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Global Combat Support Basing

Robust Prepositioning Strategies for Air Force War Reserve Materiel

Ronald G. McGarvey, Robert S. Tripp, Rachel Rue, Thomas Lang, Jerry M. Sollinger, Whitney A. Conner, Louis Luangkesorn

Prepared for the United States Air Force

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Preface

The ability to rapidly deploy forces into austere locations is essential to the global power projection concept of operation. Much of the materiel used by such expeditionary forces does not deploy with the unit. It is instead sourced from a global network of prepositioning storage locations to reduce the transportation requirements associated with the movement of such materiel.

Current storage concepts for prepositioned materiel are based on planning assumptions from the Cold War era: that deployment scenarios and their associated support requirements could be fairly well identified in advance and the necessary materiel prepositioned at anticipated deployment sites. This monograph examines alternative approaches to storing combat support materiel to see if they would provide better support to deploying forces in an expeditionary environment that more closely resembles the current Department of Defense (DoD) planning guidance: frequent force projections, of varying sizes and of unknown durations, to wide-ranging locations.

The research described in this monograph was conducted within the Resource Management Program of RAND Project AIR FORCE for the following two studies:

- A fiscal year (FY) 2006 project titled "A Global Analysis of Contingency Support Basing Options," sponsored by, at that time, Lt Gen Donald J. Wetekam, Deputy Chief of Staff, Logistics, Installations and Mission Support, Headquarters United States Air Force (AF/A4/7); and Maj Gen Gary T. McCoy, Director, Logistics Readiness, Office of the Deputy Chief of Staff, Logis-

tics, Installations and Mission Support, Headquarters United States Air Force (AF/A4R).

- An FY 2007 project titled "Combat Support Basing Options for Vehicles and Equipment War Reserve Materiel," sponsored by, at that time, Lt Gen Donald J. Wetekam, Deputy Chief of Staff, Logistics, Installations and Mission Support, Headquarters United States Air Force (AF/A4/7); Lt Gen Carrol H. Chandler, Deputy Chief of Staff, Air and Space Operations, Headquarters United States Air Force (AF/A3/5); Maj Gen Polly A. Peyer, Director, Resource Integration, Office of the Deputy Chief of Staff, Logistics, Installations and Mission Support, Headquarters United States Air Force (AF/A4/7P); and Maj Gen Gary T. McCoy, Director, Logistics Readiness, Office of the Deputy Chief of Staff, Logistics, Installations and Mission Support, Headquarters United States Air Force (AF/A4R).

The monograph should be of interest to logisticians, operators, mobility planners, and those planning for contingency operations throughout DoD, especially those in the Air Force.

RAND Project AIR FORCE

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Summary

Background and Purpose

The Air Force has transitioned into an expeditionary force to provide better support to national security in the current operational environment, which is characterized by continuous engagement across geographically disparate locations. More than two-thirds of the materiel tonnage required to support expeditionary operations (excluding fuel) is War Reserve Materiel (WRM) resources that do not belong to the flying units.[1] The rapid deployment time lines required of expeditionary forces preclude moving all heavy WRM assets from the continental United States (CONUS) to forward operating locations (FOLs) in response to emerging contingencies.[2] Instead, WRM assets are prepositioned at forward support locations (FSLs) around the globe, ready for use by deploying Air Force units.

In FY03 and FY04, the Air Force Deputy Chief of Staff for Installations and Logistics (AF/IL) sponsored RAND Project AIR FORCE research that developed an approach for considering the global prepositioning of WRM assets in an expeditionary environment. The primary contribution of the FY03 research was an optimization model

[1] Mahyar A. Amouzegar, Robert S. Tripp, Ronald G. McGarvey, Edward W. Chan, and Charles Robert Roll, Jr., *Analysis of Combat Support Basing Options,* Santa Monica, Calif.: RAND Corporation, MG-261-AF, 2004.

[2] Kristin F. Lynch, John G. Drew, Robert S. Tripp, and Charles Robert Roll, Jr., *Supporting Air and Space Expeditionary Forces: Lessons from Operation Iraqi Freedom,* Santa Monica, Calif.: RAND Corporation, MG-193-AF, 2005.

that computes a least-cost allocation of resources among existing and potential storage locations and determines a transportation network, including vehicle routings, necessary to satisfy operational requirements.[3] The FY04 analysis employed these models in a review of the global WRM prepositioning posture.[4]

In FY06 and FY07, the Air Force asked RAND to revisit global WRM prepositioning (1) to evaluate the "Virtual Afloat" concept (which was consistent with recommendations made in Amouzegar et al., 2006), wherein some WRM assets would be prepositioned in shipping containers at or near seaports and then moved to vessels to be transported by sea to support deployment requirements, and (2) to analyze the costs and benefits associated with building "reliability in the event of disruption" into the WRM prepositioning posture. This research focused on a subset of WRM, the Basic Expeditionary Airfield Resources (BEAR) that provide the capability to open an austere airbase, and WRM vehicles (WRMVs).

Results

From our analyses of WRM prepositioning strategies evaluated across a broad range of operational scenarios, we developed the following general findings and policy recommendations.

A large and geographically dispersed set of WRM FSLs is attractive when considering the balance between predictable and contingency-dependent costs. (See pp. 34–43; 64–73.) The traditional approach to identifying prepositioning postures is to select a set of FSLs that satisfies the major combat operations' (MCOs) delivery requirements while minimizing the predictable costs that can be included in the Air Force's annual budget submission. These costs include facility construction, operations and maintenance, asset procurement, and the one-time movement of assets to their new storage

[3] Amouzegar et al., 2004.

[4] Mahyar A. Amouzegar, Ronald G. McGarvey, Robert S. Tripp, Louis Luangkesorn, Thomas Lang, and Charles Robert Roll, Jr., *Evaluation of Options for Overseas Combat Support Basing*, Santa Monica, Calif.: RAND Corporation, MG-421-AF, 2006.

sites. Contingency-dependent transportation costs associated with moving assets from FSLs to FOLs typically were not included in such analyses, because MCO execution costs would be funded through a supplemental request, outside the budget submission. However, recent Office of the Secretary of Defense (OSD) guidance directs that the Armed Forces plan for continuous engagement in multiple small deployments around the globe while maintaining the capability to execute MCOs. Because many of these lesser contingencies will likely require the use of WRM, it is unclear to what extent the costs associated with moving WRM to support these smaller deployments, many of which may be exercises, should be included in the services' programmed budgets as opposed to supplemental budget requests; MCO execution costs would continue to be supplementally funded.

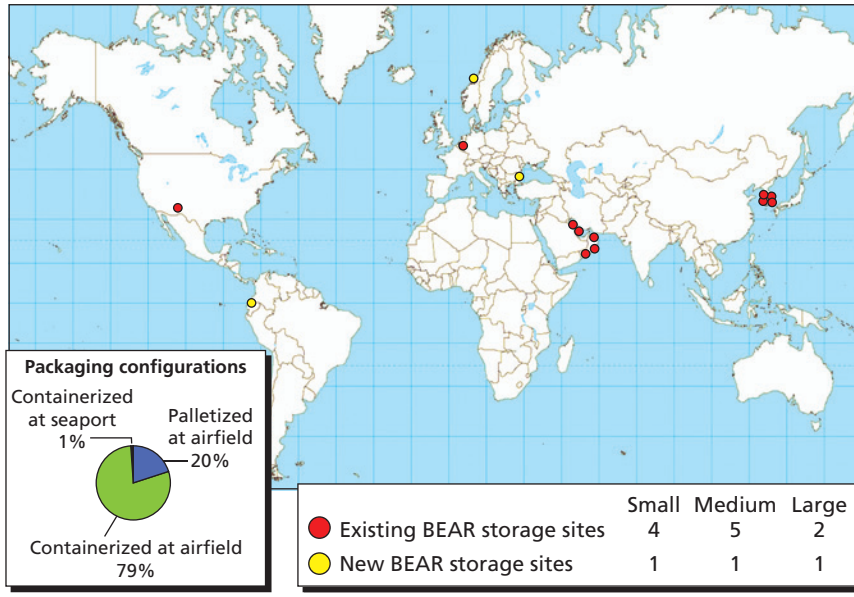
The ability to satisfy time-phased WRM delivery requirements remains the primary consideration; thus, throughout our analysis, all prepositioning postures that are presented will satisfy the deployment effectiveness constraints. Each alternative posture can then be evaluated with respect to its level of cost and risk.[5] We first used our optimization model to determine minimum-cost FSL postures that meet the future deployment requirements (both steady-state and MCO), as defined by DoD Strategic Planning Guidance (SPG), considering only predictable costs. The model identified postures that use a small number of FSLs, concentrated in existing locations, as indicated by Figure S.1 for the BEAR prepositioning posture. We then used the optimization model to identify postures that minimized the total system costs (i.e., the sum of predictable and contingency-dependent costs, excluding MCO transportation costs). These postures were geographically dispersed into a large number of FSLs, often at new locations, with most new sites storing a relatively small amount of BEAR assets,[6] as indicated by Figure S.2.

---

[5] Thus, the analysis presented in this monograph can be viewed as a constant-effectiveness, variable-cost, and variable-risk analysis.

[6] We define a "small" site as one that stores between one and six BEAR sets, a "medium" site as one that stores between seven and 15 BEAR sets, and a "large" site as one that stores 16 or more BEAR sets.

Figure S.1
BEAR Posture Optimized Against Predictable Costs



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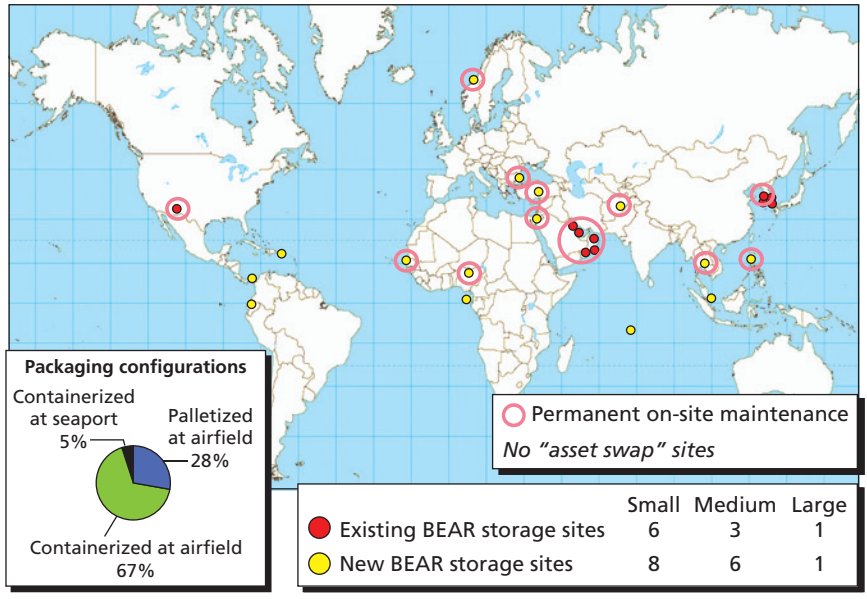
These very different WRM prepositioning strategies have significant cost implications. Figure S.3 presents the total system costs, in total present value (TPV) over six years, for the current BEAR posture (leftmost bar), the posture optimized against only predictable costs (center bar), and the posture optimized against total system costs (rightmost bar). For both the current posture and the one optimized against only predictable costs, the transportation cost associated with support to non-MCO deployments in SPG environments is significantly larger than all other cost categories combined. This suggests that excluding these costs from consideration when developing a prepositioning posture may be a flawed strategy, even if many of these costs cannot be accurately forecast.[7]

[7] Note that the costs associated with deployment in support of exercises and other planned missions can be forecasted, however.

Figure S.2
BEAR Posture Optimized Against Total System Costs



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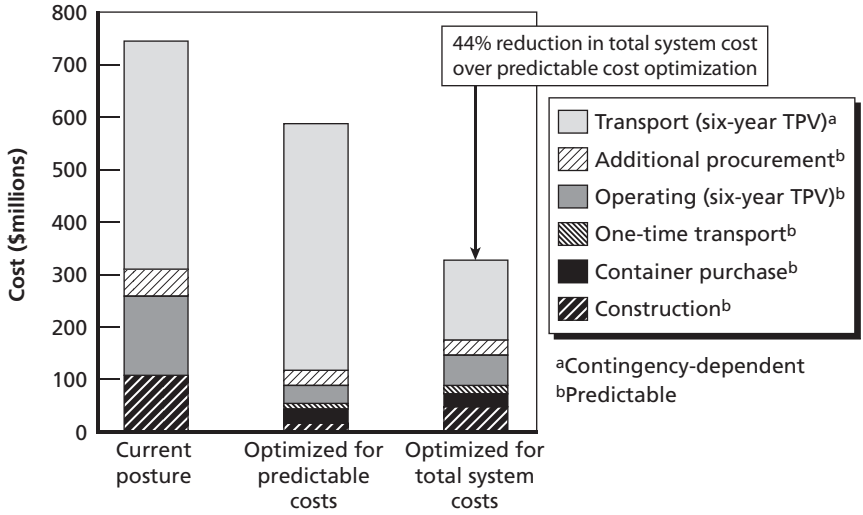
The strategy that also considers contingency-dependent transportation costs accepts additional investment in predictable costs (an investment of $176 million in TPV, compared with $118 million TPV for the posture optimized against predictable costs only), because these cost increases are more than offset by significantly reduced non-MCO transportation costs ($152 million for the total system cost optimization and $470 million for the predictable cost-only optimization). The finding that a relatively small additional investment in predictable costs for a dispersed set of WRM FSLs would be offset by much larger reductions in contingency-dependent costs held constant across all the sets of scenarios that were examined for both BEAR and WRMV, including scenarios in which the non-MCO deployment demands were reduced significantly.

Figure S.3
Cost Comparison Considering Total System Costs for BEAR



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Alternative packaging configurations and maintenance concepts can allow such dispersed WRM prepositioning postures without incurring significant investments in infrastructure construction. (See pp. 26–32; 58–63.) Policymakers may be averse to a dispersed posture, even if it achieves significant reductions in total system cost, if it required a large investment in permanent infrastructure at foreign sites. If BEAR assets, which are currently stored in warehouses on pallets, were instead packed in steel shipping containers, much of this construction cost could be avoided because these shipping containers do not require inside storage. Our optimization models found containerization to be an attractive strategy, as indicated by the pie chart in Figure S.2, with solutions across multiple scenarios storing between 70 and 75 percent of BEAR assets in containers, of which 5 to 10 percent were stored in a "Virtual Afloat" configuration at seaports.

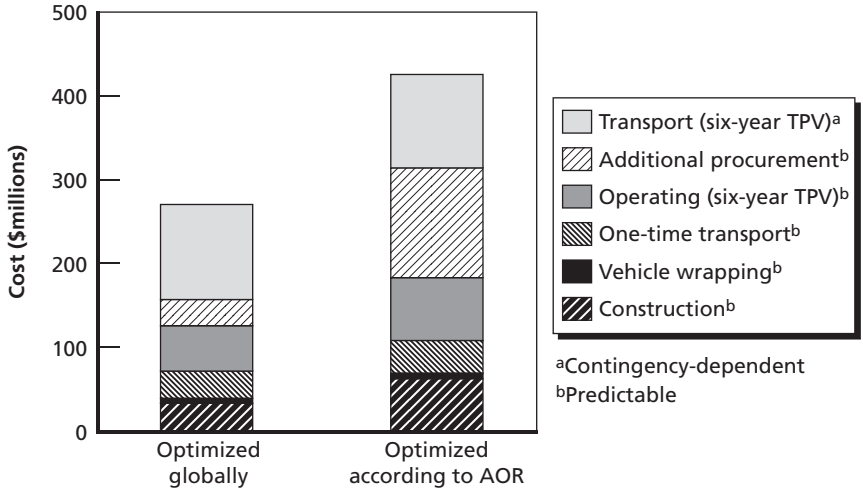
Storage in commercial containers also offers other benefits, such as allowing assets to blend in with the large number of nonmilitary containers moving through civilian supply chains. Our analysis also identified a cost-effective alternative packaging configuration for WRMV,

in which vehicles are shrink-wrapped in plastic and have preservatives added that allow the vehicle to remain ready without regular maintenance for up to three years.

This analysis also considered alternative maintenance concepts for the periodic maintenance inspections performed on WRM. The traditional approach uses a permanent maintenance capability collocated with the WRM storage site. We examined two additional concepts: traveling maintenance teams, where a team of maintainers periodically travels from a site with permanent maintenance to storage sites lacking a permanent maintenance capability, and asset swap, where assets requiring maintenance are moved out of storage sites that do not have a permanent on-site maintenance capability and are replaced with serviceable assets sent from an FSL with permanent on-site maintenance. The cost-optimized postures produced by our models made extensive use of these alternative maintenance concepts, as indicated in Figure S.2. Employing these alternative maintenance concepts at new FSLs can further lower the facility and infrastructure investments because of the reduced requirement for maintenance facilities and equipment.

Cross-AOR support can significantly reduce WRM requirements and cost. (See pp. 47–50; 73–75.) WRM assets are currently positioned on an area of responsibility (AOR)-specific basis, with a focus on support of MCOs within each AOR. Although some capability currently exists for cross-AOR support, where assets stored in one AOR are used to support operations in another, moving assets across AOR boundaries requires approval from quite high up the Air Force chain of command, which can cause such long delays that tight delivery time lines may not be met. Our analysis suggests that an optimized global WRM management construct, where assets can be moved between any FSL and FOL without any additional delay for cross-AOR shipments, can achieve large cost reductions when compared with an optimized posture that does not allow for such support. Figure S.4 depicts these cost reductions for WRMV, which occur primarily because a shared global WRM pool reduces total requirements. Further, when considering that combat operations may occur near the boundary of geographic commands (e.g., the Caucasus region near the

Figure S.4
Cost Comparison Between Global and AOR-Specific WRMV Support



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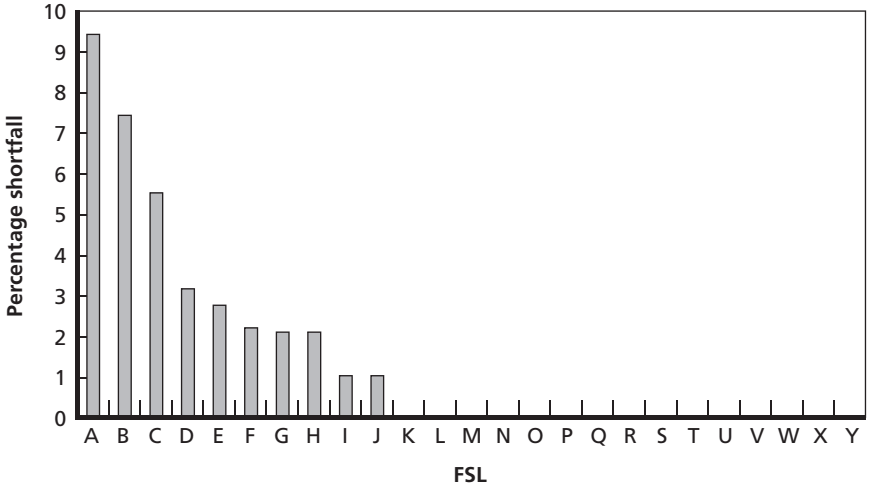
boundary of U.S. Central Command [CENTCOM] and U.S. European Command [EUCOM]), posturing WRM assets from a global perspective may enhance U.S. capabilities and responsiveness along such "fault lines."

Substantial robustness and reliability can be designed into WRM prepositioning postures at relatively little cost. (See pp. 83–95.) When a WRM posture is designed to support one set of future deployment requirements but a different set occurs, it may not be able to satisfy the time-phased demands at all FOLs. We demonstrated this concept with an example that considered three potential futures derived from the SPG. When a BEAR posture was optimized against a single future, it could not support the deployment requirements for either of the other two futures. We developed a "robust optimization" model that identified a single posture that could meet all deployment requirements across these three alternative futures, with total costs that were only 4 to 8 percent greater than the nonrobust minimum cost for each future.

The design of a prepositioning posture should also consider the effects of disruption to the network. Loss of access to a prepositioning site could occur for a number of reasons, such as a refusal on the part of the host nation to permit U.S. access to its WRM, a natural disaster, or a targeted attack on an FSL by an adversary. Unfortunately, cost-optimized network designs often generate a relatively "brittle" posture that performs poorly in the event of network disruption. This occurs because a traditional cost-optimization approach usually depends heavily on a small number of very cost effective nodes. Using such a cost-optimization strategy can lead to demands not being satisfied in the event of disruptions, particularly when an adversary can target a network's most vulnerable points.

We demonstrated this concept with an application to BEAR. As presented in Figure S.5, for the minimum-cost posture identified previously by our model, loss of access for 30 days to the most critical FSL (denoted FSL A) can cause nearly 10 percent of all time-phased

Figure S.5
Shortfall Below Demand Resulting from the Loss of an FSL, Cost-Optimized Posture for BEAR



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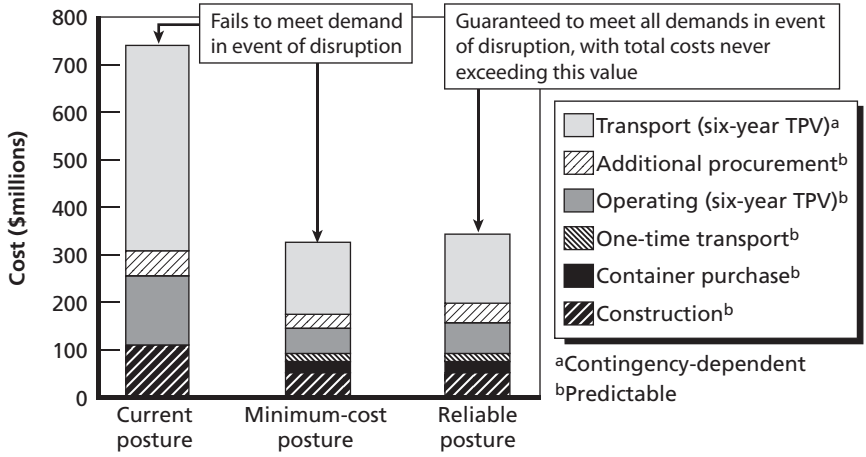
demands at FOLs to be unsatisfied. If access were lost at another particularly critical site instead (denoted FSL B), nearly 8 percent of demands would go unmet.

We developed a "reliable optimization" model that guarantees that all demands would be met in the event of such a disruption to any one FSL. This approach identified a posture whose worst-case costs are only 6 percent greater than the best-case costs for the nonreliable, minimum-cost posture (whose worst-case performance, as demonstrated in Figure S.5, leaves over 9 percent of demands unsatisfied). Both the robustness and reliability analyses identified highly dispersed WRM postures. This dispersal appears to be both cost- and risk-effective, with geographic dispersal increasing the likelihood that assets are stored near unexpected deployment locations and dispersal of assets reducing the risk associated with denial of access to any FSL.

Figure S.6
Effect of Reliability for BEAR Prepositioning



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[8] All office symbols and military ranks are listed as of the time of the research.

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As always, the analysis and conclusions are solely the responsibility of the authors.

Abbreviations

550f	550 follow-on
550i	550 initial
AB	Air Base
ACF	area cost factor
AFB	Air Force Base
AFRICOM	U.S. Africa Command
AOR	area of responsibility
APF	afloat prepositioning fleet
BEAR	Basic Expeditionary Airfield Resources
BSP	Baseline Security Posture
CCDR	combatant commander
CE	civil engineering
CENTAF	U.S. Central Command Air Forces
CENTCOM	U.S. Central Command
CONUS	continental United States
DoD	Department of Defense
DPS	Defense Planning Scenario

EUCOM	U.S. European Command
FL	flightline
FO	follow-on flightline
FOL	forward operating location
FSL	forward support location
FY	fiscal year
FYDP	Future Years Defense Program
GAMS	General Algebraic Modeling System
IO	industrial operations
JFAST	Joint Flow and Analysis System for Transport
JHSV	Joint High-Speed Vessel
LRU	line replaceable unit
MCO	major combat operation
MIP	mixed integer programming
nm	nautical mile
NORTHCOM	U.S. Northern Command
O&M	operations and maintenance
OCONUS	outside the continental United States
OEF	Operation Enduring Freedom
OIF	Operation Iraqi Freedom
OLVIMS	On-Line Vehicle Information System
OSD	Office of the Secretary of Defense
PACAF	U.S. Pacific Air Forces
PACOM	U.S. Pacific Command

PMI	periodic maintenance inspection
POM	Program Objective Memorandum
PPBE	planning, programming, budgeting, and execution
ROBOT	RAND Overseas Basing Optimization Tool
SDDC	Surface Deployment and Distribution Command
SOUTHCOM	U.S. Southern Command
SPG	Strategic Planning Guidance
SSSP	Steady State Security Posture
START	Strategic Tool for the Analysis of Required Transportation
TCTO	Time Change Technical Order
TDY	temporary duty
TPV	total present value
USTRANSCOM	U.S. Transportation Command
USAF	U.S. Air Force
USAFE	U.S. Air Forces in Europe
UTC	unit type code
VAL	Vehicle Authorization List
VEMSO	Vehicle and Equipment Management Support Office
WRM	war reserve materiel
WRMV	war reserve materiel vehicle

CHAPTER ONE

Introduction

Background

Over the last decade and a half, the Air Force has transitioned to an expeditionary force so that it can better meet the requirements that have been placed on it during the post–Desert Storm period, namely, to support continuous engagement in rotational deployments. Recent deployments have supported a full range of operations, from contingency operations in Serbia, Iraq, and Afghanistan, to deterrence operations such as Operations Southern Watch and Northern Watch, to peacekeeping, to humanitarian support.

