DISSERTATION

Zeroing In

A Capabilities-based Alternative to Precision Guided Munitions Planning

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This document was submitted as a dissertation in September, 2005 in partial fulfillment of the requirements of the doctoral degree in public policy analysis at the Pardee RAND Graduate School. The faculty committee that supervised and approved the dissertation consisted of Richard Hillestad (Chair), John Peters, and Steven Bankes.

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Acronyms

APC	Armored Personnel Carrier
CARS	Computer Assisted Reasoning System
CBP	Capabilities-based Planning
COCOM	Combatant Commander
DIA	Defense Intelligence Agency
DoD	Department of Defense
DPRK	Democratic People's Republic of Korea
FH	Fixed Hard
FS	Fixed Soft
GAO	Government Accountability Office
JDAM	Joint Direct Attack Munition
JSOW	Joint Standoff Weapon
LGB	Laser Guided Bomb
MH	Mobile Hard
MR	Munitions Requirement
MS	Mobile Soft
OIG	Office of the Inspector General of the Department of Defense
OSD	Office of the Secretary of Defense
PGM	Precision Guided Munition
pK	Kill Probability
PTD	Phased Threat Distribution
RDM	Robust Decision Making
TLAM	Tomahawk Land Attack Missile
QDR	Quadrennial Defense Review
USDP	Undersecretary of Defense for Policy and Planning

CHAPTER ONE
Introduction

Background

Over time, the Department of Defense (DoD) has institutionalized a yearly munitions planning process that plans for specific wars and results in the accumulation of large munitions stocks. It is called the DoD Munitions Requirements (MR) process. The institution's creation made sense in the context of the cold war – where the threat was of an immediate and tremendous loss (50,000 tanks crossing into Europe) that could be countered by geographically specific worst case planning.

The MR process does not make as much sense today. The DoD faces increasing uncertainty about both the threats it will face and the amount of money it will receive to prepare for them. The requirements process predicts demand for munitions based on specific scenarios, and does not include cost as an integral factor. The resulting demand, called the 'requirement,' is used to inform and justify munitions acquisitions, and shapes the structure of the industrial base. Such a process that takes mission, demand, and funding for given is perhaps no longer a good match to today's reality. Furthermore, today's rapid technological advances and diverse engagements have quickly changed tactics and weapon preferences – and can be expected to do so in the future.

The DoD recognizes the need to fundamentally change the way it plans for wars and makes purchasing decisions, and has recently begun to promote a capabilities-based planning approach over traditional requirements based approaches. As defined by Paul Davis (emphasis added):

> Capabilities-based planning is planning, *under uncertainty*, to provide capabilities suitable for a *wide range* of modern day challenges and circumstances, while working within an *economic framework*.[1]

However, as of the writing of this paper, such an approach has not been applied to complex problem of munitions planning.

Motivation

As a result of recent criticisms by the Government Accountability Office (GAO) and DoD Inspector General and a department wide push for the use of new planning methods, the DoD is re-examining the Munitions Requirements process. Concurrently, the Office of the Secretary of Defense (OSD) is looking for ways to make its precision guided munitions supply more "flexible and responsive" to the needs of policy makers and war-fighters. Precision Guided Munitions (PGM) stocks and expenditures are more sensitive to the planning process than traditional munitions because they are more expensive and complex, tend to be built by private subcontractors, are in high demand and have a short shelf life relative to traditional unguided munitions. On top of this, PGMs are rapidly

[1] Davis, Paul. "Analytic Architecture for Capabilities-Based Planning, Mission-System Analysis, and Transformation" RAND, Santa Monica, CA: 2001(?), p.1

becoming a staple rather than a niche weapon. In Desert Storm, PGMs accounted for 8% of the munitions fired. They accounted for over 60%, and possibly as much as 90%, of the weapons fired during Operation Iraqi Freedom.

Institutional Movement Toward Capabilities-based Planning

The DoD has, in the past, tried to improve its requirements system – the instruction governing the process has changed three times during the last seven years. Acquisition reform has long been a major issue for OSD and Congressional leadership. But over the last decade there have been many obstacles to change present within the DoD. Often cited obstacles include organizational inertia, 'stove-piped' management, service oriented processes, and the presence of a decentralized power structure. Military transformation has been slow, but new ways of thinking are permeating the DoD. The old paradigm has been to plan based on what Paul Davis calls 'point-scenarios.' According to Davis, point scenario planning fixates on "particular enemies, particular wars, and particular assumptions about those wars – a fixation that comes at the expense of more flexible and adaptive planning."[2] High-level policymakers have become increasingly aware of the importance of adaptability. The concept of capabilities-based planning is now moving rapidly from idea to practice. The 2001 Quadrennial Defense Review announced a new defense strategy based upon a "capabilities-based approach to defense."[3] The recently completed Joint Defense Capabilities Study recommends a joint process, centrally managed by Department of Defense and overseen by the Secretary of Defense.[4] There have been obstacles in the past, but todayÅfs leaders recognize the problems and openly voice a strong desire to reform the planning and acquisition process.

Approach

This dissertation provides an example of how the ideas of capabilities-based planning can be applied to the problem of PGM planning in the form of an illustrative, or demonstrative, analysis. Two interrelated methodologies are used in this illustrative analysis: exploratory modeling and robust planning. Recall that capabilities-based planning seeks to find capabilities that are suitable for a wide range of uncertain circumstances, while simultaneously working within an economic framework. This research shows that by applying the methodology of exploratory analysis to a single war scenario, we may come to a more complete understanding of how changes in the constraints of cost and production capacity and the uncertainty of preparation time can drastically affect the performance of a munitions portfolio. The presence of multiple war scenarios complicates this sort of analysis, and makes it impossible to find a single optimal munitions portfolio. We show that the use of robust decision-making methodologies makes it possible to analyze the effects of these

[2] Davis, Paul. "Analytic Architecture of Capabilities-Based Planning, Mission-System Analysis, and Transformation." RAND: Santa Monica CA, 2002. p. 8

[3] Office of the Secretary of Defense. "2001 Quadrennial Defense Review Report" Washington, DC, 2001. p. 13

[4] Joint Defense Capabilities Study. December 2003. p.3

constraints/uncertainties across a wide variety of scenarios thus allowing us to create improved and flexible munitions portfolios.

By accepting uncertainties and economic constraints and dealing with them in a sophisticated manner, we come to a more complete understanding of the strategy chosen, possible alternatives, and the effects of changes in the constraints. Policymakers will be able to see and understand tradeoffs across a wide variety of budget, production, preparation and threat scenarios. The ability to incorporate this kind of information will improve the decision process and make it possible to adequately prepare to meet a wide range of uncertain threats with limited resources.

The analysis provided here is meant for illustrative purposes only, and will be referred to as the illustrative or demonstrative analysis throughout the body of this paper. Much of the information used to determine an appropriate weapons mix is classified. Weapon effectiveness data, target data and, perhaps, even some of the weapons themselves are classified. Only unclassified data and sources were reviewed in the preparation of this report. The aim is not to provide a specific answer, but rather to show how a capabilities-based approach may be applied to the problem and demonstrate the advantages of doing so.

Structure

The first chapter describes the planning process that is now used to buy precision-guided weapons. The Munitions Requirements process is defined. This chapter includes a detailed discussion of documented criticisms of the process, with special attention paid to those presented by the GAO and DoD Inspector General. Such criticisms are considered overly harsh in military circles, and counter-arguments are presented where warranted.

The second chapter introduces the problem as one of resource allocation. It argues that there are several things the DoD can do differently in order to solve the munitions planning problem if it wishes to pursue a capabilities-based approach. Specifically, the DoD can deal with uncertainty explicitly and consider the economic constraints of cost and production capacity concurrently with procurement decisions.

The third chapter expands on the complex nature of the problem through a brief discussion of the two most relevant academic literatures: resource allocation and inventory control. The chapter argues that pure resource management methodologies are impractical because of uncertainties in goals and performance measures across a wide variety of war scenarios. It argues that pure inventory control methods are inadequate because of the erratic nature of PGM demand. Again, this is the heart of capabilities-based planning – finding solutions that work across a wide variety of scenarios and uncertainties while operating within an economic framework.

The fourth chapter presents the methodologies of exploratory analysis and robust/adaptive planning and shows how they are particularly suited to this problem.

The fifth chapter describes the form of the illustrative analysis that will be used and explains how it can help planners better understand the important tradeoffs. The model that will be used in the illustrative analysis is specified here.

The sixth chapter uses exploratory analysis to show that the constraints of cost, production and preparation time dramatically affect the optimal portfolio of weapons for a single scenario. Then it demonstrates that the use of robust decision-making techniques makes it possible to analyze the effects of these constraints across multiple scenarios to create improved and flexible portfolios.

The seventh chapter presents conclusions to be drawn and offers potential extensions.

CHAPTER TWO
The Munitions Requirements Process

Munitions Requirements Defined

Conventional munitions requirements are "point estimates of the quantities of munitions the services would buy to arm their planned forces if sufficient funds were available."[5] Although the estimates are not constrained monetarily in a single process, they are used as primary data to inform and justify large-scale munitions procurement decisions. The requirements do not result in automatic inventory changes, but are used by munitions planners and budgeters in entirely separate processes. The military services are responsible for having enough munitions to meet the current requirement.[6] The requirements are calculated on a yearly basis.

The calculation of the requirement clearly uses depends on classified information. Munitions effectiveness data are classified. Specific targets identified in the process are classified. Some of the munitions used may be classified. However, the process itself is not classified and will be discussed in great detail in the following sections.

The total munitions requirement is comprised of a war reserve requirement and a testing, training, and current operational requirement. The war reserve portion accounts for the vast majority of the total requirement, and is the primary subject of this research. War reserve munitions requirements are the sum of three types of requirements: combat requirements, current operations/forward presence requirements, and strategic readiness requirements. The combat requirement is the quantity of munitions needed to equip a specific force structure to achieve the planned wartime objectives of its Combatant Commander (COCOM). The current operations/forward presence requirement is the quantity needed to equip forces that are not committed to specific war plans or scenarios. The strategic readiness requirement is the quantity needed to maintain treaty agreements and support forces that are not committed to operations in major theaters of war.[7]

The documents that lay out current munitions requirements policy are known as the DoD 3000 series. The process created by these documents breaks down the complex problem of munitions planning into smaller parts. A different agency is responsible for each piece of the problem, beginning with the Office of the Undersecretary of Defense for Policy and Planning and ending with each of the services. In a different process conducted *after* the requirement is calculated, each service budgets for its own munitions requirement separately, and that budget is fit into the overall DoD budget by the Joint Chiefs in a complex and iterative process that ends when final approval comes from the White House.

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[5] Kassing, David et al "Estimating Conventional Munitions Requirements" RAND: 1991. p. 1

[6] GAO/NSAID-96-129 p. 14

[7] OIG 2000 p. 2

Current Stockpile and Annual Expenditures

> This ammunition, if loaded onto railroad cars, would stretch over 800 miles – the distance from Washington, D.C. to Orlando, Florida. *GAO*

In 1996, the General Accounting Office estimated that the services carried a stockpile of over 5 million tons of conventional ammunition that was worth approximately $80 billion.[8] The Army alone uses over 35 million square feet to store approximately 3 million tons of stock.[9] In September of 2000, the Department of Defense reported an inventory of munitions, missile systems and related equipment valued at $76.8 billion.[10] The Department spends about $5 billion on conventional munitions every year.[11] The trend towards an increased reliance on precision weapons is reflected in DoD munitions budgets. Annual expenditures for precision-guided weapons were $775 million in 1998, with a planned increase to $2 billion per year by 2003.[12] Although this is a relatively small portion of the defense budget, it can be argued that the rest of the budget is devoted to activities that support the delivery of these weapons to their targets.

The Munitions Requirement Generation Process Defined

The formal yearly process used to determine the munitions requirement is called the DoD Munitions Requirement Process. Over the last seven years, there have been three different versions of the DoD Instruction defining the process.[13] The name of the process has changed, but changes in content appear to be minimal. The document provides a fairly detailed description of how the combat requirement is to generated:

Step One: Create Scenarios and Find Targets

The process begins when the Undersecretary of Defense for Policy (USDP) develops the Defense Planning Guidance document. This document includes specific scenarios, known as "Illustrative Planning Scenarios," to be used as the primary input of the Munitions Requirement process. The USDP is tasked to "specify critical guidelines, such as relevant theaters for consideration and conflict duration."[14] The Defense Intelligence Agency (DIA) creates Threat Reports based upon the scenarios provided by the USDP. The threat reports are target lists. These lists are the "authoritative threat estimate for developing munitions requirements."[15]

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[8] GAO/NSIAD-96-129 "Significant Problems Left Unattended Will Get Worse" June 1996. p. 14

[9] Ibid. p. 15

[10] Department of Defense. "Supply System Inventory Report" September 30, 2000. p. 15

[11] Office of the Inspector General DoD. "Summary of the DoD Process for Developing Quantitative Munitions Requirements" February 24, 2000. p. 3

[12] GAO/NSAID-99-32 "Guided Weapons Plans need to be Reassessed" December 1998. p. 4-5

[13] DoD Instruction 3000.4. The different versions are dated June 16, 1997; August 10, 2001; and October 23, 2003.

[14] DOD Instruction 3000.4 October 23, 2003 p.4

[15] Ibid p. 8

Step Two: Divide Up the Targets

The Combatant Commanders responsible for regions covered in the Illustrative Planning Scenarios divide up the targets provided in the Threat Report among the services (Army, Navy, Air Force, Marines). The targets are to be distributed in accordance with the Commanders' own operational plans. This division of labor between the Services becomes actionable in a document called the Phased Threat Distribution (PTD).

Step Three: Generate the Requirement

Each service is responsible for calculating the requirement for its portion of the Phased Threat Distribution. The calculations are done by a wide variety of mathematical models. Each service uses a different model, and in many cases, uses more than one. In most cases, the models take about a year to run. The aggregate result of these calculations is the combat munitions requirement. The most recent version of Instruction 3000.4 mandates that the calculations be done twice – once constrained by inventory, and once without any constraint other than "reasonable production capacity," " weapon system capabilities," and "externally defined caps on procurement."[16] The current operations/forward presence and strategic readiness requirements are also calculated by each service separately. They are added to the combat requirement to generate the total requirement.

Cited Problems with MR Process

Between 1994 and 1999, over 20 reports issued by the GAO and DoD Inspector General's office identified systemic problems within the munitions requirements process. Easily accessible studies critical of the process date back to 1989, and the GAO has issued reports as recently as October 2002. The more recent reports not only identify possible problems, but also claim that they are not being fixed. Additionally, the DoD has had to deal with both the problem of destroying outdated and unusable munitions and the problem of replenishing newer munitions that have been expended at a rate greater than expected. According to these critiques, recent acquisition plans have been justified using requirements that are vastly overstated as a result of poor coordination between the services and faulty processes within the system. At the same time, we have faced PGM shortages during each major conflict since the Gulf War.

All criticisms may be summed up in a single sentence: "the requirements don't match the reality." The overarching story pieced together by the documents is as follows. The segmented requirements process compartmentalizes and effectively hides some of the uncertainty faced by planners in each subsequent step. In order to make up for this, planners add risk premiums to their estimates, which in the end creates a point estimate that may be difficult to justify to accounting agencies and/or change to fit available resources during the later budgeting process. In addition, critics attack the sheer numbers of methodologies used, length of the process, the assumptions used and the sensitivity

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[16] Ibid p. 9-10

of models to these assumptions. The following sections will describe how critics believe the MR process prevents planners from coming to a coherent understanding of the true risk associated with a given munitions portfolio or the tradeoffs that are possible in the production, purchase, use and storage of munitions.

Assumptions at Various Steps Can Hide the Uncertainties

Planners responsible for each step of the requirements process must make certain assumptions in order to provide the documents and data needed in subsequent steps. The USDP and DIA must decide the size, type and duration of the wars for which we should prepare so that the combatant commanders can determine which strategies they will employ, which result in the force mixes to be used. The services must build weapon choice and effectiveness (among other things) data into their simulations and models that represents current tactics and operational concepts.

We'd like to know for certain who we will fight, where we will fight, how we will fight, what forces we will fight with, and the conditions under which the fighting will be done. The DoD recognizes that in today's world we have much less certainty about such things than we did 20 or 30 years ago – hence the capabilities-based planning initiatives currently under way. But such an approach has yet to be implemented in munitions planning. A 1991 RAND review of the MR process states that "munitions requirements processes treat as known much that is, in fact, unknowable" and concludes that "effects of uncertainties in warfare are by and large ignored in the calculation of munitions requirements."[17] Rather than treat uncertainty as a core element of munitions planning, each step of the MR process tends to compartmentalize the uncertainty through a simplifying assumption in order to solve its piece of the problem. This limits the uncertainty faced in subsequent steps. In many cases, these assumptions seem perfectly reasonable, but in total (as the system works now) they preclude a complete understanding of the problem at hand – preparing for a wide variety of uncertain threats within the context of an economic framework.

The resulting requirement is a *best estimate made under certain assumptions that limit an inherently large degree of uncertainty*. The requirement is sensitive to changes in those assumptions. The reality of the type and duration of a war may or may not match the scenarios. Consider the recent number of small-scale contingencies that have been dealt with through the use of force – resulting in the use of munitions that were bought to satisfy a different and particular requirement. Combatant commanders may or may not change their strategies. Field commanders may or may not make the same decisions as the services' models. In order to make up for this, responsible planners at each level do what they can to guard against downside risk by adding a risk premium to their estimates. In the aggregate, this results in what critics call overly inflated requirements and potentially severe overbuying and stocking of particular munitions. Although carrying a large amount of safety stock may be a very good thing, it appears to be a byproduct of the planning system and not a conclusion arrived at through careful analysis.

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[17] Kassing et al p.2

Requirements are Systematically Distorted to Make Up for Hidden Uncertainty

Critics claim that those tasked with running the process inflate the requirement at every level and in almost every conceivable way. The result: overstated requirements that make it very difficult for any single person, office, or group understand the tradeoffs possible in planning or the character of risk underlying the required munitions portfolio. Even if one could, according to the GAO, "the DoD has no central oversight body or mechanism to examine guided weapons programs and to assess how many weapons are needed to meet national objectives or how many weapons the DoD can afford."[18]

Recall that the process begins when the USDP chooses specific, worst-case scenarios, creating the Illustrative Planning Scenarios. The GAO claims that the USDP continues to choose the worst case despite the "DIA's projections on recent international trends [(a reduced threat)], the sizable inventory of capable weapons, and the current budgetary situation."[19] The USDP gives no information that would indicate the likelihood of these scenarios' actual occurrence.[20] However, the argument for planning for the worst case is compelling – if we have enough munitions available to face even the worst possible adversary, we should be prepared if a lesser threat arises. This does not necessarily mean that we will be adequately prepared to face a different kind of threat.

The DIA then generates a *comprehensive* target list for the regions associated with the (already worst case) scenarios (the Threat Report). The COCOMs and services use *almost all* of the targets as inputs to their tasks, even though it is widely acknowledged to be unlikely that more than a small portion of them will actually be attacked.[21] When the GAO questioned DoD officials, they acknowledged that including nearly all the targets may inflate requirements, but said that they did "not want to risk having insufficient weapons, should some unforeseen conflict require them."[22] Again, the reasoning behind such a decision is fundamentally sound – the COCOMs want to be absolutely certain that they are able to fulfill their obligations. If they plan on being able to hit *all* targets in a region, they may be certain that the capability will be there to hit any combination of targets.

