the data are sometimes easier to understand and adjust.

Weak Thresholds Method

Submeasure Scores for the Weak Thresholds Method. Under this method, each submeasure has a threshold as well as a goal. If the threshold is not reached, the submeasure score is 0. If the submeasure reaches or exceeds its goal, the submeasure score is the submeasure score for the goal value. In between, the score is determined by a linear relationship. That is, in cases where goodness increases with raw value,

$$\begin{aligned} S_{i,j,k} &= 0 && \text{if } V < V^T_{j,k} \\ S_{i,j,k} &= G_{j,k} && \text{if } V \geq V^G_{j,k} \\ S_{i,j,k} &= T_{j,k} + \frac{V_{i,j,k} - T_{j,k}}{V^G_{j,k} - V^T_{j,k}}(G_{j,k} - T_{j,k}) && \text{if } V^T_{j,k} \leq V_{i,j,k} \leq V^G_{j,k} \end{aligned} \tag{5.4}$$

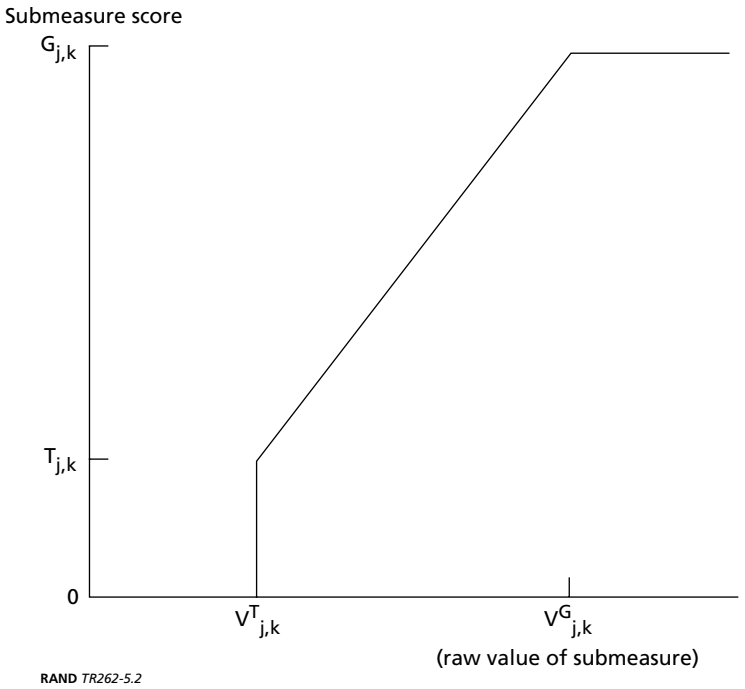
If goodness decreases with raw value, then the equations must be adjusted.

Figure 5.2 shows the resulting scoring method.

Aggregation to Measure Score for the Weak Thresholds Method. The score of measure j is again given by a linear weighted sum, as in the Goals method, but the submeasure scores are different:

$$M_{i,j} = \frac{\sum_{k=1}^{n_j} W_{j,k} S_{i,j,k}}{\sum_{k=1}^{n_j} W_{j,k} G_{j,k}} \tag{5.5}$$

Figure 5.2
Submeasure Score Versus Submeasure Raw Value for Goals and Thresholds Methods



Aggregation to Composite Score (Effectiveness) for the Weak Thresholds Method. The composite score (effectiveness) is given by a linear weighted sum, as previously, but the measure scores are different:

$$E_i = \frac{\sum_{i=1}^{m} C_i M_{i,j}}{\sum_{i=1}^{m} C_i} \tag{5.6}$$

Thresholds Method

Submeasure Scores for the Thresholds Method. Submeasure scores are calculated with the same function as that used for the Weak Thresholds method:

$$\begin{aligned} S_{i,j,k} &= 0 && \text{if } V < V^T_{j,k} \\ S_{i,j,k} &= G_{j,k} && \text{if } V \geq V^G_{j,k} \\ S_{i,j,k} &= T_{j,k} + \frac{V_{i,j,k} - T_{j,k}}{V^G_{j,k} - V^T_{j,k}}(G_{j,k} - T_{j,k}) && \text{if } V^T_{j,k} \leq V_{i,j,k} \leq V^G_{j,k} \end{aligned} \tag{5.7}$$

Aggregation to Measure Scores for the Thresholds Method. The difference in methods occurs here. If any submeasure fails to reach its threshold, the measure is assigned a score of 0:

$$M_{i,j} = \frac{\sum_{k=1}^{n} W_{j,k} S_{i,j,k}}{\sum_{k=1}^{n} W_{j,k} G_{j,k}} \quad \textit{if all} \text{ submeasures reach their thresholds}$$
$$M_{i,j} = 0 \qquad \textit{otherwise} \tag{5.8}$$

Aggregation to Composite Score (Effectiveness) for the Thresholds Method. Effectiveness is calculated precisely as before, but the measure scores are different:

$$E_i = \frac{\sum_{i=1}^{m} C_i M_{i,j}}{\sum_{i=1}^{m} C_i} \tag{5.9}$$

Weakest Link Method

The Weakest Link method is even more stringent than the Thresholds method in enforcing the "requirements" represented by thresholds.

Submeasure Scores for the Weakest Link Method. These submeasure scores are calculated with the same function as that used for the Thresholds method:

$$S_{i,j,k} = 0 \qquad \textit{if } V < V_{j,k}^{T}$$
$$S_{i,j,k} = G_{j,k} \qquad \textit{if } V \geq V_{j,k}^{G} \tag{5.10}$$
$$S_{i,j,k} = T_{j,k} + \frac{V_{i,j,k} - T_{j,k}}{V_{j,k}^{G} - V_{j,k}^{T}} (G_{j,k} - T_{j,k}) \quad \textit{if } V_{j,k}^{T} \leq V_{i,j,k} \leq V_{j,k}^{G}$$

Aggregation to Measure Scores for the Weakest Link Method. Under the Weakest Link method, the measure score is the minimum of the submeasure scores. If any submeasure fails to reach its threshold, the measure score will be 0, as in the Thresholds method, but if all submeasures reach their thresholds, the score here will be different from that for the Thresholds method and, typically, smaller:

$$M_{i,j} = \min\left\{S_{i,j,k}\right\} \tag{5.11}$$

Aggregation to Composite Score (Effectiveness) for the Weakest Link Method. Aggregation under the Weakest Link method is performed by taking the minimum measure score (which is identical to the minimum submeasure score over all submeasures). Note that

if even one submeasure in any of the measures fails to reach its threshold, effectiveness will be 0. Even if that does not happen, effectiveness will typically be smaller with this method:

$$E_i = \min\left\{M_{i,j}\right\} \tag{5.12}$$

Color Coding for the Goals and Thresholds Methods

For all the non-rankings methods in PAT-MD, the scores of the investment options can be mapped into the colors of familiar stoplight charts, where red is worst and orange, yellow, light green, and dark green are successively better. A five-color system is used for our measure-summary table because, over the decades, five has proven to be a comfortable number that makes sufficient distinctions but avoids cognitive overload. The mapping for the measure scores is shown in Table 5.3. For the Thresholds and Weakest Link methods, if any submeasure fails to reach a threshold, the cell in the measure-summary contains an F in the corner.

Table 5.3
Mapping Measure Scores into Colors

Range of Scores	Color
0 ≤ Score < 0.2	Red
0.2 ≤ Score < 0.4	Orange
0.4 ≤ Score < 0.6	Yellow
0.6 ≤ Score < 0.8	Light green
0.8 ≤ Score < 1	Dark green

Rankings Method

The Rankings method does not use goal or threshold values. Instead, for each submeasure, the investment options are simply ranked from best to worst, without regard to absolute performance. For this method, we refer to submeasure and measure ranks instead of submeasure and measure scores.

Submeasure Ranks. Let $R_{i,j,k}$ be the rank of investment option i for measure j and submeasure k. We define it as one more than the number of investment options that perform strictly better than investment option i on submeasure k of measure j. Thus, if two investment options have the same raw value, they will have the same rank.

Aggregation to Measure Ranks for the Rankings Method. The aggregation from submeasure rankings to measure rankings is again a linear weighted sum. We calculate the average rank $\overline{R_{i,j}}$ within measure j:

$$\overline{R_{i,j}} = \frac{\sum_{j=1}^{n_j} W_{j,k} R_{i,j,k}}{\sum_{j=1}^{n_j} W_{j,k}} \tag{5.13}$$

The value $\overline{R_{i,j}}$ is used to set the color (one of five shades of blue) in the measure-summary table, depending on the quintile in which the average ranking resides.

Aggregation to Composite Effectiveness for the Rankings Method. This aggregation function is best explained with words and examples. It is entirely different from the functions used in the other methods in that each measure is assigned a score based on rankings.