More than two-thirds of the materiel (by tonnage) required to support such expeditionary operations, which often occur at austere locations, consists of resources that do not belong to the flying units, including munitions, vehicles, civil engineering equipment, and other war reserve materiel (WRM).[1] The rapid deployment time lines required of expeditionary forces preclude the movement of all of these heavy WRM assets from the continental United States (CONUS) to forward operating locations (FOLs) in response to emerging contingencies.[2] Instead, WRM assets are prepositioned at forward support

[1] Mahyar A. Amouzegar, Robert S. Tripp, Ronald G. McGarvey, Edward W. Chan, and Charles Robert Roll, Jr., *Analysis of Combat Support Basing Options,* Santa Monica, Calif.: RAND Corporation, MG-261-AF, 2004.

[2] For a detailed discussion and data analysis of these effects on Operation Enduring Freedom (OEF) and Operation Iraqi Freedom (OIF), see Kristin F. Lynch, John G. Drew, Robert S. Tripp, and Charles Robert Roll, Jr., *Supporting Air and Space Expeditionary Forces: Les-*

location (FSL) storage sites around the globe, ready for use by deploying Air Force units.

Ideally, assets would be stored at their point of intended use, requiring no transport between the WRM storage site and the FOL. If the operating locations for Air Force units can be determined in advance of a specific contingency of particular importance to the United States (e.g., operations in defense of South Korea [Republic of Korea] against an attack by North Korea [Democratic People's Republic of Korea]), prepositioning at the site of intended use is an attractive strategy. In fact, Air Force WRM is currently prepositioned on the basis of geographic areas of responsibility (AORs), with a focus on support of major combat operations (MCOs) within each AOR. This is consistent with Cold War–era support planning assumptions: that deployment scenarios and their associated support requirements could be fairly well identified in advance and the necessary materiel prepositioned at anticipated FOLs.[3]

However, both recent experience and guidance from the Department of Defense (DoD) direct that the Air Force should prepare for a future in which the locations of future deployments cannot be predicted with certainty. DoD Strategic Planning Guidance (SPG) for 2004 contains Defense Planning Scenarios (DPS) to be used for programming operational and support requirements. The DPS include scenarios associated with MCOs, a Baseline Security Posture (BSP), Homeland Security (as part of the Global War on Terrorism), and Small Scale Contingencies. This guidance recognizes that the U.S. military will likely be engaged in several global operations at any given time. The guidance also recognizes that MCOs, if they occur, will likely be initiated from an already-engaged posture. This guidance, provided by the Office of the Secretary of Defense (OSD), instructs the services to size their operational and support forces to execute two MCOs while still

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sons from Operation Iraqi Freedom, Santa Monica, Calif.: RAND Corporation, MG-193-AF, 2005.

[3] A recent Air Force review states, "Requirements are currently based on largely outdated OPlans vs flexible AEF deployable capabilities." See Air Force Inspection Agency, *Eagle Look: War Reserve Materiel Vehicles (WRMV),* Kirtland Air Force Base, N.M.: AFIA, PN 07-506, March 2007; not available to the general public.

securing the homeland, implying that BSP activities may be curtailed, if necessary, to meet MCO and homeland security requirements. The 2006 DoD SPG directs the services to focus on developing the capabilities to defend the homeland, conduct irregular warfare, and conduct and win conventional campaigns. This guidance replaces the BSP with a set of Steady State Security Posture (SSSP) scenarios. An overarching theme across these SPG documents is the need for the ability to deploy U.S. forces rapidly to unanticipated locations across the globe.

Given the large number of potential FOLs and the uncertain and changing relations between the United States and the governments of the countries hosting these FOLs, the Air Force cannot plan to store WRM assets at every site of potential use. The realization that some transport will be necessary between WRM storage sites and the FOLs argues for prepositioning some WRM assets at non-FOL sites that have logistics and transportation advantages (e.g., existing infrastructure).

A related but separate argument is that a shared global pool of WRM, as opposed to AOR-specific assets, can potentially reduce the total requirements for WRM assets (unless the requirement is driven by the need to conduct all required operations simultaneously). Further, considering that potential combat operations may occur near the boundary of multiple geographic commands (e.g., the Caucasus region near the boundary of U.S. Central Command [CENTCOM] and U.S. European Command [EUCOM]), posturing WRM assets from a global perspective may enhance U.S. capabilities and responsiveness along such "fault lines."

Prior RAND Research

In response to these changes, the Air Force Deputy Chief of Staff for Installations and Logistics (AF/IL) sponsored RAND Project AIR FORCE research projects in fiscal year (FY) 2003 (FY03) and FY04 that developed an approach for considering the global prepositioning of WRM assets in an expeditionary environment. The primary contribution of the FY03 research was the development of an optimization model (later termed the *RAND Overseas Basing Optimiza-*

tion Tool, or *ROBOT*) to assist in such analysis.[4] The ability to satisfy deployment effectiveness requirements is the dominant consideration; thus, the ROBOT model identifies a least-cost allocation of resources among existing and potential storage locations and determines a transportation network, including vehicle routings, necessary to satisfy a set of time-phased operational requirements. The FY04 analysis applied these approaches and tools to a review of the global WRM prepositioning posture, concluding that marginal investments in new facility construction greatly increase global force projection capabilities and that the costs of such construction are likely to be offset by future reductions in transportation costs. This research generated a set of recommendations regarding potential WRM investment in specific geographic regions, along with the following more general conclusions:

- Using a global approach to select combat support basing locations is more effective and efficient than allocating resources on a regional basis.
- Political concerns (particularly the potential for denial of access to WRM stored in a foreign country) need to be addressed in any decision about potential overseas basing locations.
- Multimodal transportation options (including air, trucks, rail, and sea) are key to rapid logistics response.[5]

Research Detailed in This Monograph

At that time, the Air Force did not act on these recommendations, primarily because of a reluctance to move from a situation in which regional combatant commanders (CCDRs) "own" their WRM resources to a global Air Force ownership approach. Further, since these analyses suggested that the Air Force use a larger number of dispersed WRM

[4] Amouzegar et al., 2004.

[5] Mahyar A. Amouzegar, Ronald G. McGarvey, Robert S. Tripp, Louis Luangkesorn, Thomas Lang, and Charles Robert Roll, Jr., *Evaluation of Options for Overseas Combat Support Basing*, Santa Monica, Calif.: RAND Corporation, MG-421-AF, 2006.

prepositioning sites, policymakers may have been averse to making a large investment in permanent infrastructure at foreign sites. Then, in FY06, the Air Force Deputy Chief of Staff for Logistics, Installations, and Mission Support (AF/A4/7) requested that RAND revisit the topic of global WRM prepositioning. Because lessons learned from OEF and OIF indicated that 95 percent of all WRM moved for OEF/OIF was transported by surface modes and yet most WRM assets are stored in a palletized configuration designed for airlift, the Air Force was interested in potentially storing some WRM in a posture designed for rapid deployment by surface transport in response to contingency requirements.

A concept titled "Virtual Afloat" (which was consistent with recommendations made in Amouzegar et al., 2006) had been proposed by U.S. Central Command Air Forces (CENTAF), suggesting that some WRM assets be prepositioned at or near shipping ports, where combat support materiel would be stored in shipping containers and then moved to vessels to be transported by sea to support deployment requirements. A further benefit to the Virtual Afloat concept is that these shipping containers do not require inside storage, mitigating the concerns associated with infrastructure investments at foreign sites. RAND performed a detailed analysis of the Virtual Afloat concept and examined the effects of alternative WRM packaging options on storage (e.g., ease of access for periodic maintenance) and multimodal transportation. This FY06 research focused on a subset of WRM commodities—the Basic Expeditionary Airfield Resources (BEAR)—that provide an airfield operational capability to open an austere or semi-austere airbase. BEAR includes such items as tents, air conditioners, power generation units, aircraft hangars, and maintenance facilities. Within this analysis, the cost and capability effects of a pool of centrally managed BEAR assets were also contrasted with the performance of a regional AOR-specific management construct.

This analysis was extended into FY07 at the request of AF/A4/7, with the FY07 research addressing the following three tasks:

- extend prepositioning models and research to include WRM vehicles (WRMVs) and support equipment

- analyze the costs and benefits associated with building "reliability in the event of disruption" considerations into the WRM prepositioning posture
- examine options for global WRM management.

The third task area, examining options for global WRM management, is detailed in unpublished RAND research.[6] The present monograph describes all other analyses performed in support of these FY06 and FY07 research projects.[7]

How the Monograph Is Organized

This monograph has six chapters. Chapter Two describes the philosophy and methodology used to carry out the analysis. Chapter Three evaluates global prepositioning strategies for BEAR assets, with a detailed examination of alternative packaging configurations (such as Virtual Afloat) and maintenance concepts that can allow dispersed prepositioning postures without incurring significant investments in infrastructure construction. Chapter Four presents a similar analysis for WRM vehicles, detailing how the differences between vehicles and BEAR assets require a different packaging configuration (vehicle wrapping, as opposed to containerization) to achieve mitigation of prepositioning construction requirements. Chapter Five extends the prepositioning analyses to include robustness and reliability considerations, using BEAR as a case study. The final chapter presents conclusions and suggests potential areas for further analysis.

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[6] Performed by Frank Camm and Sally Sleeper in 2007.

[7] During FY06, we also performed a regional analysis supporting CENTAF in its efforts to redefine its BEAR prepositioning posture. That analysis is not presented in this monograph, but it was used to help shape the global BEAR analyses presented here.

CHAPTER TWO

Methodology

This chapter describes the methodology that RAND has developed to analyze alternative Air Force prepositioning strategies. It begins by describing the implications of the current security environment for DoD planning and programming, summarizing concepts that were presented in our prior research.[1] It then discusses how the prepositioning of Air Force WRM assets can be evaluated in such an environment. It then presents optimization models that identify minimum-cost prepositioning postures that can either meet time-phased deployment requirements across multiple potential futures or satisfy such deployment requirements even in the event of loss of access to any FSL.

The New Relationship Between Combat Support Planning and U.S. Deterrence

Amouzegar et al., 2006, present one view of the relationship between U.S. deterrence strategy and combat support capabilities, in the context of early–21st century national security.[2] Throughout the Cold War, U.S. deterrence strategy rested on the concept of assured destruction, i.e., the understanding on the part of potential adversaries (generally

[1] Amouzegar et al., 2006.

[2] Air Force Basic Doctrine defines combat support as "the essential capabilities, functions, activities, and tasks necessary to create and sustain air and space forces." See U.S. Air Force (USAF), *Air Force Basic Doctrine,* Air Force Doctrine Document 1 (AFDD-1), November 17, 2003a.

assumed to be state actors) that the United States had overwhelming nuclear capabilities and could assure the destruction of any adversary willing to launch a nuclear first strike against it. The nuclear deterrent was accompanied by the creation of a large standing conventional force that could respond decisively to conventional aggression on the part of the Soviet Union and its allies. The early post–Cold War period (pre-2001) saw the potential adversaries changed, but the basic principles underlying deterrence strategy remained constant: overwhelming nuclear strike capabilities and an unrivaled standing conventional force ready to respond to aggression in geographic areas of interest to the United States.

In the current national security environment, the threat facing U.S. interests differs, and, accordingly, U.S. focus has shifted from preparing for a small number of major conflicts (that would occur only once and would change the environment so greatly as to invalidate plans for out-years following the conflict), to supporting continuous engagement in a set of potentially recurring deployments while maintaining the ability to succeed in multiple and possibly overlapping major combat operations. As in the past, nuclear deterrence remains a fundamental aspect of the strategy against possible state actors. Less clear is whether the pre-2001 deterrence strategy associated with conventional forces remains effective.

The authors base their recommendation for a rethinking of conventional deterrence strategies on recognition of two issues: first, that U.S. interests might warrant a response nearly anywhere on the globe and, second, an understanding of the pressures, both at home and abroad, to avoid the establishment of a large, permanent U.S. military presence on foreign soil. In the context of such a security environment, deterrence strategy should focus on rapid force projection capabilities that can be demonstrated through exercises and other partnership-building activities and used, when deterrence fails, to take quick action to defeat state and nonstate actors should they threaten U.S. or allied interests in any region of the globe. Note that such deterrence is based on the repeated and continuous projection of forces to demonstrate the range of U.S. reach.

The deployment activities associated with such a strategy would place heavy demands on Air Force combat support capabilities, in particular, on the WRM assets required to enable airfield operations. Given that the relative importance of alternative deployments is likely to change frequently over time, it might be desirable to assign a global WRM manager, with authority over the positioning (and repositioning) of WRM resources and the ability to quickly shift the location of assets as priorities change. Although the regional Unified Combatant Commands would maintain their requirements for operational support during contingency operations, a global WRM manager could balance demands, such as guaranteeing a level of support to individual CCDRs while providing sufficient attention to the requirements of deterrence deployments.

The Effect on Military Planning and Programming

Amouzegar et al. (2006) discuss how such a deterrence framework requires changes to the emphasis in the Program Objective Memorandum (POM) process. The POM is the primary tool of the programming phase in DoD's planning, programming, budgeting, and execution (PPBE) process.[3] PPBE is the system currently used to create the DoD contribution to the President's budget request to Congress, with the process divided into the following four phases:

- planning: assesses capabilities, reviews threats, and develops guidance
- programming: translates planning guidance into achievable packages in a six-year Future Years Defense Program (FYDP)
- budgeting: tests for feasibility of programs and creates budgets

[3] In practice, the programming and budgeting phases are combined and POM submissions are developed in conjunction with budget estimate submissions, the primary tool of the budgeting phase.

- execution: develops performance metrics, assesses output against planned performance, and adjusts resources to achieve the desired goals.[4]

The resources included in the POM primarily focus on manpower, facilities, weapon systems, and operations and maintenance (O&M) funds. The current POM includes the resources necessary to fight and win contingencies, should the need arise, although the funds associated with actually conducting wartime operations are not included in a POM but are instead approved in a supplemental budget authorization from Congress. The new deterrence framework posited here supports an expansion of POM resources dedicated to supporting the ongoing deployment of forces to include exercises and other activities intended to provide deterrence. The costs of engaging in an MCO, should deterrence fail, would still require separate funding through the supplemental process.

Developing a Cost-Effective WRM Posture

The Air Force faces the challenge of developing a WRM posture that is flexible with respect to this broad range of potential future deployments, able to address risks, and cost-effective. WRM prepositioning decisions should address the risks associated with delays in receipt of the WRM at the FOLs, if transportation is required to move WRM assets from a storage site to the FOL. WRM posturing decisions should also consider the risks associated with potential denial of access to prepositioned assets, whether as a result of natural disaster, attack on a storage site by an adversary, or denial of access by the host nation (e.g., the difficulties of securing basing access in Turkey during OIF).

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[4] For more information on the PPBE process, see Don Snyder, Patrick Mills, Manuel Carrillo, and Adam C. Resnick, *Supporting Air and Space Expeditionary Forces: Capabilities and Sustainability of Air and Space Expeditionary Forces,* Santa Monica, Calif.: RAND Corporation, MG-303-AF, 2006, or DoD, *Planning, Programming, and Budgeting System (PPBS),* DoD Directive 7045.14, May 1984.

These WRM positioning decisions also need to trade off different types of costs. Prepositioning decisions have traditionally been made with a focus on the predictable costs that are included in the Air Force POM, addressing such costs as facility construction for WRM storage, operation and maintenance of the WRM assets, and one-time transport of the assets if they are to be moved to a different storage location. The new deterrence strategy outlined above suggests that the Air Force should give additional consideration to a set of contingency-dependent costs—those associated with the transport of WRM assets in support of deployments. We distinguish between steady-state operations and exercises, which our interpretation of SPG suggests should be primarily funded within the Air Force POM request, as opposed to MCOs, which would continue to be funded by supplemental appropriations from Congress.

Two key research questions thus need to be addressed here. First, to what extent can a WRM posture trade off the cost of building and operating storage sites (i.e., the predictable costs) with potential reductions in transport costs in support of deployments other than MCOs (i.e., the contingency-dependent costs)? Second, what are the characteristics of the trade-offs between WRM system cost and risk or, stated differently, WRM system efficiency and redundancy (i.e., what are the additional costs necessary to build prepositioning postures with varying levels of risk tolerance)?

The structure of a desirable posture will depend on the interaction between predictable and contingency-dependent costs. If predictable costs dominate, we would expect the posture to favor a small number of large sites, allowing the Air Force to potentially achieve economy-of-scale efficiencies and to take greatest advantage of its existing facilities. In this case, rapid delivery of WRM to remote FOLs might require heavy use of airlift resources, which could be problematic given that airlift is chronically in short supply in the early stages of deployment. Further, postures with a few large sites are particularly susceptible to the denial-of-access risks mentioned above.

On the other hand, if the contingency-dependent costs dominate, we would expect to see the posture favor geographic dispersal, with a large number of small storage sites. Geographic dispersal allows

greater proximity to more operating locations, reducing transport costs and potentially allowing greater use of truck transport and sealift, which are much less expensive and more readily available than airlift of WRM assets. A geographically dispersed posture offers other benefits, such as reducing bottlenecks when outloading assets from storage sites as well as mitigating the risks associated with loss of access to any individual storage site. However, a more dispersed posture could place greater demands on the command and control system linking units that demand WRM with the large number of storage sites.

Optimization Model

Over the course of RAND's multiyear analysis of Air Force prepositioning policies, we have developed an optimization model that ties location and allocation decisions to operational scenarios. The model outputs presented in this monograph can be viewed as a constant-effectiveness, variable-cost, and variable-risk analysis: All prepositioning postures that are presented will satisfy the deployment effectiveness constraints, allowing the cost and risk of each alternative posture to then be evaluated. The operational scenarios are defined by a set of deployments to be supported, which drive time-phased requirements for the delivery of WRM assets at FOLs. The model's objective function minimizes the discounted total present value (TPV) of the costs of meeting the time-phased deployment requirements for MCOs and lesser contingencies and exercises by selecting a set of WRM storage and maintenance FSLs, allocating resources across them, and determining the necessary transportation routes between FSLs and FOLs. The model's cost function focuses on programmable costs, simultaneously minimizing the construction and operating costs required to build an infrastructure and capability sufficient to meet MCO requirements (the *predictable costs* mentioned above) along with the transportation costs for conducting deterrent and engagement exercises and lesser contingencies (the *contingency-dependent* costs mentioned above). The transportation costs associated with MCOs are not included in the cost function, under the assumption

that such operations would be funded through supplemental appropriations. The model includes constraints on storage and throughput at facilities, transport vehicle availability and capacity, and time-phased demands. This approach allows alternative FSL postures to be identified and evaluated with respect to various measures of interest, such as cost, deployment time, and transportation requirements, across a broad range of scenarios. The model can compare the capability and cost consequences of alternative policies, such as global management or regional management of WRM, or the mandatory exclusion or inclusion of specific locations in the WRM posture.

It is important to note that this model is not specifically tied to any set of input scenarios, and changes to the inputs can easily be made to evaluate a prepositioning posture against different sets of deployment requirements. Of course, the quality of the input scenario data limits any analysis that attempts to link logistics resources to operational scenarios. Any solutions derived by such an analysis will be sensitive to the set of scenarios provided. Thus, a vastly different set of input scenarios will likely return a different solution set of FSLs.

Since the true "optimal" solution can be determined only if the future is known perfectly, multiple potential futures can be considered individually, with the "optimal" FSL postures identified for each. However, each of these single-future optimized postures may perform poorly if tasked with supporting an alternative future. A broad analysis is necessary to identify sets of FSLs that perform well across every envisioned future, to identify FSL postures that provide robust solutions. Thus, in this analysis, we have extended our previous modeling approach to construct a model that can simultaneously address multiple sets of future deployment requirements.

We also extended our model to capture another aspect of uncertainty, namely, the potential for unplanned network disruptions. We are not referring to a long-term disruption to the FSL posture, such as a country wanting to terminate the prepositioning arrangement with the United States. Instead, we are referring to short-term disruptions that could limit or prevent U.S. access to prepositioned materiel for a relatively brief period and which would not allow the United

States enough time to reposition WRM assets in response to emerging contingencies.

To distinguish between these two types of uncertainty, we use the terminology of Daskin, Snyder, and Berger (2005).[5] Uncertainty with respect to the set of scenarios to be supported can be viewed as "demand-side" uncertainty; we will refer to this concept as robustness. Uncertainty with respect to the availability of network locations can be viewed as "supply-side" uncertainty; we will refer to this concept as reliability.

We modified the ROBOT model to perform such robustness and reliability analyses.[6] The following section presents a simplified overview of the modified model.[7] This model is a mixed integer programming (MIP) model, developed using the General Algebraic Modeling System (GAMS).[8]

In addition to capturing robustness and reliability considerations, the ROBOT model was also extended to account for multiple packaging configurations for commodities, e.g., palletized for airlift at an airfield or containerized for surface movement at a seaport. The optimization model was further modified to address alternative concepts for maintenance of WRM assets. We assume that if WRM assets are stored at FSL b, the responsibility for their periodic maintenance inspections (PMIs) will be assigned to some FSL b' where b' may be identical to the storage location b (i.e., the WRM maintenance resources are collocated with the WRM), or b' may be a different location from the storage location b (e.g., WRM assets at b may receive their maintenance from a traveling maintenance team based offsite at b'). Both the

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[5] Mark S. Daskin, Lawrence V. Snyder, and Rosemary T. Berger, "Facility Location in Supply Chain Design," in Andre Langevin and Diane Riopel, eds., *Logistics Systems: Design and Optimization,* New York: Springer, 2005, pp. 39–66.

[6] For a complete mathematical programming formulation of the ROBOT model (including a detailed discussion), see Amouzegar et al., 2004, 2006.

[7] The complete mathematical model is described in the appendix.

[8] See Anthony Brooke, David Kendrick, Alexander Meeraus, and Ramesh Raman, *General Algebraic Modeling System: A User's Guide,* Washington, D.C.: GAMS Development Corporation, 2003.

packaging configurations and maintenance concepts will be discussed in further detail in Chapters Three and Four, in the context of BEAR and WRMV, respectively.

The decision variables in this modified model represent the following WRM posturing decisions:

- binary decision to use a potential FSL, along with the maintenance concept to be used for all WRM stored at that FSL
- number of units of each WRM commodity stored at each FSL used, and each unit's packaging configuration
- amount of new facility space to be constructed at each FSL used
- total additional units of each WRM commodity to be procured, beyond the current total authorizations
- units of each WRM commodity to be transported to each FOL from each FSL used, and the packaging configuration, transportation mode, and delivery time for each shipment
- number of vehicles used to transport WRM between each FSL-FOL pair, by transportation mode, for each time period.

The model imposes constraints on the use of FSL storage sites, the allocation of WRM assets to FSLs used, tracking of inventory at the FSLs, transportation requirements, "throughput" capability for transportation vehicles at each FSL and FOL, and time-phased demands for WRM commodities at the FOLs.[9]

To allow the robust model to account for multiple potential futures simultaneously, we define a set of alternative futures, where each future consists of a set of time-phased deployment demands for WRM at FOLs. It is then necessary to create multiple versions of all decision variables and constraints that have a temporal dimension, to track the state of the system under each alternative future. The goal is to identify a single WRM posture, defined as a set of FSLs and an allocation of WRM assets to those FSLs, that is able to satisfy the demands across all futures.

[9] Note that this model does not assign any individual FOL's demand exclusively to one FSL; instead, multiple FSLs may send commodities to an FOL, if the model finds that it would be cost-effective to do so.