In the next step, the COCOMs create the Phased Threat Distribution by dividing the targets specified in the Threat Report amongst the services. The COCOMs routinely divide the targets in such a way that the aggregate proportion of assigned targets exceeds 100%. The GAO cites an example of one COCOM who, with the objective of destroying 80% of a target type, apportioned 140% of the targets amongst the services.[23] The over assignment of targets is justified in the name of flexibility. COCOMs want to be sure that all the targets can be hit, even if plans change or assets

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[18] GAO/NSAID-99-32 p. 7

[19] GAO/NSAID-99-32 p. 34

[20] GAO –01-18 p. 9

[21] GAO/NSAID-99-32 p. 34

[22] GAO/NSAID-99-32 p. 35

[23] NSAID/GAO-96-72 p. 23

assigned to one service or another become unavailable. However, the GAO sees it differently and goes so far as to say:

> Defense Intelligence Agency officials stated that in the past, the services could, based on input from their own intelligence sources, or input from the war fighting Commanders in Chief [(COCOMs)], develop an independent threat analysis that could result in the services planning to destroy the same targets, and consequently, overstating munitions requirements.[24]

The phased threat distribution is then used by the individual services as inputs for their own detailed combat models. In order to account for uncertainty, the services have been known to both add targets before running the models – and add munitions afterwards. In its criticism of the DoD Anti-Armor Munitions Plan, the GAO identifies four specific cases of requirements inflation at the service level: The Air Force increased its target allocations by 13-21 percent, depending on the target type. The Marine Corps and Army did not always accept their methodologies' results and manually calculated higher requirements. The services' methodologies proscribed the use of expensive, high tech anti-armor weapons against unarmored targets. The services added weapons to account for uncertainties – the most shocking example being that only 3 percent of the Army's direct fire weapons would be used against their assigned target. The remaining 97 percent are for added flexibility and risk mitigation.[25] Furthermore, invisible margins of safety may be found *inside* the models. Many assumptions used in the services' models tend to increase the requirement in ways that are nearly invisible. If munitions' kill probabilities are too low, or enemy repair rates too high, the resulting requirement will be artificially high. Such assumptions take the form of parameters buried in the services' models.

Other Problems

A Myriad of Modeling Methodologies

The models used by the services have a myriad of problems identified over the last 10 years. There is no consistent methodology used to determine the combat requirement. Each service uses an entirely different analytic method and most use more than one. A RAND study identified seven different methodologies used between the four services.[26] Kassing et al go to great lengths to describe the major differences. The Army uses very detailed combat models to calculate its requirement, while the other services' models are less specific. Some methodologies set requirements based on the number of available targets, without regard for the services' ability to expend munitions. Others set requirements based on the ability to expend munitions, without regard for the number of targets that may be available. Each service has a different way of calculating the confidence level of its estimate. Each service treats re-supply of ammunition in a different way (if at all). Each service has a different way of including cost effectiveness calculations in its estimate (rudimentary or not at all). Some

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[24] GAO-01-18, p.6

[25] GAO/NSAID-00-67 p. 9

[26] Kassing et al p. 44

services assign values to various targets, while other services simply count the number of targets. A recent report by the DoD Inspector General cites further inconsistencies between the services' methodologies.[27] For example, two services included combat losses in their requirements, and two did not. Only one service considered re-supply in its calculations. Each service had a different interpretation of the current operations/forward presence requirement and strategic readiness requirement.[28]

MR is a Long and Complex Process

Even though these methodologies are applied to only one or a few scenarios, they require a significant amount of time and resources. In 1991, the requirements process for one family of Naval weapons needed 13 models, at least four different working groups (one to three star) and 10-12 months to be completed.[29] The Army needed over a year to obtain estimates for a single theater using its detailed combat model.[30] The Air Force and Marines generally need a year to complete their processes.[31] The cost of these processes in terms of dollars and time is relatively small compared to the cost of the munitions themselves, but may be quite large when compared to the usefulness and clarity of the results.

Outdated and Inconsistent Modeling Assumptions

The models used by the services characterize scenarios with a variety of assumptions that directly affect the resulting requirement. RAND says that the data used by the services is, and by nature always will be "very soft."[32] In 2000, the DoD Inspector General criticized the services because they did not validate these assumptions, and when asked, could not produce any form of documentation to support the numbers used.[33] As examples of such assumptions, the report cites the rate of repair of enemy targets, the percentage of targets that are false (one service used 80%), and the percentage of friendly forces that are lost in combat.[34] In 2001, the GAO criticized the services for using old munitions effectiveness data that had not been updated to reflect the improved accuracy of precision-guided munitions.[35] According to the GAO, the services continued to use models that included assumptions dating back to the Cold War to calculate requirements for billions of dollars worth of deep attack weapons – even after studies by the Air Force, Navy, and two DoD reviews identified the problem. The purchase of these deep attack weapons would effectively double the nations stock of precision weapons.[36] Fundamental changes in force structure, technology, weapon use and selection,

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[27] OIG p. 6

[28] At the time, the current operations/forward presence requirement was called the residual readiness requirement.

[29] Kassing et al p.1

[30] Ibid p.

[31] Ibid. p. 31

[32] Kassing et al p.33

[33] OIG p. 7

[34] Ibid

[35] GAO-01-18 "Unfinished Actions Limit Reliability of Munitions Requirements Determination Process" April 5, 2001 pp. 7&12

[36] From about 150,000 to about 300,000 PGMs.

and overall strategy/doctrine since the fall of Russia are such that the Defense Science Board and the GAO both have serious doubts about the ability of current models to depict modern warfare.[37]

Sensitivity to Assumptions

The models are very sensitive to their assumptions. This leads to highly variable results. RAND calls them 'instable' – "Requirements can shift drastically throughout whole families of munitions plans when a single parameter is changed. As a result policymakers can lose confidence in the entire requirements estimation process."[38] The DoD Inspector General calls the process 'ad hoc.'[39] Furthermore, the inputs to the models will change anytime there is a change in the Defense Planning Guidance, Illustrative Planning Scenarios, Threat Report, or Phased Threat Distributions. According to the GAO, "these process components significantly affect the numbers and types of munitions needed to meet the Commander in Chief's objectives."[40] The DoD IG says the same when discussing the analytic procedures used in conjunction with the models; "the analytic procedures have a direct and significant impact on the final calculation of requirements."[41]

Summary: How Do We Interpret These Critiques?

The criticisms cited here outline one major reason why it has been difficult for munitions planners to make the transition to capabilities-based planning – uncertainty is not dealt with adequately. The MR process attempts to predict what will occur in the future, and planners add margins of safety at each step because predictions are not enough to ensure preparedness in the event of unforeseen events. The output of the requirements process is a point estimate – the actual number of each munition required for the armed services to carry out their mission. That number is then used as a benchmark and justification in an entirely different set of budgetary processes that determine how many of each type of munition will be ordered and produced. At this point another problem surfaces that is not dealt with explicitly in the above documents, but that is nonetheless widely acknowledged within munitions planning circles.

There is no direct link between the requirements and programming/budgeting processes. The point estimate output of the requirements process is not very useful to programmers and budgeters as they try to weigh the costs and benefits of a munitions portfolio against the overall budget situation. In today's environment of shrinking funding, the process does not include integral cost considerations, nor does it appear to provide policymakers an adequate understanding of how flexibility in terms of substitute tactics, weaponry, or contracts might affect the answer. Policymakers have only a limited amount of time during the budgeting process to make decisions affecting the investment of billions of dollars and future wartime performance. The current process provides only a point estimate

[37] GAO/NSAID-99-32 pp. 7-8, 47

[38] Kassing et al p. 29

[39] DoD IG D-2000-079

[40] GAO-01-18 p. 2

[41] DoD IG D-2000-079 p. 8

requirement. There is really no way to assess the tradeoffs in cost and performance of a variety of possible portfolios. It is this fact that has drawn the ire of many critics. To date, documented reports tend to attack the MR process itself and only touch upon its tenuous link to the budgeting and programming processes.

CHAPTER THREE

Towards a Capabilities-based Approach

Towards A Capabilities-based Approach

Munitions planners face a resource allocation problem. The most basic question has always been, "how many munitions of what type should we buy in order to meet future threats?" The question has changed dramatically since the MR process was created. The DoD now has much less certainty about the exact nature of the future threat and the likelihood of receiving full funding for all of its projects. A capabilities-based phrasing of the same question is "how many munitions of what type should we buy in order to meet future threats, given that we are not exactly sure what they will be or the amount of money we will have to spend?" This phrasing reveals three structural handicaps of the current process that must be improved if the DoD wishes to move to a capabilities-based system. Namely, the MR process (and its linkage with the budgeting/programming process) does not take cost into account in an appropriate manner, it does not explicitly deal with uncertainty, and does not take steps to improve flexibility by considering industrial policies along with procurement decisions. This chapter explains why it is important to make improvements in each of these areas if the DoD wishes to implement a capabilities-based approach.

Importance of Dealing With Cost Adequately

The current decision process does not include cost as an integral factor in the resource allocation models.[43] The process is stepped – only after the requirement is determined is it constrained by cost. The goal of the requirements office(s) within each service is to win the hypothetical war in the 'best' manner. The point estimate result from the requirements models is then forwarded to programmers and budgeters who match it to the budget.

The point estimate found by the service models is the 'best' solution, independent of cost. Often times it is too expensive, and the requirement must be cut or modified in some way by the programmers. The programmers are under pressure from the budget cycle and do not have the requirements office's intricate understanding of operational tradeoffs between weapons. The requirements models take a long time to calibrate and run. This makes it hard for the programmers to give feedback and receive further guidance. As a result, the transformation from requirement to budget request tends to be ad hoc.

A concrete example might be useful here. Last year an Army general responsible for the procurement budget had a decision to make. He was told that the requirement for 155mm precision-guided

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[42] DoD IG D-2000-079

[43] In fact, the models used do not appear to be resource allocation models in the traditional sense. The constraints appear to be the platforms, doctrines, and tactics presumed to be available at the time of the war (up to 7 years in the future).

artillery was 120,000 rounds – at $110,00 apiece! That is about $13.5 billion worth of artillery, compared to an *Army wide* annual procurement budget of $10.5 billion. The general knew that he could not afford the entire requirement and also knew that there must be some mix of precision and conventional artillery appropriate to the Army's procurement budget and goals. But he could not get a quick analysis. He was unable to receive a quick and clear analysis of the tradeoffs between cost and performance of various weapon mixes. In the end, the general bought less than 75% of the requirement because that's what he thought he could afford – and noted the problem.

The key here is to understand that the 'best' solution changes depending on the amount of money available and that receiving only part of an unconstrained solution can be far worse than receiving the entirety of a cost constrained solution. One high-ranking Army official puts it this way:

> It's like calling a store and asking for the best possible computer. It costs $10,000, but you only have an $8,000 line of credit, so they send you the monitor this year and the CPU next year. If you had known what you had to spend, what everything cost and were there to make the decision, you probably would have gotten a cheaper monitor and taken the whole thing now. After all, the monitor doesn't affect your performance much – as long as you have one.

What he's saying is that there are marginal dollar tradeoffs between potential investments (munitions in this case) that greatly affect what should be bought at each level of funding. Because the two groups involved in the process have different problems to solve (win the war, and fit the programs to the budget), it is difficult to combine their efforts and take such tradeoffs into account. The Joint staff of the DoD is currently looking for ways to improve the relationship between these groups in order to become more aware of these tradeoffs.

Importance of Dealing with Uncertainty Explicitly

The previous chapter showed how each step of the MR process makes assumptions in order to pare an inherently large degree of uncertainty down to a manageable size. Such assumptions include the goals, size, type and duration of wars, the strategies and tactics employed, available equipment, and weapon choice and effectiveness. All of these factors have a direct impact on the number and type of munitions demanded by the war fighter. The inclusion of so many assumptions may make the problem easier to solve, but undermines the goal of a capabilities-based approach. CBP takes for granted that uncertainty is a fundamental part of the planning problem; that the Department must be prepared for a variety of contingencies and that such preparation must take place within some understood economic framework. In the 2001 Quadrennial Defense Review, the Bush administration announced a shift away from the traditional two major war planning requirement to a capabilities-based planning paradigm.[45]

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[44] Davis, Paul. "Analytic Architecture for Capabilities-Based Planning, Mission-System Analysis, and Transformation" RAND, Santa Monica, CA: 2001(?), p.1

[45] 2001 QDR

Unfortunately, the Munitions requirements process has changed little since that time. It is no wonder, because the MR process was created to answer a fundamentally different question. That question might be phrased as "given that I must be able to win *this* particular war and will likely be given all the resources I need, what should I ask for?" The new question is, "given that I am not exactly sure what my mission will be, how do I best prepare with the amount of money that I think will be available?" The sorts of decisions that must be made are fundamentally different – policy makers now face the problem of cost constrained resource allocation under uncertainty. The old system is simply not set up to deliver the kind of information needed – specifically, an understanding of the tradeoffs between various strategies across a multitude of budgetary and threat scenarios.

It is worth noting here that methods used for planning under uncertainty require the same level of concreteness as any other planning method. At some point, strategies must be weighed against concrete scenarios. Capabilities-based planning as described by Davis is a mission-based approach that focuses on being prepared to achieve a variety of goals, rather than being prepared to win one or two (or more) regionally specific wars.[46] The underlying character of the uncertainty must be described adequately for such methodologies to be useful. The MR process does not explicitly consider uncertainty – with the results detailed in previous sections. In later sections, this paper will characterize uncertainty as an uncertainty about target types and the length of time we have to prepare for a war. We will provide some discussion about the uncertainty of war size.

Importance of Considering Industrial Policies Concurrently With Procurement

Once one considers uncertainty and budget explicitly, strategies that can improve flexibility across a variety of contingencies suddenly become feasible and potentially very useful. In this case, such strategies might include spending some portion of money on industrial policies that can act as options in the event of a surprise war – keeping extra lines available for surge production or keeping long lead components in stock 'just in case.' The current requirements and budgeting processes process do not consider industrial policies as investments that can lead to strategic flexibility and improved wartime capability. Policymakers want to know how many of each type of weapon should be bought and stored. But as weapon costs and mission/demand uncertainties increase, it may be better to invest in production as well as in (or in some cases in lieu of) stock.

The DoD may be able to improve overall system performance by making calculated investments in PGM production technologies and processes when it cannot afford to invest as heavily in physical weaponry. Traditionally, munitions have been treated as a 'safety stock' item. Because demand for munitions is erratic, and the penalty for not having enough is so high, the DoD has, in the past, stocked 'a lot of everything.' That is, it has invested heavily in its actual physical stock of munitions. PGMs are more expensive than unguided munitions, and the DoD cannot afford to stock them in

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[46] Davis, p.8

the same manner. In some cases, the cost of a guided weapon program is comparable to the cost of a platform system.[47]

At the same time, the DoD finds itself facing a wider variety of potential missions – each of which likely has a different 'optimal' mix of weaponry. Budget constraints may force the department to prioritize preparedness between missions. The inclusion of industrial policies in the planning process has the potential to increase flexibility and performance across all missions. Specific investments in surge capacity and options in the form of stored components or shared lines can decrease the DoD's yearly procurement costs for certain weapons/contingencies. This would free up money to be spent on physical weapons that provide maximum benefit. Obviously, such decisions must be weighed carefully to ensure that the right missions have priority and that there is enough time to surge production or call in options.[48] Recent replenishment concerns suggest that making these decisions is worthwhile – recent conflicts have been characterized by post conflict rushes to reconstitute stock. Planning in advance for replenishment might make it cheaper, more efficient and less frenetic.

It appears that current production rates/characteristics are the result of compromises made by programmers and budgeters as they match the yearly budget to the requirement –rather than a premeditated decision process. The munitions industry sees demand, not in terms of targets and wars, but in terms of contracts and appropriations. It is shielded from demand uncertainties by the requirements process. Contracts are structured individually so as to deliver the required munitions over time within the appropriated budget. If an expensive weapon is deemed necessary, programmers will stretch its cost over a number of years to make it affordable. The prime contractor comes up with a design, finds suppliers, and builds an assembly line to fit that schedule. The TLAM might be a good example of this – concerns have arisen over replenishment multiple times. The weapon is expensive, at almost $1 million apiece. The assembly lines are set up to produce them at a rate of 40 per month, with a lead-time of 12 months. About 700 Tomahawks were fired during the first week of Operation Iraqi Freedom.[49] It will take 2 _ years to replenish just one week's worth of Tomahawks. At the same time, the administration had no trouble raising $80 billion in emergency appropriations to cover the costs of the war. The DoD may be able to increase the effectiveness of its yearly budget by considering production concurrently with procurement.

This paper *will not* explore the effectiveness of the surge production and option policies. Initial modeling efforts showed that to model these policies would be too complex for the purposes of this illustrative analysis (showing that exploratory analysis and robust decision making techniques can be usefully applied to the MR problem). This paper *will* explore production policy as the number of production lines of each weapon. The number of production lines for a weapon will operate as the 'production constraint,' limiting the number of weapons available for a conflict. The number of weapons available for a conflict will also be affected by the amount of time we have to prepare for a

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[47] The Tomahawk program cost is $14 B, compared to $10B for the Harrier, $8.4 B for the JSTARs, and $2.6B for the F-117a. Source: CDI, "Military Almanac: 2001-2002"

[48] Peters et al (2004) have shown that many recent contingencies have offered a significant amount of strategic warning time.

[49] Source: Global Security.org/military/ops/Iraqi_freedom-numbers.htm

war. We will find that considering production does indeed affect the viability and flexibility of a munitions portfolio.

How This Dissertation Will Address Cost, Production and Uncertainty

Cost, production and uncertainty should be considered concurrently if we wish to pursue a capabilities-based approach to munitions planning. Later chapters will present how this dissertation will examine cost and production capacity as constraints and preparation time and war scenario as uncertainties. First we will vary budget, production capacity and preparation time parametrically for a single scenario using the methodology of exploratory modeling/analysis. This exploratory analysis will demonstrate how much each factor changes the optimal munitions portfolio *and show that this information can easily be provided to a policymaker for consideration*. We will then show the usefulness of searching for a solution that is robust across a variety of uncertain scenarios. Finally, we will show that the search for a robust solution may be conducted across scenarios, budget levels, production characteristics and preparation times in order to create flexible, affordable, and effective munitions portfolios. In the meantime, the next chapter surveys other methodologies and explains why they are not as well suited to this problem.

CHAPTER FOUR
Overview of Relevant Literature

Relevant Literature

The problem faced by the DoD is a complex planning problem that involves resource allocation and inventory control under uncertainty. Planners must divide a limited number of resources (budget) across a variety of investments (munitions), the value of which depends on what actually happens in the future (war). Resource allocation and inventory control are the two most relevant academic literatures. We shall see that the character of the uncertainties faced by munitions planners is precisely what makes the problem so complex, and what set it apart from the problems typically dealt with in the two literatures.

Resource Allocation

Resource allocation models will not work for this problem because the uncertainty faced by war planners cannot be reduced to a probability distribution. At least three entire fields – economics, finance and operations research – are devoted to understanding and solving resource allocation problems. Methodologies include linear programming, optimization, portfolio techniques, profit maximization, cost minimization, and a variety of modeling and simulation techniques. The problem with simply applying one or more of these techniques alone to PGM selection is that we face a wide variety of possible futures, and these models can only capture one at a time. It is possible to model multiple futures –*if one has a clear idea of the probability of each futures occurrence and of one's own preferences*. In this case, once could create a model that maximizes expected utility, or expected return across the ensemble of futures. But is it really possible to place a probability on the occurrence of each war? Is it even possible to conceive of all the wars that may happen?