Let us assume that K investment options are under consideration, and each submeasure has $K(K-1)/2$ points to distribute among those options. If there are no ties for the values in submeasure j, then the submeasure score, $R'_{i,j,k}$, is given by

$$R'_{i,j,k} = K - R_{i,j,k} \tag{5.14}$$

If there are ties, the points that would have gone to the investment options in those positions are combined and then equally distributed among the options. For example, with ten investment options, the second- and third-place investment options would receive 8 and 7 points, respectively. If two investment options are tied for second place, they would receive (7 + 8)/2 = 7.5 points each. This scoring method is used instead of a linear transformation of the rankings to avoid artificially large numbers in the case of ties. To illustrate, if ten investment options had the same value for a submeasure, they would all tie for first. If the ranking effectiveness score did not take ties into account, each investment option would receive 9 points, so the total (unweighted) contribution to the final score (summed across investment options) by that submeasure would be 90 points. By comparison, for a submeasure where every investment option had a different value, the total (unweighted) contribution to the final score by that submeasure would be 45 points (9 + 8 + 7 + 6 + 5 + 4 + 3 + 2 + 1).[10]

As in the previous scoring methods, each submeasure $S_{j,k}$ has a weight $W_{j,k}$ in the aggregation to the measure score. Similarly, the weights C_i determine the relative contribution of each measure to the effectiveness score for each investment option. The measure score for an investment option i for measure j is

$$M_{i,j} = \frac{\sum_{k=1}^{n_j} R'_{i,j,k} W_{j,k}}{\sum_{k=1}^{n_j} (K-1) W_{j,k}} \tag{5.15}$$

Because the maximum possible value of $R'_{i,j,k}$ for each individual submeasure is $K-1$, the denominator in Equation 5.15 scales the effectiveness score to be between 0 and 1. The effectiveness score for each investment option over all measures, E_i, is given by

$$E_i = \frac{\sum_{j=1}^{m} C_j M_{i,j}}{\sum_{j=1}^{m} C_j} \tag{5.16}$$

[10] This method is a slight modification of the Borda count voting method, allowing for ties (see Ratliff, 2002). The Borda count method is used in many organizations and is also used to determine the Associated Press college football rankings.

Color Coding for the Rankings Method

Color coding on the measure-summary table for the Rankings method is different and even uses different colors, in order not to convey an impression of good and bad as the stoplight charts do for the Goals and Thresholds methods.

The weighted average rank determines the colors on the *Summary* sheet for each measure. As shown in Table 5.4, the colors go from light blue to dark blue, denoting the quintile in which the weighted average rank of the investment option lies. For example, if there were ten investment options, an investment option would receive the lightest blue color if its average rank was two or lower and would receive the darkest blue color if its weighted average rank was eight or greater. The same coloring method is used on the *Details* sheet, where the rank of each submeasure determines the color of the cell.

Table 5.5 summarizes the five methods built into PAT-MD. It is somewhat cryptic, but the compact comparison may be helpful to readers.

Table 5.4
Color Coding for the Rankings Method

Meaning	Color
(Average) rank in first quintile	
(Average) rank in second quintile	
(Average) rank in third quintile	
(Average) rank in fourth quintile	
(Average) rank in fifth quintile	

Table 5.5
Summary of Methods

Method	Submeasure Scores	Measure Scores	Composite Score (Effectiveness)	Coloring Method	Comment
Goals	0 or 1, depending on whether goal is reached	Linear weighted sum of submeasure scores	Linear weighted sum of measure scores	As in Table 5.3	Simple and common but has sharp edges
Thresholds	As in Figure 5.2	Zero if any submeasure fails to reach threshold; otherwise, linear weighted sum of submeasure scores	Linear weighted sum of measure scores	As in Table 5.3	May be appropriate if all submeasures are critical and have firm requirements
Weak Thresholds	As in Figure 5.2	Linear weighted sum of submeasure scores	Linear weighted sum of measure scores	As in Table 5.3	May be appropriate if not all submeasures are critical
Weakest Link	As in Figure 5.2	Minimum of submeasure scores	Minimum of measure scores	As in Table 5.3	May be appropriate if all measures and submeasures are critical and have firm requirements
Rankings	Modified Borda count	Weighted average of ranks for measure-summary table, linear weighted sum of Borda scores for effectiveness	Linear weighted sum of measure scores	As in Table 5.4	May be appropriate if one wishes to avoid discussion of goals and thresholds

Some Mathematical Observations

All of the scoring and aggregation functions used in PAT-MD are *monotonic nondecreasing*. Thus, improving the performance of an investment option in some submeasure cannot decrease the effectiveness score. The aggregations to an overall effectiveness score have the same property. More to the point, our scoring methods do not lead to counterintuitive conclusions (except in degenerate cases of no significance). We do not require that the functions be suitable for optimization.[11] This said, it would be desirable to have more comprehensive and structured mechanisms for exploratory analysis with PAT-MD, and this may be addressed in future work. In the meantime, much can be accomplished with the alternative-perspectives mechanism discussed in Chapters 3 and 4.

Examples of Scoring and Aggregation with the Different Methods

To provide examples for each scoring method, we will look at two measures, M_1 and M_2, each consisting of three submeasures. All submeasures have values between 0 and 10, inclusive, with 2 being the threshold value and 7 being the goal value in each case. For both measures, submeasure $S_{i,3}$ will have weights twice that of the other two submeasures, with all submeasures receiving a score of 0 for reaching the threshold value. By setting the weights of the three submeasures to 0.25, 0.25, and 0.5, the sum of the weights is 1, so there is no need to divide the sum of the submeasure scores by the sum of the weights, and we will assume the weights of the measures are equal. We will consider three investment options, denoted A, B, and C. The raw values for each option for each submeasure are given in Table 5.6.

Table 5.6
Scoring Methods for Three Investment Options

Measure	M1	M1	M1		M2	M2	M2		
Submeasure	S1,1	S1,2	S1,3		S2,1	S2,2	S2,3		
Submeasure Weight	0.25	0.25	0.5		0.25	0.25	0.5		
Goal Value	7	7	7		7	7	7		
Goal Submeasure Score	1	1	1		1	1	1		
Threshold Value	2	2	2		2	2	2		
Threshold Submeasure Score	0	0	0		0	0	0		
Investment Option A	10	10	5		5	5	5		
Investment Option B	7	5	6		8	1	10		
Investment Option C	1	5	10		10	10	10		

Goals Method

Table 5.7 presents illustrative results for the Goals method. Values that meet or exceed the goal value are highlighted in green. The table also shows the calculation of the submeasure and measure scores and the color of the measure-score cell for each measure that corresponds to the color scheme on the *Summary* sheet.

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[11] Optimization is much easier when the functions involved are convex. In the simple case of a function F(x), convexity in an interval means that the derivative of F(x) is monotonically nondecreasing. PAT-MD scoring functions violate that condition (see Figure 5.2).

Since the weights of the measures are equal, the effectiveness score is simply the average of the two measure scores. Although Option C reaches only one goal in measure M_1, that submeasure ($S_{1,3}$) is weighted twice as much as the other two, hence it has the same measure as Option A for measure M_1, which reaches two goals in measure M_1. Since Option C also reaches all of the goals on measure M_2, it has the highest effectiveness score under this scoring method.

Table 5.7
Illustrative Results for the Goals Method

Measure	M1	M1	M1		M2	M2	M2		
Submeasure	S1,1	S1,2	S1,3		S2,1	S2,2	S2,3		
Submeasure Weight	0.25	0.25	0.5		0.25	0.25	0.5		
Goal Value	7	7	7		7	7	7		
Goal Submeasure Score	1	1	1		1	1	1		
Threshold Value	2	2	2		2	2	2		
Threshold Submeasure Score	0	0	0		0	0	0		
				Measure 1 Score				Measure 2 Score	Effectiveness Score
Investment Option A	10	10	5		5	5	5		
Submeasure Score (Weighted)	0.25	0.25	0	0.5	0	0	0	0	(0.5 + 0)/2 = 0.25
Investment Option B	7	5	6		8	1	10		
Submeasure Score (Weighted)	0.25	0	0	0.25	0.25	0	0.5	0.75	(0.25 + 0.75)/2 = 0.5
Investment Option C	1	5	10		10	10	10		
Submeasure Score (Weighted)	0	0	0.5	0.5	0.25	0.25	0.5	1	(0.5 + 1)/2 = 0.75

Thresholds Method

Table 5.8 presents illustrative results for the Thresholds method. Values that meet or exceed the goal value are highlighted in green, values that meet or exceed the threshold value but not the goal value are highlighted in yellow, and values that fail to meet the threshold value are highlighted in red. In addition, the table shows the calculation of the measure scores and the effectiveness score for each investment option. The color of the Summary Score cell for each measure corresponds to the color on the *Summary* sheet for the Thresholds method. The effectiveness score (assuming the measures have equal weight) for each investment option appears in the rightmost column. In the Submeasure Score rows, xxx means that the submeasure has failed to reach the threshold value, so the measure score for the entire measure is 0.

Table 5.8
Illustrative Results for the Thresholds Method

Measure	M1	M1	M1		M2	M2	M2		
Submeasure	S1,1	S1,2	S1,3		S2,1	S2,2	S2,3		
Submeasure Weight	0.25	0.25	0.5		0.25	0.25	0.5		
Goal Value	7	7	7		7	7	7		
Goal Submeasure Score	1	1	1		1	1	1		
Threshold Value	2	2	2		2	2	2		
Threshold Submeasure Score	0.5	0.5	0.5		0.5	0.5	0.5		
				Measure 1 Score				Measure 2 Score	Effectiveness Score
Investment Option A	10	10	5		5	5	5		
Submeasure Score (Weighted)	0.25	0.25	0.3	0.8	0.15	0.15	0.3	0.6	(0.8 + 0.6)/2 = 0.7
Investment Option B	7	5	6		8	1	10		
Submeasure Score (Weighted)	0.25	0.15	0.4	0.8	0.25	xxx	0.5	0 (Failure)	(0.8 + 0)/2 = 0.4
Investment Option C	1	5	10		10	10	10		
Submeasure Score (Weighted)	xxx	0.15	0.5	0 (Failure)	0.25	0.25	0.5	1	(0 + 1)/2 = 0.5

If an investment option reaches the goal, the weighted submeasure score is 1 times the submeasure weight. If the raw value is between the threshold and the goal—say, 5—then since 5 is 60 percent of the way from the threshold (2) to the goal (7), the unweighted submeasure score would be 0.6, which is then multiplied by the submeasure weight to get the weighted submeasure score. In this case, since Option A did not fail to reach any of the threshold values, it has the highest effectiveness score, even though Option C meets four out of six goals.