Because this model addresses performance across multiple futures, the meaning of an objective function that "minimizes cost" is somewhat ambiguous, depending on a decisionmaker's level of risk tolerance and the relative weighting associated with each potential future. Define the following cost functions:

- *CommonCost*: equal to the system cost components that are common across all sets of future deployment scenarios, including an FSL opening cost, a facility expansion cost, an operations and maintenance cost assessed against the commodities stored at a given site, and a procurement cost for additional WRM assets
- $FutureCost_d$: equal to the system costs that are unique to potential future $d \in \mathbf{D}$, including the non-MCO deployment transportation cost and the procurement cost for additional WRM delivery vehicles.

Two alternative objective functions are then defined below:

$$\min CommonCost + \max_d \left\{ FutureCost_d \right\} \tag{2.1}$$

$$\min commonCost + \frac{\sum_d FutureCost_d}{\|\mathbf{D}\|} \tag{2.2}$$

Objective 2.1 uses a minimax approach, minimizing the maximum cost across all futures, a highly risk-averse position. Objective 2.2 minimizes the average cost across all considered futures. Other alternatives include incorporating some sort of weighting system onto objective 2.2, where alternative futures are weighted according to, e.g., their relative likelihood of occurrence or relative importance.

With a few minor changes to our mathematical model, we can develop a reliable optimization approach to identify a prepositioning posture that is able to satisfy WRM delivery requirements even in the event of loss of access to any prepositioning facility. We will assume

that, if access is lost to FSL b, following the end of the disruption period, the assets at FSL b will again become available for use. For this reliability model, we will assume that only one set of future deployment scenarios will be addressed for each model run.[10]

This model should not be structured in such a way that it identifies one set of actions in advance of a loss of access to FSL b_1 and another set of actions in advance of a loss of access to FSL b_2. The aim of this analysis is to identify an FSL posture that retains flexibility for the decisionmaker in the event of an unexpected loss of access to any FSL. If the model were focused on the loss of access to a specific FSL, and was allowed to have knowledge about the time and specific location at which the loss of access occurs, it could "look ahead" and take such actions as minimizing the inventory at the affected FSL in advance of the loss of access to mitigate these effects.

Instead, our model generates a single set of decisions for time periods up to *FailTime*, the point at which loss of access to an FSL occurs, allowing the posture to retain the necessary flexibility at *FailTime* to satisfy all future demands regardless of the FSL to which access is lost. Note that our approach allows the model foresight with respect to the time of failure but not to any specific location. Then, following *FailTime*, a separate set of decisions needs to be tracked in the event of each possible FSL failure. Thus, the model needs to develop multiple versions of all variables and constraints that have a temporal dimension to account for the potential failure events at each FSL. We then add a set of simple constraints enforcing that no assets can be drawn from each potential failed FSL during the failure interval.

Because this model addresses performance across potential disruption to every FSL, the meaning of an objective function that "minimizes cost" is again somewhat ambiguous. One alternative is to define an objective function similar to 2.1, using a minimax approach that minimizes the maximum cost across all potential FSL disruptions, a

[10] It is possible to extend these concepts to build a model that could simultaneously address both reliability against disruption and robustness to uncertain future demands, but such a model would require many more variables and constraints than the models presented here, which are already so large as to approach the computational limits of current desktop computers.

highly risk-averse position. Another option is to minimize a weighted average cost across all potential FSL disruptions, similar to function 2.2, where alternative futures are weighted according to, e.g., a relative likelihood of loss of access to a particular FSL.

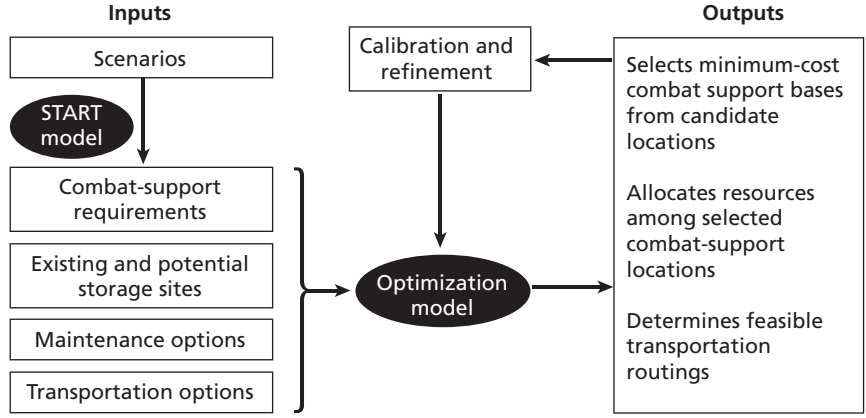
The model is solved by finding a set of decision variables that minimizes the desired objective, which is a function of the costs of building a WRM prepositioning posture and conducting a set of exercises and lesser contingencies, while constraining the solution set to have an infrastructure capable of supporting MCO requirements if deterrence should fail, with this single WRM posture able to satisfy all deployment demands either across all considered futures or in the event of loss of access to any individual FSL. As discussed above, because the costs associated with conducting MCOs cannot be programmed for, we include the demand constraints associated with MCOs but do not include their transportation costs in any optimization objective function.

Using the Model in a Larger Analytic Process

The optimization model described above is only one piece of a larger analytic framework that we use to evaluate alternative WRM prepositioning postures. Figure 2.1 presents a schematic of this data-driven analytic approach.[11] Significant analysis must be performed to generate the set of model inputs, presented on the left side of the figure. Then, once the optimization model generates the set of outputs presented on the right side of the figure, a significant amount of analysis remains to be performed to refine and calibrate these model results and to address the effects of additional considerations that fall outside the scope of such quantitative models (e.g., evaluating the potential WRM postures from a political point of view). Such additional considerations (e.g., the exclusion of some FSLs suggested by the model because of political

[11] More details on the set of model inputs will be presented in Chapters Three and Four.

Figure 2.1
Analytic Process



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constraints) may inform the inputs to another iteration of model runs. Such analysis can help to demonstrate the capability and cost consequences associated with such additional considerations. This post-optimality analysis can then iterate until an acceptable set of alternatives is determined. The ultimate goal is to present policymakers with alternative FSL postures, along with a global perspective of the postures' relative effectiveness and efficiencies.

Chapters Three and Four now take the optimization model and apply it within this analytic process to determine minimum-cost prepositioning postures for BEAR and WRMV, respectively, optimizing against a single set of future scenarios and assuming that access is always guaranteed to all FSLs. Chapter Five then contrasts the performance of these minimum-cost postures with alternative postures that are designed to consider robustness and reliability.

CHAPTER THREE

Evaluation of Prepositioning Strategies for BEAR Assets

As presented in Figure 2.1, the analytic process has four primary categories of inputs: combat support requirements (derived from the sets of deployment scenarios to be supported), a set of existing and potential FSLs and FOLs, a set of maintenance options to be evaluated, and a set of transportation options that include commodity packaging alternatives. In the next section, we discuss each of these in more detail, as applied to our global analysis of Basic Expeditionary Airfield Resources prepositioning.

Inputs to the Analysis

BEAR provides an airfield operational capability to open an austere or semi-austere airbase. BEAR includes such items as tents, air conditioners, power generation units, aircraft hangars, and maintenance facilities. BEAR commodities are aggregated into the following six basic "sets":

- Swift BEAR: an initial set of assets, sized to fit on a single C-17, that deploy into an FOL for initial site preparation
- 550 initial (550i) housekeeping: assets that provide housing, sanitation, and food-preparation facilities for the initial 550 personnel deployed to an FOL

- 550 follow-on (550f) housekeeping: assets that, when added to a 550i set, provide basic housing facilities for additional increments of 550 personnel deployed to an FOL
- industrial operations (IO): assets that provide work space for deployed operational personnel (e.g., maintenance facilities) at an FOL
- flightline (FL): assets that provide flightline support to an initial squadron of deployed aircraft at an FOL
- follow-on flightline (FO): assets that, when added to an FL set, provide flightline support for an additional squadron of deployed aircraft at an FOL.

The analysis in this monograph focuses on the 550i, 550f, IO, FL, and FO sets. It does not address the positioning of Swift BEAR sets because (a) these sets are designed to be transported on a single C-17 and thus can easily and rapidly be transported to any location around the globe (meaning that their prepositioning is not affected by the considerations included in this analysis, such as multimodal transport and alternative packaging) and (b) the sets are much smaller and less expensive than the other BEAR sets.

We emphasize again that this analysis begins with a focus on support to military operations. Combat support requirements link our models to sets of deployment scenarios. For a given scenario, we define combat support requirements as the WRM assets that are required at each FOL in the scenario, along with the required time line for their delivery. For example, a particular scenario might require that one 550i set be delivered to FOL *c* within 10 days of the start of an engagement. We draw these requirements from the RAND-developed Strategic Tool for the Analysis of Required Transportation (START) model, which converts the operational capability required at a deployed location into a list of resources (including WRM) necessary to generate that capability.[1] The START model can tailor the requirement based

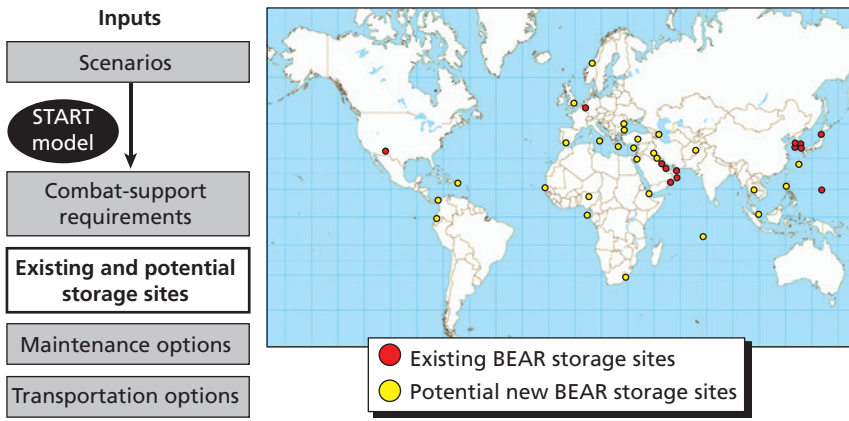
[1] Donald Snyder and Patrick Mills, *Supporting Air and Space Expeditionary Forces: A Methodology for Determining Air Force Deployment Requirements,* Santa Monica, Calif.: RAND Corporation, MG-176-AF, 2004.

on the existing infrastructure assumed to be available at the FOL. Our analysis identified BEAR requirements based on the DoD SPG scenarios. These scenarios were used to identify a set of multiple potential futures, where each future contains a large set of deployment scenarios, including MCOs, training missions, and lesser contingencies, with each future covering a six-year interval.

Prepositioning Sites

Once the sets of operational requirements and associated combat support resource requirements are determined, a set of existing and potential storage sites is needed. Figure 3.1 depicts the set of all sites considered; note that this is not a solution obtained by the model but rather a set of potential FSLs included in the analysis.[2] The set of existing BEAR storage sites, of which there are 13, is denoted by red circles on the map. The existing FSLs are fairly concentrated geographically, with five in Southwest Asia and four on the Korean peninsula. For each of these sites, we identified the current number of BEAR assets authorized

Figure 3.1
Set of Potential BEAR Storage Sites Included in the Analysis



[2] Note that we will use the term *FSL* to refer to both OCONUS (outside the continental United States) and CONUS (i.e., Holloman Air Force Base [AFB]) sites.

for storage at the site, the existing warehouse and maintenance space available to BEAR assets, the amount of space available for potential expansion, and each location's throughput ability to process air, land, and sea vehicles.

We also consider a set of 27 potential new storage sites, denoted by the yellow circles on the map. Many of these sites offer storage near seaports as well as airports and ground transportation links. One could argue that some of these FSLs (e.g., Afghanistan) are unlikely locations for a U.S. prepositioning site because of political considerations. This analysis deliberately included a broad set of potential sites to identify what set of facilities is best suited to support the deployment requirements envisioned in the SPG and also to provide information on the cost and capability implications of potentially excluding a site that is desirable from a logistics standpoint based on other considerations (such an analysis will be presented below). Data were collected on the available space at these sites (in case there was vacant U.S. military warehouse space available), the maximum space available for potential new construction at each site, and each location's throughput capacity.

Each FSL included in this analysis was at an airfield, with one exception, the existing storage site at Sanem, Luxembourg (from which one could move materiel by truck to Ramstein Air Base [AB]). Because one of the primary research tasks to be addressed here was to evaluate the Virtual Afloat concept, in which some fraction of the assets is stored at a seaport, for each FSL we identified the nearest seaport and included an option for assets to be stored there, as well as at the FSL's primary airfield location. An exception was made for FSL sites that were more than 250 nautical miles (nm) from their nearest seaport, in which case seaport storage was not allowed.[3] This list of existing and potential FSLs is presented in Table 3.1.

[3] Unless noted otherwise, all distance data used in this monograph come from U.S. Transportation Command (USTRANSCOM), "Joint Flow and Analysis System for Transport 8.0," September 6, 2002.

Table 3.1
Set of Potential BEAR Storage Sites Included in the Analysis

Existing FSLs	Potential New FSLs
Shaikh Isa, Bahrain	Bagram, Afghanistan
Andersen AFB, Guam	Baku, Azerbaijan
Misawa, Japan	Burgas, Bulgaria
Sanem, Luxembourg	Akrotiri, Cyprus
Holloman AFB, New Mexico	Djibouti-ambouli, Djibouti
Masirah, Oman	Cotopaxi, Ecuador
Seeb, Oman	Souda Bay, Greece
Thumrait, Oman	Balad, Iraq
Al Udeid, Qatar	Sigonella, Italy
Kimhae, South Korea	Kadena, Japan
Kwang Ju, South Korea	Aqaba, Jordan
Suwon, South Korea	Al Jaber, Kuwait
Taegu, South Korea	Kaduna, Nigeria
	Orland, Norway
	Tocumen, Panama
	Clark AB, the Philippines
	Luis Muñoz MarÍn, Puerto Rico
	Constanta, Romania
	São Tomé-salazar, São Tomé
	Dakar-yoff, Senegal
	Paya Lebar, Singapore
	Louis Botha, South Africa
	Rota, Spain
	U-Tapao, Thailand
	Incirlik AB, Turkey
	Diego Garcia, UK
	Fairford, UK

Maintenance Options

The third set of analysis inputs provides details on the maintenance options to be considered. Within this BEAR analysis, we assume that the assets at any FSL will be supported by one of three policy options:

- *Permanent on-site maintenance*, which is how BEAR assets are prepositioned today. An FSL has the necessary infrastructure and assigned personnel to maintain the assets stored at that site.
- *Traveling maintenance team*, in which a team of maintainers travels from a storage site that has permanent on-site maintenance to an FSL that lacks this permanent maintenance capability and performs whatever maintenance is necessary on the assets. FSLs that are maintained using this concept require some maintenance facilities on-site for use by the traveling teams.
- *Asset swap*, in which assets requiring maintenance are moved out of storage sites that do not have a permanent on-site maintenance capability and are replaced with serviceable assets sent from an FSL with permanent on-site maintenance. Some pipeline of in-transit assets is necessary to ensure that the supported FSL maintains its authorized level of BEAR assets, so we require that an additional pool of assets be assigned to support commodities that are unavailable in the transport pipeline.

The final set of inputs addresses transportation considerations. This is a multimodal analysis, including transport options for movement via air, sea, and land. We assumed that air movements would use a C-17, land movements would use a standard tractor-trailer truck, and sea movements would employ a Joint High-Speed Vessel (JHSV)-style catamaran.[4] The relative capabilities of these vehicles were assumed to conform to standard Air Force planning factors for the C-17,[5] prior

[4] For more details on the JHSV concept, see Amouzegar et al., 2004, 2006; and John F. Schank, Irv Blickstein, Mark V. Arena, Robert W. Button, Jessie Riposo, James Dryden, John Birkler, Raj Raman, Aimee Bower, Jerry M. Sollinger, and Gordon T. Lee, *Joint High-Speed Vessel: Analysis of Alternatives,* Santa Monica, Calif.: RAND Corporation, MG-501-A, 2006, not available to the general public.

[5] USAF, 2003b.

RAND JHSV analysis, and commercial standards for trucks.[6] Transport times between FSLs and FOLs were computed as follows. Truck movements were assumed to travel directly between the FSL and FOL at 194 nm/day in more developed countries (United States, Western Europe, Japan, and South Korea) and at 70 nm/day in less-developed countries. The maximum one-way range for a truck shipment was assumed to be 1,000 nm, with a delay of 24 hours added for each border crossing necessary. We assumed that airlift had a standard speed of 400 nm/hour and that the airlifters traveled directly to the FOL, since each FOL was at an airfield. If transport was necessary from the storage location to the FSL's airfield (either because assets were stored at the seaport, or for the case of Sanem, Luxembourg, because the assets were assumed to be trucked to Ramstein AB, Germany, for air transport), a delay for truck shipping was added, assuming the truck land speeds mentioned above. A standard speed of 35 nm/hour was assumed for sealift, assuming a maximum one-way range of 2,500 nm per sea shipment, with an additional 24-hour delay added for each Suez Canal and Panama Canal transit. If transport was necessary between the storage location and the FSL's port (because assets were stored at the FSL's primary location) or between the FOL's port and the FOL (for FOLs not at seaports), a delay for truck shipping was added, assuming the truck land speeds described above.

Transportation costs were computed as follows. Airlift costs were based on FY06 DoD Channel Tariff Rates. Sealift and truck costs were based on the Amouzegar et al. analyses (2004, 2006) and assumed to be $0.33 per ton-mile for sealift and $2.50 per ton-mile for trucking. All trucking costs (including additional trucking necessary for airlift or sealift) were adjusted for local cost variations using area cost factors (ACFs),[7] to account for the fact that procuring goods and services is less expensive in some countries than in others. For all shipments, it was

[6] We assumed that each vehicle's cargo-carrying capacity was defined as the more stressing of, for C-17, 45 tons or 18 pallet positions and, for JHSV, 500 tons or 23,000 square feet. Data regarding the number of trucks necessary to move each BEAR set were provided by CENTAF; the numbers range from 5 to 25 trucks (for FO and FL sets, respectively).

[7] U.S. Army Corps of Engineers, "DoD Area Cost Factors (ACF)," *PAX Newsletter,* No. 3.2.1, Table B, February 13, 2006a.

assumed that the retrograde movement of assets, from the FOL back to the FSL following the end of the contingency at the FOL, would be accomplished using the least-expensive mode of transport possible (generally sealift).

Asset Packaging

Two alternatives for asset packaging were examined in this analysis, which affected both the transportation and storage of BEAR commodities. All BEAR assets have traditionally been stored in a *palletized* configuration designed for airlift, but that is less well suited for movement by sea or truck. An alternative packaging configuration was analyzed, in which BEAR assets are *containerized*, or stored in sea shipping containers. A containerized configuration is the greatly preferred option if assets are going to move by sea. In fact, when palletized assets are to be moved by sea, those assets are frequently packaged into sea shipping containers at the seaport, incurring additional cost and delay in movement, before being moved by sea, as opposed to break-bulk shipping of palletized assets. However, containerized assets are not well suited for airlift and are typically removed from their shipping containers before airlift, because the steel shipping containers are so heavy that they consume a large amount of the aircraft's carrying capacity.

In this analysis, it is assumed that all assets to be moved by air will be palletized before loading onto the aircraft. Thus, for containerized assets that are to be airlifted, there is an additional packing and unpacking cost ($400 per container, adjusted by ACF) associated with palletizing the assets, and an additional delay (18 hours) associated with this unpacking beyond the aircraft loading time delay of six hours. Similarly, it is assumed that all assets moved by sea will be containerized before loading onto the sea vessel. Thus, palletized assets will incur a packing and unpacking cost, to include rental of a container at the port ($1,600–$1,900 per container, adjusted by ACF, depending on the type of container), and an additional delay (18 hours) associated with the packing beyond the vessel loading time delay of six hours per

truckload loaded onto the ship.[8] The weight of the containers, which can be substantial, was added to the sea shipping costs. It is assumed that trucks can move assets in either palletized or containerized configuration, although it requires fewer trucks to move each BEAR set when assets are containerized because of more efficient packaging (for containerized assets, the requirement ranges from three to 20 trucks, for FO and 550i sets, respectively). Truck loading times are assumed to be three hours for containerized assets and 12 hours for palletized assets.

This analysis assumes that assets stored at an FSL's primary airfield location may be either palletized or containerized. Assets stored at an FSL's seaport must be containerized. A key difference between the storage of containerized and palletized assets is that, whereas palletized assets require inside warehouse storage for the majority of BEAR commodities, for containerized assets, the container functions as the warehouse, with no additional facilities required.[9] Thus, storage of BEAR assets in a containerized configuration can significantly reduce the facility space requirement associated with BEAR prepositioning. This characteristic might make containerization of assets particularly attractive, to the extent that the U.S. government is averse to building large permanent infrastructure at overseas locations. Containerization offers other, less quantitative benefits as well. If assets are stored in commercial shipping containers, the assets would not appear noticeably different from the large number of nonmilitary containers moving through civilian supply chains. Furthermore, because no permanent facility construction is necessary, containerized assets can be used in a "dynamic positioning" concept, where containers are quickly and easily moved from one location to another in response to emerging changes in the security environment yet are not noticeable to most observers as military cargo.

[8] Note the implicit assumption that in such a situation, containers can be readily rented from the commercial market as needed.

[9] As of September 2007, the 49th Materiel Maintenance Group at Holloman AFB was conducting tests to determine if use of desiccants and coatings could lessen the effects of high heat and humidity buildup inside shipping containers used for BEAR storage.

Containerization also affects O&M costs. Loose assets stored in a warehouse require a regular counting and inspection of inventory, but containerized assets have a seal placed on the container to indicate whether the container doors have been opened or tampered with, allowing containerized assets to be inventoried simply by counting the number of containers and ensuring that the seals remain intact, resulting in a significant reduction in O&M costs.

We obtained data on the number of standard 20-foot containers required to store BEAR sets from CENTAF/LGXR; with the exclusion of the FO set, which requires six containers, each of the other sets was estimated to require between 24 and 35 containers. In addition, 40-foot flatracks (containers without solid sides and tops, used primarily to transport wheeled vehicles) were needed for the 550i and 550f sets to store large generators that would not fit into standard containers, requiring five and two flatracks, respectively. It was assumed that these flatracks would require inside warehouse storage. Container purchase costs were estimated at $5,700 per 20-foot container and $6,200 per 40-foot flatrack.

We based our estimates of storage costs on data provided by CENTAF. Annual storage costs for palletized assets ranged from $99,000 to $207,000 per set, excluding the small FO set, whose annual storage cost was estimated at $9,000. Container storage costs were estimated to range from $30,000 to $65,000 for the housekeeping sets (which require inside storage for generators) and $2,100 to $13,000 for the other sets.

Other Costs

The costs associated with conducting periodic maintenance on these assets were excluded from the storage costs mentioned above. Estimates of these costs were also obtained from CENTAF, ranging from $21,000 to $33,000 per year per set, with the exception of the FO set, whose cost was $3,500. These PMI costs were applied to all sets, both palletized and containerized. Note that these storage and PMI costs assume no economies of scale in these FSL operations.

For assets stored at seaports but receiving PMI from permanent on-site maintenance, it was assumed that the assets would be moved by

truck between the seaport and the FSL's primary storage site, using the truck costs discussed in the transportation section above.

For assets maintained using the traveling maintenance team concept, an additional travel cost (i.e., temporary duty [TDY]) for the maintenance team was applied. These cost estimates were obtained from CENTAF, and ranged from $9,000 to $14,000 per year per set, with the exception of the small FO set, whose annual TDY cost was $1,500.

To estimate the cost associated with the asset swap maintenance concept, CENTAF provided estimates of the inspection intervals associated with each set. All sets have relatively few assets requiring annual inspection, a somewhat larger fraction of assets requiring inspection every three years, and the majority of assets requiring inspection every five years. We then obtained shipping costs using FY06 Military Surface Deployment and Distribution Command (SDDC) Liner Ocean Transportation Program Billing Rates,[10] applying the appropriate rates to containerized cargo (we assumed that palletized assets stored under the asset swap concept would pay a container rental and packing fee before swapping of assets, using the costs discussed in the transportation cost section above).