The events that war planners contend with are fundamentally not probabilistic. But the services use resource allocation methodologies now, with a wide variety of simplifying assumptions aimed at getting around the problem of uncertainty. The USDP actually prescribes the wars that will occur, giving each war a de facto probability of %100. From that first assumption stem many more – the number of targets by type, the amount of time we have to prepare, our tactics etc. Unfortunately, it is not clear in the resulting point-estimate which or how many of these assumptions have been made, or *how a change in them will affect the performance of the recommended portfolio*. Resource allocation methodologies are incredibly useful to the DoD, but must be placed within the context of multiple missions and uncertainty about the likelihood of each occurring.

Inventory Control

The field of inventory control is a subset of operations research and uses many of the same methodologies. The goal of inventory control is to find the appropriate balance between stock and productive capacity to ensure that, on the one hand, resources are not being wasted on unneeded stock, and on the other hand, that there is always enough stock to meet demand.[50] Dynamic programming, linear programming, Markovian processes and simulation figure prominently in the literature. However, each methodology requires an estimation of demand, usually in the form of a probability distribution. 'True' demand for munitions is virtually impossible to predict or fit to a distribution in advance. It depends on many factors, such as the size duration and goal of a military action, as well as tactics, equipment, terrain and weather. Furthermore, the nature of combat operations results in long periods of low demand (peacetime training) followed by huge spikes during wartime. There is a documented hole in the literature surrounding the issue of erratic or 'lumpy' demand.[51]

As we have discussed, the services have dealt with the problem of erratic demand by stocking more than is needed – by holding a large 'safety stock.' A safety stock is the inventory held above 'normal' to serve as a buffer against production problems and demand swings. Indeed, the ad hoc modifications made to the MR process today appear to speak to this strategy. Unfortunately, unless something changes, the sheer cost of PGMs precludes the use of excessive safety stocks. However, the literature supports the notion that changes in the production process can positively affect the resource allocation problem by reducing the required safety stock. Papers by David A Collier and Kenneth R Baker show that increases in component commonality decrease the amount of safety stock required.[52] Donald Gross and A. Soriano show that decreases in manufacturers lead times decrease the amount of safety stock required.[53]

This paper will not deal explicitly with lead-time and component commonality issues. Our primary emphasis is in demonstrating a methodology that allows munitions planners to implement the ideas of capability based planning. This paper will show that by using exploratory modeling and robust analysis, we may choose our safety stock wisely even when facing budget constraints and an uncertain future. That is, we will be able to see which weapons should be stocked for each level of budget, production and preparation time first for a single war, and second across a wide variety of potential wars.

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[50] Supervision of the supply, storage, and accessibility of items in order to insure an adequate supply without excessive oversupply. Hyperdictionary online

[51] Silver, Edward A. "Operations Research in Inventory Management: A Review and Critique" Operation Research, Vol.29, No4 1981: p.640

[52] Collier, David A. "Aggregate Safety Stock Levels and Component Part Commonality" Management Science, Vol. 28, No.11, 1982 ; Baker, Kenneth et al "The Effect of Commonality on Safety Stock in a Simple Inventory Model" Management Science, Vol. 32, No. 8, 1986

[53] Gross, Donald and Soriano, A. "The Effect of Reducing Lead Time on Inventory Levels – Simulation Analysis"

Conclusions

Pure resource allocation models are impractical because it is impossible to fit the uncertainty associated with the occurrence and nature of a war to a probability distribution. Pure inventory control models are impractical for the same reason - because demand for munitions is uncertain and erratic. Although we cannot find the 'optimal' solution, we *do* have tools available *now* that can provide better answers than the ones we have now. These methods, detailed in the next section, enable policymakers to understand the economic tradeoffs made with various resource allocation strategies across a wide variety of constraints and war scenarios. In "Research Portfolio for Inventory Management and Production Planning" Harvey M. Wagner hints at a methodology similar to the one that will be proposed in the next chapter:

> Most planning models do not attempt intrinsically to account for uncertainties, such as the range of variability in future demand. If the analyst can identify a few parameters, each of which possibly has several different values, then a set of case studies can be run to investigate the differential impact. For example, a base case can be constructed and compared with optimistic and pessimistic scenarios. Still, rarely are the results of a planning model analysis couched as a contingency plan reflecting future uncertainties. Yet, in real situations, the results of planning analysis almost always are revised as the uncertainties are resolved. Currently, companies use ad hoc procedures to alter plans to reflect realized deviations in model input assumptions. Operations researchers ought to examine effective processes for transforming planning model solutions into contingency rules.54

Wagner tells us that it is actually quite common for organizations to gloss over uncertainties during model creation, make ad hoc changes to their plans to account for it. He points out that by identifying an uncertain variable and exploring the effect of changing its value, we can understand how it might affect our plans. We can learn how the uncertainty itself shapes the strategy we should choose.

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[54] Wagner, Harvey M "Research Portfolio for Inventory Management and Production Planning", Operation Research, Vol 28, No. 3 1980: p.457

CHAPTER FIVE
Exploratory Analysis and Robust Decision Making

Overview

This report provides an alternative capabilities-based framework for munitions planning that allows policymakers to see and understand the tradeoffs involved in their decisions, taking into account the uncertainties and constraints specific to this problem – namely the constraints of budget and production and the uncertainties of preparation time and occurrence of war. This paper proposes the employment of exploratory modeling and robust/adaptive planning to represent the budget, production constraints, preparation time and war in such a way that planners can see potential sources of flexibility (and limitation) in precision guided munitions planning. By using these methods, we will avoid making many premature assumptions about the future we face and will be better able to create strategies that perform well across a variety of futures while *simultaneously* operating within an economic framework.

A Resource Allocation/Inventory Management Problem?

Munitions procurement can be thought of as a straightforward resource allocation problem, combined with inventory management. There is a budget. There is a cost to production, procurement and storage. There is some value associated with having a particular mix of weaponry during a war. There is also some penalty associated with having a shortage. Each weapon also has a set of production characteristics that may improve or deteriorate its availability. What makes munitions procurement different from traditional problems of this sort are the number and type of uncertainties with which the buyer contends. We know what it costs to buy, store, and dispose of weapons. We also know how long it takes to build weapons. But we can't make a resource allocation or inventory control model because we *don't know* aggregate demand[55] – the size, location and politics of war), enemy targets and tactics, value of the war, penalty for a shortage, amount of warning, or probability of occurrence. The vast majority of these variables directly affect demand. If these variables were known with certainty, it would be possible to calculate an optimal, cost-effective portfolio of weaponry and the productive capacity needed to build it in time. The MR process systematically generates a point estimate for each uncertainty. This simplifies the problem, but at the expense of understanding potential tradeoffs. If it is assumed that only one scenario will occur, we have a set number of years to prepare, and that cost is no object, then the answer for that scenario can be calculated, and there is no need to consider tradeoffs.

A traditional resource allocation model will not solve this problem because we cannot put a probability on the occurrence of any single war. A traditional inventory model will not solve this problem for the same reason – we don't know what demand will be, cannot predict it, and cannot fit

[55] Peters, John et. al. "Satisfying Demand for Selected Munitions : a Production Enhancement Study" RAND, 2003.

it to a distribution. However, we *can* use a resource allocation model combined with inventory policies as the foundation for an exploratory model that would allow us to understand how those uncertainties affect a strategy. Such an approach will allow us to vary the uncertainties affecting demand and create a strategy that works fairly well across multiple scenarios. Furthermore, this approach will enable us to understand why a particular strategy works, what its limitations are, and what the tradeoffs are between scenarios and strategies.

What is Exploratory Analysis?

'Traditional' policy analysis has tended to attack problems of deep uncertainty by narrowing down the possible futures to those that are most likely to occur and devising the most optimal strategy for each future. The traditional approach asks first, 'what is most likely to occur?,' creates a scenario, and then finds the most optimal solution to that particular scenario. Such planning tools have, at times, worked well in the past, and may be useful in dealing with problems that have very few key uncertainties and/or uncertainties that create futures with only slight differences. However, strategies based on a 'prediction' of the future can fail spectacularly if that future fails to materialize. Take, for example, a fund manager who in 1994, believed that there would be a bear market for the next five years – or a fund manager who in 1998 believed the market would continue to rise through 2003.

Exploratory analysis, on the other hand, refrains from making assumptions about the future and is the first part of a methodology that asks, 'what strategy will deal best with the uncertainty we face?' To be more specific, an exploratory analysis is the first step in answering this question. Such an analysis generates a range, or 'landscape' of all plausible futures in order to understand how uncertainty can affect a problem, which uncertainties are critical to a problem, and when such uncertainties matter. Robert Lempert and George Park (1998) put it best:

> One reason our approach is useful is that there is often a great deal of information about a problem that, although insufficient for making accurate predictions, is nonetheless useful for making decisions. (…) While it may seem that abandoning a best estimate for a large set of plausible futures complicates the decision-making problem, the large set of plausible scenarios often represents real and very useful information. Perhaps surprisingly, when we trade the question 'What is most likely to happen in the future?' for 'Which policy choice deals best with the uncertainties we face?' the complexity posed by an unpredictable future often falls away and reveals a set of clear choices.[56]

In an exploratory analysis, the fund managers mentioned above would relax their assumptions and forecast a large number of possible futures by varying the interest rate, the performances of various markets, and a variety other important factors. They would then examine this range of possible futures, looking for relationships in the key uncertainties that would change the nature of the problem or force them to change strategies.

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[56] Park, George S. and Robert J. Lempert, *The Class of 2014 – Preserving Access to California Higher Education*, Santa Monica (CA): RAND Education, 1998. p. 5

Exploratory analysis is a distinctly quantitative tool. It is therefore helpful to recant the discussion in modeling terms. Models are often used as optimizing tools – designed to find the optimal value of one or more input variables, given a specified objective and limited by constraints in other input variables. For optimization to work, all aspects of the model other than the parameters of interest must be defined as clearly as possible. Therefore, traditional optimization techniques involve the creation of best estimate current or most likely future scenarios that are built into the model in the form of parameter values and constraints. Uncertainties are individually identified and dealt with *before the model is run*, as in the case of the MR Process. Once an optimal value has been found, a sensitivity analysis is conducted to determine how much the 'value' of the objective would change as a result of variations and/or errors in the inputs.

An exploratory analysis does not optimize for one particular scenario, but forecasts the value of the objective function over a whole range of possible scenarios. The model is run many times – each time varying inputs and constraints to create a landscape of possible futures. In examining this landscape, a skilled analyst comes to a better understanding of how the various parameters and uncertainties surrounding them affect the problem.

The basic idea behind exploratory analysis is not new, but until recently it has been difficult to put into practice for problems of more than just a few variables –it becomes impossible for the human brain to conceptualize uncertainty beyond a few factors. Recent improvements in computing – cheap memory, fast, networked processes and powerful visualization tools – have made it increasingly possible to apply these ideas in a useful way. The interpretation of an exploratory analysis remains something of an art form. The analyst must find ways to display and conceptualize the multiple dimensions considered mathematically in order to *gain useful insight*. Those researchers conducting such analyses readily admit this fact and remark that work is currently being done to improve the ability of computers to mimic/improve upon human abstraction and display multidimensional information. An example is the Computer Assisted Reasoning system (CARs) developed by Evolving Logic, which allows the analyst to store and visually represent massive amounts of multi dimensional data in new and useful ways.

A Pertinent Example – 'Weapon Mix and Exploratory Analysis'

"Weapon Mix and Exploratory Analysis," a 1997 RAND report by Arthur Brooks, Steve Bankes and Bart Bennett, provides an excellent example of exploratory analysis applied to a problem similar to this one. The body of the report is devoted to highlighting the advantages of exploratory analysis to the practicing analyst. The study demonstrates the difference between conventional and exploratory analysis in the context of a weapons mix problem. The problem is that of choosing an appropriate stockpile of weapons for a specific war scenario. In this respect it is not unlike the modeling portion of the current MR process. In fact, the weapons mix study even uses a model similar to the one used in the Air Force's Deep Attack Weapons Mix Study discussed above.[57] While traditional

[57] Borkks, Arthur et. al. "Weapon Mix and Exploratory Analysis: A Case Study" RAND. Santa Monica, 1997. p. 6

optimization yields only one optimal[58] result for the scenario, the exploratory analysis found 196 solutions that were very close to the optimal. They were close to optimal in the sense that none of the new solutions increased the length of the war by more than 24 hours.

The presence of multiple, near-optimal solutions gives the analyst much more flexibility in analyzing performance with any number of other measures. For example, once the optimal weapon bundles are found, the analyst can look at the cost of each and compare that cost to the marginal change in performance. The analyst can also look at how the various bundles fare when scenario parameters change. The Weapon Mix Study, for example, examines the performance of the 196 near-optimal bundles under varying weapon reliability scenarios, shows which bundles are 'robust' to reliability changes, and explains why. Additionally, one could compare solutions across scenarios, examining how they fare in each. Traditional analysis takes the single 'most optimal' solution as a given and then conducts a sensitivity analysis in order to understand its limitations. Exploratory analysis seeks to understand the limitations and tradeoffs of multiple near optimal solutions at once. In doing so, it provides the decision maker with increased flexibility and a better understanding of the problem and the forces that shape the region of feasible solutions.

The weapons mix study is important because it provides ample evidence for the effectiveness of exploratory analysis in dealing *with this particular* problem. The key differences between that research and the research proposed here are the audience and the scope of the problem. The audience for this research will be the policymaker rather than the analyst. The work will focus more on the strategic choices than the inter-theater tactical ones. This research will look for strategies that work well across multiple war scenarios, rather than alternative strategies within a particular scenario.

How Does Exploratory Analysis Fit into the Planning Process?

Problems with multiple objectives, challenges and alternative strategies require an assessment and understanding of tradeoffs across multiple dimensions – systems analysis looking at costs, effectiveness versus cost, and various intangibles. As such, Exploratory Analysis is most useful in the initial stages of strategy development. It is best used in situations where several strategies are debated on different but apparently valid terms. Exploratory Analysis can prevent the decision-maker/analyst from making premature decisions about what constitute the key factors of risk or most likely circumstances. Such an analysis encourages one to remain open-minded to a wide variety of alternative solutions to a particular problem that may intuitively seem unrealistic.[59]

What is Robust/Adaptive Planning?

Robust/Adaptive Planning seeks to identify strategies that perform well across a range of possible futures – i.e. strategies that are robust to the key uncertainties of a problem. It is the second part of

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[58] The study's primary performance measure is time to complete the war.

[59] Davis, Paul K. and Richard Hillestad, *Exploratory Analysis for Strategy Problems with Massive Uncertainty*, unpublished manuscript, Santa Monica (CA): RAND, 2000. p.32

the tool that asks, 'given we cannot predict the future, what actions should we take?'[60] After examining the landscape of possible futures provided by the exploratory analysis, the analyst creates strategies and simulates their performance across all futures. The relative performance of each strategy may be measured by compiling the expected *regret* of alternative strategies across scenarios. Regret is the difference between the expected performance of a strategy being tested on a scenario and the performance of the optimal strategy under perfect information.[61] Computer search routines are used to find, first, strategies whose expected regret is never large compared to the alternatives, and second, key tradeoffs among strategies and assumptions that drive the choice among strategies.[62]

Such searches are used both to suggest strategies for consideration and to test hypotheses about strategies. The search may show that one strategy performs well against one set of scenarios, and another performs well for a different set. The analyst may then create a combination of the two strategies and test to see whether the combined strategy is indeed more robust across the entire range of scenarios. In this manner, the situations under which a promising strategy fails are uncovered, and the analyst is able to further shape the strategy through the use of *hedges* or other modifications. Often times, an adaptive or sequential strategy that allows for either organic or planned policy changes to occur in response to new information is the most robust strategy.

Davis and Hillestad identify a number of general ways to address risk and uncertainty that may be considered in the creation of a strategy.[63] They suggest ignoring uncertainty when the worst-case consequences are tolerable. Risk can be reduced by, first, eliminating particular sources of risk (for instance, buying out the competition, or blowing up a bridge), and second, improving the quality of prediction. Management can insure against problems by purchasing insurance, hedging or a portfolio approach. Finally, uncertainty can be dealt with by increasing adaptiveness, pooling of resources and making decisions sequentially.

How Does Robust/Adaptive Planning Fit into the Planning Process?

Robust/Adaptive Planning is best used after an exploratory analysis has been conducted. As the search for a strategy that works well across a variety of futures, it is perhaps most useful to decision makers working at the highest level. When combined with an Exploratory Analysis, it is indeed a very powerful tool that forces a decision maker to keep his/her options open, and think about ways in which strategies can be improved in certain areas without being weakened in others.

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[60] Lempert, Robert J. and Michael E. Schlesinger, Robust Strategies for Abating Climate Change, *Climatic Change*, 45 (1), pp. 387-401, 2000. p. 391

[61] Ibid.

[62] Ibid p.392

[63] Dais and Hillestad, 2000. p. 30

CHAPTER SIX
Setting Up the Illustrative Analysis

Overview

This section is devoted to describing the models that will be used in our illustrative analysis. In order to simultaneously include cost, production and performance under uncertain circumstances, we address the following two questions:

1. How do the constraints of budget and available production lines and the uncertainty of preparation time before a war affect the optimal munitions portfolio when we assume we know which war scenario will occur?

2. Given that we do not know which war will occur, how do we find a portfolio of munitions that works well across a variety of scenarios, taking into account the aforementioned uncertainty and constraints?

Our policy lever is the reserve portfolio – a planned stock of each type of precision-guided munition. A war scenario is a set of targets. The planned portfolio is not always what we have ready when a war occurs. It is affected by the budget, production capacity and amount of time we have available to produce before the war. We therefore use two models. The first model calculates an optimal portfolio given the constraints of budget and production lines available, and the uncertainties of preparation time and war scenario. This model shows us the correct choice, supposing we have complete information. The second model uses a planned portfolio as an input, and calculates its performance given values for budget, production, preparation time, and war scenario. In this model, the planned portfolio is affected by available funds, production and warning time to create a 'war ready stock' of munitions, which is then distributed across targets. This model shows us how the performance of a planned portfolio is be affected by changes in the constraints and uncertainties. We use one model to calculate the optimal portfolio for a set of circumstances and use the other to see how it performs when those circumstances change. In addition, we can use the second model to test the performance of a large number of portfolios across a wide variety of circumstances. Both models use a linear program to simulate Combatant Commanders' wartime preferences as they match munitions from the portfolio to targets in the scenario.

Terminology: Portfolios and Scenarios

It is helpful to define two terms that will be used throughout the course of the illustrative analysis. *Portfolio* refers to the munitions portfolio, a reserve stock of five different types of munitions. The portfolio is the only policy lever used in the approach presented here. Other policy levers that affect the flow of munitions in addition to the stock were considered, but were deemed to make the model too complex for the purposes of this dissertation.[64] The munitions used to create portfolios are the Joint Direct Attack Munitions (JDAM), Laser Guided bomb (LGB), Tomahawk Land Attack Munition (TLAM), Joint Standoff Weapon (JSOW), and the Maverick anti-tank missile. The characteristics of these weapons are described in Appendix 1. A portfolio consists of some fixed number of each weapon, chosen by the policymaker. This is by no means an exhaustive list of PGMs – other munitions were considered. However, it was decided to keep the number to a minimum in order to ease the computational requirements of the model. These five weapons are currently the most commonly used munitions, and provide a good variety in terms of cost and effectiveness against each target type.