Weak Thresholds Method

Table 5.9 presents illustrative results for the Weak Thresholds method. Values that meet or exceed the goal value are highlighted in green, values that meet or exceed the threshold value but not the goal value are highlighted in yellow, and values that fail to meet the threshold value are highlighted in red. The table also shows the calculation of the measure scores and the effectiveness score for each investment option. The color of the Summary Score cell for each measure corresponds to the color on the *Summary* sheet for the Weak Thresholds method. The effectiveness score (assuming the measures have equal weight) for both measures appears in the rightmost column. Note that even though Option C fails for submeasure $S_{1,1}$, reaching the goal value on four of six submeasures makes its effectiveness greater than that of the other two options.

Table 5.9
Illustrative Results for the Weak Thresholds Method

Measure	M1	M1	M1		M2	M2	M2		
Submeasure	S1,1	S1,2	S1,3		S2,1	S2,2	S2,3		
Submeasure Weight	0.25	0.25	0.5		0.25	0.25	0.5		
Goal Value	7	7	7		7	7	7		
Goal Submeasure Score	1	1	1		1	1	1		
Threshold Value	2	2	2		2	2	2		
Threshold Submeasure Score	0	0	0		0	0	0		
				Measure 1 Score				Measure 2 Score	Effectiveness Score
Investment Option A	10	10	5		5	5	5		
Submeasure Score (Weighted)	0.25	0.25	0.3	0.8	0.15	0.15	0.3	0.6	(0.8 + 0.6)/2 = 0.7
Investment Option B	7	5	6		8	1	10		
Submeasure Score (Weighted)	0.25	0.15	0.4	0.8	0.25	0	0.5	0.75	(0.8 + 0.75)/2 = 0.775
Investment Option C	1	5	10		10	10	10		
Submeasure Score (Weighted)	0	0.15	0.5	0.65	0.25	0.25	0.5	1	(0.65 + 1)/2 = 0.825

Weakest Link Method

Table 5.10 presents illustrative results for the Weakest Link method. Values that meet or exceed the goal value are highlighted in green, values that meet or exceed the threshold value but not the goal value are highlighted in yellow, and values that fail to meet the threshold value are highlighted in red. The table also shows the (unweighted) submeasure score, the measure score (the minimum of the submeasure scores for each measure), and the effectiveness score (the minimum of the measure scores). Note that the weights of the submeasures do not apply here. The color of the effectiveness-score cell for each measure corresponds to the color on the *Summary* sheet for the Weakest Link method. Since Option A is the only option that does not fail on any submeasure, it has the highest effectiveness score under this scoring method.

Table 5.10
Illustrative Results for the Weakest Link Method

Measure	M1	M1	M1		M2	M2	M2		
Submeasure	S1,1	S1,2	S1,3		S2,1	S2,2	S2,3		
Submeasure Weight	0.25	0.25	0.5		0.25	0.25	0.5		
Goal Value	7	7	7		7	7	7		
Goal Submeasure Score	1	1	1		1	1	1		
Threshold Value	2	2	2		2	2	2		
Threshold Submeasure Score	0	0	0		0	0	0		
				Measure 1 Score				Measure 2 Score	Effectiveness Score
Investment Option A	10	10	5		5	5	5		
Submeas. Score (Unweighted)	1	1	0.6	0.6	0.4	0.4	0.4	0.4	0.4
Investment Option B	7	5	6		8	1	10		
Submeas. Score (Unweighted)	1	0.4	0.6	0.4	1	0	1	0 (Failure)	0
Investment Option C	1	5	10		10	10	10		
Submeas. Score (Unweighted)	0	0.4	1	0 (Failure)	1	1	1	1	0

Rankings Method

In this example, the summary and effectiveness weights are identical (the third submeasures of each measure have twice the weight of the other two), as shown in Table 5.11.

The average rank and measure-score calculations are compressed slightly, and all values are rounded to two decimal places. For the measure score, the sum of the submeasure scores is divided by the product of the maximum submeasure score per measure (2) and the sum of the weights (1). The effectiveness value is simply the average of the measure scores. Because Option C has the best value for four of six submeasures, it is clearly the best option under the Rankings method.

Table 5.11
Illustrative Results for the Rankings Method

Measure	M1	M1	M1		M2	M2	M2		
Submeasure	S1,1	S1,2	S1,3		S2,1	S2,2	S2,3		
Submeasure Weight	0.25	0.25	0.5		0.25	0.25	0.5		
				Avg Rank/Meas Score				Avg Rank/Meas Score	Effectiveness Calc
Investment Option A	10	10	5		5	5	5		
Rank * Weight	1*0.25	1*0.25	3*0.5	0.25 + 0.25 + 1.5 = 2	3*0.25	2*0.25	3*0.5	0.75 + 0.5 + 1.5 = 2.75	
Submeasure Score * Weight	2*0.25	2*0.25	0*0.5	(0.5 + 0.5 + 0)/2 = 0.5	0*0.25	1*0.25	0*0.5	(0 + 0.25 + 0)/2 = 0.13	**(0.5 + 0.13) / 2 = 0.32**
Investment Option B	7	5	6		8	1	10		
Rank * Weight	2*0.25	2*0.25	2*0.5	0.5 + 0.5 + 1 = 2	2*0.25	3*0.25	1*0.5	0.5 + 0.75 + 0.5 = 1.75	
Submeasure Score * Weight	1*0.25	0.5*0.25	1*0.5	(0.25 + 0.125 + 0.5)/2 = 0.44	1*0.25	0*0.25	2*0.5	(0.25 + 0 + 1)/2 = 0.63	**(0.44 + 0.63) / 2 = 0.54**
Investment Option C	1	5	10		10	10	10		
Rank * Weight	3*0.25	2*0.25	1*0.5	0.75 + 0.5 + 0.5 = 1.75	1*0.25	1*0.25	1*0.5	0.25 + 0.25 + 0.5 = 1	
Submeasure Score * Weight	1*0.25	0.5*0.25	2*0.5	(0.25 + 0.125 + 1)/2 = 0.69	2*0.25	2*0.25	2*0.5	(0.5 + 0.5 + 1)/2 = 1	**(0.69 + 1) / 2 = 0.85**

Marginal and Chunky Marginal Analysis

Introduction

In marginal analysis, small changes to key variables in a system are considered one at a time, and the resulting changes to the outputs are observed. Marginal analysis is often used to find which variables are most responsible for affecting outcomes. When the key variables are investments, marginal analysis helps to determine where "the next dollar" (or million dollars) should be allocated (or where it should be removed) in order to maximize the capability of

the resulting collection of investments. Ideally, the small changes in each variable are equivalent in magnitude, enabling relevant comparisons between options. Although marginal analysis can be used for a variety of systems, we will restrict our discussion to the marginal analysis of investments.

Marginal analysis is not appropriate for all situations. For example, small deviations in investments may have absolutely no effect on the outputs of a system, particularly when investments are tied to purchases of discrete objects. An extra dollar invested in the acquisition of a radar system has absolutely no impact when a single component costs thousands or millions of dollars. Similarly, investments in systems that require a large buy-in before they become effective have no impact until the buy-in is reached, at which point there may be a large discontinuity in capability.

Conversely, small deviations in investments may have a disproportionate effect on the outputs of the system. Budgeting 90 percent of the cost to acquire a missile does not result in the acquisition of 90 percent of a missile. Likewise, small reductions in investment do not lead to proportionate reductions in system capability. The analysis of small deductions in investments to acquire missiles, radars, and so forth is potentially misleading, as it tends to highlight the systems whose removal has the least impact on overall capability. However, this analysis does not take into account how much those less-effective systems actually cost.

Marginal analysis tends to be more meaningful when the options that result from constant deductions to each investment are really of equal value. Consider a situation where $16 million is spent to acquire three different types of missiles and each individual missile costs $1 million. Assume further that the current plan is to purchase one missile of the first type, five of the second type, and ten of the third type. Three equal-cost investment options that could result from a $1 million cut in funding correspond to not purchasing one missile of each type. In contrast, consider a situation where $16 million is spent in the acquisition of three missiles, one costing $1 million, one costing $5 million, and one costing $10 million. A cut of $1 million from any of the three purchases results in not getting the missile, so this cut actually results in a comparison of three cases in which $6 million, $11 million, and $15 million are spent to acquire two of the three types of missiles.

This suggests a variant of marginal analysis in which the changes to the current set of investments represent the removal (or addition) of whole purchases. As with marginal analysis, these purchases are removed individually from the current investment, with each possible removal defining a new investment option. The costs of the resulting cases provide another measure that can be used as a basis of comparison. Often the important question is not "Where do we spend the next dollar?" but rather "How do we invest this extra $50 million?" (Pessimists or realists will suggest that the question asked is more often "How do we handle this $50 million budget cut?") This *chunky* marginal analysis method will be described in more detail in the next section, as will the application of PAT-MD to assist with it.