This analysis assumed that all facilities required for BEAR storage and maintenance would be constructed, including those at existing FSLs currently lacking sufficient facility space. It should be noted that a large number of palletized BEAR assets are currently stored outside, on the ground, in the CENTAF AOR.[11] The effects of extreme heat, sand, and humidity have a detrimental effect on BEAR assets, but facility space is currently not available at these sites. Our analysis assumes that additional facilities are to be constructed, even at existing storage sites, such that all assets are stored in accordance with their

[10] Military Surface Deployment and Distribution Command, FY2006 Liner Ocean Tranportation Program Stabilized Container Billing Rates, Scott AFB, Ill., 2006.

[11] Members of the research team made multiple visits to prepositioning sites in Southwest Asia, most recently in June 2008, and on every occasion have observed a large number of these palletized assets stored outside with no protection from the elements.

design requirements.[12] An exception is made for storage at seaports, for which we assume that commercial facility space will be leased at the port to accommodate storage and maintenance facility requirements. Port lease costs are included in the storage costs discussed above for containerized assets. However, if assets stored at the seaport are to be maintained by traveling maintenance teams, an additional requirement exists for the lease of PMI space at the port for the team to perform its work. Using CENTAF data, we estimated these costs to range from $37,000 to $76,000 annually per set, excluding the small FO set, whose cost was $7,000. New facility construction costs were based on Unit Costs for Army Facilities–Military Construction,[13] FY08 rates. Inside storage was computed using a baseline of $95 per square foot, with outside storage at $9 per square foot (for a concrete surface) and maintenance facilities at $112 per square foot.

No explicit "FSL opening" cost was included in this analysis. Instead, it was assumed that any FSL used was required to store at least six BEAR sets, with the costs associated with this minimum size accounting for the "opening" costs.

If BEAR assets are to be stored at a new FSL or if they are to be moved to or from an existing FSL, a one-time movement cost is associated with relocating these assets. These costs were computed using the SDDC Liner Costs mentioned above, assuming containerized shipping of assets emanating from a port on the East Coast of the United States.

Our model allows additional BEAR sets to be procured, if the model determines this to be a cost-effective strategy.[14] Additional procurement costs for BEAR sets ranged from $5.6 million to $10.5 million per set, excluding the small FO set, whose procurement cost was estimated at $1.7 million.

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[12] Some fraction of BEAR sets are considered appropriate for outside storage even when not containerized (e.g., metal pipes).

[13] U.S. Army Corps of Engineers, "Unit Costs for Army Facilities–Military Construction," *PAX Newsletter,* No. 3.2.2, Appendix A, March 30, 2006b.

[14] It was assumed that, for all additional BEAR sets that were procured, delivery was completed by the beginning of the six-year modeling time frame.

The model's cost function also allows additional transport vehicles to be obtained, beyond the initial allotment made available. Within this analysis, we assumed that no additional vehicles could be procured. A pool of 40 C-17s, four JHSVs, and 2,000 trucks was made available, with an additional 10 C-17s made available to support MCO periods. This relatively small pool of aircraft reflects the fact that airlift is often in short supply in the early stages of a contingency, since many airlifters would be tasked with other, higher-priority, missions when BEAR assets required movement. A relatively small number of JHSVs was made available to test the performance and desirability of such a vessel for such a mission. Essentially, an unlimited number of trucks was made available, reflecting the assumption that trucks could always be rented locally for any contingency.

It was assumed that many costs were incurred at the beginning of the analysis period, namely, facility construction, additional procurement of assets, purchase of shipping containers for containerized assets, and the one-time movement of assets to new storage locations. Because the objective function in this analysis takes a TPV approach, it is necessary to discount the value associated with all costs incurred after the first year of the analysis period, namely, operating and maintenance costs and non-MCO deployment transportation costs, to allow the analytic procedure to balance up-front investments in infrastructure with potential cost reductions in future years. A default discount rate of 2.8 percent was applied to all costs incurred after the first year of the analysis period.[15] These discounted costs were then summed over the analysis horizon (six years) to produce a TPV.

Construction, storage, and maintenance costs were all adjusted using the ACFs described above to account for relative differences in the cost of procuring goods and services in different countries. The ACFs were adjusted slightly to reflect the fact that certain countries (for example, South Korea) bear some fraction of the costs associated with

[15] This percentage is the Office of Management and Budget rate for projects with a 10-year payback period. See Office of Management and Budget, The Executive Office of the President, "Discount Rates for Cost Effectiveness, Lease Purchase, and Related Analyses," "Real Discount Rates," Circular No. A-94, Washington, D.C., n.d.

storage of WRM assets on their territory. This contribution, which can be quite significant, as is the case in South Korea, can be viewed as a demonstration of host nation support to the United States. Naturally, the existence of such cost-sharing agreements makes storage in such countries an attractive option. Within this analysis, we assume that such cost-sharing arrangements currently exist at only the South Korean sites. However, we wanted to examine the effects of such cost-sharing arrangements on the attractiveness of potential new storage sites. Thus, as an illustration, we assumed that a cost-sharing arrangement could also exist at a potential new site in Norway. U.S. Air Forces in Europe (USAFE) staff informed our research team of the existence of a Norwegian site that had previously been used by the U.S. Marine Corps as a prepositioning location; in 2006, the Marine Corps decided to remove its assets from this site. Suppose that the Norwegian government were interested in maintaining a U.S. presence in these existing facilities and were willing to offer a 100 percent cost-share agreement, in which all of the storage and maintenance costs would be paid for by the Norwegian government with the United States responsible only for providing the materiel associated for the storage and maintenance of those assets. We chose this site for an illustration because it is very remote from likely deployment locations, in order to examine the interaction between reduced O&M and construction costs and increased transportation costs.

Given this set of inputs, we now employ the optimization models presented in Chapter Two to analyze minimum-cost BEAR prepositioning postures. An analysis of robust and reliable BEAR postures is presented in Chapter Five.

Identification of Minimum-Cost BEAR Prepositioning Postures

Recall from Figure 3.1 that the current BEAR prepositioning posture consists of 13 sites heavily concentrated in Southwest and Northeast Asia. Many of these locations have a large allocation of BEAR sets: three FSLs are relatively "small" (authorized six or fewer BEAR sets),

six FSLs are relatively "medium"-sized (authorized between seven and 15 BEAR sets), and four FSLs are relatively "large" (authorized 16 or more BEAR sets). We evaluated the performance of this prepositioning posture[16] against a single set of global deployments, drawn as discussed above from the SPG, assuming that access would be guaranteed at all times to all FSLs.[17] We assumed a 10- to 20-day delivery requirement for all BEAR assets at all FOLs, with all 550i sets and the first 550f set due at a location within 10 days of the contingency start time and all other demands required to be delivered within 20 days of the contingency start time. The existing BEAR posture was able to meet those requirements if additional BEAR assets could be procured[18] and if additional airlift assets were made available (increasing the steady-state pool of available C-17s from 40 to 80 and increasing the MCO-period pool of available C-17s from 50 to 125).

We next evaluated a case in which the optimization model was used in a manner consistent with the traditional approach that focuses solely on predictable costs and ignores the contingency-dependent transportation costs. We adjusted the objective function to exclude these transportation costs and focus solely on the predictable costs. The optimization model identified a posture able to meet this same set of deployment time line requirements without requiring additional airlifters. Figure 3.2 shows the results of the optimization output. This posture is also fairly geographically concentrated. We note that it has opened three new sites (Norway, Bulgaria, and South America), and it has closed two of the existing Pacific sites. Note also that this posture uses more small FSLs and fewer large FSLs than does the existing BEAR posture.

Recall that we have assumed that the Norwegian government would be willing to offer a 100 percent cost-sharing agreement at its

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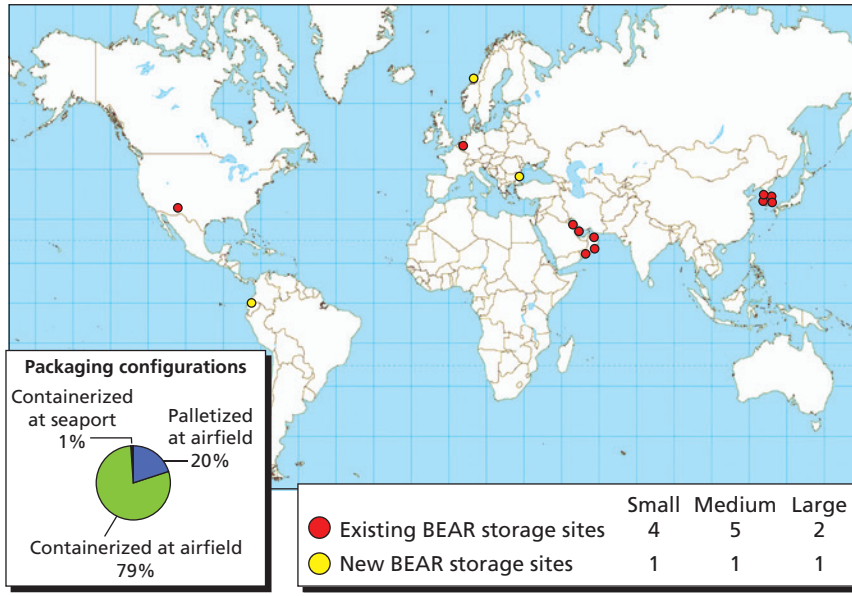
[16] By the term *prepositioning posture* we are referring to both the set of locations used and the allocation (authorization levels for BEAR assets) at each FSL.

[17] We use our modeling approach to capture robustness considerations for the BEAR posture in Chapter Five.

[18] It was assumed that all additional sets procured for the existing posture would be stored in a palletized configuration.

Figure 3.2
BEAR Posture Optimized Against Predictable Costs



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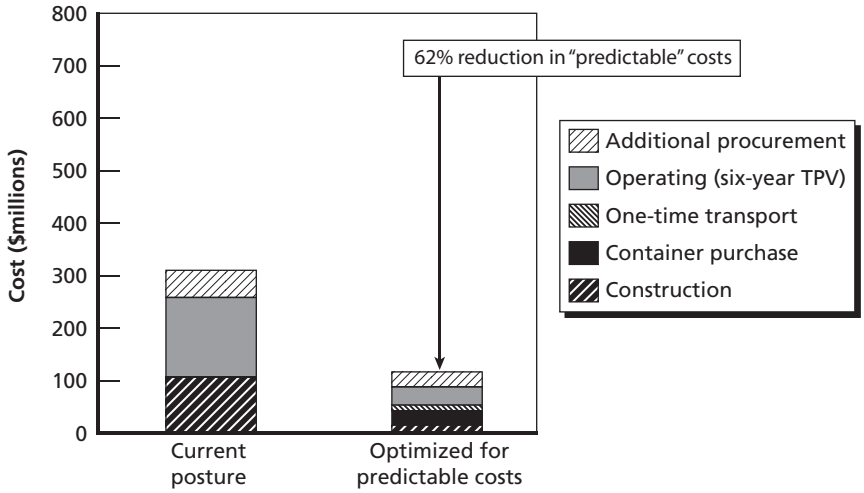
candidate FSL. What should be emphasized here is not the specific site in Norway or the accuracy of the assumption that the Norwegian government would be willing to offer such a cost-sharing agreement. Rather, the most appropriate conclusion to draw is that with sufficient cost-sharing, a storage location that is very remote from current and likely deployment locations (such as Norway) can still be very attractive because of the considerable savings afforded in O&M and construction costs, if transport costs are not considered. Because some fraction of assets likely require airlift in any case, delivery time lines for airlifted assets are not greatly affected by the length of the flight. Put another way, the aircraft loading, unloading, and throughput constraints have a much greater effect on airlift delivery time lines than do flight times, suggesting that for assets that need to be airlifted, storage in a low-cost remote location can be attractive.

If the objective function is restricted to include only the predictable costs, the optimization model identifies a posture that reduces

these costs significantly. Figure 3.3 contrasts the costs incurred by the current BEAR posture with those incurred by the posture that is optimized against predictable costs. The graph presents the set of costs considered by the optimization model, including those associated with the construction of new facilities, container purchases, one-time transportation costs associated with moving assets from their current site to a new storage location, procurement costs for any additional BEAR sets that are required, and an operating cost presented here as a six-year TPV.

Note that a fairly substantial construction cost is identified for the current posture. This occurs for two reasons. First, as mentioned above, we assume that facilities will be built for all assets that require inside storage. Thus, we are presenting a construction cost for a relatively large number of assets currently stored outside in Southwest Asia. Second, note that an additional procurement of BEAR assets was necessary to support the requirements of this set of deployments. The facility requirements to support these additional assets also generate some construction costs.

Figure 3.3
Cost Comparison When Optimized for Predictable Costs Only



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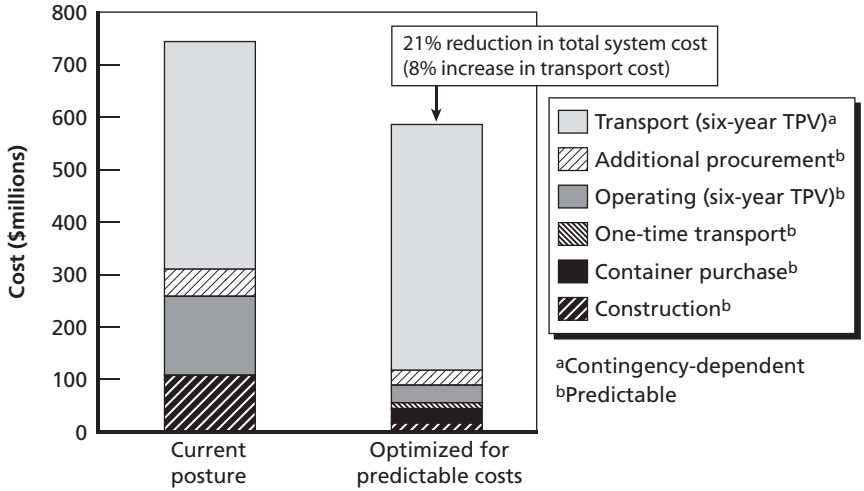
Observe the large difference in operating costs between the current posture on the left and that optimized for predictable costs on the right. This difference primarily results from the differences discussed above between containerized and palletized storage. For the current posture, we assumed the current allocation of assets to FSLs and enforced the current policy of having all assets (including any additional assets that were procured) stored in a palletized configuration. The optimized posture, however, makes extensive use of containerization (green and black segments of the pie chart in Figure 3.2), allowing for greatly reduced storage costs. Note that the optimized posture uses permanent, on-site maintenance at all FSLs, as does the current posture. Figure 3.3 demonstrates that the optimization model was able to find a posture that meets the same set of deployment time line requirements but does so with over 60 percent reduction in predictable costs.

However, designing a prepositioning posture with an aim to minimizing predictable costs can have a detrimental effect on the contingency-dependent transport costs associated with non-MCO deployments. Figure 3.4 contrasts the cost performance of these same two postures with respect to the total system costs, i.e., the sum of the predictable costs and the contingency-dependent non-MCO transport cost. Observe first the relative magnitude of these costs: The transportation cost associated with support to non-MCO deployments is, for both postures, significantly larger than all other cost categories combined. This suggests that excluding these costs from consideration when developing a prepositioning posture may be a flawed strategy, even when one accepts that many of these costs cannot be accurately forecasted.[19] Note that the posture that is optimized for predictable costs is actually susceptible to a slightly larger transportation cost than is the current posture. That increase is primarily due to the new FSLs that were opened in this posture and their relative lack of proximity to the deployment locations. Note, however, that the posture optimized for predictable costs still achieves a roughly 20 percent reduction in total system cost across the six-year horizon of the analysis.

[19] Note, however, that the costs associated with deployment in support of exercises and other planned missions can be forecasted.

Figure 3.4
Cost Comparison When Contingency-Dependent Costs Are Included

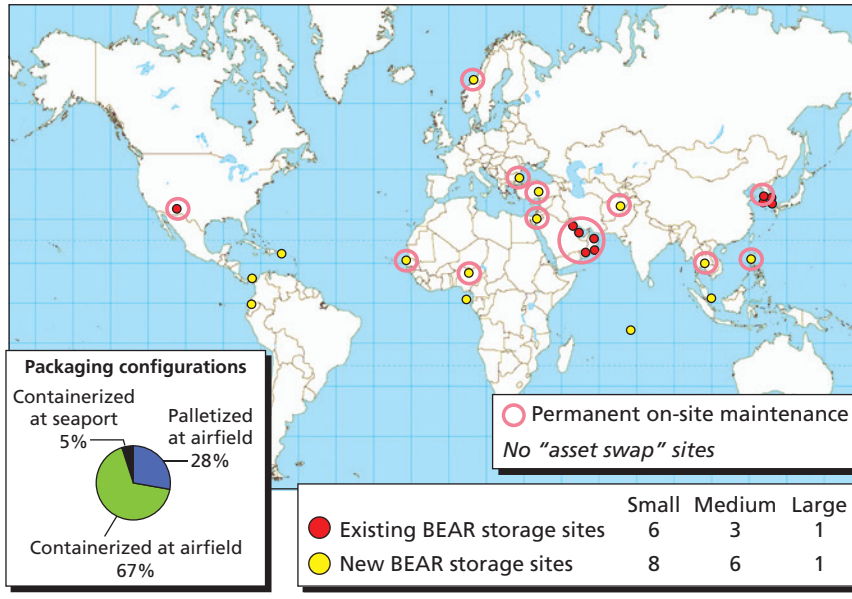


RAND *MG902-3.4*

We next allowed the optimization model to identify a posture that minimizes the total system costs, that is, both the predictable and contingency-dependent components, against the same set of deployments. Figure 3.5 presents the set of 25 FSLs that were selected by this total system cost optimization. The model identified a cost-optimal posture with a large number of geographically dispersed sites. This posture includes a fairly large number of new FSLs, covering many regions in which there are no current storage locations, along with the closing of a handful of existing FSLs. Observe again that with sufficient cost-sharing (as with the notional site in Norway), a storage location that is very remote from current and likely deployment locations remains an attractive option for the storage of some WRM assets, even when transport costs are included.

Observe that the posture presented in Figure 3.5 makes extensive use of containerization, with over 70 percent of the assets stored in containers (green and black segments of pie chart), although most of these containerized assets are stored at the FSL's airfield locations, rather than the ports associated with the FSLs. Thus, such a posture does not

Figure 3.5
BEAR Posture Optimized Against Total System Costs

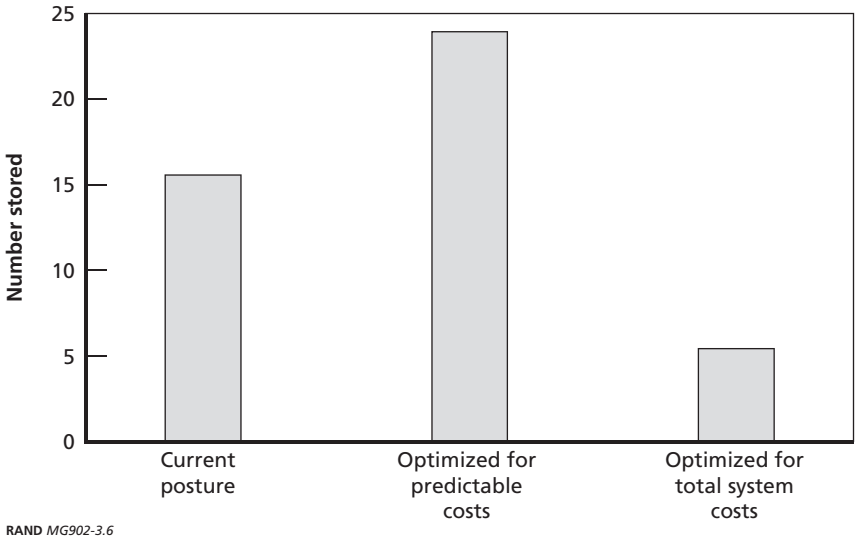


RAND *MG902-3.5*

require a large investment in facility construction at overseas locations, which might make it even more attractive to U.S. policymakers. Further, note that this posture makes use of network maintenance, with seven FSLs lacking a permanent on-site maintenance capability and instead supported via traveling maintenance teams.

Not only does the total system minimum-cost posture open a larger number of FSLs than the other two postures examined thus far, but it also uses many more small FSLs and disperses BEAR assets more evenly across those facilities. Figure 3.6 presents the standard deviation of the number of BEAR sets stored at each FSL, across these three postures. Note that the posture optimized against the total system cost has a much smaller standard deviation than the other postures, indicating that its assets are allocated more evenly across its set of FSLs. Contrast this with the posture optimized against solely the predictable costs: This posture has a large standard deviation, consistent with a posture that has a few FSLs with a very large allocation of BEAR sets, and

Figure 3.6
Standard Deviation of Number of BEAR Sets Stored per FSL



RAND *MG902-3.6*

many other FSLs with a relatively small allocation of BEAR sets. Such a posture depends heavily on this small number of large FSLs.

Table 3.2 presents a consolidated view of the geographic dispersal associated with these various BEAR prepositioning postures.[20] Observe that the posture optimized against total system costs uses between four and eight FSLs in each AOR, whereas the current posture uses a single FSL in two AORs and the posture optimized for predictable costs uses only between two and five FSLs in each AOR. Further, the minimum total system cost posture uses a relatively large number of small and medium-sized FSLs, which are relatively evenly distributed across EUCOM, U.S. Pacific Command (PACOM), and CENTCOM.

Figure 3.7 contrasts the cost performance of this total system cost optimization against the current posture and the posture optimized

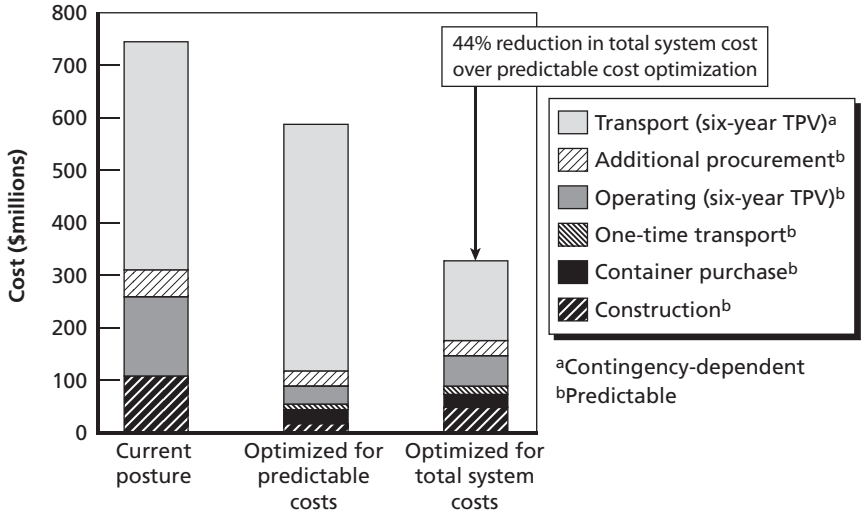
[20] Because this analysis was performed before U.S. Africa Command (AFRICOM) was established, here we use the definitions of EUCOM and CENTCOM circa FY07. Note also that we present the total FSLs used across both U.S. Northern Command (NORTHCOM) and U.S. Southern Command (SOUTHCOM) in a single category.

Table 3.2
BEAR Storage Sites Used by Various Prepositioning Postures

	Current Posture	Optimized for Predictable Costs	Optimized for Total System Costs
EUCOM			
Small	0	2	2
Medium	1	0	3
Large	0	1	1
PACOM			
Small	3	1	7
Medium	3	3	1
Large	0	0	0
CENTCOM			
Small	0	2	4
Medium	2	2	3
Large	3	1	0
NORTHCOM/ SOUTHCOM			
Small	0	0	1
Medium	0	1	2
Large	1	1	1

against predictable costs only. Note that the total system cost optimization, presented by the right-most bar in the figure, accepts an increase in the predictable costs over the predictable costs-only optimization, presented by the center bar in the figure, because that slight increase (concentrated in construction, one-time transport, and operations costs) allows a large reduction in the contingency-dependent transportation costs. The posture that is optimized against total system costs achieves

Figure 3.7
Cost Comparison Considering Total System Costs

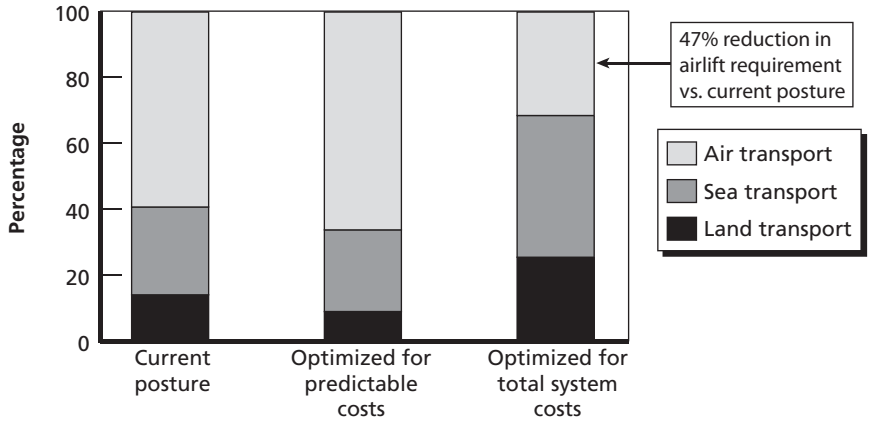


RAND *MG902-3.7*

a 44 percent reduction in total costs over the previous optimization. Note further that the posture optimized against total system costs is less expensive than the current posture in terms of both the predictable and contingency-dependent cost components.