Scenario refers to a war scenario, which is defined by the number of each type of target presented to a combatant commander. This demonstrative analysis reduces the world of available targets to four types. Mobile Hard Targets are tanks. Mobile Soft Targets are trucks, armored personnel carriers (APCs), jeeps and the like. Fixed hard targets are bunkers and hardened facilities. Fixed soft targets are buildings, radar installation, and airfields. We recognize that this is a very simplified way of describing a war scenario – there are many other factors that have a large impact on the characteristics of a war. For example, terrain, weather, technology and tactics can each have a tremendous affect on the nature of a war. By choosing to use a simple definition, we have sacrificed some resolution so that we may run many models and understand how the constraints and uncertainties affect the problem in a relatively short amount of time. We will be able to make broad observations, and this does not take away from the value of more detailed analysis.

Steps of Exploratory Analysis and Robust Decision Analysis

The first practical steps of an exploratory analysis are to describe the scope of the analysis and construct a scenario generator. Defining the scope includes defining the questions to be addressed, the constraints, uncertainties, policy levers, performance measures and relationships found in the problem. In order to construct the scenario generator, one must then create a conceptual model; prioritize the constraints, uncertainties, policy levers, and performance measures; and finally, code the model in a computer language appropriate to the software that will help analyze the results. After this is done, we examine the effects of changing constraints and uncertainties in the case of a single war. Then we generate a range of plausible future wars, and examine the performance of various munitions portfolios, looking for portfolios that perform well across the entire range of wars.

Scope of the Illustrative Analysis

We ask two questions. First, "how does changing the budget, production constraint, and amount of preparation time affect the optimal portfolio given that we know which war will occur?" Next we

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[64] Examples of these levers include options to purchase weapons with a strike price and date, and changes in production processes like decreased lead times and line sharing. Such policies merit a thorough investigation, but to do so in this paper would dilute its ability to concisely present the usefulness of the exploratory modeling and robust analysis methodologies.

ask, "given that we do not know which war will occur, how do we find a solution that works well across a variety of possible wars?" In Chapter Two, we identified several ways the DoD could improve its Munitions Requirements process. We claimed that by simultaneously considering cost, production constraints, and the uncertainties of war, the DoD can come to a better understanding of the problem and possible tradeoffs, and can begin to make plans that prepare for the uncertainty it faces. The first part of illustrative analysis in the following chapter will use exploratory modeling and analysis to show how changing the budget and production line constraints and the uncertainty of how much time we have to prepare for a war affect the optimal portfolio in the case of a single war. But we also face the larger uncertainty of *which* war might occur. The second part of the illustrative analysis will show how the search for a robust solution can lead us to a portfolio that performs well across a range of possible wars under many different budgets, production line setups, and preparation times.

Constraints and Uncertainties

The major constraints considered are those of budget and production. How much money is available to spend on weapons? How many production lines are available to produce each weapon? The amount of money available to spend and number of lines available to produce munitions could easily be considered policy levers rather than constraints. We take the perspective of an officer in the Joint Staff responsible for determining the munitions requirement. To such an officer, these variables are constraints within which he must operate as he determines the number of munitions we should order. However, the results of this kind of analysis may be used to show others (e.g. Congress), for whom budget and production decisions *are* policy levers, how their decisions affect the DoD's ability to prepare for war.

The major uncertainties considered here have to do with the wars we prepare for. Where will the wars be fought? How many targets will be there? What types of targets must we hit? How many years do we have to prepare for each war? The answers to these questions drastically affect the definition of the best portfolio, and the performance of sub-optimal portfolios. Each war scenario is defined by its size (number of targets), mix of targets (proportion of targets by types), and number of years before it occurs (preparation time). Each of these variables is uncertain.

Policy Lever

The policy lever used by this illustrative analysis is a basic inventory decision. How many of each type of weapon do we plan keep in stock? The inventory levers used will be the number of each type of weapon carried in the stockpile. This is the policy decision made by the Joint Staff and recommended to the President and then Congress in the final budget. The best answer depends on the actual budget, the war that occurs, the preparation time before a war, and the number of production lines available. The resulting portfolio ultimately affects wartime performance by constraining usage decisions made by the Combatant Commanders on the ground.

Performance Measures

We will use two simple, aggregate performance measures. We acknowledge that there are a large number of performance measures, and choose measures that may be made more specific to the needs of the Joint Staff with additional data. We are interested in the performance of each portfolio relative to the others across one or many war scenarios. We look first at the proportion of targets that are covered by a portfolio. Could the munitions portfolio chosen cover all targets in a war? If not, the portfolio is considered unviable. Second, given that a portfolio can cover all targets, we look at the number of munitions it uses to do so. A lower number is better. We assume that that by using fewer weapons per target, collateral damage is kept down, sorties are reduced, and risks to pilots and aircraft are lessened. Given more data and time, we could actually calculate the performance measures for which aggregate weapon usage is a proxy.

The Variables

Table 1 lists the variables discussed above. There is a type of variable listed here that has not yet been discussed, called 'Weapon Characteristics.' These variables describe the fundamental differences between each weapon. Unit cost is the average unit cost of a munition, as reported by the Selected Acquisition Report for that weapon. The total unit cost of the munitions in a portfolio is the cost that is weighed against the budget constraint. Production rate by weapon is the monthly production rate for a single line of each weapon. This number determines the maximum available production for each weapon over the course of the preparation time available. 'Effectiveness by target type' is used by the combat simulator to distribute weapons to targets according to the preferences of the Combatant Commander. The variable represents the number of munitions required to have a 95% chance of killing a target.

Table 1: Variables Used in Illustrative Analysis

Uncertain Variables	Outputs
War Scenario = Targets (MH, MS FH, FS)	Percent of Targets Hit
Preparation Time (Years Before the War)	Percent of Targets Hit with Preferred Munitions
Policy Lever	Unit Cost of Munitions Portfolio
Planned Portfolio by Munitions Type	Weapons Used
Constraints	
Budget	
Number of Lines per Munitions Type	
Weapon Characteristics	
Unit Costs	
Production Rate by Weapon	
Effectiveness by target type	

Two Different Models

We will employ two different models – one calculates the optimal portfolio and the other tests planned portfolios. The first model calculates an optimal *portfolio* given the constraints of budget and production lines available, and the uncertainties of preparation time and war *scenario*. Holding budget, production, preparation time, and war scenario constant, this model selects the optimal number of each type of weapon to hold in the portfolio. It answers the question, "given that *x* will occur and we face *y* constraints, what should we do?" By varying the parameters of the budget, production lines, preparation time, and scenario, we may come to understand the extent to which they affect the optimal solution and the nature of such effects. This is in fact exactly what we will do in the first part of the next chapter.

The second model is used to test the performance of a *planned* portfolio. This model might be thought of as the inverse of the one described above. It uses a portfolio as an input, and calculates its performance given values for budget, production, preparation time, and war scenario. It answers the question, "given that we have chosen to commit to portfolio *x*, how does it perform when we face constraints *y* and uncertainties *z*?" where the constraints are budget and production capacity and the uncertainties are the preparation time and war scenario. This model will be used throughout the course of the illustrative analysis to show how the optimal portfolios perform when something else occurs, and to test a large number of potential portfolios across a wide range of scenarios in the search for a robust solution.

The Combat Simulation Module

Both models use a combat simulation module, and we will describe it here before talking about the individual models. A linear program will be used for the combat module. The purpose of the combat model is to allocate resources (weapons) amongst targets so as to maximize (or minimize) the objective of combatant commander. In the first model, this module simulates how a combatant commander (or his/her surrogate in the requirements office) would *choose a not yet determined* portfolio were he/she to have complete foreknowledge of the circumstances under which the portfolio would be used (which war, how much warning, budgetary and production constraints). In the second model, this module is used to simulate how a combatant commander would *use a predetermined* portfolio under various circumstances. This use of the module is meant to reflect the fact that, although Pentagon policymakers determine the weapons available for use, commanders in the field decide which ones to actually use.

There are many ways to optimize, but linear programming is chosen here for several reasons. First, methods of computation such as the use of calculus and Lagrange multipliers become exceedingly difficult and memory intensive as the number of variables increases. Second, such methods are not practical when constraints come in the form of inequalities. Third, linear programming is one of the most highly developed and widely used types of operations research. This means that computations may be done fairly quickly, and that many tools are available to enhance the model's flexibility. By using a linear program, we will have a model that can be modified relatively easily as the illustrative analysis progresses.

There are several assumptions that must be made in order to solve this problem as a linear program. It is important to be aware of them. The first assumption is proportionality. This means that if it takes two of a weapon to destroy one target 95% of the time, it will take four to destroy two targets with the same accuracy. The second assumption is that of infinite divisibility – that is that the input and output variables may be divided into fractions. Although it is odd to think of using 1-_ weapons on a target, it is unlikely to change the insights gained due to the large numbers of targets and weapons considered.

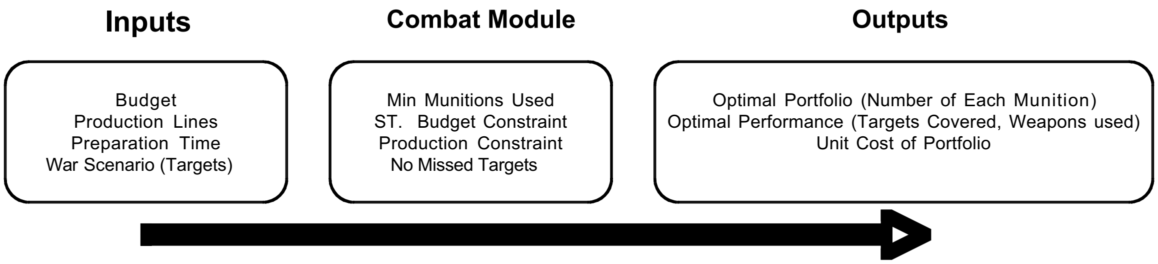
The combat model allocates weapons to targets in accordance with the combatant commander's objective function. It is important to note that this model is an optimizer, and therefore assumes that combatant commanders act optimally given their preferences, resources, and constraints. The objective function must be expressed in the form, "max/min variable x subject to the constraints y." The constraints may be equality constraints or inequalities. For example, suppose that we believe that the commanders want to (1) destroy all the targets with 95% accuracy and (2) hit them with the best available weapons. The objective would be phrased as, "minimize the number of weapons used subject to the constraints that all targets are destroyed with 95% accuracy and that no more weapons are used than are in stock." With this objective, the model would be solved so that commanders first try to hit all the targets. If the budget, production capacity (or in the case of the second model, portfolio) is too low to do so, they will hit as many as possible. If all targets can be hit, commanders will try to hit them using the fewest number of weapons – this is equivalent to using the most accurate weapon for each target.

One of the benefits of using a linear program is the ease with which the constraints and objectives may be changed. This makes it possible to modify the model after we have learned more about the problem, or have different questions to ask. It would be easy to add a constraint specifying that some stock must be held in reserve in case of another war – or that a certain number of SAM sites (fixed soft targets) must be destroyed in order to complete the mission. Additionally, the commander's objective can be changed. For instance, if the commanders are more interested in saving pilot's lives than in the effectiveness of the weapon per se, we could make the objective that of minimizing loss of life. All that would be needed is an estimate of the number of sorties flown (derived from the number of each type of weapon used) and the probability of downed aircraft per sortie.

The First Model: Used to Find an Optimal Portfolio

The figure below provides a concise representation of the important relationships in the optimizing model. This model uses the combat module to calculate the optimal munitions portfolio, given the inputs of maximum budget, preparation time, production lines, and war scenario.

Figure 1: Model Used to Find Optimal Portfolios



By multiplying the number of production lines available by the monthly production of each and the amount of preparation time we arrive at the production constraint for each weapon. This number is the maximum number of each type of weapon that may be place in the portfolio. The combat module then calculates a portfolio that minimizes the number of munitions used by matching munitions to targets found in the scenario subject to the following constraints:

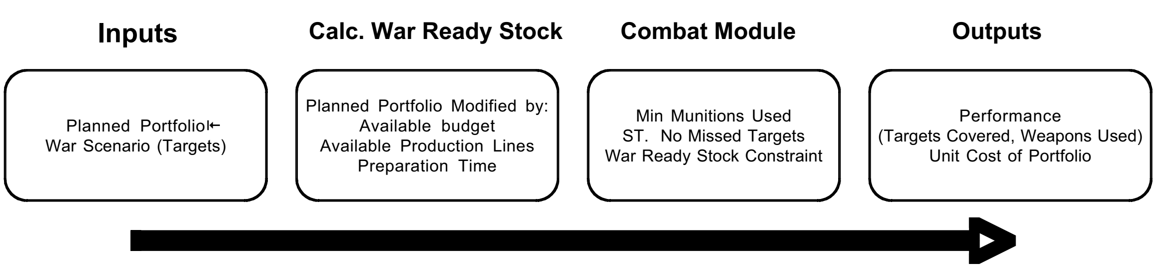
1. All targets are covered (hit with enough weapons to guarantee a 95% chance of destruction)
2. The total unit cost of the portfolio does not exceed the budget constraint.
3. The number of each type of weapon chosen does not exceed its production constraint.

This optimization assumes that the commander's objective is (1) hit all targets and (2) use the best possible (lowest sortie) weapon on each target whenever possible. As we discussed above, low weapon usage is a proxy for other good things, like risk of collateral damage and pilot loss.

The Second Model: Used to Test Portfolios Across Scenarios and Constraints

The figure below provides a concise representation of the important relationships in the testing model. This model uses a planned portfolio as an input. The planned portfolio is then transformed into a war ready portfolio as it is affected by the budget/production constraints and the uncertainty of preparation time. This model uses the combat module to simulate how a combatant commander would use the war ready portfolio for a given war scenario.

Figure 2: Model Used to Test Planned Portfolios



The two major inputs are a planned portfolio – designated as a number of each type of weapon that we would like to have in stock – and a war scenario – the target mix for a specific war. The planned portfolio operates through three major variables – the budget, number of production lines and warning time – in order to calculate the number of weapons available at the time of a conflict. The budget affects the number of weapons that are actually bought – as opposed to the number planned. If the budget is sufficient to pay for the planned inventory, then the entire planned inventory is available. However, if the budget is less than the cost of the planned inventory, the inventory is cut according to an algorithm. The default algorithm cuts planned inventory evenly across all munitions in order to meet the budget constraint. Other algorithms could, for example, cut expensive weapons first. The amount of warning time, in conjunction with the available production lines, determines the amount of inventory available from the assembly lines. If the plan calls for more inventory of a weapon than can be produced before the time of the war, the war ready stock is cut back to the maximum number available.

The Combat Module (a linear programming model) determines how a combatant commander would use the combat ready portfolio against the input scenario. In this case, the module calculates a portfolio that minimizes the number of munitions used by matching munitions to targets found in the scenario subject to the following constraints:

1. All targets are covered (hit with enough weapons to guarantee a 95% chance of destruction)
2. The combatant commander does not use more of any weapon than the war ready stock allows.

The module provides us with two performance outputs: the proportion of targets covered (destroyed with a 95% probability) and the number of munitions used.

CHAPTER SEVEN

Illustrative Analysis of A Capabilities-based Approach

Overview

Here we perform an illustrative analysis using the approach described in the last chapter, which allows planners to find solutions that provide a wide range of capabilities within an economic framework under conditions of uncertainty. The first part of this chapter uses exploratory analysis, an extreme form of traditional sensitivity analysis, to show that the constraints of cost, production and preparation time dramatically affect the optimal portfolio of weapons for a single scenario. But we never know which scenario will occur – and different portfolios (capabilities) work better for some scenarios than others. The second part of this chapter demonstrates that the use of robust decision-making techniques makes it possible to analyze the effects of these constraints across multiple scenarios and create improved and flexible portfolios.

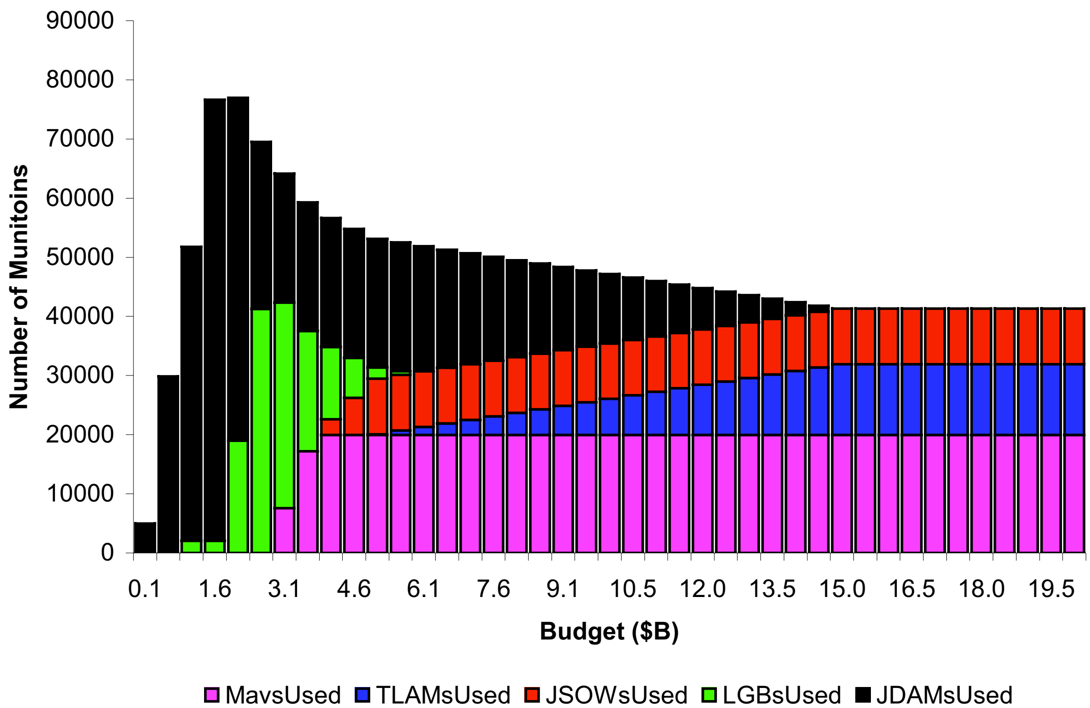
Part One: Exploratory Analysis

The Budget Constraint

In the MR process, a surrogate combatant commander (the requirements office of each service) determines the combat requirement with the goal of *winning the war in the best possible way*. The munitions budget is not an integral part of the office's calculations. If a combatant commander were told in advance how much money he/she had to spend, he/she would prefer different mixes of weapons at different levels of funding. A commander given one billion dollars would buy a different mix of weapons than a commander given ten billion dollars. Under the current MR process, it is difficult, if not impossible to see these preferences.

Figure 3 below shows the preferred weapon mixes for a large, hypothetical South East Asia war scenario over forty different budget scenarios ranging from $100 million to $20 billion.

Figure 3: Combatant Commanders' Preferred Portfolios By Budget Level, SE Asia Scenario



The goal of the commander is to minimize the number of weapons used, subject to the constraint that all targets are hit. For every budget level, the commander's first priority is to cover all the targets. His/her second priority is to use as few weapons as possible. Weapon usage is treated here as a proxy for other performance measures. The assumption is that by using fewer weapons per target, collateral damage is kept down[65], sorties are reduced, and risks to pilots and aircraft are lessened.