Chunky Marginal Analysis

We consider as a base case a fixed collection of BMDS investments over time in both R&D and acquisitions. We generate a collection of investment options by taking steps away from the base case. These steps are large-scale additions to (or subtractions from) the base case. Some examples would be the cancellation of R&D on a particular program or a reduced (or

increased) acquisition of a radar system or interceptor. The steps should not be so small that it is impossible to discern between the base case and the BMDS associated with the new investment option, but they should not be so large that they could be decomposed into a collection of smaller, meaningful steps. Thus, a step should not consist of the cancellation of three unrelated programs; rather, three new options should be defined by the cancellation of each individual program. In addition, a step should be maximal in the sense that any program that is made unnecessary (or necessary) by the cancellation (or addition) of one program should also be cut (or included) along with that program. For example, cutting the development of a radar platform should also cut the development of any battle-management suite associated with it (unless the suite can also be used for other radar systems under development).

Once these steps are defined, each investment option consists of the base case and one (or more) of these steps. As the number of steps increases, the number of possible investment options increases exponentially. Analysis should probably be restricted to options that are at most a fixed number of steps away from the base case. With n possible steps, there are roughly $n^2/2$ options that are at most two steps away from the base case and about $n^3/6$ options that are at most three steps away from the base case. The number of investment options under consideration should also be tempered by the ability to determine the costs associated with each, as well as the ability to analyze the BMDS that results from each. PAT-MD can store thousands of investment cases and can display some or all of those cases on its output sheets.

The output sheet that is perhaps most useful in assisting with chunky marginal analysis is the *Scatter Plot* sheet, where the user can select the x-axis from a collection of cost metrics (over various time periods, restrained to R&D investment or deployment investment only, etc.) and up to two different evaluation metrics as the y-axis. Investment options are plotted on the display as points of different colors (and different shapes if more than one measure is displayed on the y-axis). This is particularly useful for determining which investment option is best (and the corresponding programs that should be cut) if the budget is reduced from the amount allocated in the base case.

Consider a notional base case that consists of investments in three ESGs: one boost phase, one midcourse, and one terminal phase (based in the United States). There are three obvious steps away from this base case, namely, the cancellation of programs specific to each phase of the defense (defense systems from different phases may share tracking systems, so a cut of a particular phase of the defense would not necessarily eliminate all programs associated with that phase). Because the number of steps is so small, there is no reason not to consider the eight investment options corresponding to all the subsets of the phases of defense that can be implemented.

Next, consider the probabilities of engagement versus a single attacker shown in Table 5.12 for four different scenarios: HD, HD with no boost-phase access, HD with advanced countermeasures, and DODF/DOFA.

Assuming that the performances of the systems in each phase are independent of one another, we can compute the probability that a single missile is intercepted for each of the eight investment options, as well as for each of the four scenarios, which can be thought of as measures. If we set a threshold value of 0.5 and a goal value of 0.8 for each scenario, we get the color scheme shown in Table 5.13 (which would appear on the *Details* sheet) under the default (Thresholds) scoring method.

Table 5.12
Contrived Data for Illustrative Problem

	Probability of Engagement				
Phase of Defense	HD	No Boost Phase	Advanced Countermeasures	DODF/DOFA	Cost (billions of $)
Boost phase (B)	0.7	0.0	0.5	0.7	9
Midcourse (M)	0.6	0.6	0.4	0.6	6
Terminal (T)	0.5	0.5	0.3	0	3

Table 5.13
Performance of the Investment Options in Different Scenarios

	Probability of Engagement				
Phase of Defense	HD	No Boost Phase	Advanced CMs	DODF/DOFA	Cost (billions of $)
B + M + T	0.94	0.8	0.79	0.88	18
B + M	0.88	0.6	0.7	0.88	15
B + T	0.85	0.5	0.65	0.7	12
M + T	0.8	0.8	0.58	0.6	9
B only	0.7	0.0	0.5	0.7	9
M only	0.6	0.6	0.4	0.6	6
T only	0.5	0.5	0.3	0	3
None	0	0	0	0	0

Treating the individual scenarios as measures (or to be accurate, treating each column as a measure consisting of a single submeasure), we can calculate the effectiveness of each investment option for the Thresholds scoring method. Assuming all scenarios are equally weighted, with a submeasure score of 0.5 for reaching the threshold value and a value of 1 for reaching the goal value for each scenario, the effectiveness score of each investment option is as shown in Table 5.14. The numbers in brackets are the submeasure scores for each submeasure.

Table 5.14
Costs and Effectiveness Comparisons: Equal Emphasis on All Scenarios

	Probability of Engagement and Effectiveness Score					
Phase of Defense	HD	No Boost Phase	Advanced CMs	DODF/DOFA	Effectiveness (Sum/4)	Cost (billions of $)
B + M + T	0.94 [1]	0.8 [1]	0.79 [0.98]	0.88 [1]	0.996	18
B + M	0.88 [1]	0.6 [0.67]	0.7 [0.83]	0.88 [1]	0.875	15
B + T	0.85 [1]	0.5 [0.5]	0.65 [0.75]	0.7 [0.83]	0.771	12
M + T	0.8 [1]	0.8 [1]	0.58 [0.64]	0.6 [0.67]	0.7	9
B only	0.7 [0.83]	0.0 [0]	0.5 [0.5]	0.7 [0.83]	0.542	9
M only	0.6 [0.67]	0.6 [0.67]	0.4 [0]	0.6 [0.67]	0.5	6
T only	0.5 [0.5]	0.5 [0.5]	0.3 [0]	0 [0]	0.25	3
None	0 [0]	0 [0]	0 [0]	0 [0]	0	0

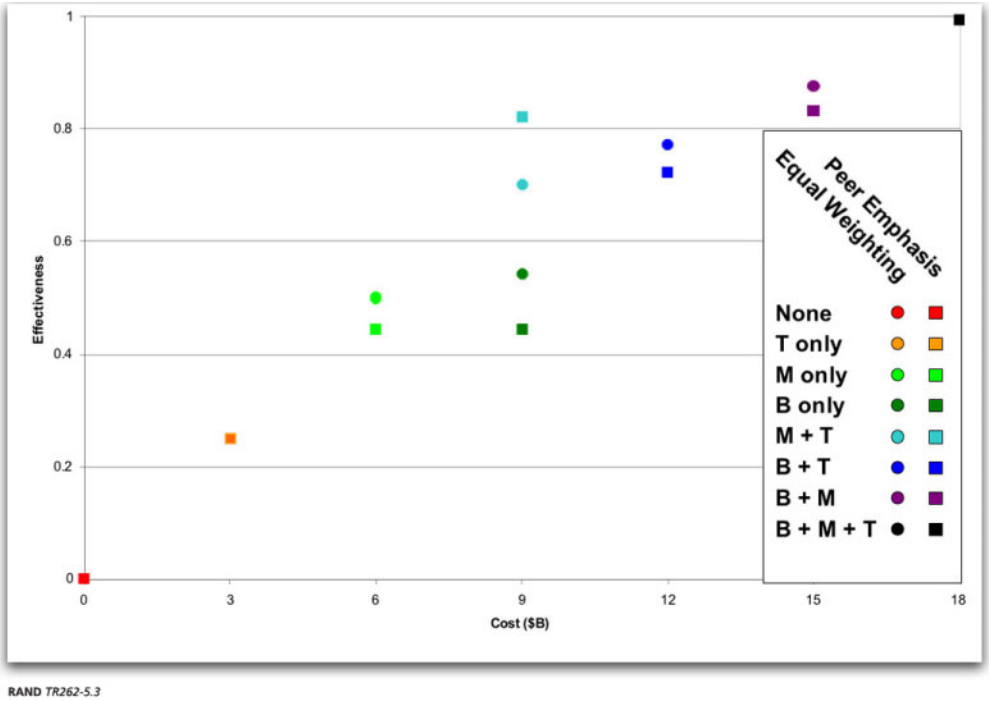
To put greater emphasis on dealing with a peer threat that can deny boost-phase access and implement advanced countermeasures, we can weight those two scenarios twice as much as the other two (with the numbers in brackets now representing the submeasure/measure score times the weight of the measure). The effectiveness of each investment option for this case is shown in Table 5.15.

The *Scatter Plot* sheet can be used to display the effectiveness of each investment case for both perspectives, with the cost of the investment option as the x-axis (see Figure 5.3).

Table 5.15
Costs and Effectiveness Comparisons: Extra Emphasis on Peer Threat

	Probability of Engagement and Effectiveness Score					
Phase of Defense	HD	No Boost Phase	Advanced CMs	DODF/DOFA	Scaled Effectiveness (Sum/6)	Cost (billions of $)
B + M + T	0.94 [1]	0.8 [2]	0.79 [1.96]	0.88 [1]	0.994	18
B + M	0.88 [1]	0.6 [1.33]	0.7 [1.67]	0.88 [1]	0.833	15
B + T	0.85 [1]	0.5 [1]	0.65 [1.5]	0.7 [0.83]	0.722	12
M + T	0.8 [1]	0.8 [2]	0.58 [1.28]	0.6 [0.67]	0.822	9
B only	0.7 [0.83]	0.0 [0]	0.5 [1]	0.7 [0.83]	0.444	9
M only	0.6 [0.67]	0.6 [1.33]	0.4 [0]	0.6 [0.67]	0.444	6
T only	0.5 [0.5]	0.5 [1]	0.3 [0]	0 [0]	0.25	3
None	0 [0]	0 [0]	0 [0]	0 [0]	0	0

Figure 5.3
Cost-Effectiveness Comparisons for Two Perspectives



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The scatter plot view provides a straightforward comparison of the investment options under both perspectives. The chart is unconventional, however, so reading it requires some instruction. Suppose that the budget must be cut to a level of $9 billion (a cut of $9 billion). At that level (x-axis), the best option from the first perspective (squares) is M + T (elimination of boost phase). That is, the topmost square has the color associated with the M + T option in the legend box to the right. When PAT-MD is being used live, we would identify that topmost square by merely passing the mouse over it and seeing its name pop up.