Optimizing against total system costs not only significantly reduces total expenditures for this set of scenarios but also significantly reduces the reliance on airlift. Figure 3.8 demonstrates that the total system minimum-cost posture can satisfy the same set of time-phased deployment requirements with a 47 percent reduction in the tonnage of BEAR assets transported by airlift over the current posture. When one considers the limited availability of airlift assets in the early stages of a deployment, this makes a further wartime effectiveness argument for the use of such a dispersed posture, beyond the potential reductions in contingency-dependent costs.

Figure 3.8
Percentage of Tonnage Transported, by Mode



NOTE: The percentage presented as land transport also includes those assets that require no transportation, i.e., assets deployed to the FOL from a collocated storage site.

RAND *MG902-3.8*

Sensitivity Analyses for BEAR Prepositioning Posture

We next use this analytic approach to perform a number of sensitivity analyses with respect to the BEAR prepositioning posture, evaluating the effect of other policy decisions, such as varying levels of demand and risk tolerance, an AOR-specific management option, and a demonstration of how this approach can be used to address political considerations.

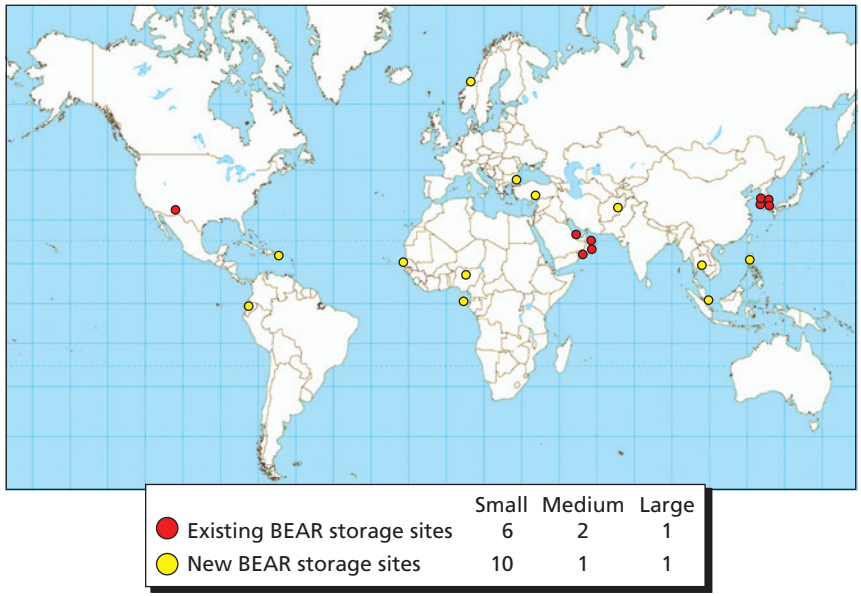
Varying Demand Levels

When considering the relationship between predictable and contingency-dependent costs, it is clear that greater risk is associated with the contingency-dependent costs, since the Air Force would necessarily be accepting the predictable costs associated with building any posture, whereas the contingency-dependent costs would depend on the extent to which the Air Force is actually required to deploy and use these assets. Recall that the non-MCO transport costs presented above accounted for a very large percentage of the total system costs. To the extent that

the set of scenarios considered in this analysis is overly stressing, these transportation requirements would be overstated.

Therefore, we evaluated an alternative future in which the deployment requirements for BEAR, which were computed based on the SPG, are reduced by 50 percent. That is to say, we examined the effect of decreasing the deployment requirement by one-half, to observe how the relationship between predictable and contingency-dependent costs affects the optimized prepositioning posture. The posture identified by this optimization is presented in Figure 3.9. Observe that even if the deployment demands for BEAR assets are reduced by 50 percent, the optimization model still identifies a geographically dispersed posture, with four fewer FSLs than in the posture identified in Figure 3.5, but still much more dispersed in terms of number of sites and their geographic locations than is the existing posture. Note that under such

Figure 3.9
Total System Minimum-Cost BEAR Posture If Demands Are Reduced by One-Half



RAND *MG902-3.9*

a scenario, the posture primarily uses small FSLs. If the deployment demand levels are reduced even further, to 25 percent of the SPG-based demands, the optimized posture uses only 16 FSLs. Although this number of FSLs is comparable to the 13 FSLs used in the current posture, these 16 sites are significantly more geographically dispersed than in the current posture. This sensitivity analysis suggests that increasing the dispersal of BEAR assets appears to be a fairly robust recommendation with respect to varying levels of demand.

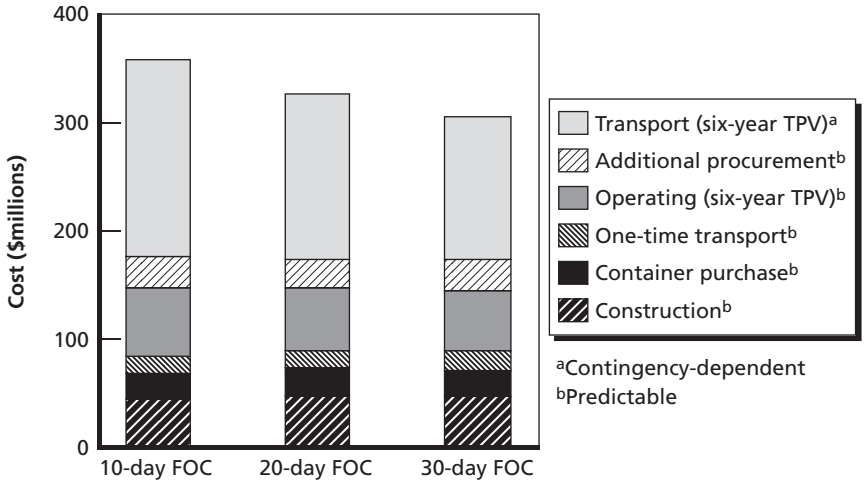
Varying Risk Tolerance

Recall the assumption that for all analyses presented thus far, a 10- to 20-day time line was imposed on the delivery of BEAR assets to all FOLs. We modified these time lines to require that the model identify postures capable of addressing a more stressing scenario, supporting a 6- to 10-day delivery time line, along with a posture that tolerates greater risk, in which the time line is extended to 15 to 30 days. In both cases, the optimization model returned a dispersed posture. For the more stressing 6- to 10-day delivery requirement, the total system minimum-cost posture used 23 FSLs. This posture was very similar to the 25-FSL posture presented in Figure 3.5 (which supported the baseline 10- to 20-day delivery requirement), with the only differences being that the 6- to 10-day delivery posture closed two FSLs (one in South Korea and the Diego Garcia site), and it slightly modified the posture in Southwest Asia, closing the FSL at Incirlik AB, Turkey, and opening a new one at Al Jaber, Kuwait.

For the 15- to 30-day delivery requirement, a similarly dispersed posture was identified, also with 23 FSLs. This posture was also very similar to the Figure 3.5 posture, with the only differences being that the 15- to 30-day delivery posture closed the FSLs at Aqaba, Jordan, and Masirah, Oman.

Figure 3.10 demonstrates the effect on total system cost as the deployment delivery time lines are varied. Not surprisingly, as one relaxes the acceptable time lines for delivery of BEAR assets, both predictable and contingency-dependent costs can be reduced. Contingency-dependent costs decline because extending time lines allows the use of less expensive means of transportation, such as truck or sealift. One also

Figure 3.10
Total System Cost Across Varying Levels of Risk Tolerance



RAND *MG902-3.10*

observes a very small reduction in predictable costs, because more assets can now be moved to FSLs that have lower storage costs but that were not previously able to make extensive use of truck and sealift because of the tight delivery time lines.

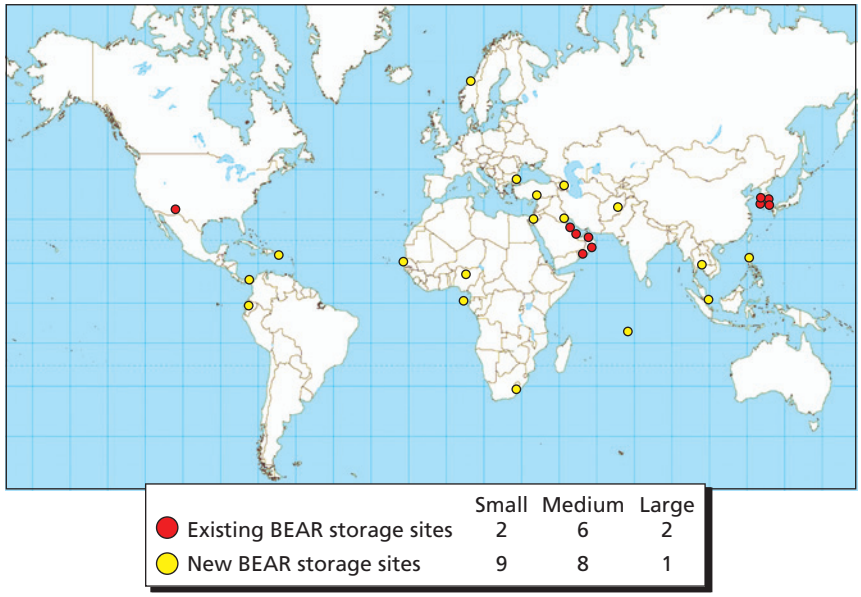
AOR-Specific Options

We also performed some sensitivity analyses focusing on the relationship between global and regional-specific management. Presented in Figure 3.11 is a minimum-cost posture that does not allow cross-AOR support. That is to say, assets that are stored in one region may be used to support deployments only within that AOR. Note that we blurred the distinction between NORTHCOM and SOUTHCOM for any assets stored in the western hemisphere and allowed them to be used for operations within either North or South America.[21]

This approach allows us to demonstrate the cost effects of allow ing cross-AOR support by means of a global manager. The bar on

[21] As mentioned above, because this analysis was performed before the establishment of AFRICOM, here we use the definitions of EUCOM and CENTCOM circa FY07.

Figure 3.11
Prepositioning Posture Allowing for No Cross-AOR Support

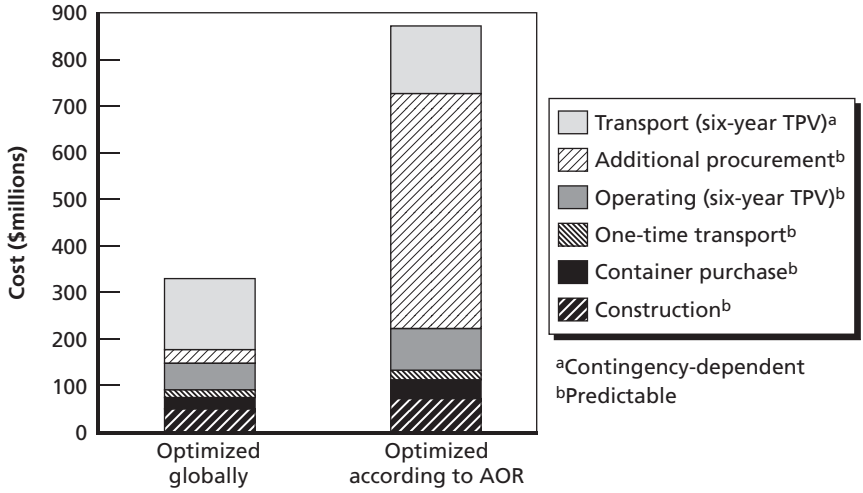


RAND *MG902-3.11*

the left within Figure 3.12 presents the total system costs for the posture presented in Figure 3.5 that is optimized against total system costs; note that for this posture, we assume that a global manager controls the pool of BEAR assets and can use assets stored in one AOR to support operations in another region. The rightmost bar presents the minimum-cost posture identified when we optimize according to AOR, assuming that assets cannot be used to support operations across AOR boundaries. This difference in cost is almost entirely due to the large additional procurement necessary if it is assumed that BEAR assets cannot be used to support operations across AOR boundaries; the other cost categories are comparable between the two postures.

The assumption that assets stored in one AOR cannot be used to support operations in another is not exactly comparable to the current WRM management construct. Although WRM requirements are still computed AOR by AOR, there is currently some capability for cross-

Figure 3.12
Cost Comparison of Global and AOR-Specific Support



RAND *MG902-3.12*

AOR support, although it requires that approval be obtained from quite high up the Air Force chain of command, which can cause such long delays that tight delivery time lines may not be met. The results presented here could also be interpreted as presenting the results of an alternative in which cross-AOR support is allowed but requires a delay of 20 days for approval of moving assets across regional boundaries (thus exceeding the delivery time lines assumed for these optimization runs). Other management options exist, such as giving the global manager coordination authority instead of tasking authority over BEAR movements, allowing the regional CCDRs to comment on cross-AOR movements before such movements are made. One could envision other alternatives, such as allowing each AOR to retain control over an "MCO-supporting" fraction of its assets, with all other assets managed globally by a central manager. However, these alternatives could create some additional delay in responding to contingencies.

It should be noted that all of the analyses presented elsewhere in this chapter assumed that cross-AOR support was possible, with no delays necessary to move assets across regional boundaries. Thus, the

results presented above as representing the current posture are not a perfect representation of the current system, in that they allow such global management of BEAR assets.

Political Considerations

We performed an additional set of analyses to demonstrate how optimization can be used to demonstrate the effects of considerations outside the scope of such quantitative models, such as political constraints. The analysis presented in this monograph does not claim to offer an expert understanding of political considerations. Instead, we use models to specify the cost and capability implications of certain political constraints, potentially demonstrating to policymakers the value of certain locations to the total prepositioning system.

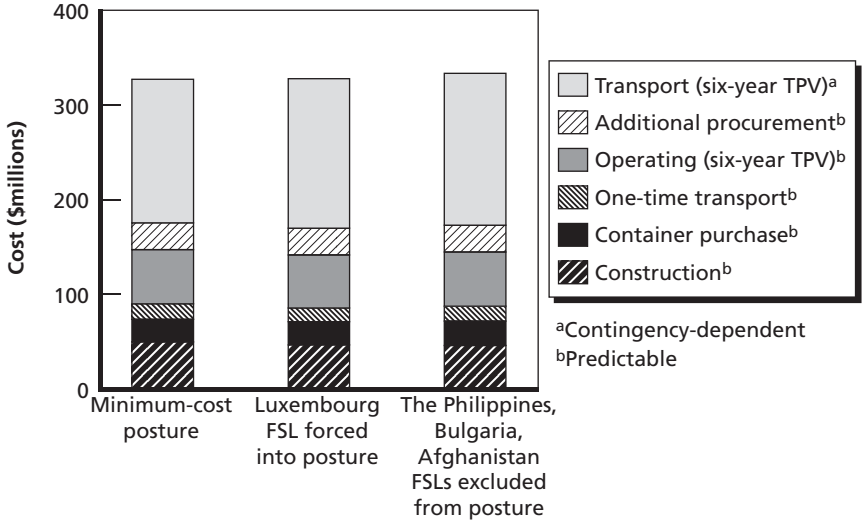
Assume, for example, that political constraints require the inclusion of the existing FSL at Sanem, Luxembourg, in the BEAR posture. The optimization model can be modified to add a constraint requiring that the FSL at Luxembourg be used for BEAR storage. The minimum-cost posture that results is rather similar to the posture identified when no such constraint is placed on the Sanem FSL.[22]

The optimization tool allows us to measure the effect on cost and capabilities of such a political constraint, as presented in Figure 3.13. Observe that in this case, if we force the Luxembourg site into the posture, the same set of deployment requirements can be satisfied, and the effect on total system cost is barely discernable, causing a total cost increase of less than 1 percent. The inference to be drawn here is that if the use of a site at Luxembourg is desirable for reasons outside the scope of this model, there is very little penalty associated with modifying the posture to include the Sanem site.

One could also imagine political constraints that exclude certain sites from the posture. Observe that the minimum-cost postures as identified by the model have frequently included storage at FSLs in Clark AB, the Philippines; Bagram, Afghanistan; and Burgas, Bul-

[22] The FSLs at Aqaba, Jordan; Shaikh Isa, Bahrain; and Diego Garcia are no longer used, FSLs are opened at Sanem, Luxembourg; and Rota, Spain.

Figure 3.13
Cost Effects of Forcing FSLs Into or Out of the BEAR Posture



RAND *MG902-3.13*

garia. If it were assumed that opening FSLs at such sites was not palatable because of political constraints, the model can similarly add constraints that eliminate these sites from the list of potential FSLs and then reoptimize. The minimum-cost posture that is obtained from such an optimization is again rather similar to the total system minimum-cost posture identified above.[23] As demonstrated in Figure 3.13, if these three FSLs are necessarily excluded from the BEAR posture, an alternative posture can be identified that meets all deployment requirements and increases total system costs by only 2 percent.

Rather than focusing on the precise locations that were forced into or out of the BEAR posture in this section, note the general lack of a large cost effect when the BEAR prepositioning posture is modified for "other" reasons. This is desirable, because it demonstrates a relative lack of sensitivity with respect to the precise FSLs that are used, allow-

[23] The FSLs at Clark AB, the Philippines; Bagram, Afghanistan; Burgas, Bulgaria; and one in South Korea are no longer used; and new FSLs are opened at Misawa, Japan; Constanta, Romania; and Rota, Spain.

ing considerable latitude for qualitative concerns outside the scope of the math models, with little effect on cost or capability.[24]

[24] Although there is no guarantee that similar insensitivity would be observed for any other set of included or excluded FSLs, the three FSLs that were excluded in this section were selected because of their expected significant detrimental effect on the BEAR posture's performance.

CHAPTER FOUR

Evaluation of Prepositioning Strategies for WRMV Assets

The conclusions drawn from the BEAR analysis of Chapter Three may not apply to WRM vehicles and support equipment. The analysis that recommended a more dispersed BEAR posture was based on the trade-off between transportation cost and storage and maintenance costs. BEAR assets have relatively small maintenance requirements and a relatively large deployment transportation cost, favoring a more dispersed prepositioning posture. Vehicles and support equipment are likely to have a higher maintenance workload and a smaller deployment transportation cost. The use of containerized storage of assets may be less practical for WRMV and support equipment than it is for BEAR assets. Finally, it may be possible to lease certain types of vehicles from the local economy on an as-needed basis during contingencies, unlike BEAR. For these reasons, we applied our analytic approach to a review of the prepositioning of WRM vehicles.

Inputs to the Analysis

The Air Force owns and operates a vast array of support equipment to enable the successful execution of Air Force activities. The term *support equipment* refers to a specific class of commodities. The DoD *Dictionary of Military and Associated Terms* (DoD, 2009) defines *equipment* as, "In logistics, all nonexpendable items needed to outfit or equip an individual or organization," and *nonexpendable supplies and materiel* as, "Supplies not consumed in use that retain their original identity during

the period of use, such as weapons, machines, tools, and equipment"; note that equipment does not include *end items* such as aircraft. Thus, *support equipment* in this context is composed of such items as trucks or avionics test sets. The scope of Air Force support equipment is rather broad, containing 2.3 million assets with a total replacement cost of $28.6 billion.[1]

The Air Force employs a set of "use codes" to identify the deployment intent for support equipment authorizations, as follows:

- A: mobility—asset is in a unit type code (UTC)
- B: in-garrison use only
- C: joint-use—WRM in use in-garrison
- D: "pure" WRM.

Because this is an analysis of the prepositioning of WRM assets, we can immediately exclude use code A and B assets from our scope. We will further eliminate use code C assets from our scope because joint-use equipment has a nondeployed use at its storage location, which limits the ability of the Air Force to relocate such assets to alternative locations. We further restrict our analysis to include vehicles only, out of all Air Force support equipment, because a very rich data source exists for the operation and maintenance of vehicles (On-Line Vehicle Information System, or OLVIMS) that does not exist for other support equipment. Moreover, this still allows the scope of our analysis to capture a significant amount of investment, as shown in Figure 4.1.[2]

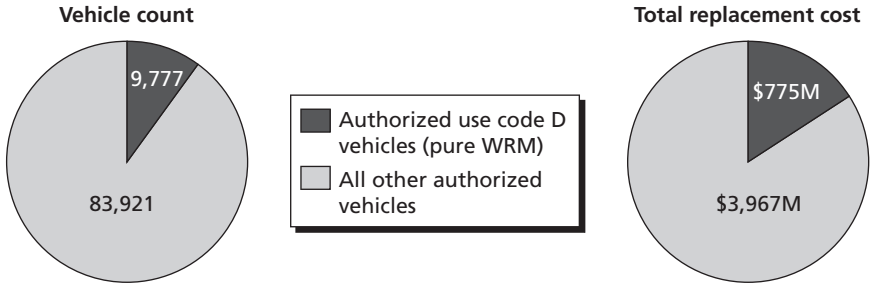
Air Force vehicles are further classified according to a set of management codes, which categorize vehicles according to function. The first character of a management code identifies a vehicle's functional grouping:

---

[1] RAND analysis of Air Force Equipment Management System database by Pat Mills, 2007.

[2] Vehicle count data were obtained from the worldwide Vehicle Authorization List (VAL); replacement cost data were obtained from the Air Force Vehicle and Equipment Management Support Office (VEMSO). Note that joint-use WRM, which has been excluded from the scope of this analysis, accounts for 1,669 vehicle authorizations and $163 million in replacement costs.

Figure 4.1
WRM Vehicles as a Fraction of Total Vehicles



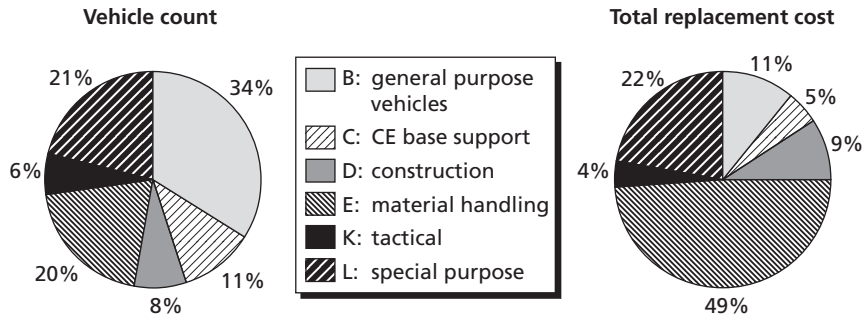
RAND *MG902-4.1*

- B: general purpose (e.g., pickups, sedans, ambulances, and buses)
- C: civil engineering base support (e.g., dump trucks, refrigeration, sewer, and mobile aircraft support such as deicers)
- D: construction (e.g., rollers, graders, dozers, and loaders)
- E: material handling (e.g., aircraft loaders, forklifts, and tugs)
- K: tactical (e.g., HUMVEE and medium tactical)
- L: special purpose (e.g., refuelers, armored, and up-armored vehicles).

Pure WRM vehicles are distributed across all management code groups, as shown in Figure 4.2.

The set of pure WRM vehicle authorizations spans 137 unique management codes. This is a substantially larger scope than in the BEAR analysis, for which there were only five separate sets to include in the analysis. To keep the analysis at a tractable size, we focused on a subset of WRMV management codes. We identified a set of 19 management codes that accounts for 51 percent of the pure WRM vehicle count and 63 percent of the associated total replacement costs. Table 4.1 presents more details on this set of 19 vehicle management codes. It should be noted that some of these management codes can be used as substitutes for one another (e.g., E956 and E958 are both 10K forklifts).

Figure 4.2
Distribution of Pure WRM Vehicles, by Management Code



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Recall that our analytic approach for evaluating WRM prepositioning postures begins with a focus on support to military operations, using combat support requirements to link our models to sets of deployment scenarios. The SPG scenarios were used to generate a potential future containing a large set of deployment scenarios, including MCOs along with training missions and lesser contingencies, covering a six-year interval.