At high levels of funding, the commander prefers to use Mavericks, TLAMs and JSOWs. As funding decreases, the commander replaces these weapons with less expensive LGBs and JDAMs. The tradeoff is that it takes more of the cheaper weapons to ensure equivalent coverage of the targets.

Figure 4 shows the tradeoffs in a more direct way, displaying the performance of the cost constrained portfolios in terms of the percentage of targets hit and the percentage of targets that are hit with the 'best' weapon.[66] By changing the composition of the portfolio, a combatant commander is able to hit all the targets with as little as $2.1 billion. However, such a solutions uses approximately twice

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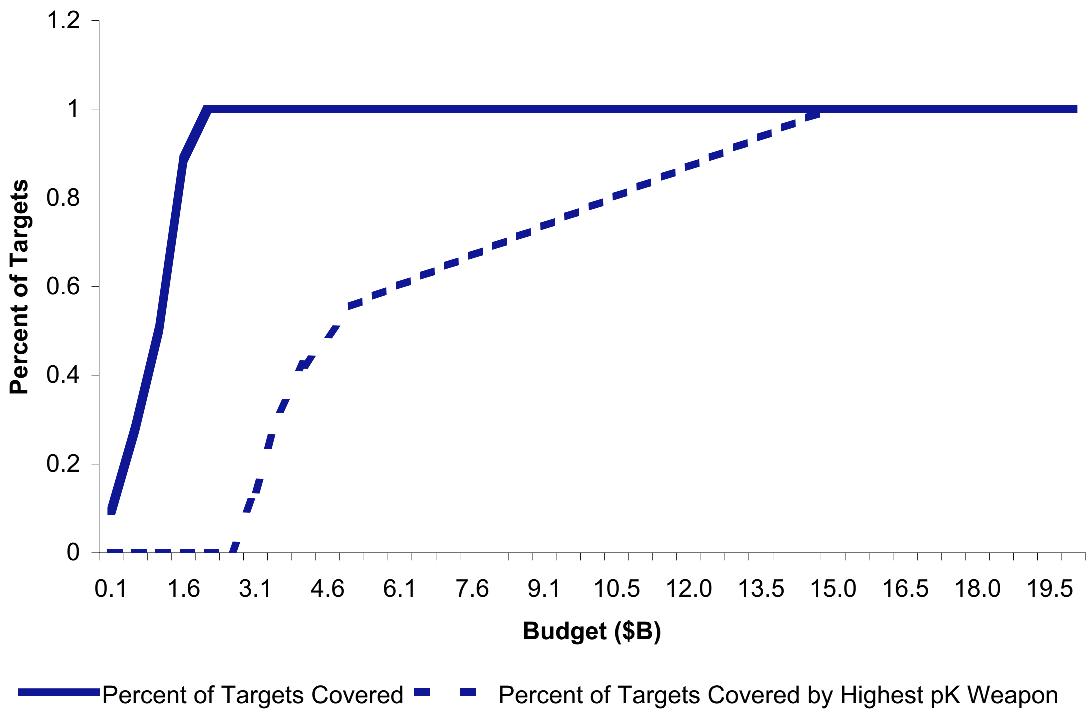
[65] Collateral damage calculation is very complex issue and this is an admittedly very simplified assumption. There are many ways to lessen collateral damage that have little to do with which weapon is used – aiming at specific parts of a target or using different fuses, for example.

[66] The 'best' weapon is defined as the weapon with the highest single shot probability of destroying a target. Using the best weapon is preferred as it destroys the target faster and with less follow on strikes, increasing the speed of an operation and reducing pilot risk and collateral damage.

the number of weapons (80,000 vs. 40,000) as the $15 billion solution and hits none of the targets with the best weapon.

Figure 4: Performance of Preferred Portfolios in Terms of Targets Hit and Targets Hit With the 'Best' Weapons, SE Asia Scenario



Under process we use today, a surrogate combatant commander (the requirements office) determines the combat requirement with the goal of *winning the war in the best possible way*. The result is equivalent an 'un-cost-constrained' optimal – the far right portfolios in

Figure 3, which cost approximately $15 billion. Entirely separate groups of officers are then tasked to fit this requirement to the budget. Unless ad hoc changes are made to the requirement, the results of such planning can be disastrous. As an example, the following figures show what happens when planners decide to use an unconstrained solution, but are forced to cut it due to budget constraints. In this example, if there is not enough money available to pay for the unconstrained portfolio, the order is cut uniformly across weapons to match the available budget.

Figure 5 represents this visually. The solutions at the far right are the ones that the combatant commander would choose, were he/she given no budget constraint. As the budget declines, the order is cut back equally across all weapons.

Figure 5: Unconstrained Portfolio Subsequently Modified by Budget, SE Asia Scenario

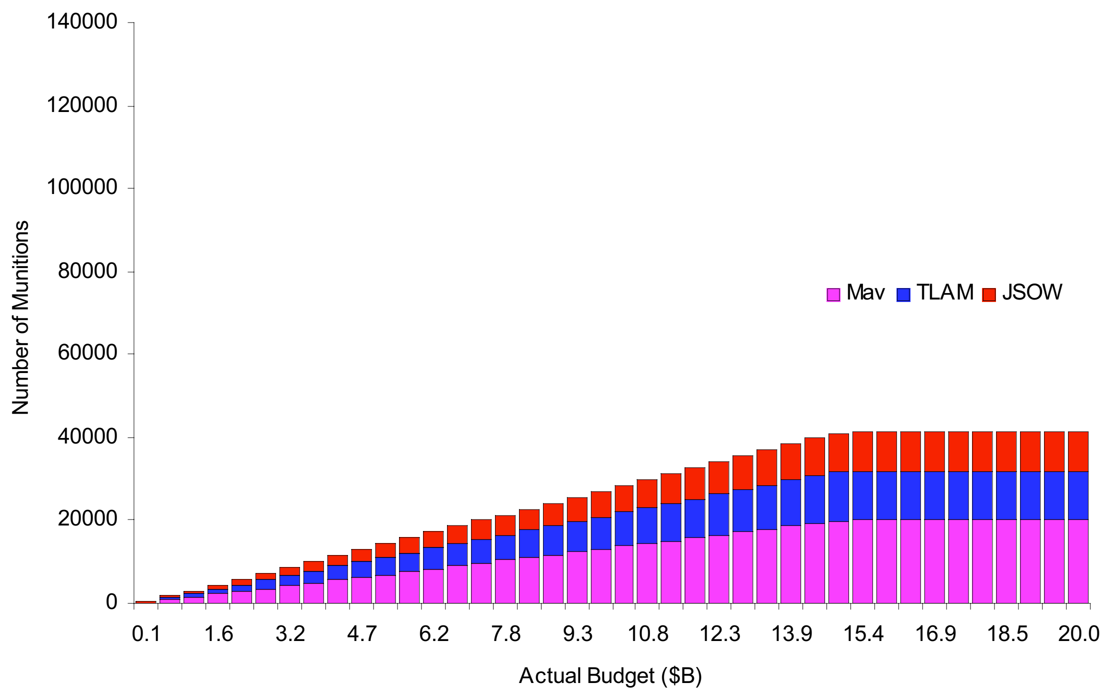
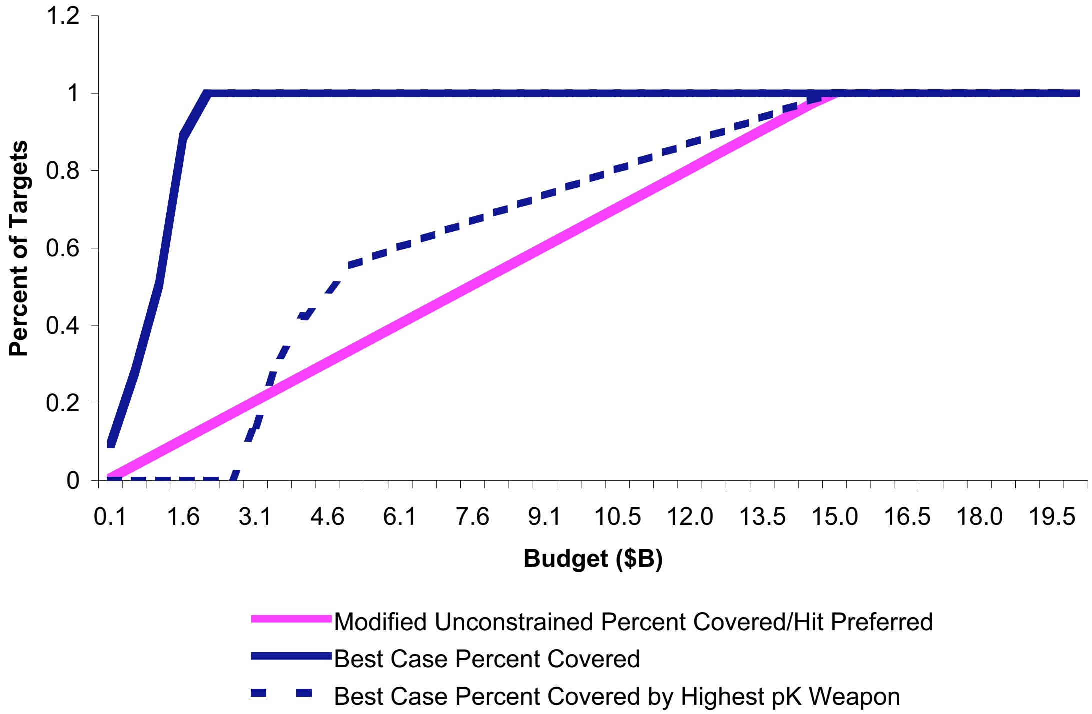


Figure 6 below compares the performance of the unconstrained portfolio with the cost constrained portfolios across the same twenty budget scenarios. It is readily apparent that there is a tremendous benefit to considering the available budget as a constraint during the requirements process. By doing so, commanders are able to cover all the targets with as little as $2 billion. On the other hand, the unconstrained portfolio performs poorly across budget scenarios. If the actual budget is greater than or equal to the cost of the unconstrained portfolio (about $15 billion), all the targets are hit, and hit with the best weapon. But the number of targets hit decreases linearly with the budget because the combatant commanders and their surrogate requirements officers are not able to trade away preferred weapons in order to cover all the targets. The result is a portfolio that performs worse over every budget scenario less than $15 billion, and no better for scenarios over $15 billion.

Figure 6: Comparing Performance of Unconstrained Portfolio with Cost Constrained Portfolios Across Budget Levels, SE Asia Scenario



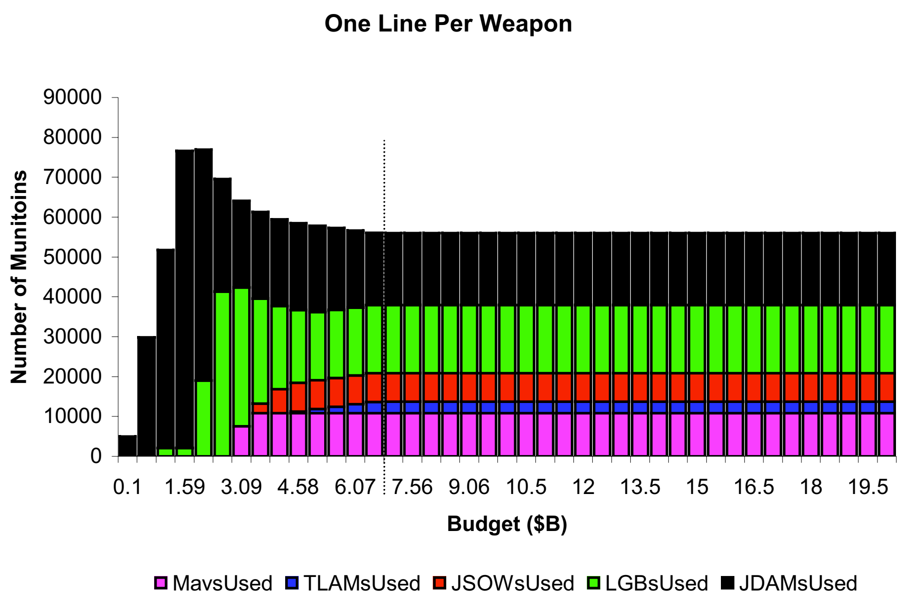
The example given here is extreme, but not improbable. The practice of distributing decrements to budgets equally across programs, colloquially known as 'salami slicing,' is not uncommon within the DoD. Budgeters do not understand how a commander's preferences might change with a smaller or larger budget. They do understand that they must fit all DoD programs into the budget. The MR process hedges against salami slicing by inflating the requirement so that each 'slice' has a smaller chance of damaging the portfolio to a point where performance is unacceptable. Requirements officers are excellent war planners and have an intimate knowledge of weapon effectiveness. If they were given some idea of the true budget *before* creating the initial requirement, the requirement and budget would match up – and budgeters would not *need* to slice. Furthermore, the DoD would be getting the best possible portfolios for its money, and its requirements would have some credibility.

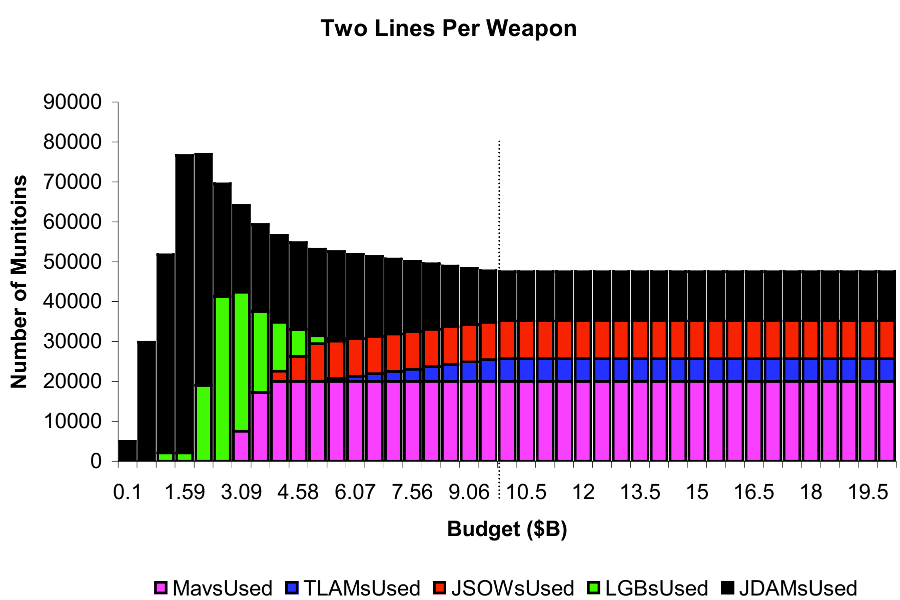
The Production Constraint

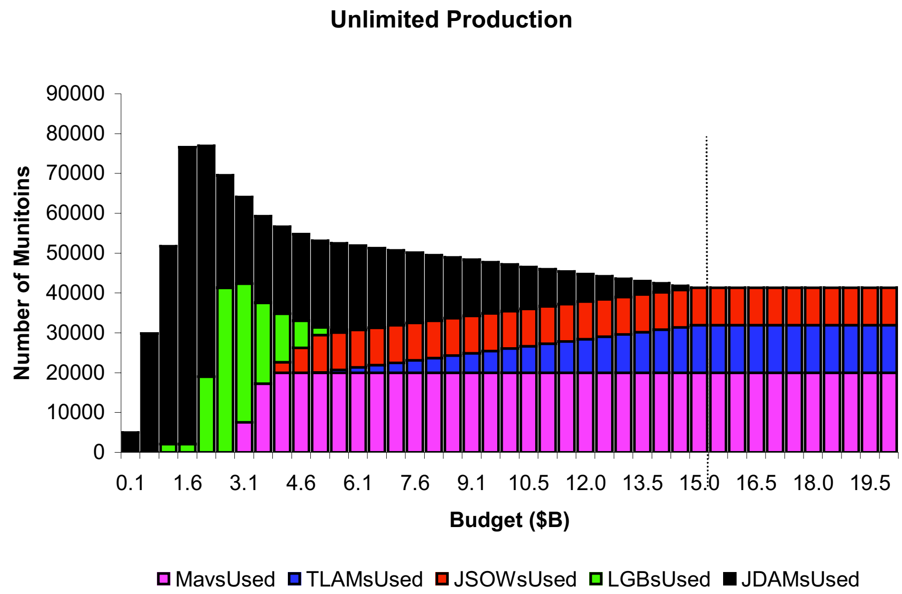
A second constraint that is not considered concurrently with either the requirements generation process or buying decisions is the production constraint. The example provided above assumes that we can produce as many of each weapon type as are needed. The reality is that we only have so many production lines for each weapon, and that those lines are capable of providing only a fixed amount of production over the course of a year. For the purposes of the following charts, we assume a 7-year planning cycle, meaning that each line can produce 6 years' worth of weapons before the conflict.

Figure 7 below shows how the optimal portfolios change depending on whether we have 1, 2 or unlimited production lines available for each weapon.

Figure 7: Optimal Portfolios by Available Production Lines, SE Asia Scenario



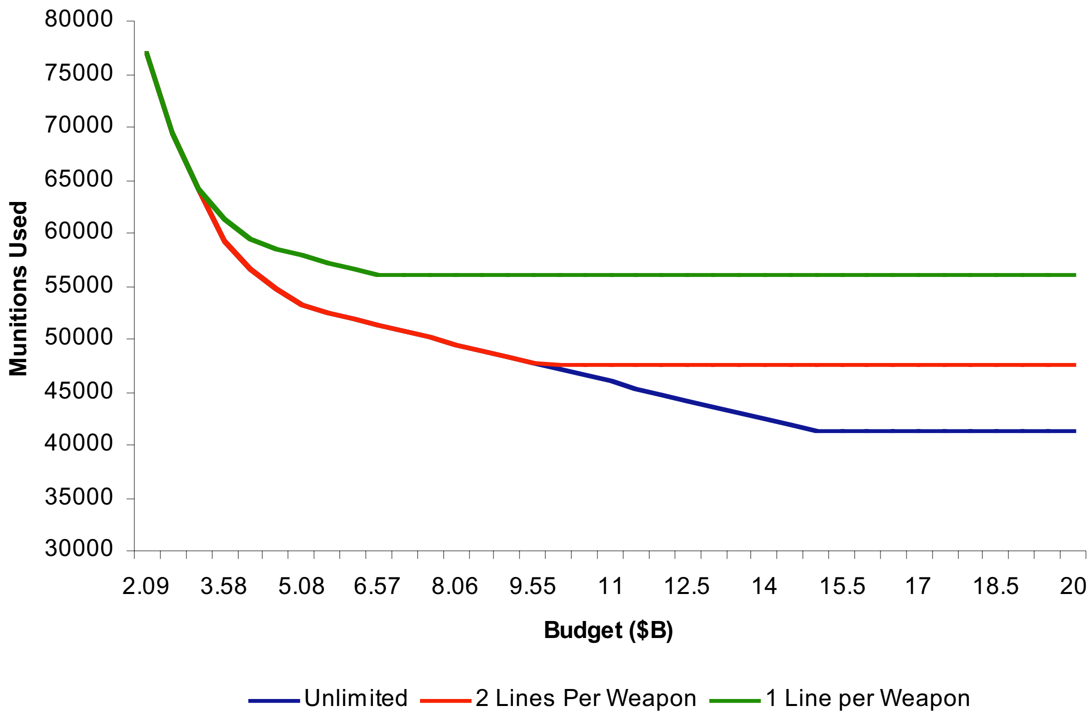




The optimal portfolio changes depending on available production. When there are not many lines (one line per weapon), the commander uses more JDAMs and LGBs because one line can build many of these weapons. He would prefer to use other weapons, but cannot buy more than are available. Maverick, JSOW, and TLAM buys are capped by the number that can be produced in six years. With unlimited production (i.e. no production constraint), the commander would choose to buy many more Mavericks and JSOWS at low budget levels and increase TLAM buys at high budget levels.