If we are more concerned about the peer threat to the homeland, we look at the effectiveness scores shown in the circles and find that the same investment option is best. That certainly might not have been the case. For example, consider budget cuts of $3 billion, $6 billion, and $9 billion. As indicated in Figure 5.3, in this contrived example, the terminal phase, midcourse, and boost-phase ESG should be canceled, respectively, to maintain the greatest effectiveness for the equal-weighting perspective. Although the boost-phase ESG costs as much as retaining the midcourse and terminal phase ESGs, the capability is much lower. This is amplified under the peer emphasis perspective (the squares), when the effectiveness score of the midcourse-ESG-only and the boost-phase-ESG-only options are nearly equivalent. For budget cuts between $3 billion and $9 billion, the cancellation of the boost-phase-ESG option has a higher effectiveness than does the cancellation of the less-expensive midcourse-ESG option. Thus, depending on the perspective, different priorities are placed on the retention of different phases of defense.

In general, the steps will be much smaller than the cancellation of entire ESGs. Cancellations (or delays) of single components of an ESG should be the options under consideration. Chunky marginal analysis is particularly illuminating when components under consideration are used across multiple ESGs, assisting with large-scale investment decisions.

6. Concluding Observations

Purpose and Function of PAT-MD

PAT-MD is not a model; rather, it is an "empty-vessel" tool. Its purpose is to help frame, manipulate, and present multifaceted information to decisionmakers, particularly with capabilities-based planning in mind. It is designed to work in parallel with a capabilities model (CAMMD) for the missile-defense problem and to use diverse information such as structured expert judgment and management philosophy (e.g., whether decisionmakers in a particular meeting or study are seeking hard-nosed "requirements-based" system assessments or more of a progress assessment).

Limitations and Cautions

At first glance, PAT-MD (or the related tool, DynaRank) may appear to be useful for optimizing resource allocation mathematically. The mechanism for calculating cost-effectiveness might seem to imply that the objective is or should be to maximize that quantity. That would be a misreading of our intentions, and indeed of the philosophy underlying our approach. The most important outputs of PAT-MD are (1) the portfolio-style scorecards in which alternative investment options are assessed simultaneously by a number of very different measures and costs; and (2) the next layer of scorecard detail to which the viewer is able to zoom in order to understand the basis of the color-coded summary assessment and to change higher-level assumptions or priorities that affect the assessments.

We believe that further aggregation to a single number, as in cost-effectiveness calculations, should be deferred to a kind of refinement stage, a stage in which the user is tidying up and thinking about communicating results of decisions. Cost-effectiveness calculations depend sensitively on the assumptions and priorities that go into them, which is precisely what decisionmakers are paid for. They are the people responsible for worrying about, say, the "balance" of a portfolio across missions, the extent of risk to be taken, and the ways in which risk can be managed. To do so, they need to reason at the portfolio level, not at the level of merely comparing cost-effectiveness numbers.

It follows from this that PAT-MD should not be seen as a tool for mathematical optimization, much less, simple do-it-by-the-numbers optimization. PAT-MD provides a number of ways to assess alternatives and some useful, albeit limited, mechanisms for exploring the consequences of alternative assumptions and priorities, but that is very different

from optimization. PAT-MD is intended to facilitate finding strategies that are flexible, adaptive, and robust.[1]

PAT-MD as Software

This first version of PAT-MD is not industrial-strength software; rather, it is a tool developed for analysis in certain contexts. It has been tested to a significant degree but undoubtedly has residual problems (both bugs and features). Users are encouraged to contact PAT-MD's programmer, Paul Dreyer, at dreyer@rand.org, if they discover mistakes or have questions about the operation of PAT-MD.

PAT-MD checks for most mistakes that a user can make (for example, entering an investment option or measure in the *Summary* table that does not exist on the *Data Entry* sheet). However, it has not been "gorilla-proofed." For example, the *Dropdown* sheet, which stores all of the entries for the dropdown menus, cannot be locked to prevent user manipulation as it is frequently updated by PAT-MD. Tinkering with the entries on that sheet would lead to errors in PAT-MD. *Because of this, we encourage users to keep a clean copy of the PAT-MD template available in the unlikely event that something occurs to make the software unusable.*

The proper use of PAT-MD also requires considerable discipline. With the *Template Builder* sheet, we have attempted to simplify much of the initial setup of a portfolio view, but other operations require consistency. For example, if one edits the values on the *Details* sheet, it is necessary to click on the Modify Data Entries button in order for those changes to propagate through the rest of the tool. Similarly, the *Scatter Plot* and *Spider Chart* sheets are not automatically updated when changes are made to the *Data Entry* sheet, so it is necessary to click on the Generate Scatter Plot and Generate Spider Chart buttons on the applicable sheets to see how the changes in the data have changed the outputs.

PAT-MD allows considerable flexibility in what users can change without having to regenerate the portfolio view, as described above. Weights on measures and submeasures, threshold and goal values, scoring methods, and data values can be changed easily. However, one should be cautious when adding or removing ESGs, BMDS components, investment options, measures, or submeasures, as they appear in several places throughout PAT-MD (and in some cases, in very particular order). Again, we caution that an unblemished copy of the PAT-MD template should be kept along with any portfolio tools developed, in order to be able to easily reconstruct a portfolio view if several new objects need to be added.

The only constraints on the numbers of investment options, measures and submeasures, etc., are those imposed by the ability of an EXCEL spreadsheet to hold all of the input data. An EXCEL spreadsheet can have up to 65,536 rows and 256 columns, so it can contain up to 255 submeasures, 251 ESGs, and 255 perspectives, and the only constraint on the number of investment options is that the cost data must fit on a single spreadsheet (so the product of the number of BMDS components and investment options cannot exceed 65,536). This should provide more than enough room to store all investment options of interest.

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[1] This emphasis in RAND work has been articulated in a number of monographs (Davis, 1994; Davis, 2002), including some concerned with very long-range planning (Lempert, Popper, and Bankes, 2003). It is quite consistent with the approach to capabilities-based planning first emphasized by DoD in the 2001 Quadrennial Defense Review (Department of Defense, 2001) and subsequently reinforced.

The Importance of the Measures, Submeasures, and Methods Used

As with all scorecard methods, considerable care must be taken in the development of the measure/submeasure structure for any analysis using PAT-MD. Similar care should be taken with selection of the scoring method and the parameters and weights for the scoring functions and effectiveness calculations. If PAT-MD used only linear weighted sums, the methodology would be simpler, but it would be less satisfactory for systems analysis.

Although we cannot itemize here all the considerations that an analyst should have in mind, a few are particularly worth mentioning:

- Measures and submeasures chosen should be adequately complete in the assessment they provide.
- Ideally, measures would be independent, and the submeasures of each measure would be independent. When that is not appropriate—i.e., when correlations exist—weighting factors should be chosen so as to avoid results being overly sensitive to a single underlying issue.[2]
- The choice of scoring and aggregation methods merits particular thought. If all of a measure's submeasures are individually critical, the threshold method may be called for. If all of the measures are also individually critical, the Weakest Link method may be appropriate. If these conditions do not apply, however, and it is more important to see progress than to flag problems, the Goals method may be appropriate. The Rankings method can be helpful when, for one reason or another, it is inappropriate to discuss goals and thresholds.
- In any case, it is essential to plan for systematic exploration of the ways assumptions on the above matters affect both results and perceptions, and to tune assumptions so that they provide a set of baseline results that are as robust as possible. For example, it would serve decisionmakers poorly if color-coded conclusions were to change markedly when a few low-level assumptions were changed slightly (e.g., moving a goal from 0.89 to 0.9 should not change results dramatically).
- A consequence of the above admonition is that goals and thresholds need to be seen as heuristics, not as absolutes to be accepted mindlessly as impossible-to-question "data."

Finally, we note that many of these issues are generic and there is a considerable literature dealing with multi-attribute measures and objectives that discusses approaches to weighting these measures, obtaining utilities from individuals or groups, and the use of other aggregation rules.[3]

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[2] For example, an option could obviously be made to look better by piling on a number of measures, each of which is driven by something accomplished well by the option. Similarly, an option may appear worse than it probably should if the measures chosen reflect a pure worst-case perspective.

[3] Some of these appear under discussion of multi-attribute utility theory (Keeney and Raiffa, 1976; Kirkwood, 1997), value-focused thinking (Keeney, 1992; Parnell, 2004), and balanced-scorecard methods used in business (Kaplan and Norton, 1996). The original DynaRank documentation (Hillestad and Davis, 1998) also includes some such discussion.

Next Steps

Over time, PAT-MD will be improved and enhanced, building on experience and use. Suggestions will therefore be appreciated. In addition to correcting any errors that are discovered and improving user-friendliness, we are currently thinking about at least the following possibilities for enhancement:

- An additional layer of hierarchy for zooming.
- Permitting different scoring and aggregation methods to be used for different measures or for calculation of cost-effectiveness rather than measure scores.
- The ability to generate the measure of cost used in cost-effectiveness as a linear weighted sum of the various costs provided as inputs.
- A richer and more structured mechanism for exploratory analysis, probably building on the alternative-perspectives mechanism. This could include limited mechanisms for search (e.g., finding what combinations of key parameters would cause a particular option to be assessed well or poorly).