As with the BEAR analysis, we based the set of time-phased demands for WRMV at FOLs on outputs from other RAND research.[3] However, because the analytic tools developed by this other RAND project did not address any general purpose (management code B-type) vehicles, we extrapolated those requirements from the general purpose vehicle authorizations at 7th Air Force WRM locations in South Korea, calculated as a function of the numbers and types of aircraft planned for deployment at those locations.

[3] For more information on this analytic approach, see Don Snyder, Patrick Mills, Adam C. Resnick, and Brent Fulton, *Assessing Capabilities and Risks in Air Force Programming: Framework, Metrics, and Methods,* Santa Monica, Calif.: RAND Corporation, MG-815-AF, 2009.

Table 4.1
Set of WRMV Management Codes Included in This Analysis

Management Code	Noun	WRM Authorizations	Replacement Cost ($M)
B180	MAINT UTIL DEL V	711	15.6
B204	TRK PU 4X2 4600-	518	3.8
B222	TRK PU 4DR 4X4 7	293	7.1
B409	S TLR LB 20T 40 F	308	4.5
C355	BOBTAIL	533	11.1
C359	TRAC, TOW FLT 4X4	99	3.0
C601	DEICER TRK	29	5.0
C604	APO TRUCK STAIRCASE DRIVABLE	66	4.2
E822	6K FORKLIFT	127	3.0
E936	APO LOADER 25K NGSL	241	112.9
E945	APO LOADER 60K	139	185.7
E949	HYSTER FORKLIFT	19	0.6
E956	APO FORKLIFT 10K ALL-TERRAIN	739	22.3
E958	TRK FL 10K AT 46	388	30.4
L145	VEH WG P-19 CRASH RES FFV	83	29.7
L275	VEH WG R-11 6000 GL TK TRK	422	40.3
L350	VEH WG MB-2 ACFT TOW TRAC	93	5.5
L351	VEH WG MB-4 ACFT TOW TRAC	144	3.9
L461	A1B FUEL BOWSER	30	0.4
Totals		4,982	488.9

Prepositioning Sites

We used the same set of existing and potential storage sites as were used in the BEAR analysis (see Table 3.1). The existing FSL posture for WRMV differs slightly from that currently in use for BEAR prepositioning. The BEAR FSLs at Seeb and Masirah, Oman, were identi-

fied as not having any authorizations for this set of 19 WRMV management codes. In addition, existing WRMV FSLs were identified at Fairford, United Kingdom; Diego Garcia; and Kadena, Japan; none of which were included in the existing BEAR posture. Note that although WRMV assets are authorized to a very large number of U.S. locations, for simplification purposes within this analysis we assumed that all vehicles authorized to U.S. locations were at Holloman AFB, New Mexico (except for vehicles at Andersen AFB, Guam).

For each of these existing sites, we identified the current number of WRMV assets authorized for storage at the site, the existing warehouse and maintenance space available to WRMV assets, and the amount of space available for potential expansion. Data were also collected on the available existing space at the potential new WRMV FSL sites (in case vacant U.S. military warehouse space was available), along with the maximum space available for potential new construction at each site. For all FSLs, data were obtained estimating the location's throughput ability to process air, land, and sea vehicles. This set of throughput data was also collected for all FOLs.

We again evaluated a port storage option for WRMV in which some fraction of the assets is stored at a seaport. We used the same set of "nearest seaports" for each FSL as was used in the BEAR analysis and included an option for assets to be stored at that nearest seaport, as well as at the FSL's primary airfield location.

Maintenance Options

Within the WRMV analysis, we included two of the three maintenance policy options that were evaluated in the BEAR analysis. It was assumed that the WRMV assets at any FSL would be supported using either permanent on-site maintenance or traveling maintenance teams. The asset swap option was not evaluated for WRMV, because of the frequency and duration of WRMV actions: There is a requirement to perform a brief quarterly inspection, in which the vehicle is operated for 20–30 minutes and reviewed for discrepancies. Contrast this with BEAR assets, for which most items require a PMI action every three to five years. It would not be practical to ship a vehicle between two sites to perform such an inspection. Thus, the only "networked mainte-

nance" concept evaluated here will be the traveling maintenance team option.

This WRMV prepositioning analysis also requires a review of transportation considerations and data inputs. Again, this is a multimodal analysis, including transport options for movement by air, sea, and land. We assumed the same set of transport vehicles as in Chapter Three (C-17s, JHSVs, and trucks) using the same data for vehicle capacity, transport times between FSLs and FOLs, and transport costs.[4]

Asset Packaging

This analysis examined two alternatives for vehicle packaging, which affected both the transportation and storage of BEAR commodities. Containerization and palletization are not viewed as viable options for the storage of WRM vehicles. Currently, WRM vehicles are generally stored in one of two configurations: Active vehicles are "ready to roll" and required for use by initial incoming forces at a location; inactive vehicles are in a "deep storage" configuration but can fairly rapidly be brought into mission-capable status.[5] An alternative packaging configuration for WRM vehicles has been tested in the U.S. Pacific Air Forces (PACAF) since 2003, in which inactive stored WRM vehicles are wrapped in plastic, with preservatives used in the engine, transmission, etc. Figure 4.3 presents a before and after image of a vehicle undergoing the wrapping process.

The motivation for wrapping vehicles is clear. Direct labor accounts for over 60 percent of WRMV maintenance costs. Wrapped vehicles are stored for three years, receiving only quarterly visual inspections, to check for damage to the wrapping material, although annually 5 percent of the wrapped fleet at a location undergoes a sampling inspection to ensure that the larger pool of wrapped vehicles remains in acceptable condition. Because this inspection regime

[4] Unlike BEAR, for which we were provided the number of trucks necessary to move each set, for WRMV, we assumed a transporter truck capacity of the more constraining of 35 tons or 480 square feet.

[5] U.S. Pacific Air Forces, *Preservation and Storage of War Reserve Materiel Vehicles and Equipment,* Hickam AFB, Hawaii, PACAF Handbook 24-3, December 29, 2003.

Figure 4.3
WRM Vehicle Wrapping Process

SOURCE: James Brant, 607 ASG/LGPW, "FW: RAND Visit," email to the authors containing PowerPoint briefing attachment, Cortec Cost Savings Brief (1).ppt, May 2, 2007.

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is much less labor-intensive than the inspection requirements for unwrapped vehicles (which includes both the quarterly operational test mentioned above and a weekly walk-through inspection to check tire inflation, unusual leaks, and other obvious defects[6]), vehicle wrapping can significantly reduce operations and maintenance costs.

We based our estimates of maintenance costs for unwrapped vehicles on data from the OLVIMS database covering the period 2002–2006. These data, which are contained in the database at the level of individual vehicle records, were aggregated by management code. The database makes it possible to identify vehicle maintenance costs and man-hours associated with vehicle accidents separate from all other maintenance actions. Since pure WRM vehicles are not typically in active use, we excluded accident costs (which are substantial) to obtain an annual average maintenance cost and maintenance man-hour requirement for each WRMV management code. These annual PMI costs ranged from $500 to $7,500 per unwrapped vehicle.

6 PACAF, 2003.

Data provided by PACAF suggest that the wrapping of a vehicle requires an average of $550 in material costs and four man-hours of labor.[7] Other data provided by PACAF estimate a cost of $1,500 for each wrapped vehicle that undergoes the annual 5 percent sampling inspection.[8] Adding in additional maintenance man-hours associated with the quarterly visual inspections and the reemergence of wrapped vehicles following the three-year storage period, and using a baseline cost of $25 per man-hour, we obtain an annual maintenance cost of $300 per wrapped vehicle. Note that the data we received for vehicle wrapping costs did not distinguish the cost by the type of vehicle, thus this $300 cost is applied to all wrapped vehicles included in the analysis.

Vehicle storage costs were estimated at $9.10 per square foot of warehouse space (allowing for some additional space along the outer dimensions of each vehicle), using a warehouse cost similar to the overall average used in the BEAR analysis of Chapter Three, and ranged from $1,300 to $8,300 per vehicle per year, applied to both wrapped and unwrapped vehicles.

Other Costs

For assets that were maintained using traveling maintenance teams, an additional travel cost for the maintenance team (i.e., TDY) cost was applied. These cost estimates were based on the overall average costs employed in the BEAR analysis, which suggested that annual TDY costs associated with traveling maintenance teams were equal to approximately 8 percent of the sum of an asset's annual storage and maintenance costs. This generated annual costs ranging from $170 to $1,000 per vehicle, applied to both wrapped and unwrapped vehicles.

This analysis assumes that assets stored at an FSL's primary airfield location may be either wrapped or unwrapped. Assets stored at an FSL's seaport must be wrapped. It is assumed that all vehicles, whether wrapped or unwrapped, must be stored inside warehouses.

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[7] Brant, 2007.

[8] Davis DuFour, PACAF/A4PX, "RE: RAND Request for PACAF Vehicle Indoor/Outdoor Storage," email to the authors, November 29, 2007.

It was further assumed that all facilities required for WRMV storage and maintenance would be constructed, if sufficient facilities did not exist at the storage location. As was noted for BEAR assets, currently a large number of WRM vehicles are stored outside, in both the CENTAF and PACAF AORs.[9] The effects of extreme heat, sand, and humidity have a detrimental effect on the vehicles, but facility space is currently not available at these sites. Our analysis requires that all necessary facilities be constructed, even at these existing storage sites, such that all assets are stored inside. An exception is made for storage at seaports, for which we assume that commercial facility space will be leased at the port to accommodate storage and maintenance facility requirements.[10] The port lease costs were estimated to range from $12,000 to $53,000 annually per vehicle. New facility construction costs were based on the same rates and assumptions that were employed in the BEAR analysis.

Based on discussions with VEMSO,[11] it was assumed that any WRM vehicle transported in support of a deployment requirement would be transported in a "roll-on roll-off" configuration. That is to say, the vehicle would not be palletized or containerized for transport but would be ready to drive onto and off the transporter. Thus, a loading time of one hour was assumed for all transporters. If the vehicle had been wrapped, it would have to be unwrapped, undergo the necessary maintenance to return it to operational status, and then be loaded onto the transporter. Following its reconstitution and return from deployment, wrapped vehicles would then require a rewrapping before returning to their storage site. Thus, for wrapped vehicles that are to be transported in support of a deployment, an additional unwrapping and rewrapping cost applies ($730) and an additional delay (three hours)

[9] Members of this research team have observed such unwrapped vehicles stored outside in both Southwest Asia and, to a lesser extent, in Korea.

[10] Seaport storage of wrapped vehicles in leased space may be more attractive than similar storage of unwrapped vehicles, since the wrapping provides some protection against pilferage or damage to vehicles stored outside Air Force facilities.

[11] Randy Livermore, AF/AFELM VEMSO, "RE: RAND Question," email to the authors, August 21, 2007.

associated with this unwrapping in addition to the transporter loading time delay.

The construction, storage, and maintenance costs were all adjusted using the area cost factors described above to account for relative differences in the cost of procuring goods and services in different countries. Exceptions for the existing cost-sharing agreement in South Korea and a notional new cost-sharing agreement in Norway were implemented in the same manner as for the BEAR analysis.

No explicit "FSL opening" cost was included in this analysis. Instead, it was assumed that a minimum size exists for any opened FSL, assumed to be storage of at least 25 vehicles, with the costs associated with this minimum size accounting for the opening costs. One-time movement costs associated with changing the vehicle allocation at any FSL were computed as was done for the BEAR analysis.

Additional procurement of vehicles was allowed, if this was determined to be a cost-effective strategy,[12] using the vehicle replacement costs presented above, which range between $7,400 and $470,000 per vehicle, with the exception of the 60,000-lb. loader (management code E945), whose replacement cost was $1,300,000.

As with the BEAR analysis, we assumed that no additional transport vehicles (C-17s, JHSVs, or trucks) could be procured. A slightly larger pool of C-17s was made available, with 50 aircraft available during non-MCO deployments and an additional 75 aircraft available to support MCOs. The pools of four JHSVs and 2,000 trucks were unchanged from the BEAR analysis.

The total present discounted value approach that was used for the BEAR analysis was also applied to the WRMV analysis. These discounted costs were again summed over the analysis horizon (six years) to produce a TPV.

Given this set of inputs, we can now use the optimization models to perform an evaluation of WRMV prepositioning postures.

[12] It was assumed that, for all additional vehicles that were procured, delivery of the vehicle was completed by the beginning of the six-year modeling time frame.

Identification of Minimum-Cost WRMV Prepositioning Postures

The current WRMV prepositioning posture consists of 14 sites and, like the set of BEAR FSLs, is concentrated heavily in Southwest and Northeast Asia. Many of these locations have a large allocation of authorized WRMV: One FSL is relatively "small" (authorized 100 or less vehicles), nine FSLs are relatively "medium"-sized (authorized between 101 and 500 vehicles), and four FSLs are relatively "large" (authorized 501 or more vehicles). We evaluated the performance of this prepositioning posture[13] against a single set of global deployments, drawn as discussed above from the SPG, assuming that access would be guaranteed at all times to all FSLs.[14] The existing WRMV posture was able to support those requirements, assuming a 20-day delivery requirement for all WRMV assets at all FOLs, if additional WRM vehicles could be procured.

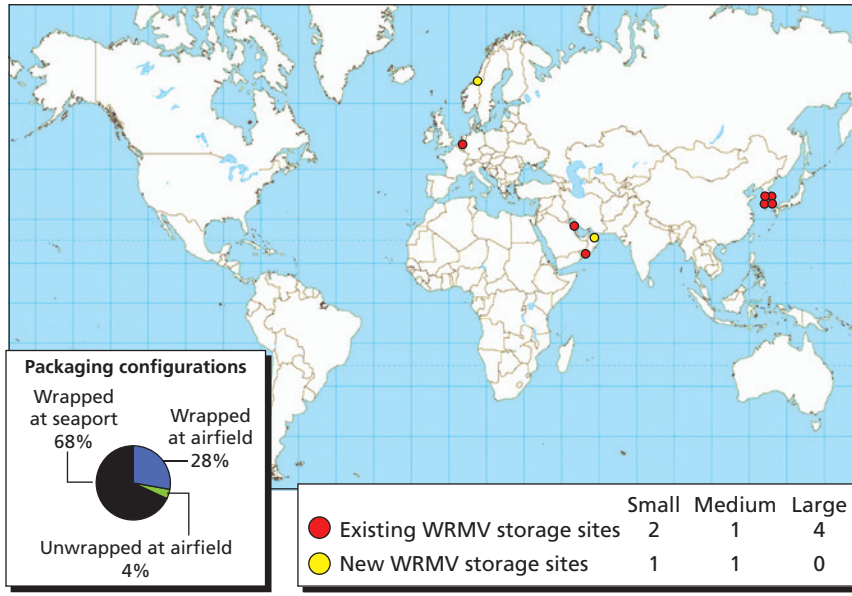
We next evaluated a case in which the optimization model was used in a way that was consistent with the traditional approach that focuses solely on predictable costs and ignores the effect of the contingency-dependent transportation costs. We adjusted the objective function to exclude these transportation costs and focus solely on the predictable costs. The optimization model identified a posture that is able to meet this same set of deployment time line requirements. Figure 4.4 shows the posture obtained by this optimization. This posture is even more concentrated than the existing posture, with a total of only nine FSLs employed, with new sites opened in Seeb, Oman; and Norway,[15] and existing FSLs closed in Misawa, Japan; Kadena, Japan; Andersen AFB, Guam; Al Udeid, Qatar; Fairford, United Kingdom; Holloman

[13] By the term *prepositioning posture* we are referring to both the set of locations used, along with the allocation (authorization levels for vehicles) at each FSL.

[14] We use our modeling approach to capture robustness considerations for the BEAR posture in Chapter Five; note, however, that this monograph does not present such robustness analysis for WRMV.

[15] As was discussed in detail in Chapter Three, recall that we have assumed, as an illustration, that the Norwegian government would be willing to offer a 100 percent cost-sharing agreement at this location.

Figure 4.4
WRMV Posture Optimized Against Predictable Costs



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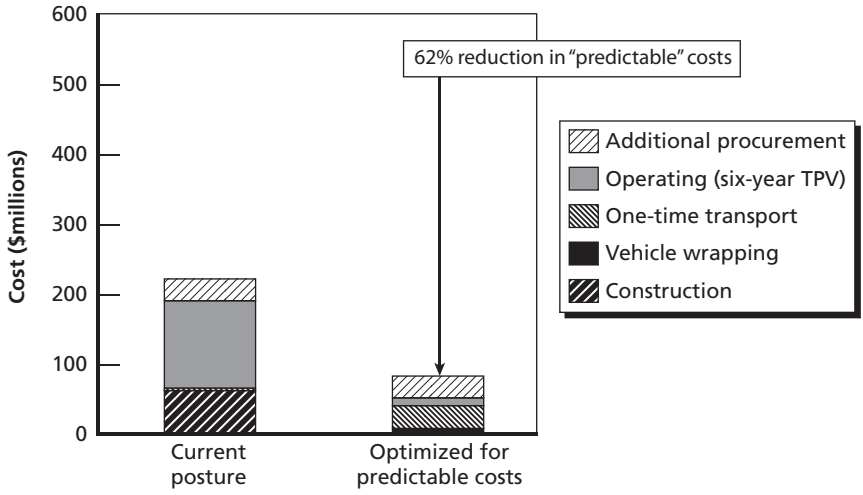
AFB, New Mexico; and Diego Garcia. Note also that this posture uses more "small" FSLs and fewer "medium" FSLs than does the existing WRMV posture.

If the objective function is limited to only predictable costs, the optimization model identifies a posture that reduces these costs significantly. Figure 4.5 contrasts the costs incurred by the current WRMV posture with those incurred by the posture that is optimized against predictable costs. The graph presents the set of costs considered by the optimization model, including those associated with the construction of new facilities, vehicle wrapping costs for those vehicles stored in a wrapped configuration, one-time transport costs associated with moving assets from their current site to a new storage location, and additional procurement costs for any additional vehicles that are required. The operating cost presented here is a six-year TPV.

A fairly substantial construction cost is identified for the current posture. This occurs for two reasons. First, as mentioned above, we

Figure 4.5
Cost Comparison When Optimized for Predictable Costs Only



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assume that all vehicles require inside storage and that all required facilities must be built. Thus, we are presenting a construction cost to house the relatively large number of assets currently stored outside. Second, note that an additional procurement of vehicles was identified as necessary to support the requirements of this set of deployments.[16] The facility requirements to support these additional assets also generate some construction costs.

Observe that there is an extremely large difference in operating costs between the current posture on the left and that optimized for predictable costs on the right. This difference is primarily due to the differences discussed above between wrapped and unwrapped vehicles. For the current posture, we assumed the current allocation of assets to FSLs and assumed that all vehicles (including any additional vehicles that

[16] Some of this additional procurement could potentially be offset by joint-use WRMV assets, which were excluded from this analysis.

were procured) would be stored unwrapped.[17] The optimized posture, however, makes extremely high use of vehicle wrapping (blue and black segments of the pie chart in Figure 4.4), allowing for greatly reduced storage costs. Note that the optimized posture uses permanent, on-site maintenance at all FSLs except one in South Korea, whereas the current posture has an on-site maintenance capability at all WRMV storage locations. Figure 4.5 demonstrates that the optimization model was able to find a posture that meets the same set of deployment time line requirements but does so with over 60 percent reduction in predictable costs.

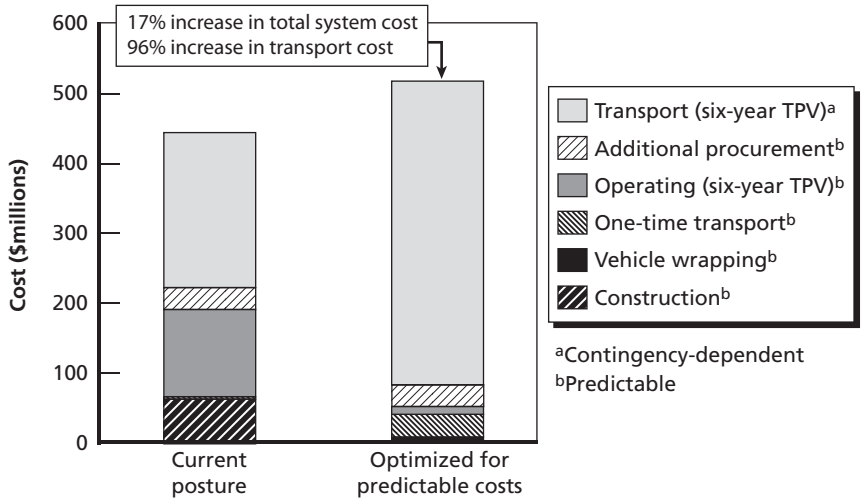
However, designing a prepositioning posture with an aim to minimizing predictable costs can have a detrimental effect on the contingency-dependent transport costs associated with non-MCO deployments. Figure 4.6 contrasts the cost performance of these same two postures with respect to the total system costs, i.e., the sum of the predictable costs and the contingency-dependent non-MCO transport cost. Observe first the relative magnitude of these costs: The transportation cost associated with support to non-MCO deployments is, for the existing posture, approximately equal to the sum of all other cost categories and is over four times larger than this sum for the optimized posture. This suggests that excluding these costs from consideration when developing a prepositioning posture may be a flawed strategy, even when one realizes that many of these costs cannot be accurately forecasted.[18] Note that the posture that is optimized for O&M and construction is susceptible to a larger total system cost than is the current posture. That increase is primarily due to the more centralized nature of this posture and its relative lack of proximity to the deployment locations.

We next allowed the optimization model to identify a posture that minimizes the total system costs, that is, the sum of both the predict-

[17] This is not entirely accurate, since a small number of PACAF vehicles are wrapped as part of the testing program, but this is a small enough effect to have little bearing on the overall cost presented here.

[18] Note that the costs associated with deployment in support of exercises and other planned missions can, however, be forecasted.

Figure 4.6
Cost Comparison When Contingency-Dependent Costs Are Included



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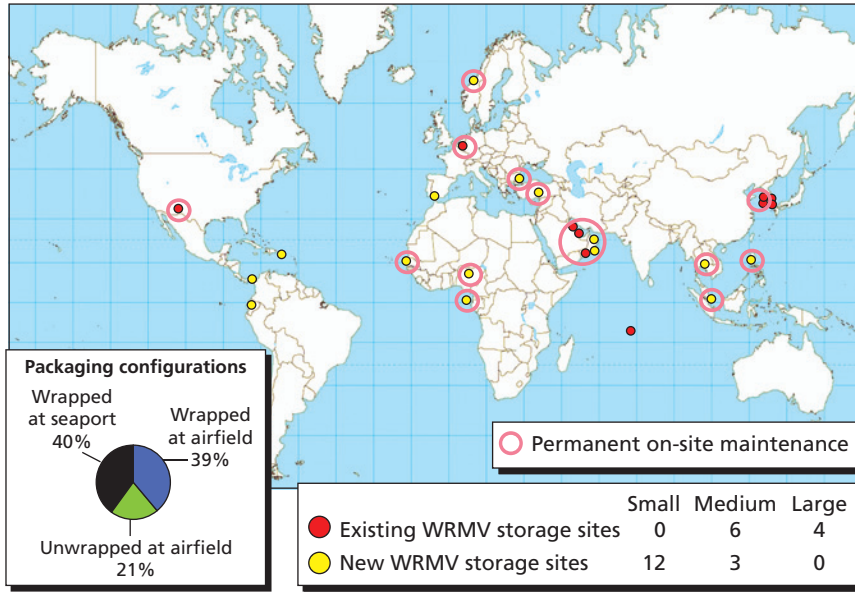
able and contingency-dependent components, against the same set of deployments. Figure 4.7 presents the set of 25 FSLs that were selected by this total system cost optimization. As with the BEAR analysis, the model again identified a cost-optimal posture with a large number of geographically dispersed sites for WRMV. This posture includes a fairly large number of new FSLs, covering many regions where there are no current storage locations, along with the closing of a handful of existing FSLs. Most of these sites also appeared in the cost-optimal BEAR postures identified in Chapter Three, which is not unexpected, since this WRMV analysis used a set of scenarios that were identical to this set of deployment FOLs (although the demanded assets at those FOLs were naturally different). What was not so readily expected, because of differences in maintenance and storage costs between BEAR and WRMV, was that a broadly dispersed posture would also be desirable for WRMV.

Observe that the posture presented in Figure 4.7 makes extensive use of vehicle wrapping, with nearly 80 percent of the vehicles wrapped (blue and black segments of pie chart) and with the wrapped assets distributed evenly across the FSLs' airfields and associated seaports.