Limited production decreases the effectiveness of each dollar spent on weapons and places an upper bound on the amount of money that should be spent on munitions. Figure 8 shows how the number of munitions used changes depending on the budget and production constraint. The figure shows these data for budget levels that allow complete target coverage (budgets greater that $2 billion).

Figure 8: Performance in Terms of Munitions Used by Budget Level for 3 Different Production Constraints, SE Asia Scenario



As the production constraint is loosened, combatant commanders are allowed to choose portfolios that can hit all the targets with fewer weapons. If there is only one production line for each weapon, a commander with $7 billion could hit all the targets with about 57,000 munitions. However, if there are two production lines available, he could do it with about 50,000 munitions – *without changing his budget*.

Furthermore, we see that with one production line for each weapon, there is no point in spending more than $7 billion. Spending more does not improve performance because the trades the commander would like to make are limited by production! With two production lines, there is no reason to spend more than $10 billion and with unlimited production, there is no reason to spend more than $15 billion.

Preparation Time

A final constraint is preparation time – the number of years before the war occurs. Thus far, we (like the DoD requirements office) have assumed that the war occurs 7 years in the future. In reality, we do not know when a war will occur. It could happen in 7 years, or it could happen tomorrow. The preparation time constraint operates in a similar manner to the production constraint. It limits the number of munitions available at the time of the conflict.

If we create a portfolio believing that we have 6 years of production available and the war sooner we are forced to go to war with a partial portfolio. The result is poor performance. Table 2 shows the maximum available production over six years if we have one production line for each weapon.

Table 2: Maximum Production: One Line per Weapon, Six Years of Preparation

JDAM	TLAM	JSOW	LGB	Maverick
216000	2880	7200	115200	10800

If cost were no object, a commander would choose the following portfolio at a price of $7.2 billion:

Table 3: Optimal Portfolio: One Line Per Weapon, Six Years of Preparation

JDAMs	TLAMs	JSOW	LGB	Maverick
11250	2880	7200	31860	10800

Note that TLAM, Maverick and JSOW inventories are each constrained by available production as discussed above. This portfolio would cover all targets and use 63,990 weapons in the process. Now, suppose the war occurs two years earlier than expected. Maximum available production drops by 1/3 to:

Table 4: Maximum Production: One Line per Weapon, Four Years of Preparation

JDAM	TLAM	JSOW	LGB	Maverick
144000	1920	4800	76800	7200

The portfolio we originally chose will now be missing some weapons – namely the TLAMs, JSOWs, and Mavericks that have yet to be produced. Table 5 compares the originally planned portfolio with the munitions that are actually available for combat.

Table 5: Comparing the Six-Year Planned Portfolio With Combat Ready Munitions After Four Years

	JDAMs	TLAMs	JSOW	LGB	Maverick
Original Planned Portfolio	11250	2880	7200	31860	10800
Actual Munitions Ready for Combat	11250	1920	4800	31860	7200

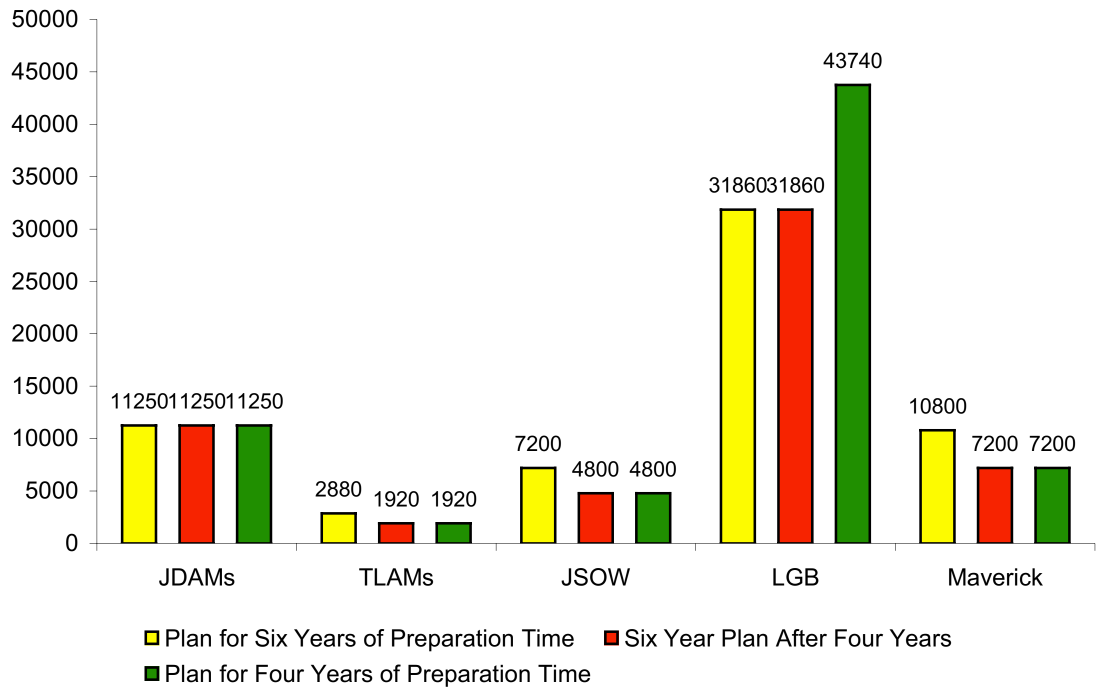
The result is a portfolio that only hits 77% of the targets (shown in Table 7). If the combatant commander knew that there would only be four years to prepare for the war, he/she would have chosen the following solution at a cost of $5.96 billion:

Table 6: Optimal Portfolio: One Line Per Weapon, Four Years of Preparation Time

JDAMs	TLAMs	JSOW	LGB	Maverick
11250	1920	4800	43740	7200

If the commander knew in advance that he/she would have only 4 years of preparation time, the JSOWs, Mavericks and TLAMs would be replaced by increased orders of LGBs. Figure 9 shows this visually.

Figure 9: Visual Representation of Portfolios: Six Year Plan after Four and Six Years, Four Year Plan



The four-year plan portfolio covers all targets, using 68,908 weapons. The difference in performance between the six year and four year plans is shown in Table 7 below.

Table 7: Performance of Six Year and Four-Year Planned Portfolios After Four Years

	Percent of Targets Covered	Munitions Used
Six Year Plan After Four Years	77%	63,990
Plan for Four Years of Preparation Time	100%	68,909

What does this tell us? First, that it can be dangerous to assume the war will occur at any set point in the future and *plan only for that occurrence*. Second, there are very specific strategies that can improve performance in the event of an early war. By exploring the optimal solutions, we found that if we knew an early war was coming, we would buy more LGBs. The implication here is that if we are concerned about an early war, we can *selectively* overstock the weapons that will be useful. This is a far cry from an ad hoc inflation of the requirement. We have direct evidence supporting the need for more of a certain type of weapon to hedge against an early war. Furthermore, we have a chart showing the benefits of doing so.

Scenario Uncertainty Complicates Matters

Thus far we have shown that it is possible to rigorously examine the effects of changing the constraints of budget, production and preparation time for a single war scenario. In doing so, we have learned several valuable lessons. First, it is important to include the budget in the MR process – and allow those with intimate knowledge of weapon effectiveness to do the integration. Second, it is important to include production constraints in one's evaluation, as the number of lines available can increase performance at lower budget levels and cap it at higher levels. Third, we should be careful about our assumptions regarding warning time, as surprises can severely limit the performance of a portfolio. At the same time, we have created charts that can show policymakers exactly how the optimal solution and its performances changes with budget, production, or preparation.

It is not difficult to examine the effects of varying constraints for a single scenario. But planners face an even larger problem – they must be prepared, not for any one particular war, but for the war that actually occurs. We do not know where the next war might occur, and the penalty for preparing for the wrong one can be steep. It is therefore important to consider the cross scenario performance of a munitions portfolio. What happens if we prepare for one scenario, and another one occurs? We want a munitions portfolio that will serve us well across a wide range of scenarios *and* constraints. When we must operate within the constraints of cost, production, and preparation time, it is very difficult – if not impossible – to mathematically construct a solution that is optimal across scenarios.

The following sections will demonstrate that the robust decision making methodology allows us to easily find portfolios that perform well across a wide range of scenarios and changing constraints. The optimal solution for one war may perform very poorly if another war occurs. By identifying a measure of regret and seeking solutions that minimize regret between scenarios, we can choose portfolios that do not perform the best in any one scenario, but that perform very well across all of them. Regret is the difference between the expected performance of a strategy being tested on a scenario and the performance of the optimal strategy under perfect information.

Characterizing Scenario Uncertainty

Before we proceed, we must settle upon an appropriate characterization of the uncertainty that we face. Here we show that using current 'Axis of Evil' scenarios to describe scenario uncertainty may be misleading as a large disparity in scenario size leads to the myopic conclusion that it is best to prepare for the largest scenario. Suppose that the DoD planning guidance tells us to be prepared for the following scenarios – DPRK (North Korea), Syria, Iraq (2001) and Iran and we are given a target list by the Defense Intelligence Agency (DIA). Such a target list might look like Table 8 below. (Numbers are taken from unclassified NAVY Periscope and Strategic Studies Institute databases)

Table 8: Scenario Descriptions – Number of Targets By Type

	Mobile Hard	Mobile Soft	Fixed Hard	Fixed Soft	Total
DPRK	4700	9990	1030	10890	26610
Syria	4500	6050	570	490	11610
Iraq -2001	3100	3150	950	1900	9100
Iran	1170	3050	1540	1050	6810

Uncertainty is characterized here simply as uncertainty about *which scenario will occur*. Already, we can see that, with the exception of the large number of fixed hard targets in Iran, the targets found in Syria, Iraq and Iran are a subset of the targets found in North Korea. Assuming we face no constraints, the optimal solution for each scenario would look like Table 9 below.

Table 9: Optimal Unconstrained Portfolio By Scenario

	JDAM	TLAM	JSOW	LGB	Maverick
DPRK	0	11920	19980	0	9400
Syria	0	1060	12100	0	9000
Iraq (2001)	0	2850	6300	0	6200
Iran	0	2590	6100	0	2340

Table 10 displays the performance of the four optimal portfolios across each war scenario in terms of the percentage of targets that are covered. Table 11 displays the performance of the same portfolios across the wars in terms of the number of weapons used.

Table 10: Percentage of Targets Covered: Preparation vs. Actual Scenario

Portfolio	DPRK	Syria	Iraq 2001	Iran
DPRK Unconstrained	100	100	100	100
Syria Unconstrained	44	100	100	100
Iraq 2001 Unconstrained	34	63	100	100
Iran Unconstrained	26	46	75	100

Table 11: Amount of Ordinance Dropped, Excluding Scenario/Strategy Combinations with Missed Targets

	DPRK	Syria	Iraq 2001	Iran
DPRK Unconstrained	41300	22160	15350	11030
Syria Unconstrained	-	22160	17140	13040
Iraq 2001 Unconstrained	-	-	15350	11030
Iran Unconstrained	-	-	-	11030

The DPRK portfolio is the most robust – faring the best across all scenarios, both in terms of number of targets hit and the number of weapons used. In fact, it does as well as the Syria, Iran and Iraq optimal portfolios for both performance measures. The Iran portfolio, on the other hand, is not robust. It performs quite well if the Iran scenario occurs, but very poorly in the event of any other scenario. The reason why the DPRK portfolio is robust is straightforward. DPRK is by far the largest scenario, as demonstrated by Table 8. The targets of the other scenarios are subsets of the DPRK targets. The optimal portfolios for the other scenarios are subsets of the DPRK optimal portfolio.

This tells us that it is far better to prepare for a large scenario than to prepare for a small one. It is extremely expensive to prepare for such a large scenario, especially if we want the best possible portfolio. Additionally, we are not simply interested robustness to scenario size. We could go further here and examine how changing the constraints might alter the robust portfolio – but to do so would not be interesting. The DPRK scenario is so much larger that the others that it will always be the most robust – preparing for anything smaller (e.g. any of the other scenarios) results in disaster. The hidden assumption here is that the largest scenario will look like DPRK. Military tactics and force structures change – especially now. Preparing for the largest *current* threat may not be enough. What if DPRK ceases to be our largest adversary? What if we must fight simultaneous wars against smaller adversaries whose force structure is entirely different from that of DPRK? We want a portfolio that is robust not just to war size, but also to target type uncertainty. We also want to be able to make compelling arguments about why/when we should choose certain munitions over others so that intelligent decisions can be made within a constrained budgetary environment.

To this end, we will characterize our uncertainty as 'target type' uncertainty. We assume that most of the uncertainties associated with our own tactics and our adversaries' identity, equipment and tactics can be summed up by the types of targets that need to be hit. We want to find a cost effective portfolio that is robust to target type uncertainty. In order to do so, we look for solutions that perform well across five equally sized scenarios made up of different target types. The scenarios used are slightly larger in size than the DPRK scenario above. Each contains 30,000 targets and is shown in Table 12 below. Four of the scenarios are designed to test targeting extremes. These four contain 70% of one target type (mobile hard, mobile soft, fixed hard, or fixed soft) and 10% of each of the other target types. The fifth scenario is a balanced one that contains 25% of each target type.

Table 12: Scenarios To Be Used

	Fixed Soft	Fixed Hard	Mobile Soft	Mobile Hard
Buildings	21000	3000	3000	3000
Bunkers	3000	21000	3000	3000
APCs	3000	3000	21000	3000
Tanks	3000	3000	3000	21000
Balanced	7500	7500	7500	7500

We have chosen to characterize the uncertainty we face as target type uncertainty and have picked scenarios that reflect the extreme target mixes we might face in the futures. We have also assumed that we will face a war or combination of wars that will include no more that 30,000 targets (although the solutions given below are likely scalable to larger or smaller wars). The next section begins our exposition of the robust decision making methodology.

Part Two: Searching for Robust Solutions

We search for a robust solution in cases where it is impossible to find a globally optimal solution across scenarios. In this case, we could find an optimum quite easily if we chose to place a probability distribution on the event of each war occurring. However uncertainty about the war we will face in two, four or seven years cannot be fit to any distribution. The distribution would simply be an opinion of what is most likely to occur. In fact, we place such probabilities on the occurrence of wars right now – when the Defense Planning Guidance says to prepare for a war, it is implicitly placing a 100% probability on the occurrence of that war. That probability is derived from discussions and opinions within the office of the Secretary of Defense for Policy and Planning. The war may occur, or it may not. But it is *impossible* to properly estimate the probability of any single war occurring sometime in the future. We will show that by searching for robust portfolios we can find solutions that are successful across a range of wars while refraining from making conjectures about the future. Furthermore, successful robust portfolios can be created within the context of budget, production and preparation constraints, and the tradeoffs involved may be easily understood.

This illustrative analysis finds robust portfolios by creating a large pool of portfolios and testing them in each of the scenarios. There are many ways to create such a pool. One way might be to run through all the permutations of weapons stocks based on current production. However, doing so would create too many portfolios to test in a reasonable amount of time. We use a Latin Hypercube generator to create 10,000 random portfolios, constrained by the amount of production available. The number of each type of weapon found in a portfolio is a random number from 0 to the maximum available production based on the production constraints and warning time being tested.

Each portfolio is then tested in each scenario. The 'test' is a linear program that allocates a portfolio's munitions across targets in a way that simulates how they would be used by a combatant commander. The first goal is to cover all targets, and the second goal is to use as few weapons as possible. The major performance measures are whether or not all the targets are covered and, if they are, how many weapons need to be dropped to do so.

The first thing we do when choosing the most robust portfolio is drop all portfolios that cannot cover targets in every scenario. These portfolios do not meet the most basic criteria for success. Then we search for portfolios that use the least number of weapons across scenarios. Some scenarios are more difficult than others and portfolios do not perform equally across scenarios. For that reason we compare the number of weapons a portfolio uses to cover all targets in each scenario with that scenario's optimal portfolio weapon usage and calculate the difference. That difference is called the regret – it answers the question, "how much better could I have done in a perfect world?" Then, we rank the portfolios by the maximum regret across scenarios. This means that we view a portfolio as being only as good as its worst performance among the scenarios. The portfolio with the least regret in its worst performing scenario is our robust portfolio.

Finding a Robust Solution

This section shows that by finding a robust solution, we can avoid the pitfalls of planning for the wrong scenario. Suppose we have $8 billion, one production line for each weapon, and six years of preparation time. We can easily calculate the optimal solution for each of the scenarios shown in Table 12. These solutions are shown in Table 13 below.

Table 13: Optimal Portfolios for Each Scenario, $8 Billion, One Line and 6 years of Preparation

Scenario	Optimal Portfolio					Munitions Used
	JDAM	TLAM	JSOW	LGB	Maverick	Total
APC	240	2,880	7,200	51,000	10,800	72,120
Balanced	9,240	2,880	7,200	33,000	10,800	63,120
Building	42,000	2,880	6,000	240	6,000	57,120
Bunker	240	2,880	6,000	42,000	6,000	57,120
Tank	240	2,880	7,200	58,200	6,000	74,520

The total number of munitions used represents the absolute best we can do in each scenario, given the constraints of the budget, production and preparation time. The solutions are all different, both in terms of weapons mix and total size. If we plan for any one of these wars we can rest assured that we can do no better *if that war occurs*. But the results can be disastrous if we plan for one scenario and a different one occurs. Suppose, for example, that we plan for a scenario that is very heavy in mobile soft targets – an agile, mobile force. How does such a solution fare if we find, after six years, that we must fight a different enemy who has entrenched himself in a complex of bunkers or has a larger army of tanks? I turns out that the building solution cannot even cover all targets in *any* of the other scenarios. The penalty for guessing wrong is steep, as shown by Table 14.