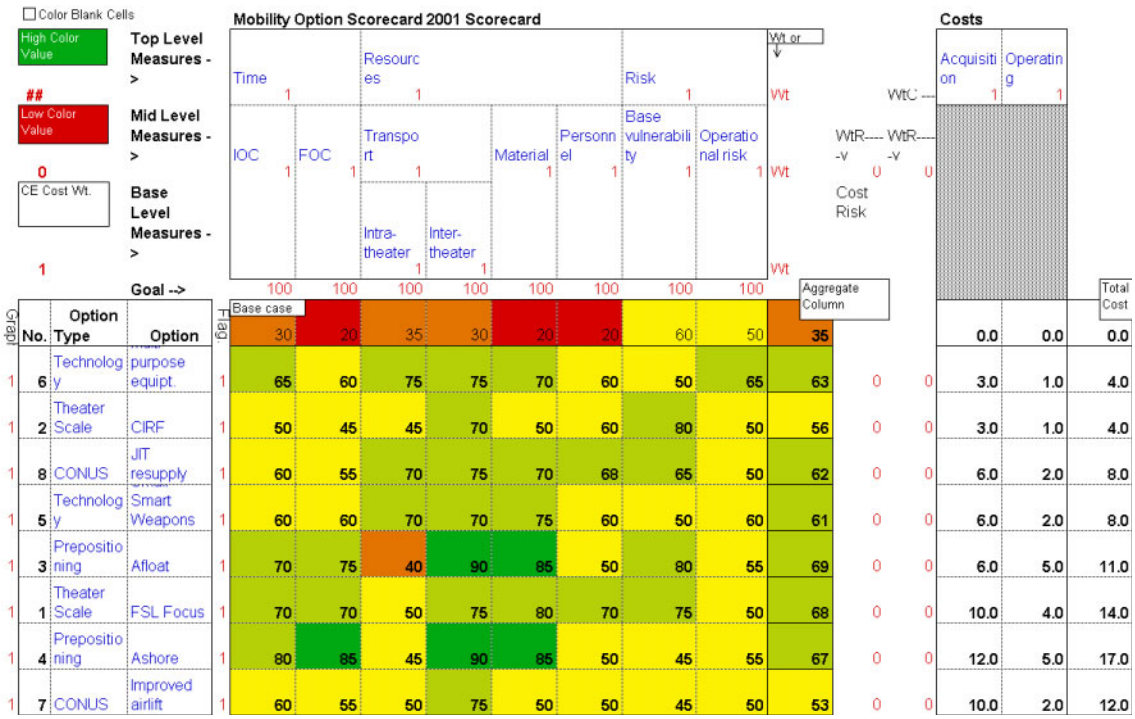
Appendix A

Comparison of Features of PAT-MD and DynaRank

What Is DynaRank?

DynaRank is a hierarchical scorecard tool developed by RAND for portfolio analysis (Hillestad and Davis, 1998). It is very flexible and allows for high-level integration of cost and performance data across one or more objectives. A sample DynaRank scorecard is shown in Figure A.1. As in PAT-MD, rows on the scorecard correspond to the different investment (or strategic) options; columns correspond to the measures used to evaluate the investment options. DynaRank has a three-level structure of measures (top, mid-level, and base). Values in individual tables are all measured on the same scale, with increasing values implying increasing utility.

Figure A.1
DynaRank Scorecard



In Figure A.1, the first column corresponds to the mid-level measure of IOC, which is subordinate to the top-level measure of time, while the fourth column corresponds to the base-level measure of intertheater (transport), which is subordinate to the mid-level measure of transport, which is subordinate to the top-level measure, resources. The values of measures can be aggregated up to the mid level or top level, using either weighted linear sums of subordinate values or a minimum-value aggregation, where the aggregate value of a mid-level (or top-level) measure is the smallest value among the subordinate base-level (or mid-level) measures. The values in the cost column are marginal costs of the options relative to a base case (the measure scores of which are in the top row of the table). Colors of the values range from red to green, based on a 0 to 100 scale (this scale can be changed).

What Is the Same in Both Tools? What Is Different?

DynaRank is the inspiration for PAT-MD, and both are written in Visual Basic with an EXCEL front end; both provide dynamic views of information (allowing changing of weights, scoring methods, and views on the fly). Both provide means of comparing investment and/or strategic options via aggregations of diverse measures that can come from other models, quantitative assessments, and/or subjective judgments. In addition, both use color-coded scorecards to present information, although the methodologies underlying how those colors are determined differ somewhat between the two tools. In addition, both incorporate cost data into their displays and present the cost-effectiveness of options. Both provide displays that rank investment options under multiple perspectives (weights on measures, etc.), and both can display a subset of the entire set of investment options (which is useful when there are many options). However, the two tools have completely different code underlying their construction, and the manner in which they present results differs considerably. Similarities and differences between DynaRank and PAT-MD are shown in Table A.1.

When to Use DynaRank and When to Use PAT-MD

Both tools are highly flexible in the ways they can present information. If setting goal and threshold values for the submeasures is reasonable and straightforward, or if a rankings-based aggregation method is appropriate for comparing options, one should use PAT-MD. PAT-MD also provides more options for the display of information than DynaRank does, and it may be a better tool for the presentation of results. While PAT-MD can be used for marginal analysis, the user who is willing to use linear aggregation methods to compare options will probably find DynaRank the right tool for the job. Currently, PAT-MD is specialized for analysis for MDA, but it could easily be modified to apply to a wide variety of problems. In fact, much of the functionality in DynaRank is replicated in PAT-MD in some fashion. However, DynaRank is more flexible in the sense that it can be used as a scorecard for any multi-measure, multi-objective problem. At this stage, it has also been tested more extensively and has been used in a number of studies.

In summary, we developed PAT-MD for the MDA application because it was important to incorporate both goals and thresholds into our analysis, to have some new output

displays, to have specialized input sheets, to have more flexibility in aggregation methods, and to introduce new functionality such as the IOC-to-cost-data calculations.

Table A.1
Comparison of DynaRank and PAT-MD

	DynaRank	PAT-MD
Data	Three levels of measures (top, middle, and base). All data values have the same scale and imply increasing utility as values increase. Can have multiple datasets and scorecards per workbook.	Two levels of measures (measures and submeasures). Data can have different scales and can have both high and low values as good values. One dataset per workbook.
Investment options	Options are intended to be marginal steps away from a base case (although the base case can be empty). Cost data for each option are the marginal cost away from the base case.	No base case is assumed (although chunky marginal analysis can still be done). Cost data represent the cost of the entire investment option (as a collection of investments in components over time).
Aggregation methods	Aggregate by linear weighted sums or weighted minimum values (the smallest subordinate value propagates upward).	Goal- and threshold-based, Weakest Link, or rankings-based aggregations. Can use different aggregation methods for different displays.
Displays	Can display scorecards for any level of measure with cost data. Can have hierarchies of scorecards or multiple scorecards on same sheet. Colors on scorecards are directly related to scores in cells by a single aggregation method. Can plot cumulative costs and effectiveness for different perspectives.	Main display can show both measure and submeasure data, plus cost data. Can highlight risk on *Summary* sheet along with submeasure values and cost data. Colors on scorecards depend on aggregation method. Spider charts, scatter plots, cost and ESG information graphs.
Exploration across different perspectives	Yes (called *views* in DynaRank).	Yes.
Computing investment program from time goals	No.	Yes (the *IOC to Cost Data* sheet).

Appendix B

Building a Portfolio View from the PAT-MD Template

PAT-MD can be used to develop different sets of displays for different purposes (e.g., strategic planning versus on-the-margin budget scrubs). These displays are called *views*.[1] Creating one is an excellent way to become familiar with the nuts and bolts of entering values into PAT-MD.

Given an empty PAT-MD workbook, a user can build a results display using whatever investment options, measures, and submeasures he or she desires. Before any display is developed, the user must generate the following lists of objects used in the analysis (and the names used to identify them, which must be consistent throughout the tool):

1. *Investment options.* The options that are being evaluated in PAT-MD.
2. *Measures and submeasures.* Criteria on which the investment options are evaluated. Each measure consists of an aggregation of submeasures; measures do not need to have the same submeasures.
3. *BMDS components.* The investment options allocate different amounts of funding over time to each BMDS component under consideration (for both RDT&E and deployment).
4. *Engagement sequence groups (ESGs).* For an ESG to be considered a potential option, all of the BMDS components it comprises must be completed.
5. *Time frame.* The years the analysis and cost data should cover.

Once these have been determined, the user can begin to fill in the input sheets. At the end of this appendix, we describe the *Template Builder* worksheet, which simplifies the setup of all of the PAT-MD worksheets.

Filling in the *Data Entry* Sheet

1. Add the names of the investment options to the first column, starting in the row below the yellow bar (row 10).
2. Fill in the measures and submeasures information. Starting with column B, for each measure/submeasure pair, put the name of the measure in row 1 and the name of the submeasure in row 2. Submeasures of the same measure must appear in consecutive columns. To include a risk column for a measure, input it as a submeasure with the name *Risk*.

[1] A "view" in DynaRank is called a "perspective" in PAT-MD.