Figure 4.7
WRMV Posture Optimized Against Total System Costs



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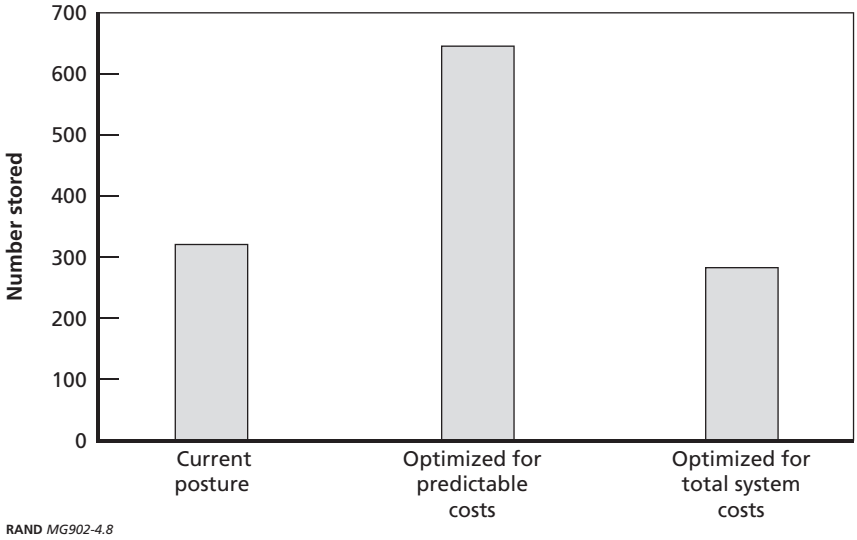
Because 40 percent of the vehicles are stored at seaports in rented facilities, such a posture does not require as large an investment in facility construction at overseas locations as might be expected of a posture with so many new FSLs, which might make it even more attractive to U.S. policymakers. Further, this posture makes significant use of network maintenance, with seven FSLs lacking a permanent on-site maintenance capability and instead supported via traveling maintenance teams.

Not only does the total system minimum-cost posture open a larger number of FSLs than the other two postures examined thus far, it also uses many more "small" FSLs and disperses WRMV assets more evenly across those facilities. Figure 4.8 presents the standard deviation of the number of vehicles stored at each FSL, across these three postures. Note that the posture optimized against the total system cost and the current posture have comparable standard deviation values (the optimized posture's standard deviation is 12 percent smaller); however,

Figure 4.8
Standard Deviation of Number of Vehicles Stored per FSL



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the posture optimized against only predictable costs has a standard deviation that is over twice as large as the value for the other two postures. This much larger value for the posture optimized against solely the predictable costs is consistent with a posture that has a few FSLs with a very large allocation of vehicles and other FSLs with a relatively small allocation of vehicles. Note that such a posture depends heavily on this small number of large FSLs.

Table 4.2 presents a consolidated view of the geographic dispersal associated with these various WRMV prepositioning postures.[19] Observe that the posture optimized against total system costs uses at least four FSLs in each AOR, whereas both the current posture and the posture optimized for predictable costs use four or more FSLs in only one region. Further, the minimum total system cost posture uses three or more "small" FSLs in every AOR except CENTCOM, whereas the

[19] As noted in Chapter Three, because this analysis was performed before AFRICOM was established, here we use the definitions of EUCOM and CENTCOM circa FY07. Note also that we present the total FSLs used across both NORTHCOM and SOUTHCOM in a single category.

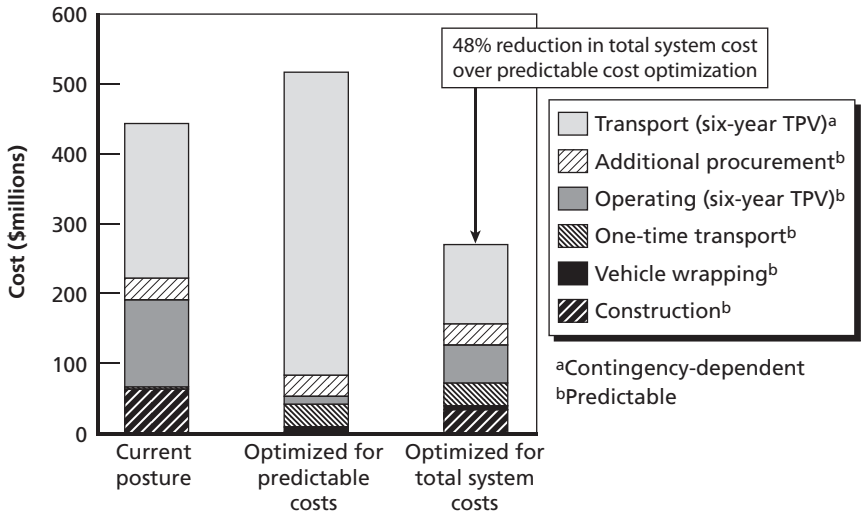
Table 4.2
WRMV Storage Sites Used by Various Prepositioning Postures

	Current Posture	Optimized for Predictable Costs	Optimized for Total System Costs
EUCOM			
Small	1	1	5
Medium	1	1	3
Large	0	0	0
PACOM			
Small	0	0	3
Medium	7	0	2
Large	1	4	3
CENTCOM			
Small	0	2	1
Medium	1	1	4
Large	2	0	0
NORTHCOM/ SOUTHCOM			
Small	0	0	3
Medium	0	0	0
Large	1	0	1

current posture only uses a single "small" FSL, and the posture optimized for predictable costs uses multiple "small" FSLs in only one AOR.

Figure 4.9 contrasts the cost performance of this total system cost optimization with the current posture and the one optimized against predictable costs only. Note that the total system cost optimization, presented by the right-most bar in the figure, accepts an increase in the predictable costs over that in the predictable-costs-only optimization, presented by the center bar in the figure, because that slight increase (concentrated in construction and operations costs) allows for a large reduction in the contingency-dependent transportation costs. The

Figure 4.9
Cost Comparison Considering Total System Costs



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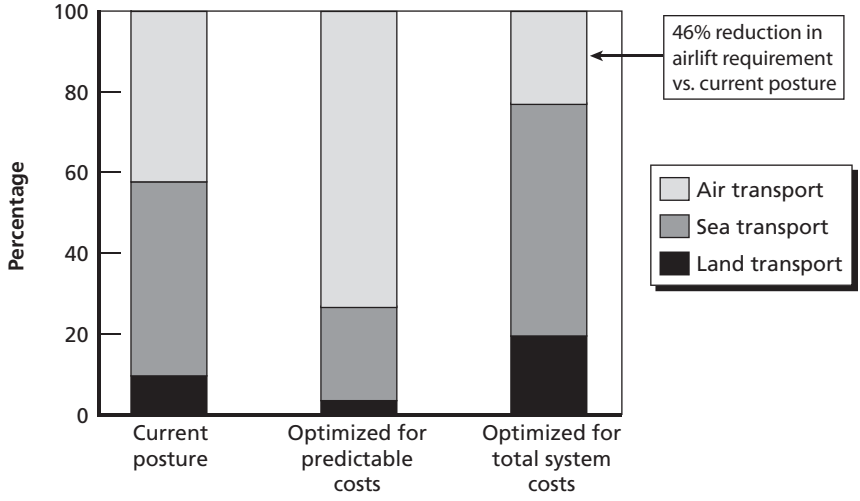
posture that is optimized against total system costs achieves a 48 percent reduction in total costs over the previous optimization. Note further that the posture optimized against total system costs is less expensive than the current posture in terms of both the predictable and contingency-dependent cost components.

Optimizing against total system costs not only significantly reduces total expenditures for this set of scenarios, but also allows for a significant reduction in the reliance on airlift. Figure 4.10 demonstrates that the total system minimum-cost posture can satisfy the same set of time-phased deployment requirements with a 46 percent reduction in tonnage of WRMV transported by air over the current posture. When one considers the limited availability of airlift assets in the early stages of a deployment, this makes a further wartime effectiveness argument for the use of such a dispersed posture, beyond the potential reductions in contingency-dependent costs.

Figure 4.10
Percentage of Tonnage Transported, by Mode



NOTE: The percentage presented as land transport also includes those assets that require no transportation, i.e., assets that are deployed to the FOL from a collocated storage site.

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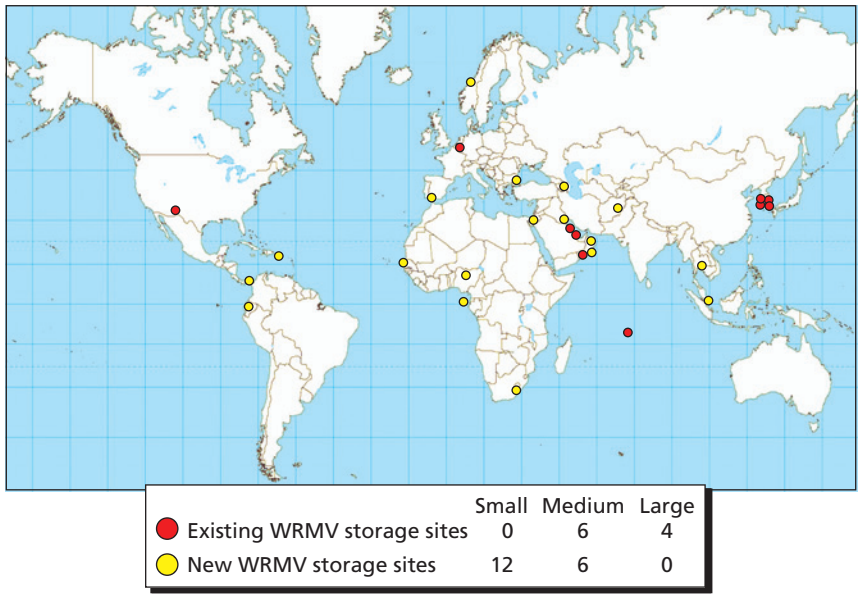
Sensitivity Analyses for WRMV Prepositioning Posture

We also used this analytic approach to perform a number of sensitivity analyses with respect to the WRMV prepositioning posture, evaluating the effect of other policy decisions, such as an AOR-specific management option, decreasing WRMV demands for general purpose vehicles, and modifying the assumptions made about vehicle wrapping, such as allowing wrapped vehicles to be stored outside or limiting the total fraction of vehicles that can be wrapped.

AOR-Specific Options

As with the BEAR analysis in Chapter Three, we performed sensitivity analyses focusing on the relationship between global and regional management. Presented in Figure 4.11 is a minimum-cost posture that allows no cross-AOR support. That is to say, assets that are stored in

Figure 4.11
Prepositioning Posture Allowing for No Cross-AOR Support



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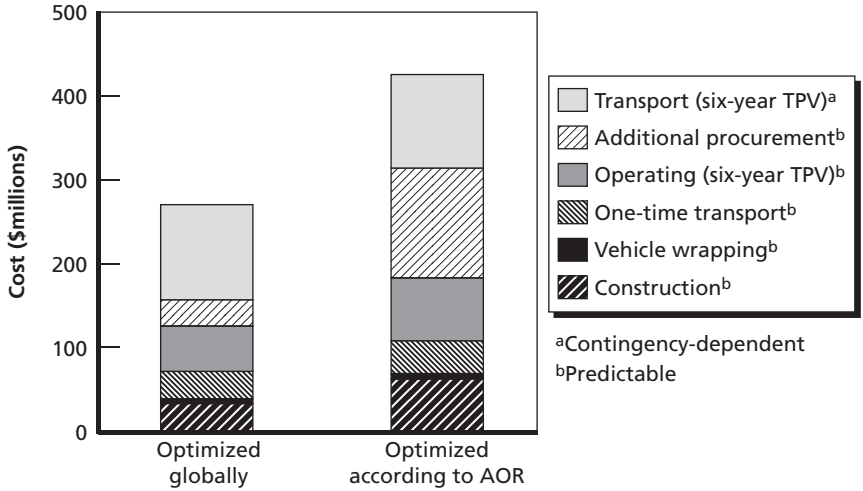
one region may be used to support deployments only within that AOR. Note that we again blurred the distinction between NORTHCOM and SOUTHCOM for any assets stored in the western hemisphere and allowed them to be used for operations within either North or South America.

This approach allows us to demonstrate the cost effects of allowing cross-AOR support by means of a global manager. The bar on the left within Figure 4.12 presents the total system costs for the posture presented in Figure 4.7 that is optimized against total system costs; note that for this posture, we assume that a global manager controls the pool of WRMV and is able to use assets stored in one AOR to support operations in another region. The rightmost bar here is the minimum-cost posture identified when we optimize according to AOR, assuming that assets cannot be used to support operations across AOR boundaries. This difference in cost is primarily due to the large additional procurement necessary if it is assumed that WRMV cannot be used to support

Figure 4.12
Cost Comparison Between Global and AOR-Specific Support



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operations across AOR boundaries, with the attendant increases in facility construction and operations driven by this increased procurement.

Recall that, as was discussed in the AOR-specific management section of Chapter Three, the assumption that assets stored in one AOR cannot be used to support operations in another AOR is not exactly comparable to the current WRM management construct, wherein assets can be moved across regional boundaries, albeit with significant delays associated with the granting of approval to make such movements. Note that the results presented here could also be interpreted as presenting the results of an alternative in which cross-AOR support is allowed but requires a delay of 20 days for approval of moving assets across regional boundaries (thus exceeding the delivery time lines assumed for these optimization runs).

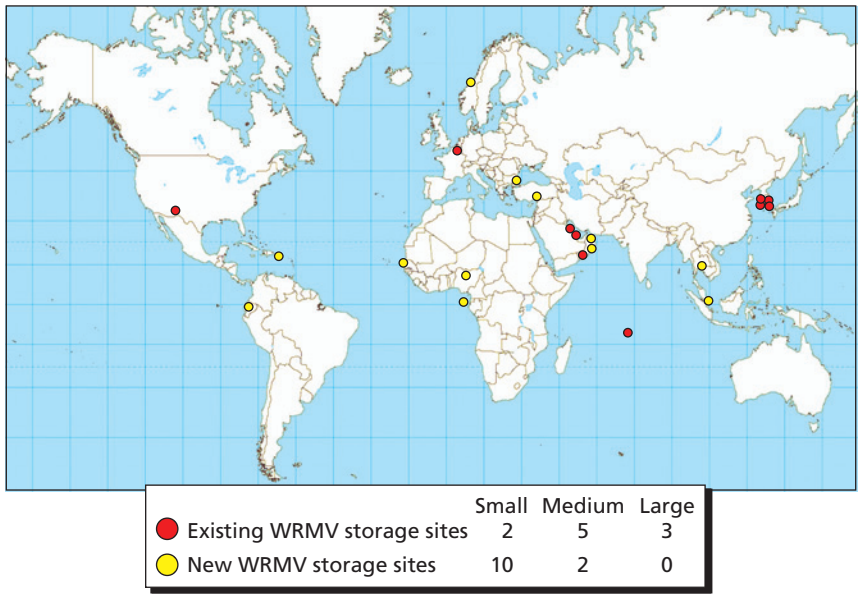
Reducing Demands for General Purpose Vehicles

For many general purpose vehicles, the Air Force currently has fewer vehicles in inventory than appear in its authorization documents. There has been some thought that the Air Force might accept this risk, under

an assumption that it may be possible to lease certain general purpose vehicles when they are needed as contingencies occur, particularly in more developed countries. This strategy would allow the Air Force to reduce its WRMV requirement which would thus affect the prepositioning posture.

We performed an optimization run wherein we reduced the demands for all general purpose WRMV by one-half, to determine the effect of an assumption that the Air Force could lease 50 percent of its general purpose vehicle requirement during contingencies.[20] The posture identified by this optimization is presented in Figure 4.13. Observe that even if the deployment demands for general purpose vehicles are

Figure 4.13
WRMV Posture Assuming Reduced Demands for General Purpose Vehicles



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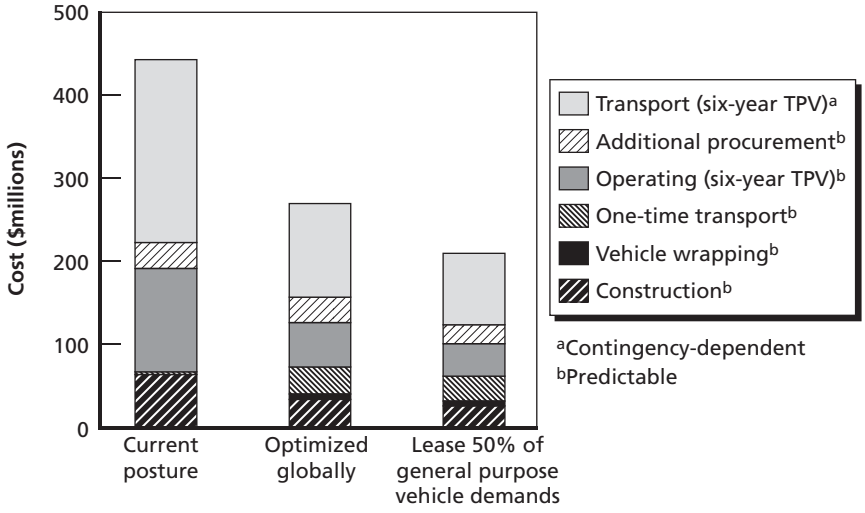
[20] Note that we reduced the demands for general purpose WRMV at all FOLs, including FOLs in less developed countries.

reduced by one-half, the optimization model still identifies a geographically dispersed posture, with two fewer "medium"-sized FSLs and one fewer "large" than the posture identified in Figure 4.7, but one still much more dispersed in terms of number of sites and their geographic locations than in the existing posture. This sensitivity analysis suggests that increasing the dispersal of WRMV assets appears to be a fairly robust recommendation with respect to varying levels of WRMV demand.

Figure 4.14 presents the cost implications of the assumption that general purpose vehicle WRM deployment demands can be reduced by 50 percent. The leftmost and center cost bar present the current WRMV posture and the total system minimum cost WRMV posture, respectively; for each posture, it was assumed that all general purpose vehicle WRM demands had to be satisfied from Air Force WRMV inventories. The rightmost bar presents the costs associated with the posture that requires that only one-half of general purpose vehicle WRM demands be drawn from the WRMV inventory. This provides

Figure 4.14
Cost Effect of Reducing General Purpose WRMV Demands



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a considerable savings of $60 million, over a six-year interval, for the four general purpose vehicle management codes included in this analysis. These four vehicle types, which include two types of pickup truck, a delivery van, and a 40-foot trailer, account for 54 percent of the total general purpose WRM vehicle count and 38 percent of the associated total replacement cost, suggesting that the total cost effect could be much larger if all general purpose vehicle WRM were included. However, these savings would have to be offset by the lease costs associated with obtaining these vehicles at the outset of contingencies, which might be considerably higher than lease costs at other times, as a result of a likely increase in demand for commercial vehicles in such an environment. This set of deployment scenarios and leasing assumption generated a requirement for nearly 3,800 vehicle leases. When considered against the $60 million total savings, this implies that if the vehicles could be leased for less than $16,000, on average, then such a leasing strategy would be less expensive than maintaining all WRMV requirements in the Air Force inventory, for this set of scenarios.

A RAND analysis of contingency contracting purchases in support of OIF developed a database of contingency contracting transactions that included many vehicle leases.[21] From this database, a set of 133 transactions was identified for the lease of commercial vehicles such as trucks, vans, and buses. Across this data set, the average monthly lease cost was $1,444, the maximum monthly lease cost was $6,431, and 60 percent of the monthly lease costs lay between $400 and $1,200.

Note that the average monthly lease costs from this data set are less than one-tenth the $16,000 per-vehicle lease savings calculated above. Because these OIF lease costs are presented on a monthly basis, as long as the average deployment duration lasted 10 months or less, this vehicle lease strategy could be less costly than maintaining all general purpose WRMV in the Air Force inventory. Of course, there is no guarantee that these OIF data would be representative of vehicle

[21] Laura H. Baldwin, John A. Ausink, Nancy F. Cambell, John G. Drew, and Charles Robert Roll, Jr., *Analyzing Contingency Contracting Purchases for Operation Iraqi Freedom,* Santa Monica, Calif.: RAND Corporation, MG-559/1-AF, 2007.

lease costs in other scenarios. Further, the Air Force would be assuming some risk if it were to pursue such a policy, since there is no guarantee that the desired vehicles could be leased at the time of need. An option that might warrant further examination is to make standing lease agreements with commercial firms at certain strategic locations, so that the Air Force is guaranteed access to a certain number of general purpose vehicles as needed, with some negotiated advance notice required for access. Such an arrangement might also allow some cost control in the uncertain environment associated with the early stages of a contingency.

Allowing for Outside Storage of Wrapped Vehicles

For the WRMV analyses presented thus far, we have assumed that all vehicles must be stored inside warehouses. The PACAF WRM vehicle handbook states that vehicles can be stored outside at certain locations (South Korea and mainland Japan) if 10-millimeter plastic wrap is used.[22] This handbook does not authorize outside storage at certain locations, such as Alaska or Diego Garcia, because of their extreme weather conditions. However, this can be viewed as a conservative restriction, since the plastic material and the preservatives used in the wrapping process are designed to allow outside storage of vehicles even in cold or hot and humid conditions.

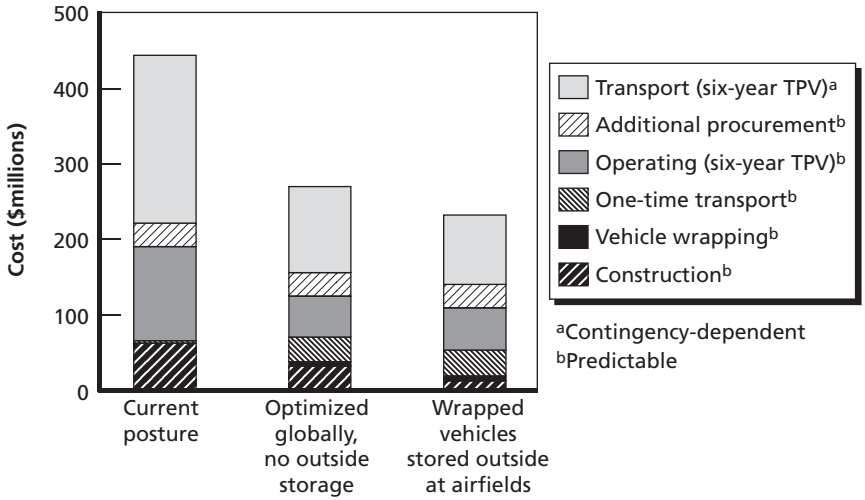
Thus, we performed a sensitivity analysis wherein we still required that all unwrapped vehicles be stored inside warehouses, but we allowed wrapped vehicles to be stored outside at all FSLs. We used the total system minimum-cost optimization model, which returned a set of opened FSLs that was identical to the set of FSLs presented in Figure 4.7, the total system minimum-cost posture that assumed that wrapped vehicles required inside storage. However, the allocation of WRMV to FSLs changes somewhat when wrapped vehicles are permitted to be stored outside, with more "medium"-sized FSLs used, and considerably more WRMV stored in a wrapped configuration at FSLs' airfield sites (56 percent compared with 39 percent in the Figure 4.7 posture), and a smaller proportion of WRMV stored in the other con-

[22] PACAF, 2003.

figurations (18 percent stored unwrapped at the airfields and 26 percent stored wrapped at the FSLs' associated seaports, compared with 21 and 40 percent, respectively, for these configurations in the Figure 4.7 posture).

Figure 4.15 demonstrates the effect on total system cost if wrapped WRMV are permitted to be stored outside. Such a policy reduces the total system cost, presented by the rightmost cost bar in the figure, by 14 percent when contrasted with the minimum cost possible when all vehicles must be stored inside, presented by the center cost bar in the figure. Most of this cost reduction comes from a reduction in the facility construction costs. However, there is also a sizable reduction in deployment transportation costs when wrapped vehicles are stored outside. Much of this reduction in transportation costs is achieved because the WRMV posture when all assets must be stored inside of warehouses has 83 percent of its vehicles stored at existing FSLs, whereas the minimum-cost posture when wrapped vehicles are allowed to be stored outside allocates only 69 percent of its vehicles to existing

Figure 4.15
Cost Effect of Allowing Wrapped WRMV to Be Stored Outside



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locations. Eliminating the inside storage requirement allows more assets to be stored at locations that do not have an existing facility infrastructure, placing more assets nearer to potential FOLs.