Table 14: Performance of Optimal Portfolios Across Scenarios in Terms of Munitions Used, $8 Billion, One Line and 6 Years of Preparation

("-" Denotes that portfolio did not cover all targets)

Planned Portfolio	Actual Scenario				
	APC	Balanced	Building	Bunker	Tank
APC	72120	67620	-	57120	-
Balanced	-	63120	-	60800	-
Building	-	-	57120	-	-
Bunker	-	-	-	57120	-
Tank	74520	70020	74520	57120	74520

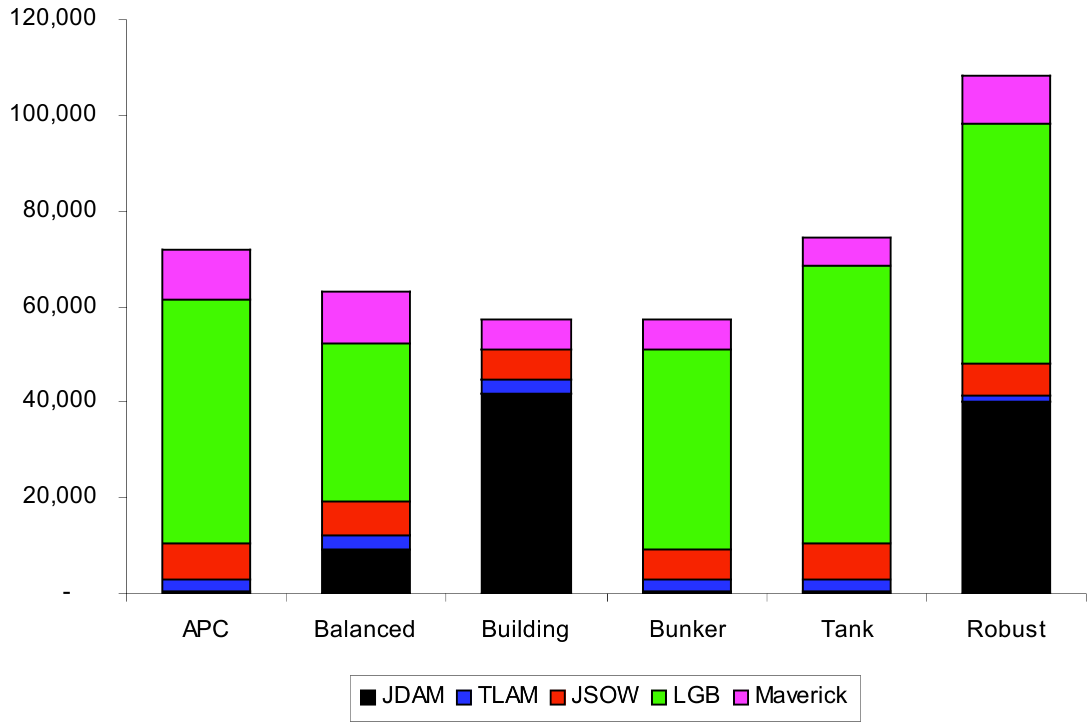
Only by preparing for the tank scenario are we assured of covering all targets regardless of which war actually occurs. If we had prepared for any other war, we would be unable to cover targets had another war occurred! Even the optimal portfolio for the balanced scenario fails to cover targets in three other wars. The tank portfolio is somewhat robust in the sense that it covers targets in all over the wars. However, it uses 30% more weapons than the optimal would have used in the building scenario. This is the regret – we could have don 30% better had we known the building scenario would occur. In addition, in order to have the tank portfolio, we would have needed to guess that our opponent was going to have an army full of tanks. We can do better – by searching through our randomly generated portfolios for a solution that minimizes the maximum regret across wars. This search reveals the portfolio shown in Table 15as the most robust.

Table 15: Composition of the Robust Portfolio, $8 Billion, One Line and 6 Years of Preparation

JDAM	TLAM	JSOW	LGB	Maverick
40003	1362	6823	50227	9775

This portfolio is quite different from any of the others – it is almost, but not quite, an additive combination of the five optimals. It is a compromise between the five that allows for near optimal performance in each. A visual representation of the differences in the five portfolios is shown below.

Figure 10: Comparing the Robust Portfolio With the Optimal Portfolios for Each War



How close to optimal performance do we get with the robust solution? Table 16 shows the percent increase in munitions used to cover all targets when compared to the optimal solution assuming complete foreknowledge. For example, if we choose the $8 tank portfolio and the Building scenario occurs, we must use 30% more weapons to cover the targets than we would use if we had planned for the building scenario's occurrence. If we choose the $8 billion building portfolio and the tank scenario occurs, we cannot cover all the targets. If we choose the robust portfolio, we cover all targets in all wars and *never do more than 4% worse than the best possible solution no matter which war occurs.*

Table 16: Regret –Percentage Increase of Munitions Used Over the Best Case, , $8 Billion, One Line and 6 Years of Preparation

Planned Portfolio	Actual Scenario					Worst Performance
	APC	Balanced	Building	Bunker	Tank	
APC	0%	7%	-	0%	-	-
Balanced	-	0%	-	6%	-	-
Building	-	-	0%	-	-	-
Bunker	-	-	-	0%	-	-
Tank	3%	11%	30%	0%	0%	30%
Robust	***3%***	***4%***	***3%***	***3%***	***3%***	***4%***

By choosing a robust solution we are guaranteed target coverage *and* a low regret no matter which war occurs! We do not have to run the risk of being disastrously unprepared by guessing which war will occur. By searching through the space of non-optimal portfolios, we have found one that performs *almost as well* as the optimal in every single scenario.

Changing the Budget

As we showed in the first part of this chapter, changing the budget changes the nature of the optimal solution. It does not, however, change the benefits of looking for a robust solution. Table 17 shows the composition of the optimal portfolios for each scenario and robust portfolio when the budget is reduced to $5 billion. The far right column shows the number of weapons required to cover all targets by the optimals. As we would expect, this number has increased with the decrease in budget – the best possible solution is not quite as good because we can no longer afford to buy many of the more expensive weapons like TLAM and JSOW.

Table 17: Optimal and Robust Portfolios: $5 Billion, One line, Six Years

	JDAM	TLAM	JSOW	LGB	Maverick	Munitions Used
APC	6,000	-	3,676	56,286	10,800	76,762
Balanced	15,000	283	7,200	32,435	10,800	65,718
Building	42,000	2,373	6,000	1,253	6,000	57,626
Bunker	6,000	1,038	6,000	39,923	6,000	58,961
Tank	6,000	-	5,487	60,769	6,000	78,256
Robust	41,796	79	855	13,786	6,000	-

Figure 11 shows the composition of each portfolio visually. We can see that the robust portfolio is no longer an additive compromise – at $5 billion we can not afford to buy all the JDAMs we would like in the building optimal *and* all the LGBs we would like for the other optimals. Instead a compromise is reached where we would buy enough JDAMs to cover the building scenario, and as many LGBs as possible after that.

Figure 11: Optimal and Robust Portfolios: $5 Billion, One Line, Six years

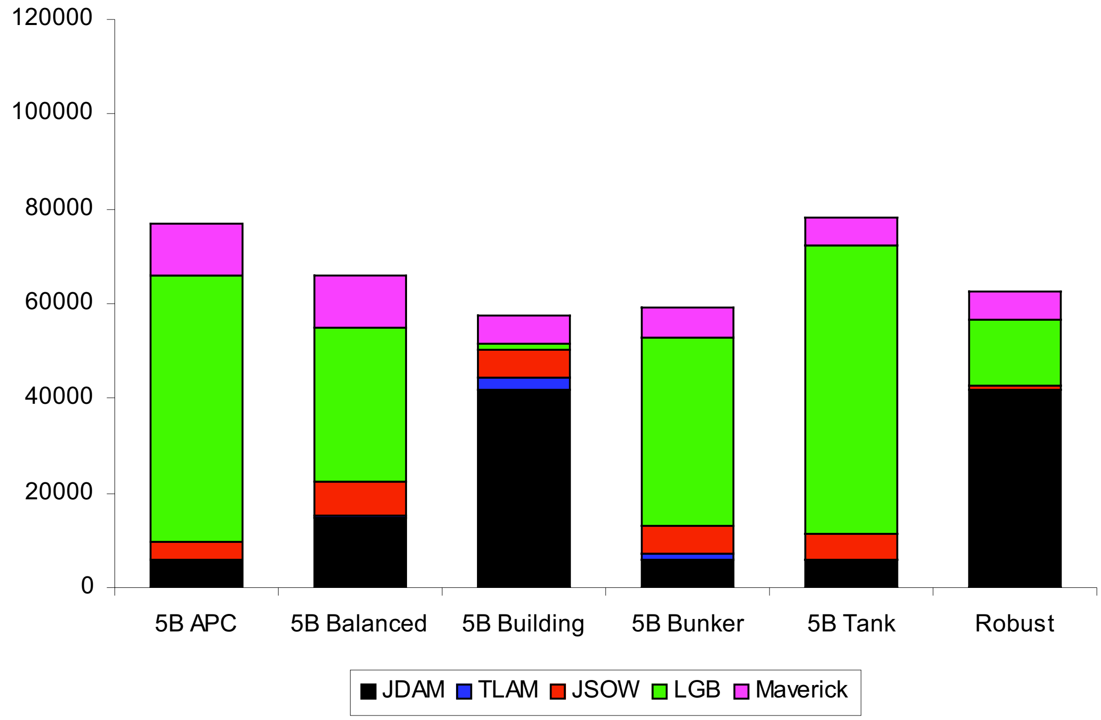


Table 18 shows the regret of each portfolio across the war scenarios. At $5 billion, we face the same dilemma as before if we try to guess which war will occur. In most cases, planning for the wrong war results in us being unable to cover all the targets. Again, the tank portfolio can cover targets in every war, but performs very poorly in the building war. Once again, the robust portfolio performs quite well across the range of wars, covering all targets and removing the need to guess which war will occur. The robust portfolio has a bit more regret in each war at $5 billion than it did at $8 billion – but it still saves us from a catastrophe in any single war. The lower budget makes it more difficult to buy weapons that perform very well against specific target types *and* can hit multiple target types – like JSOW. In other words, the flexibility of the robust portfolio is limited because some trades between weapons are no longer affordable. This is exactly what happens with the optimal portfolios – as the budget declines, optimal performance decreases.

Table 18: Regret - Percentage Increase of Munitions Used Over the Best Case, $5 Billion, One Line, and Six Years

Planned Portfolio	Actual Scenario					Worst Performance
	APC	Balanced	Building	Bunker	Tank	
APC	0%	10%	-	4%	-	10%
Balanced	-	0%	-	-	-	-
Building	-	-	0%	-	-	-
Bunker	-	-	-	0%	-	-
Tank	2%	12%	36%	2%	0%	36%
Robust	***8%***	***9%***	***8%***	***6%***	***6%***	***9%***

Changing the Production Constraint

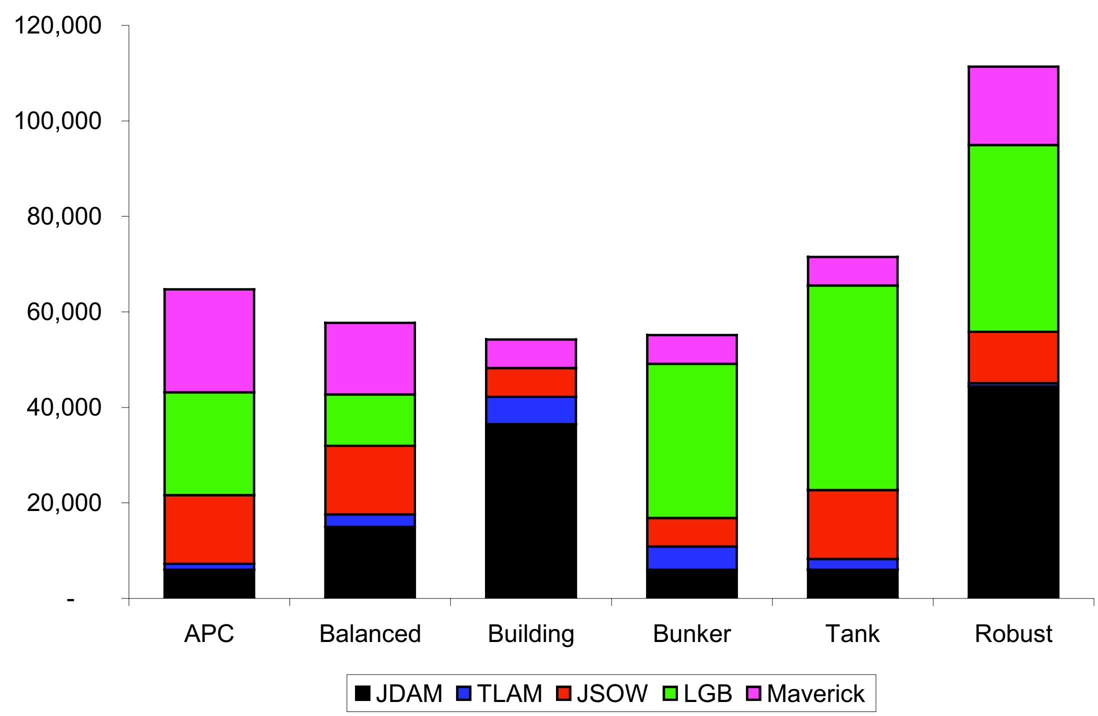
We already showed that increasing production capacity could improve the performance of mid to low budget portfolios and increase the maximum amount that can be usefully spend on munitions. In this example, we show that by adding an extra line of JSOW, TLAM, and Maverick, we can improve performance in each scenario individually *and by looking for a robust portfolio* we can improve performance across all scenarios. For this example, we return to a budget of $8 billion. Table 19 shows the optimal portfolios for each war given an $8 billion budget and an extra production line for JSOW, TLAM, and maverick. It also shows the composition of the most robust $8 billion portfolio we could find in a search through 10,000 randomly generated portfolios.[67] The far right columns compare the performance of the portfolios listed with the performance of the optimals found in Table 13 above (when there is only one line per weapon). As we expect, the best possible performance of an $8 billion portfolio has improved with a slackening of the production constraint. When commanders are allowed to buy more TLAMs, JSOWs and Mavericks, performance improves. Figure 12 shows the 2 line portfolios visually.

[67] A new set of portfolios was generated here, based on 6 years worth of production from one line of LGB's and JDAMs and two lines of JSOWs, TLAMs, and Mavericks.

Table 19: Optimal and Robust Portfolios: $8 Billion, Two Lines for JSOW, TLAM, and Maverick, Six Years Preparation

	JDAM	TLAM	JSOW	LGB	Maverick	Munitions Used	Munitions Used (From Table 12) 1 Line
APC	6,000	1,253	14,400	21,494	21,600	64,747	72,120
Balanced	15,000	2,586	14,400	10,729	15,000	57,715	63,120
Building	36,480	5,760	6,000	-	6,000	54,240	57,120
Bunker	6,000	4,875	6,000	32,251	6,000	55,126	57,120
Tank	6,000	2,281	14,400	42,839	6,000	71,520	74,520
Robust	*44,410*	*696*	*10,751*	*39,110*	*16,377*		

Figure 12: Optimal and Robust Portfolios: $8 Billion, Two Lines for JSOW, TLAM, and Maverick, Six Years Preparation



Although the performance of the optimal solutions has improved with the added lines, we still face the same danger if we plan only for one scenario. Table 20 shows the regret of preparing for each scenario in terms of the number of weapons used. Once again, we find that preparing for any specific scenario will leave us unable to cover targets should a different scenario occur. Again, the optimal tank portfolio can cover all targets in each scenario but does poorly in the building scenario. But the robust portfolio covers all targets in all scenarios and does no more than 9% worse than the optimal in *any single scenario*.

Table 20: Regret - Percentage Increase of Munitions Used Over the Best Case

("-" Denotes that portfolio could not cover all targets)

Planned Portfolio	Actual Scenario					Worst Performance
	APC	Balanced	Building	Bunker	Tank	
APC	0%	8%	-	-	-	-
Balanced	-	0%	-	-	-	-
Building	-	-	0%	-	-	-
Bunker	1%	3%	-	0%	-	-
Tank	10%	12%	28%	5%	0%	28%
Robust	***8%***	***6%***	***9%***	***9%***	***6%***	***9%***

Thus far we have compared the 2 line robust solution with the 2 line optimal solutions. It has more regret than did the 1 line robust solution compared to the one line optimals. How does the two line robust solution compare with the one line robust solution? Do the added lines improve the performance of the robust solution? We would expect so. Table 21shows us that this is to some extent true.

Table 21: Difference in Performance: Robust with One Line and Robust With Added Lines

	APC	Balanced	Building	Bunker	Tank
Robust - One Line	74,390	65,339	58,638	58,638	76,906
Robust - Added Lines	69,740	61,429	59,304	60,053	75,593
Difference	-6%	-6%	1%	2%	-2%

The robust portfolio with added lines does slightly better in the APC and balanced scenarios, marginally better in the Tank scenario, and marginally worse in the building and bunker scenarios. The reason for the worse performance in the Building and Bunker scenarios is likely as result of either sampling error or the fact that the improvements gained from adding munitions used in the other scenarios outweighed the slight decrease in performance.

Changing the Preparation Time

Suppose we are concerned about being surprised. What if the war occurs before we expect? As we showed in the first part of this illustrative analysis, a surprise war can drastically reduce the effectiveness of a portfolio. This section will show that by searching for robust portfolios we can find a solution that works well across wars, even in the event of an early war. In this example, we have a budget of $8 billion, one production line for each weapon, and two year's less time to prepare. Table 22 shows the optimal and robust portfolios for each war scenario, given 4 years preparation time, an $8 billion budget, and one production line for each weapon. The far right column shows how the optimal solutions given 6 years of preparation time fare when the war actually occurs in 4 years. None of the 6 year optimals can cover all targets in 4 years. Figure 13 visually compares the optimal portfolios with the robust portfolios.

Table 22: Composition Of Robust and Optimal Solutions: $8 B, 1 Line, 4 Years of Preparation

	JDAM	TLAM	JSOW	LGB	Maverick	Munitions Used	Munitions Used - 6 Year Optimals
APC	2,160	1,920	4,800	60,000	7,200	76,080	-
Balanced	11,160	1,920	4,800	42,000	7,200	67,080	-
Building	42,000	1,920	4,800	3,960	6,000	58,680	-
Bunker	2,160	1,920	4,800	43,800	6,000	58,680	-
Tank	2,160	1,920	4,800	61,800	6,000	76,680	-
Robust	*54,994*	*1,714*	*4,800*	*59,420*	*7,200*		

Figure 13: Optimal and Robust Portfolios: $8 B, Two Lines for JSOW, TLAM, and Maverick, Six Years Preparation

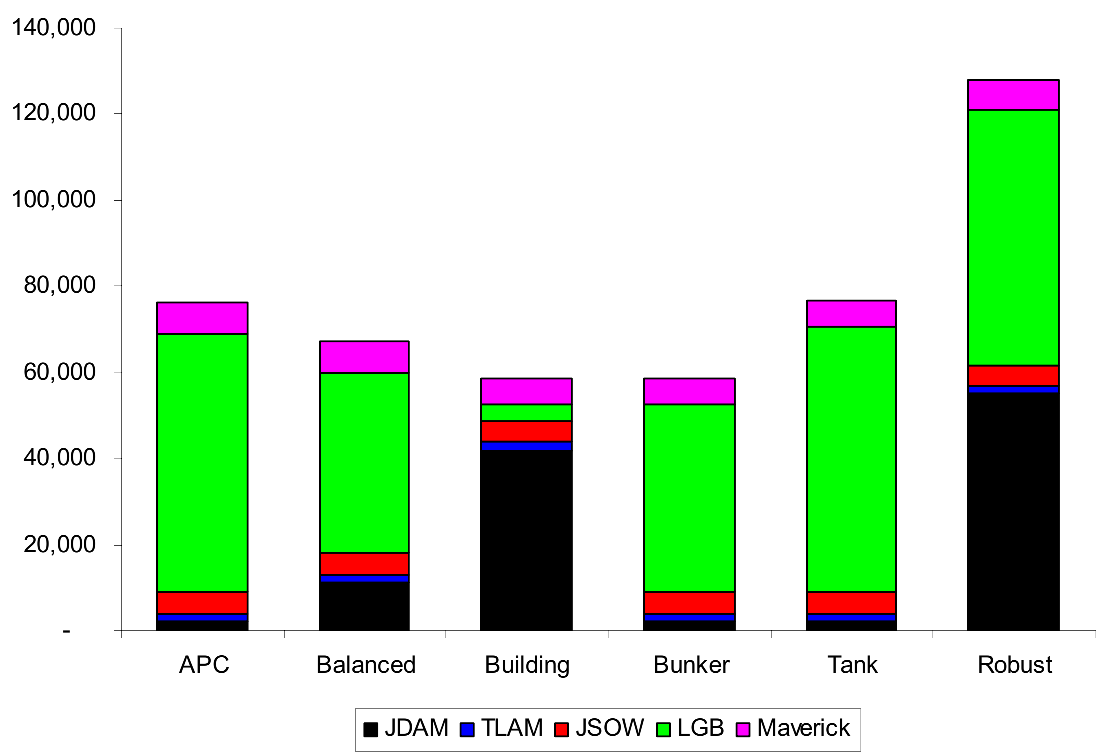


Table 23 shows what we saw for both the budget and production examples above. The robust portfolio insulates us from the risk of planning for the wrong war by containing weapons that perform well across the range of possible wars. In this case, there is almost no difference in performance between the robust portfolio and the optimal portfolio for each war. But, if we had chosen to prepare for only one of the wars, we would have run the risk of being unable to cover targets should a different war occur.