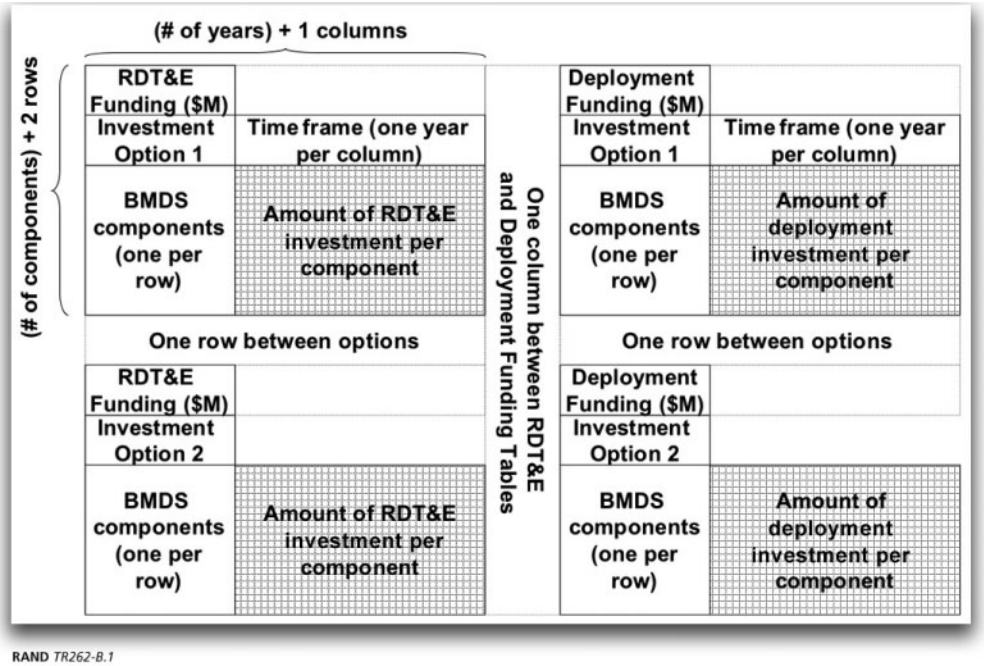
3. Fill in the parameters (weights for effectiveness and summary calculations, threshold and goal values, etc.) for each submeasure in rows 3 through 8. If a measure has a risk column, these values should be left blank.
4. Fill in the (numeric) values for each submeasure for each investment option in the corresponding row and column. The only column that should have nonnumeric values is the Risk column.

Filling in the *Cost Data* Sheet

The *Cost Data* sheet consists of a collection of blocks of cost numbers that represent the amount of RDT&E or deployment funding per BMDS component per year for an investment option. These blocks and how they are arranged have a very particular structure, as shown in Figure B.1.

1. The cell in the first row and column of each block denotes whether the block describes RDT&E funding or deployment funding.
2. The second row of the block has the name of the investment option in the first column and the list of years in the time frame under consideration in each successive column.
3. The successive entries in the first column are the names of the BMDS components, and the entries in the cells show the amount of funding for each component for each year.

Figure B.1
Block Structure of *Cost Data* Sheet for Two Investment Options



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The resulting block should have two more rows than the number of components and one more column than the number of years in the time frame. The RDT&E block for the first investment option must have its upper left-hand corner in the upper left-hand corner of the *Cost Data* sheet. The RDT&E and deployment blocks for the same investment option should be side-by-side, separated by a single column. A single row should separate blocks for consecutive investment options. The sheet should fill 2Y + 3 columns, where Y is the number of years in the time frame, and I(C + 3) – 1 rows, where I is the number of investment options and C is the number of BMDS components. The BMDS components must be in the same order in each block.

Filling in the *ESG Data* Sheet

1. The names of the BMDS components should be entered in column E, starting in row 2 in the same order as on the *Cost Data* sheet.
2. For each component, the amount of investment to complete the RDT&E should appear in the first column.
3. The B, C, and D columns should contain 0/1 flags to denote whether the component is intended for use in a boost-phase, midcourse, or terminal-phase ESG. These flags are used to produce the phase-specific cost tables on the *ESG Table* sheet.
4. The names of the ESGs should be placed in consecutive cells in row 1, starting with column F.
5. Each cell corresponding to a BMDS component and an ESG should contain a 1 if the BMDS component is a part of the ESG and a 0 (or blank) otherwise.

Filling in the *Perspective Cases* Sheet

Defining a new perspective case is equivalent to changing by hand the parameters for the submeasures on the *Data Entry* sheet, as well as the weights associated with each measure on the *Measure Comments and Weights* sheet. The different perspectives are defined by creating copies of the first eight rows of the *Data Entry* sheet, keeping measures and submeasures in the same order.

1. Each block of eight rows has a header row (highlighted in yellow). The first entry in the header row should contain the name of the perspective case defined below it.
2. The weight of each measure on the *Measure Comments and Weights* sheet should be entered in a cell in the header row above any submeasure of that measure.
3. Each block should be filled with the desired weights, threshold and goal values, and effectiveness parameters for a submeasure.

The header row separates consecutive perspective cases, so the completed *Perspective Cases* sheet should have 9P rows and S + 1 columns filled, where P is the number of perspective cases and S is the number of submeasures. Although the template gives the row headings for four perspective cases, more perspectives can be defined below these cases.

Filling in the *Measure Comments and Weights* Sheet

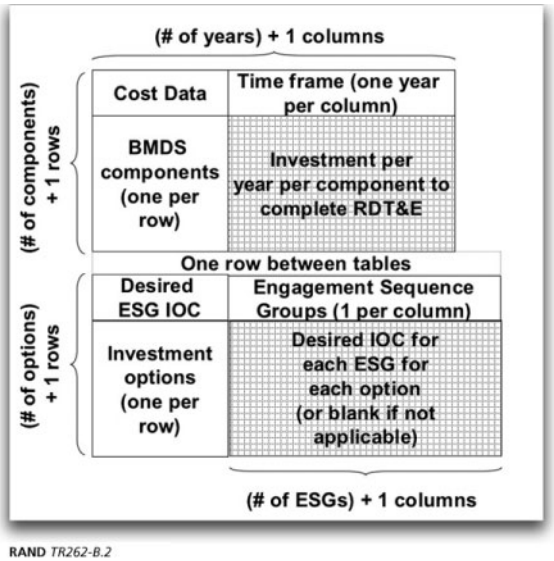
Starting in row 2, put the name of each measure in the first column, a brief comment (which appears when the cursor moves over the name of the measure in the *Summary* sheet) in the second column, and the weight of the measure for effectiveness calculations in the third column.

Filling in the *IOC to Cost Data* Sheet

Although this sheet is not required for PAT-MD to run, it does allow the quick generation of RDT&E annual investments for each BMDS component by defining the desired IOC date for each ESG for each investment option. The sheet consists of two blocks, one containing the current annual RDT&E investment for each BMDS component (this also assumes that RDT&E for the BMDS components is completed in the time frame under consideration) and the other containing the names of investment options and the desired IOC date for each ESG. These blocks and their arrangement are shown in Figure B.2.

1. For the first block, the first row (starting in column B) lists the years in the time frame under consideration in consecutive columns.
2. The first column (starting in row 2) lists the BMDS components (in the same order in which they appear on the *Cost Data* sheet).
3. The entries in the table are the RDT&E investments for each component in each year to complete the component's RDT&E. It is assumed that the last non-zero entry in the row is the year in which the RDT&E for the component is complete.

Figure B.2
Block Structure of *IOC to Cost Data* Sheet



4. In the second block (which should be separated from the first block by a single row), the first row (starting in column B) lists the ESGs (in the same order in which they appear on the *ESG Data* sheet).
5. The first column of the block (starting in the second row) lists the investment options.
6. The entries in the table are the desired IOC for each ESG for each investment option. If an ESG is not a part of an investment option, the cell should be left blank.
7. Clicking on the Generate Cost Data button will produce on the *IOC to Cost Data Output* sheet blocks identical to the ones that appear in the *Cost Data* sheet. One block will be generated for each investment option, and the RDT&E streams are such that every component is done on time for each ESG to be completed by the desired IOC date.

Filling in the *Summary* and *Details* Sheets

There are three main displays on the *Summary* sheet: the nine-column color-coded measure-summary table, four columns containing values of individual submeasures, and nine columns of cost data.

1. Starting in row 3, enter the names of the investment options that are to be displayed on the *Summary* sheet (as well as all other output sheets) in the first column. It is not necessary to include all of the investment options on the *Summary* sheet, nor is it necessary for the investment options to appear in the same order as they do on the *Data Entry* sheet.
2. To display a measure in the measure-summary table, enter the name of the measure in the first row above the column in which it is to be displayed. The measures do not all need to appear on the *Summary* sheet, nor must they appear in the same order in which they appear on the *Data Entry* sheet.
3. To make a submeasure appear in one of the submeasure columns, enter in the first row the name of the measure that the submeasure is associated with, followed by two colons (::), followed by the name of the submeasure (e.g., A::B would access submeasure B of measure A).
4. To make a cost metric appear in the cost-data columns, the column heading should have the format *type* cost: *year-range*, where *type* is either RDT&E, Deployment, or Total (RDT&E + deployment) and *year-range* is either a single year in the time frame (e.g., 2005) or a start year and an end year separated by a dash (e.g., 2005–2010). A sample cost-column heading would be "RDT&E Cost: 2005–2010."
5. Click the Populate Scroll Bars button. This will populate all of the dropdown menus used in all of the output sheets.
6. Click on the Modify Summary button. This will fill in all of the information on the *Summary* sheet.
7. To display the details of a measure that is a column on the *Summary* sheet, click on the Detail button for that column. Similarly, clicking the Related Details button under a submeasure column will display a *Details* sheet with all of the submeasures that share the measure of the submeasure in that column.
8. When the *Details* sheet is open, changing the measure name in cell B1 and clicking on the Get Details button will display all of the submeasures of that measure.