Table 23: Regret - Percentage Increase of Munitions Used Over the Best Case - $8 B, One Line, 4 Years of Preparation Time

("-" Denotes that portfolio could not cover all targets)

Planned Portfolio	Actual Scenario					Worst Performance
	APC	Balanced	Building	Bunker	Tank	
APC	0.0%	6.7%	-	0.0%	-	-
Balanced	-	0.0%	-	0.0%	-	-
Building	-	-	0.0%	-	-	-
Bunker	-	-	-	0.0%	-	-
Tank	0.8%	7.6%	30.7%	0.0%	0.0%	30.7%
Robust	***0.3%***	***0.3%***	***0.4%***	***0.4%***	***0.3%***	***0.4%***

A Note About the Tank Scenario Solutions

The tank scenario optimal portfolios tend to perform fairly well across scenarios independent of changed in the constraints. The reason for this is likely the munitions intensive nature of the tank scenario. What I mean is that the tank scenario always requires more weapons, therefore the optimal solution to the scenario will have more weapons to work with should another scenario arise. The fact remains that without having done this analysis *we never would have known that the tank solutions tend to be somewhat robust.*

CHAPTER EIGHT
Conclusions and Limitations

Benefits of This Approach

Recap

We opened this paper by expressing the DoD's desire to implement capabilities-based planning, describing the current PGM requirements process, and presenting the official critiques of that system. We argued that a capabilities-based approach would need to take into account the uncertainties that are inherent to the problem within the context of economic constraints. The specific constraints and uncertainties examined in the illustrative analysis provided here are the budget, the number of production lines available for each munition, the amount of time we have to prepare for a war, and the uncertainty of the war itself. We showed that due to the nature of the uncertainties, traditional methodologies do not solve this problem. We cannot place a probability on which war will occur or how long we will have to prepare for it. We therefore turned to the methodologies of exploratory analysis and robust decision-making and showed the usefulness of the two methodologies in answering the following policy questions:

1. How do the constraints of budget and available production lines and the uncertainty of preparation time before a war affect the optimal munitions portfolio when we assume we know which war scenario will occur?
2. Given that we do not know which war will occur, how do we find a portfolio of munitions that works well across a variety of scenarios, taking into account the aforementioned uncertainty and constraints?

These are questions that high-level policymakers ask the requirements office right now. A general in the Joint staff would want to know how a changing the budget affects his ability prepared for a war (or wars). The Secretary of Defense would want to know that we are prepared to fight a multitude of different kinds of wars. The current requirements and budgeting processes cannot answer them as well as many would like.

Exploratory Modeling

In the first half of the last chapter we used exploratory analysis to show the effects of changing the constraints of budget and available production lines as well as the uncertainty of preparation time for a single war. We found that planning for only one assumed future can lead to poor performance when something else occurs. A combatant commander prefers different portfolios of weapons at different budget levels. When we make plans assuming that we have no budget limit, we choose a portfolio that performs very poorly if it is later constrained by a budget. In many cases, the binding constraint on a commander's preferred portfolio is not the budget, but rather the number of certain types of munitions that we can produce. We found that increases in production capacity can improve performance at many budget levels, and make expensive portfolios more viable. If a war occurs with less warning than we expect, we may be stuck without enough munitions to cover all targets. We found that by examining the effects of changing the preparation time, we can find specific portfolios that guard against an early war.

By using the technique of exploratory analysis we are able to show the tradeoffs that are made as each variable changes. This information is useful to policymakers because it allows them to understand exactly how their decisions (and the decisions of others) affect the outcome under a wide variety of circumstances. In the DPRK analysis above, we showed that changes in the budget and number of production lines can dramatically improve performance. The degree of improvement depends on the current level of spending and production. Using an analysis similar to the one we have provided here, DoD officials can make a solid case to congress that more money or production is needed and *explain why*. They can ask themselves how they might change their own portfolio to prepare for the event of a surprise war, and *understand why* specific changes help. In addition, these kinds of analyses may be done relatively quickly.

Robust Decision-Making

In the second half of the last chapter we used robust decision-making techniques to find portfolios that work well across a wide variety of disparate wars. The fact we cannot predict which war might occur makes it impossible to determine an optimal portfolio of weapons, even when other constraints and uncertainties are fixed. Planning for only a single war can be catastrophic should a war with very different attributes occur. We showed that by searching for a robust solution, it is possible to find a portfolio that does not perform optimally in any single war, but performs almost as well as the optimal portfolio across all wars. We also showed that robust decision-making techniques can also be used to examine how the best robust portfolio changes with changes to the constraints of budget and production capacity and the uncertainty of preparation time. We found that robust portfolios do exist and that these portfolios do change as the constraints and other uncertainties are altered.

Such information is useful to policymakers because it demonstrates the nature of the uncertainty they face and provides a way to plan even in the face of it. That is, we are shown the consequences of an incorrect prediction – planning for one war and having another one occur. But we are also shown that it is possible to create a portfolio that is flexible enough to perform well *across all wars*. In addition, we can vary the constraints and uncertainties in order to see how they shape the robust solution. As before, we can see the degree to which changes in the constraints of budget and production and the uncertainty of preparation time affect our ability to choose a good portfolio. Except, in this case, a good portfolio is *robust across scenarios* rather than *optimal for one*.

Implementation and Institutional Issues

There are two ways this kind of approach could be implemented: either as a replacement to the current system or as a secondary process that operates outside, but in conjunction with the budgeting and requirements processes. The first option is not immediately practical. There are a plethora of offices inside the DoD and armed services whose sole purpose is to calculate the annual requirement, and maintain the manpower and models needed to do so. Furthermore, there are a large number of outside contractors whose main source of income is derived from supporting the process. To completely dismantle and restructure a planning system of this size is a policy problem in and of itself that would require considerable organizational and political expertise to solve. It is well beyond the scope of this dissertation. It would involve taking apart and changing an organizational structure that is embedded deeply within each layer of the defense department, and would greatly affect how the defense contracting industry does business. In addition, it would be a mistake to completely replace the current system with one that has not been thoroughly tested in the actual planning/budgeting/programming environment.

An appealing alternative would be to house such an approach within an independent office inside the office of the Joint Staff of the DoD or inside the services themselves. The staff would immediately benefit by having a way to link the requirements and budgeting processes. An advantage of the approach outlined here is the speed with which the models can be run and rerun with new data. Such an office could use the estimate generated by the current requirements process as an initial input to models like the ones shown here, which could then assess how the requirement might perform under varying circumstances and economic constraints. This would provide the staff with a way of quickly understanding the strengths and weaknesses of the initial requirement and making adjustments based on budgetary and other concerns within the narrow time frame allowed by the budgeting process. Furthermore, this would be a good way to see how a capabilities-based approach performs in practice relative to the current processes. We would not need to make premature changes to a system that, while flawed, has served us well for decades. If the results are good, further modifications and study would likely be needed prior to a larger scale application.

Improvements and Extensions

Our demonstration of this approach has shown that applying the methodologies of robust decision-making to the problem of munitions planning to the problem of PGM requirements generation, it is possible to not only do better, but also to show why we might need more or less money/production and understand why we would choose some mixes over others. However, there are many ways the illustrative analysis presented here could be improved upon. We can examine robustness across multiple dimensions and mission goals. We can include current the current stockpile in our calculations. We can include more sophisticated production strategies that affect the flow of munitions as well as the stock in our analysis. We can include a more sophisticated war model. Finally, we must use more accurate data on weapon effectiveness before we can begin to make policy based on our results.

Robustness Across Multiple Dimensions

In this illustrative analysis, we only considered robustness across a single dimension – the war scenario. We looked for portfolios that performed well across all war scenarios at various fixed levels of budget, production and warning time. It is possible to search for a robust solution across multiple dimensions. For example, we could search for portfolios are robust to both preparation time and the war scenario. This search would entail testing portfolios across all possible combinations of the war scenarios and warning times. It would, however, be useful to policymakers who are worried about the potential for a surprise war, but also want to be prepared very well for a war that occurs a long way off.

Investigating Robustness Across Mission Goals

We assumed that the goal of a war is to cover all the targets and use a small number of munitions in doing so. In this day and age, we can expect to fight wars with widely varying mission goals. For example, we might fight a war as a tank vs. tank melee, a counter-insurgency, a 'shock and awe' campaign, or a series of urban battles depending on our goals and the tactics of our enemy. Each type of war brings with it a different set of objectives and performance measures. In choosing to examine the uncertainty of target mix, we neglected to consider the uncertainty of mission goal. However, we believe it would not be difficult to incorporate into an additional analysis.

Inclusion of Current Stockpile

The model used here did not take into account the currently owned stockpile – rather it assumed that we were building a stockpile from scratch. The reality is that yearly investments in munitions act as marginal changes to the stockpile we already have. Inclusion of the current inventory would constrain the optimal solutions, and make some strategies more desirable than others in ways that cannot necessarily be predicted in advance. However, one of the benefits of using a linear programming technique is the ease with which we may add to the model a base inventory that has already been paid for.

Investigation of Strategies that Affect the Flow of Munitions as well as the Stock

We considered only one production policy – the number of lines available – and we considered it as a constraint rather than a policy lever. In Chapter Two, we pointed out that system performance could be improved by making investments in production technologies and options in addition to physical stock. However, we did not have time to thoroughly investigate such policies. Production line sharing, surge production, and options all have the potential to improve performance across scenarios by enabling us to create more flexible portfolios. An analysis examining the effects of these policies could be revealing to the PGM community.

More Sophisticated War Model

Our war model was very simple. It matched five munitions to four target types. In reality, there are many different types of targets and munitions. There is also more to a war than simply hitting all of the targets. The timing of attacks and order in which targets are hit can make a crucial difference in the outcome. We dealt only with the uncertainties of target type and war timing. There are many more uncertainties that can affect a munitions portfolio's performance. For example, the weather and terrain type can drastically affect the effectiveness of munitions. The use of a more sophisticated war model was considered, but deemed unnecessary for the purposes of this demonstration.

Better Munitions Effectiveness Data

The true effectiveness (pK) of each munition against each target type is classified. For this reason, I had to make an educated guess about how effective each weapon is against each target. In doing so, I reviewed unclassified data on usage in past wars, and documents describing each munition's attributes. In all likelihood, the relative effectiveness of the weapons against each target is accurate. But there may be errors and the overall precision of these weapons may be over or underestimated in the illustrative analysis presented above. In addition, this approach did not consider traditional munitions as an alternative to PGMs (a change that could be made easily). As a result, the models provided here should not be used to determine specific requirements or policies. It would, however, be a simple matter to replace the effectiveness data with the actual numbers. The models could be rerun in a day's time. Changing the effectiveness data would not change the major conclusions of this report. It would, however, change the composition of optimal and robust portfolios and the specific tradeoffs preferred by commanders under various circumstances.

APPENDIX A
Data Used In Illustrative Analysis

Notional Number of Weapons Needed to Cover a Single Target
(Used as model inputs – 'covering' a target is having a 95% chance of destroying it)

	Mobile Hard	Mobile Soft	Fixed Hard	Fixed Soft
JDAM	4	4	8	2
TLAM	-	-	1	1
JSOW	2	2	3	2
LGB	3	3	2	3
Maverick	3	2	-	-

Weapon Cost and Production Data

	JDAM	TLAM	JSOW	LGB	Maverick
Weapon Unit Cost ($M)	0.02	.88	.21	.05	.13
Monthly Production of a Single Assembly Line	3000	40	100	1600	150

Source: Estimates derived from Selected Acquisition Reports for each munition.

Ranking of Weapons Based on Number Needed to Cover a Target

	Best	2nd Best	3rd Best	4th Best
Mobile Hard	JSOW	LGB/Maverick	JDAM	
Mobile Soft	JSOW/Maverick	LGB	JDAM	
Fixed Hard	TLAM	LGB	JSOW	JDAM
Fixed Soft	TLAM	JDAM/JSOW	LGB	

Ranking of Weapons Based on Cost per Covered Target

	Best	2nd Best	3rd Best	4th Best	5th Best
Mobile Hard	JDAM	LGB	Maverick	JSOW	
Mobile Soft	JDAM	LGB	Maverick	JSOW	
Fixed Hard	LGB	JDAM	JSOW	TLAM	
Fixed Soft	JDAM	LGB	JSOW	HARM	TLAM
Hard SO	JSOW	TLAM			
Soft SO	JSOW	TLAM			

Here are the actual "Cost per target covered" numbers used to create the above ranking:

Unit Cost Per Target Covered ($M)

	JDAM	TLAM	JSOW	LGB	Maverick
Mobile Hard	0.08	-	0.42	0.15	0.38
Mobile Soft	0.08	-	0.42	0.15	0.25
Fixed Hard	0.16	0.88	0.63	0.10	-
Fixed Soft	0.04	0.88	0.42	0.15	-
Weapon Unit Cost ($M)	0.02	0.88	0.21	0.05	0.13

APPENDIX B
Munitions Considered In This Report

AGM-65 Maverick

The AGM-65, commonly known as Maverick, first entered service in the mid 60s. The weapon has been continuously upgraded since then. It is a rocket-powered missile, originally designed for use against tanks and hardened targets. Variants of the maverick use three different targeting systems. The A, B, H, J and K variants use a TV tracker that locks onto a television picture that the pilot takes in the cockpit. The missile then homes in on that target. The F, F and G variants use an imaging infrared (IIR) seeker. This seeker operates similarly to the TV guidance, except that it locks onto an infrared image rather than a visual one. These variants are designed to operate better in low visibility conditions. The E variant is guided by a semi-active laser. This missile requires a separate laser, either on the aircraft or operated by a third party, to mark the target. The missile then homes in one the laser energy reflected from the target. According to Jane's Online, over 30,000 AGM-65 A/Bs have been produced and over 35,000 of the other variants have been ordered. In addition, many of the older models have been and are continuing to be upgraded.

Joint Direct Attack Munition (JDAM)

The JDAM family of munitions is the result of a joint Navy/Air Force program to find inexpensive ways to deliver conventional bombs with increased accuracy. The program was begun in the late 1980s. JDAM is a kit that is added to a conventional bomb. The kit is comprised of a GPS guidance system and a set of steering fins. While in flight, the fins move to home the bomb into a programmed set of GPS coordinates. JDAM comes in 4 variants. The major difference between variants is the size of the bomb the kit is added to. The GBU-31 fits on a 2000 lb general purpose or penetrating warhead, the GBU-32 Fits on a 1000 lb general purpose warhead, the GBU-35 fits on a 1000 lb general purpose warhead, and the GBU-38 fits on a 500 lb general purpose warhead. As of June 2004, over 100,000 JDAMs had been produced. One advantage of the JDAM kit is its price – it costs about $30,000 per kit – very cheap compared to other precision-guided weapons. In addition, it can be used against any kind of target. However, it is not as accurate as other PGMs. Jane's online reports a 42.9 ft circular probable error, meaning that the Air Force officially classifies the weapon as "near precision weapon." The JDAM kit does not provide any power to the warhead – it only assists the glide.

AGM-154 Joint Standoff Weapon

JSOW is the result of a joint program by the USAF and Navy to develop an inexpensive precision standoff weapon. The program was begun in 1992, and low rate production began in 1998. The JSOW is an unpowered glide bomb, fitted with wings like an aircraft, which has the ability to carry and dispense a variety of sub munitions. The JSOW is intended to be a partial replacement for a variety of older PGMs. There are currently three major variants of the JSOW, each capable of destroying a different target type. The AGM-154A carries 145 combined effect bomblets for destroying soft targets, the AGM-154B carries six bomb dispensers (each of which can dispense four anti tank bomblets), and the AGM-154C carries a single warhead designed specifically for penetrating fixed hardened targets. All JSOW variants carry a GPS for guidance, and the C variant also has the ability to be guided by an imaging infrared seeker. Because it is a glide bomb, the range of the JSOW varies depending on the altitude at which it is dropped. A variety of sources cite ranges of anywhere between 5 miles to 40 miles (from a high altitude launch). In 1994, Raytheon developed a powered version of the JSOW, with a reported range of 120 miles – but the weapon was never ordered.[68] However, the capability to produce the powered version remains. The JSOW carries a set of preprogrammed targets, but may also be retargeted manually from the cockpit. About 19,000 JSOWs have been order by the Navy, Air Force, and Marine Corp, although it was reported in January 2003 that the Air Force had decided to abandon the project in favor of the Wind Corrected Munitions Dispenser. However, that system has been marked for cancellation in the 2006 budget.

UGM-109 Tomahawk Land Attack Missile (TLAM)

The Tomahawk is a truly long-range standoff weapon, fired from a ship or submarine. It comes in four variants – the TLAM-N, designed to carry nuclear warheads; the TASM, designed to destroy ships; the TLAM-C, designed to destroy conventional fixed targets, and the TLAM-D, which carries conventional sub munitions. Range varies by type, but the conventional variants have a reported range of 500 nautical miles. The missile launches from its tube like a rocket. After launch, wings extend from the sides of the weapon, and it then cruises under the power of a turbofan jet engine. The missile then follows a preplanned route to its target using on board navigational systems and terrain mapping guidance. As it nears the target, the missile switches to a terminal guidance system that matches a digital image of the target with images from an onboard camera. Recent upgrades allow the missile to be retargeted during flight from a satellite uplink. The first Tomahawk entered service in 1983, with a planned buy of approximately 2,500 conventional TLAMs. The actual number held is stock is closely guarded. There were many unconfirmed reports of a serious shortage after Operation Iraqi Freedom.

Paveway II and III, Laser Guided Bombs (LGB)

The Paveway system is a bomb kit, much like JDAM, except that it is guided to its target by a laser. There are two pieces to the kit. The first piece bolts on to the front of the bomb and provides guidance and control. This piece carries the laser seeker and four fins used for control. The second piece bolts on to the back of the bomb and contains four fixed wings that stabilize the bomb during freefall. The original Paveway entered service in the late 1960s. Paveway II entered service in 1976 – with major improvements in electronics, guidance, and maneuverability. Paveway III entered service in 1986 – with the major upgrades of low altitude and longer standoff range capability. On all Paveway systems, the laser guidance requires a target to be marked by a laser designator that may be located either on the aircraft or a third party on the ground or in the air. Recent upgrades have

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[68] Janes All the World's Munitions Online "JSOW"

added a GPS guidance system that allows for better performance in low visibility conditions. The bomb is guided near the target using the GPS, and then switches to a laser seeker for terminal guidance. There are at least 7 different variants of the Paveway. The major difference between variants is the warhead size. Two exceptions are the GBU-27 and GBU-28 that were designed specifically for deep bunker penetration. Janes Online reports that the Air Force used 8,400 LGBs during the Gulf war, and still had an inventory of approximately 27,000 afterwards.