An Example of Building a Portfolio View

Figures B.3 through B.10 present a template for a very simple example. The example has two investment options, two measures (each consisting of two submeasures), three BMDS components, and two ESGs.

Figure B.3
***Data Entry* Sheet**

Measure (Modify Summary)	Measure 1	Measure 1	Measure 1	Measure 2	Measure 2	Measure 2
Submeasure	Submeasure 1.1	Submeasure 1.2	Risk	Submeasure 2.1	Submeasure 2.2	Risk
Weight of Submeasure in Scoring Functions (0 to 1)	0.5	0.5		0.5	0.5	
High or Low Values Desired?	High	High		High	High	
Threshold Value	1	1		1	1	
Goal Value	2	2		2	2	
Submeasure Score for Threshold Value (0 to 1)	0.5	0.5		0.5	0.5	
Submeasure Score for Goal Value (0 to 1)	1	1		1	1	
Investment Option						
Option A	1	1.5		2	2	
Option B	2	1.5		1.5	0	Element of Risk

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Figure B.4
***Cost Data* Sheet**

Export Cost Data

RDT&E Cost				Deployment Cost		
Option A	2005	2006		Option A	2005	2006
Component 1	5	5		Component 1		20
Component 2	10	10		Component 2		50
Component 3				Component 3		
RDT&E Cost				Deployment Cost		
Option B	2005	2006		Option B	2005	2006
Component 1				Component 1		
Component 2	10	10		Component 2		30
Component 3	15	15		Component 3		60

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Figure B.5
***ESG Data* Sheet**

Cost to complete system ($M)	Boost-Phase Investment	Mid-Course Investment	Terminal Phase Investment	System\ESG	ESG 1	ESG 2
10	1			Component 1	1	
20	1	1		Component 2	1	1
30		1		Component 3		1

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Figure B.6
Portion of *Perspective Cases* Sheet

Emphasis on Measure 1	2			1		
Measure	Measure 1	Measure 1	Measure 1	Measure 2	Measure 2	Measure 2
Submeasure	Submeasure 1.1	Submeasure 1.2	Risk	Submeasure 2.1	Submeasure 2.2	Risk
Weight of Submeasure in Scoring Functions (0 to 1)	0.5	0.5		0.5	0.5	
High or Low Values Desired?	High	High		High	High	
Threshold Value	1	1		1	1	
Goal Value	2	2		2	2	
Submeasure Score for Threshold Value (0 to 1)	0.5	0.5		0.5	0.5	
Submeasure Score for Goal Value (0 to 1)	1	1		1	1	
Emphasis on Measure 2	1			2		
Measure	Measure 1	Measure 1	Measure 1	Measure 2	Measure 2	Measure 2
Submeasure	Submeasure 1.1	Submeasure 1.2	Risk	Submeasure 2.1	Submeasure 2.2	Risk
Weight of Submeasure in Scoring Functions (0 to 1)	0.5	0.5		0.5	0.5	
High or Low Values Desired?	High	High		High	High	
Threshold Value	1	1		1	1	
Goal Value	2	2		2	2	
Submeasure Score for Threshold Value (0 to 1)	0.5	0.5		0.5	0.5	
Submeasure Score for Goal Value (0 to 1)	1	1		1	1	

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Note that the weights on the measures change with the different perspectives.

Figure B.7
***Measure Comments and Weights* Sheet**

Measure	Comment	Weight
Measure 1	This is Measure 1	4
Measure 2	This is Measure 2	4

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Figure B.8
Truncated *Summary* Sheet (Unfilled and Filled)

Measure	Measure 1	Measure 2		Measure 1:: Sub-measure 1.1		RDT&E Cost: 2005	RDT&E Cost: 2006	Total Cost: 2005-2006		Relative Effective-ness	Relative Cost-Effective-ness
Investment Option	Detail	Detail		Related Details		Cost Detail	Cost Detail	Cost Detail			
Option A											
Option B											

Measure	Measure 1	Measure 2		Measure 1:: Sub-measure 1.1		RDT&E Cost: 2005	RDT&E Cost: 2006	Total Cost: 2005-2006		Relative Effective-ness	Relative Cost-Effective-ness
Investment Option	Detail	Detail		Related Details		Cost Detail	Cost Detail	Cost Detail			
Option A				1		15	15	100		1	1
Option B				2		25	25	140		0.5	0.36
Color Code											
% of Goals Reached	100%	75-100%	50-75%	25-50%	0-25%	No data incl. in summary calculation					

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Figure B.9
Truncated *Summary* Sheet (with Results)

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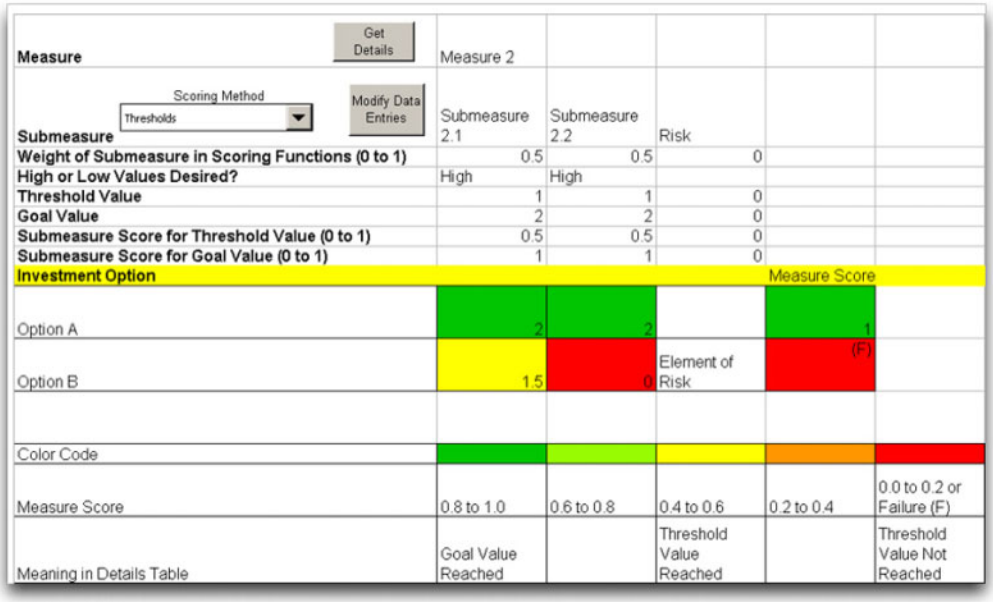
Figure B.10
***Details* Sheet**



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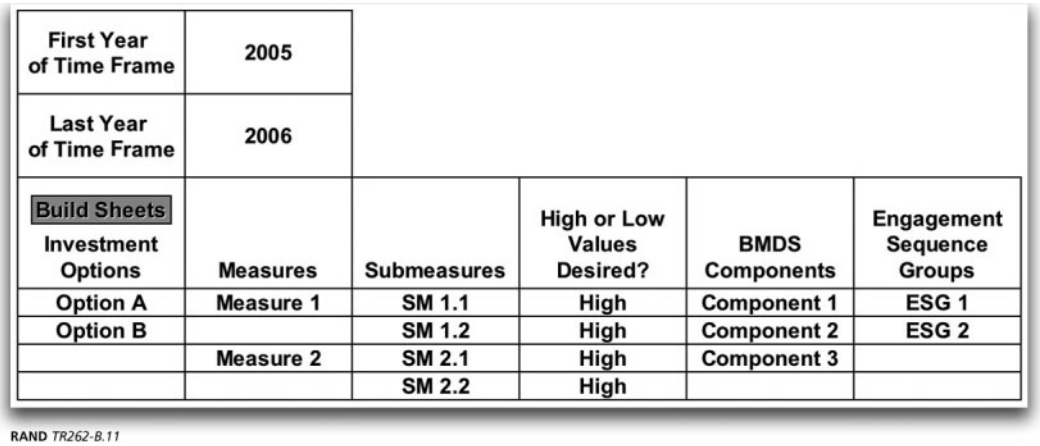
Template Builder Sheet

To facilitate the setup of worksheets, we have included a *Template Builder* sheet (sketched in Figure B.11) as the last sheet in the PAT-MD workbook. All of the names of the investment options, measures and submeasures, and so forth can be entered on the *Template Builder* sheet. The first and last years of the time frame under consideration are entered in the first two rows, and the names of the investment options are entered in the first column. The name of each measure is entered in the second column once for each collection of submea-

Figure B.11
***Template Builder* Sheet**



First Year of Time Frame	2005				
Last Year of Time Frame	2006				
Build Sheets Investment Options	Measures	Submeasures	High or Low Values Desired?	BMDS Components	Engagement Sequence Groups
Option A	Measure 1	SM 1.1	High	Component 1	ESG 1
Option B		SM 1.2	High	Component 2	ESG 2
	Measure 2	SM 2.1	High	Component 3	
		SM 2.2	High		

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sures. The names of the submeasures associated with each measure are entered in consecutive rows in the third column, with "High" or "Low" entered in the fourth column to denote whether high or low values are desired for the submeasure. The names of the BMDS components are entered in the fifth column, and the names of the ESGs are entered in the sixth column.

Every time a new PAT-MD template is built (by clicking on the Build Sheets button), all of the data currently on all of the worksheets are removed. The user is warned that this deletion will occur and has the option of canceling before proceeding with building a new PAT-MD template. The row and column labels for all of the tables on all of the sheets and the entries for all of the dropdown menus are generated, but the data must still be entered by other means.

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