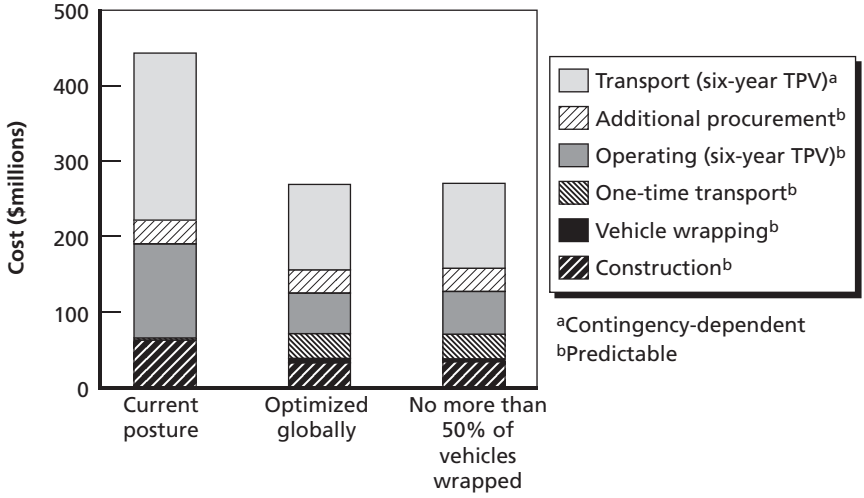
Limiting the Fraction of Wrapped Vehicles

Observe that in the optimized WRMV postures that have been presented thus far, a large fraction (80–85 percent) of the total vehicles have been stored in a wrapped configuration. Although data provided by PACAF suggest that wrapped vehicles can actually be brought out of storage and prepared for use more quickly than unwrapped inactive stored vehicles, such wrapped vehicles would require more time to prepare for use than would active stored vehicles, particularly when considering that wrapped vehicles would not have received any Time Change Technical Order (TCTO) maintenance during the period in which they were wrapped; if such maintenance had to be performed before a wrapped vehicle could be used in a contingency, a considerable delay could be incurred.

To test the sensitivity of the optimization solutions to this heavy reliance on vehicle wrapping, we added a constraint that limited the total number of wrapped vehicles to no more than one-half of the total WRMV count. It was assumed that all vehicles must be stored inside warehouses. The minimum-cost posture obtained from this optimization uses 24 FSLs, differing from the set of opened FSLs in the total system minimum-cost posture presented in Figure 4.7 by one location: The FSL at Rota, Spain, is no longer used. The allocation of vehicles to FSLs is very different, however, with 24 percent of the vehicles wrapped at the FSLs' airfields, 26 percent wrapped at the FSLs' associated seaports, and 50 percent unwrapped at the airfields. Further, this posture uses fewer "small" FSLs and more "medium"-sized FSLs than does the posture presented in Figure 4.7.

Figure 4.16 demonstrates the cost effect of constraining the number of wrapped vehicles to be no more than one-half of the total. The rightmost cost bar in this figure presents the total system cost incurred by adding such a constraint. Observe that this cost is an increase of less than 1 percent over the total system cost when no such constraint is imposed, presented by the center cost bar. Note further that both of

Figure 4.16
Cost Effect of Limiting the Number of Wrapped WRMV



RAND *MG902-4.16*

these FSL postures—one with 50 percent of its WRMV wrapped and the other with 80 percent—achieve significant cost reductions over the current posture's total cost (indicated by the leftmost bar in the figure). Thus, these cost reductions do not depend entirely on extremely high use of vehicle wrapping but appear to result primarily from the more dispersed nature of the optimized FSL postures, with considerable latitude existing with respect to the storage configuration of WRMV.

CHAPTER FIVE

Identifying Robust and Reliable Prepositioning Postures

In Chapter Two, we presented mathematical models for identifying WRM prepositioning postures that address either *robustness to uncertain future requirements*, producing an FSL posture capable of satisfying the time-phased demands for assets at FOLs across multiple sets of potential future deployments, or *reliability in the event of unplanned network disruptions*, producing an FSL posture that is able to satisfy such demands even in the event of a short-term loss of access to prepositioned material at any single FSL. In this chapter, we apply these robustness and reliability concepts to analyses of the global BEAR posture.[1]

Robustness to Uncertain Future Requirements

The analyses presented in Chapters Three and Four focused on determining minimum-cost FSL postures, subject to varying additional constraints, but all were evaluated against a single set of deployment requirements. Such an approach, even if it focuses on a "most likely" set of future scenarios, is not adequate in the current security environment, where the Air Force faces significant uncertainty with respect

[1] Note that we performed no such robustness or reliability analyses for WRMV in this research project. Such computations could have been performed, using a similar approach, but the BEAR example presented was thought to provide a sufficient example of the robustness and reliability concepts under consideration.

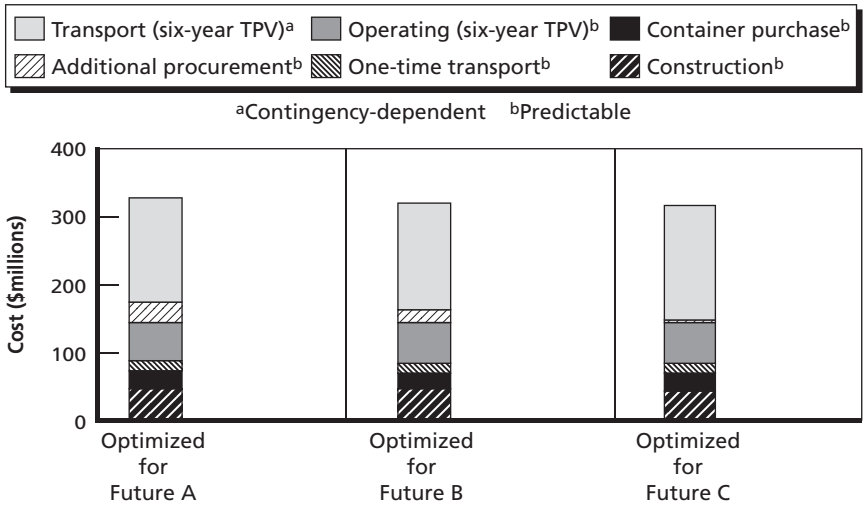
to the location, timing, and intensity of future deployments. As was discussed in Chapter Two, we modified our optimization models to include an ability to identify robust prepositioning postures that perform well across multiple possible futures. In this section, we will use these models to evaluate BEAR prepositioning postures against multiple sets of deployment requirements.

We created three alternative futures based on scenarios from the SPG. Each future consists of a six-year interval with a set of deployments supporting lesser contingencies and exercises, and deployments supporting MCOs; we label them Future A, Future B, and Future C. Future A corresponds to the set of scenarios analyzed in Chapter Three.

We first performed three separate runs of the optimization model to find the minimum-cost BEAR posture for each individual future. The only input data varied across these three model runs were the set of deployment requirements. Using this procedure, the model identified a different minimum-cost posture for each future. In Figure 5.1, we present the total system cost associated with each of these optimization runs. Note that each bar represents the minimum total system cost that can be achieved for an individual future and that the posture achieving this minimum cost differs for each future. The cost bar associated with Future A is identical to the total system minimum cost presented in Figure 3.7

However, optimizing for a single future can generate a posture that performs poorly if evaluated against a different set of deployment requirements. Consider the posture that was optimized against the requirements of Future C. If we take that posture and evaluate its performance against the set of deployments contained in either Future A or Future B, we observe that it cannot satisfy the demands of either alternative future. That is, starting from the Future C posture, it is not possible to deliver the required BEAR assets to the FOLs in Future A or Future B within the 10 to 20 day delivery time lines. In fact, there is no guarantee that a posture optimized against any one of these futures can satisfy the deployment requirements of any other future.

Figure 5.1
Cost Performance of Postures Optimized Against Alternative Futures

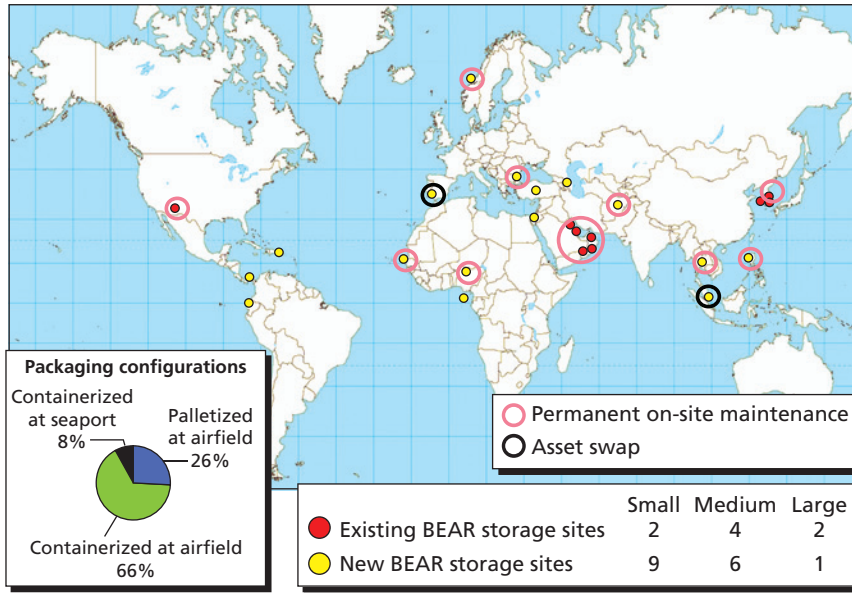


RAND *MG902-5.1*

Using the robust optimization of Chapter Two, we allowed the mathematical models to identify a posture that can meet the deployment requirements for any of these three alternative futures, while minimizing the average total cost across all futures.[2] The BEAR posture returned by this robust optimization is presented in Figure 5.2. This robust posture is also quite dispersed, employing 24 FSLs. Many of these FSLs also appeared in the posture of Figure 3.5 that was optimized against only Future A; the robust posture differs in that it opens additional FSLs in Rota, Spain; and Baku, Azerbaijan; it does not use FSLs in Seeb, Oman, and Diego Garcia; and it closes one of the South Korean FSLs. The robust posture uses more "medium" and "large" FSLs than does the posture of Figure 3.5. This robust posture is also similar to the posture of Figure 3.5 in that it makes heavy use of

[2] As discussed in Chapter Two, many options exist for a minimum-cost objective function in a multiscenario setting. One could minimize the maximum cost incurred in any single scenario (worst-case approach) or minimize a weighted average across the scenarios. The results presented here minimize the average cost across all scenarios, with no weighting of any scenario as more important or likely than others.

Figure 5.2
BEAR Posture That Performs Well Across Multiple Futures



RAND *MG902-5.2*

containerization (green and black segments of the embedded pie chart), storing nearly three-quarters of the BEAR assets in containers. The robust posture also makes fairly significant use of network maintenance concepts, with two FSLs supported by asset swap and nine FSLs supported by traveling maintenance teams.

Table 5.1 presents a consolidated view of the geographic dispersal associated with these various prepositioning postures.[3] Observe that the robust posture is very similar to the three postures that are optimized against individual futures with respect to the geographic distribution of FSLs. In fact, the primary differences appear to be the fact that the robust posture uses more "medium"-sized FSLs in PACOM

[3] As noted in Chapter Three, because this analysis was performed before AFRICOM was established, here we use the definitions of EUCOM and CENTCOM circa FY07. Note also that we present the total FSLs used across both NORTHCOM and SOUTHCOM in a single category.

Table 5.1
BEAR Storage Sites Used by Robust and Nonrobust Prepositioning Postures

	Optimized for Future A	Optimized for Future B	Optimized for Future C	Robust Posture
EUCOM				
Small	2	4	4	3
Medium	3	2	3	3
Large	1	1	1	1
PACOM				
Small	7	6	3	3
Medium	1	2	2	3
Large	0	0	0	0
CENTCOM				
Small	4	3	5	4
Medium	3	3	2	2
Large	0	0	0	1
NORTHCOM/ SOUTHCOM				
Small	1	1	0	1
Medium	2	2	2	2
Large	1	1	1	1

than the other postures; and the robust posture also uses a "large" FSL in CENTCOM, unlike the other three postures. Thus, it appears that rather minor modifications to the posture can provide robustness across multiple futures.

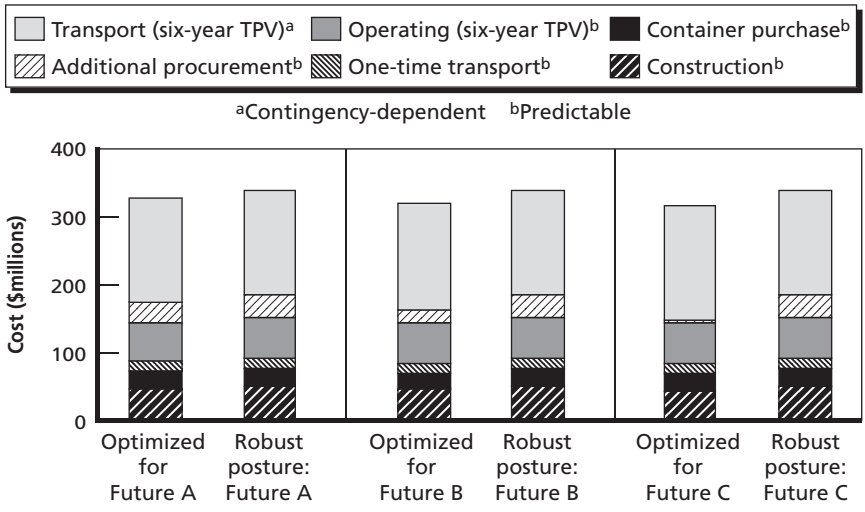
A proper analysis of robustness considerations should demonstrate the cost associated with building varying levels of robustness into a system. It is possible that, in order to achieve a specified level of robustness across multiple sets of scenarios, the cost of the prepositioning

posture becomes prohibitively more expensive than the cost associated with a posture that is able to support a "most likely" set of scenarios.

Figure 5.3 presents the costs associated with this robust posture across the three alternative futures. The three cost bars labeled "robust posture" present the costs that are incurred if the robust prepositioning posture is implemented and each of the three futures occurs. Note that the predictable costs remain constant across the three robust posture cost bars, because the same set of BEAR storage and maintenance locations and allocation of BEAR assets is implemented in each. The only differences in cost are the contingency-dependent non-MCO transport costs, which vary according to the set of deployments included in each future.

Focus now on the two leftmost bars. The left of that pair presents the minimum achievable cost for a BEAR posture that can support the requirements of Future A and is associated with a posture that was optimized against solely that future. The cost bar immediately to its right demonstrates that the robust posture is more expensive in support of

Figure 5.3
Cost Comparison of Robust and Single-Future Optimized Postures



RAND *MG902-5.3*

Future A, which is to be expected when any alternative is compared to the minimum-cost posture. Note, however, that this penalty is not very large—a total cost increase of only 4 percent. This is likely a small premium to pay for the ability to support multiple alternative futures. Similar results apply to the other two futures analyzed, with total costs increasing only 6 to 8 percent for the robust posture. This suggests that it is possible to identify a robust BEAR prepositioning posture that can both support the deployment requirements associated with multiple alternative futures and incur a only a small cost increase over the minimum cost that can be achieved for any single future.

Reliability in the Event of Network Disruption

Loss of access to a prepositioning site could occur for a number of reasons. A host nation that was not willing to support U.S. involvement in a particular contingency could deny the Air Force access to its assets. Events during the buildup to OIF, such as the difficulties securing basing access in Turkey, underscore the importance of developing a reliable prepositioning posture that retains options for U.S. forces. Such difficulties can potentially be expected from even the closest U.S. allies, as was demonstrated by the resistance of the United Kingdom to grant overflight rights to the United States during operation Nickel Grass, the U.S. airlift to Israel during the 1974 Israeli-Arab conflict.[4] The Air Force could also potentially lose access to a prepositioning site as a result of a natural disaster, such as the Southeast Asian tsunami of 2004 or the Mount Pinatubo volcano eruption in 1991, if the Air Force were to have storage sites in locations affected by the disaster. One could also envision potential attack by an adversary on a prepositioning site, particularly during the early days of a contingency, when WRM assets are most needed.

[4] David A. Shlapak, John Stillion, Olga Oliker, and Tanya Charlick-Paley, *A Global Access Strategy for the U.S. Air Force,* Santa Monica, Calif.: RAND Corporation, MR-1216-AF, 2002.

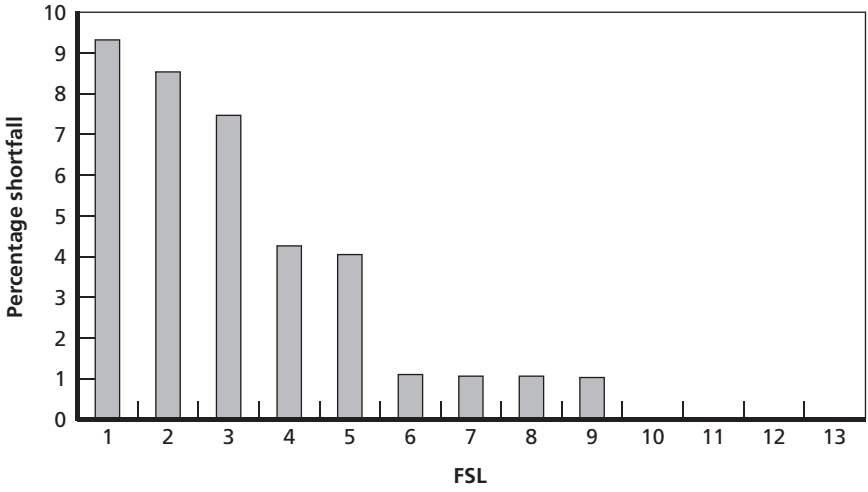
Unfortunately, cost minimized network designs often produce a relatively brittle posture, which performs very poorly in the event of disruption to the network. This occurs because a traditional cost optimization approach typically relies on a small number of very cost-effective nodes. That is to say, these optimization approaches generally identify a set of highly cost-effective facilities and then heavily utilize these facilities. Such a strategy can lead to very poor performance in the face of disruptions, particularly when an adversary can target a network's most critical nodes or links. However, as was presented in Chapter Two, we have produced an optimization approach to identify a prepositioning posture that is able to satisfy WRM delivery requirements even in the event of loss of access to any prepositioning facility. We will assume that, if access is lost to FSL *b*, following the end of the disruption period, the assets at FSL *b* will again become available for use. Recall that for this reliability model, we will assume that only one set of future deployment scenarios will be addressed for each model run.[5]

To demonstrate this concept, we consider a scenario in which access is lost to a single BEAR storage facility for a period of 30 days in year 6 of Future A.

First, let us consider the performance of the current posture, should such a disruption occur. Consider the existing BEAR posture presented in Chapter Three, for which sufficient additional inventory was added to the current authorization levels to allow all demands to be satisfied. Figure 5.4 shows the percentage of demands for BEAR assets that are unsatisfied if access is lost to a single facility over such a 30-day interval. A single bar is presented for each of this posture's 13 facilities, demonstrating the effect if that particular FSL were to be temporarily lost as a result of disruption. For example, the leftmost bar shows the worst-case situation; loss of access to this single facility would result in

[5] It is possible to extend these concepts to build a model that could simultaneously address both reliability against disruption and robustness to uncertain future demands, but such a model would require many more variables and constraints than the models presented here, which are already so large as to approach the computational limits of current desktop computers.

Figure 5.4
Shortfall Below Demand Resulting from the Loss of an FSL, Current BEAR Posture

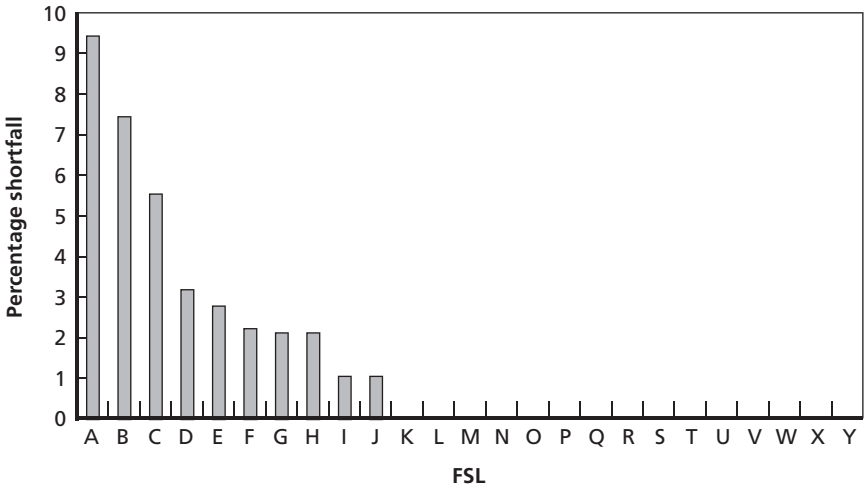


RAND *MG902-5.4*

over 9 percent of the worldwide BEAR delivery requirements during the failure interval being unsatisfied. The bar immediately to the right of this demonstrates what happens if the posture's second most critical facility were to be temporarily lost, and so on. Note that there are four FSLs for which all demands could be satisfied even in the event of loss of access to the FSL. These are likely small storage sites that do not play a significant role in the overall BEAR posture.

In a similar manner, we can also evaluate the effect of facility disruption on the total system minimum-cost posture presented in Figure 3.5. Figure 5.5 presents the percentage of demands for BEAR assets that are unsatisfied if access is lost to a single FSL in this optimized posture over such a 30-day interval. This minimum-cost posture is equally vulnerable to the loss of its most critical FSL as was the current posture, with the worst-case shortfall approaching 10 percent of BEAR demands worldwide, because of the relative brittleness of this posture.

Figure 5.5
Shortfall Below Demand Resulting from the Loss of an FSL, Cost-Optimized BEAR Posture



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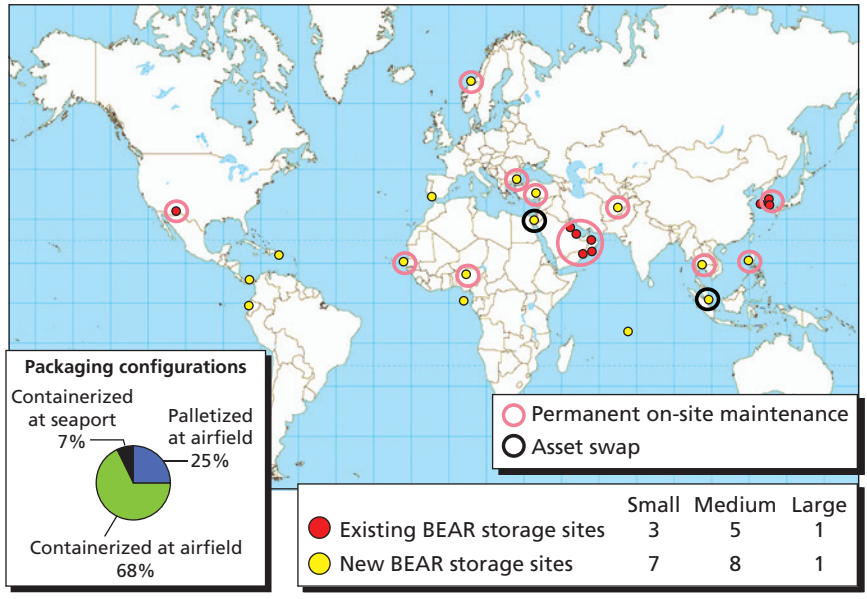
We next used the modified math model presented in Chapter Two to identify a BEAR prepositioning posture that can satisfy all deployment demands even in the event of loss of access to any FSL, while simultaneously minimizing the worst-case cost.[6] Figure 5.6 presents this reliable BEAR prepositioning posture. Observe that the set of FSLs opened in this posture is nearly identical to the set of sites determined from the minimum-cost optimization model that did not address potential loss of access to FSLs, differing by only one FSL, with one of the South Korean sites in the earlier, non-reliable, posture being closed and replaced by an FSL at Rota, Spain, in the reliable posture. When compared with the posture identified in Figure 3.5, the reliable posture uses fewer "small" FSLs and more "medium"-sized FSLs. The reliable posture again makes significant use of containerization, storing

[6] As was discussed in Chapter Two, for such models there are multiple ways to identify a "minimum-cost" objective; the approach presented here is a "minimax" approach that minimizes the maximum cost possible across all potential FSL failures.

Figure 5.6
BEAR Posture That Is Reliable in the Event of Disruption



RAND *MG902-5.6*

three-quarters of BEAR assets in containers. This reliable posture also makes considerable use of networked maintenance concepts, with the asset swap concept used at two FSLs and the traveling maintenance team concept employed at seven FSLs.

However, when considering reliability in the event of potential disruptions, one also needs to address the cost associated with building the necessary redundancy into the system to provide such reliability. Figure 5.7 presents such details.

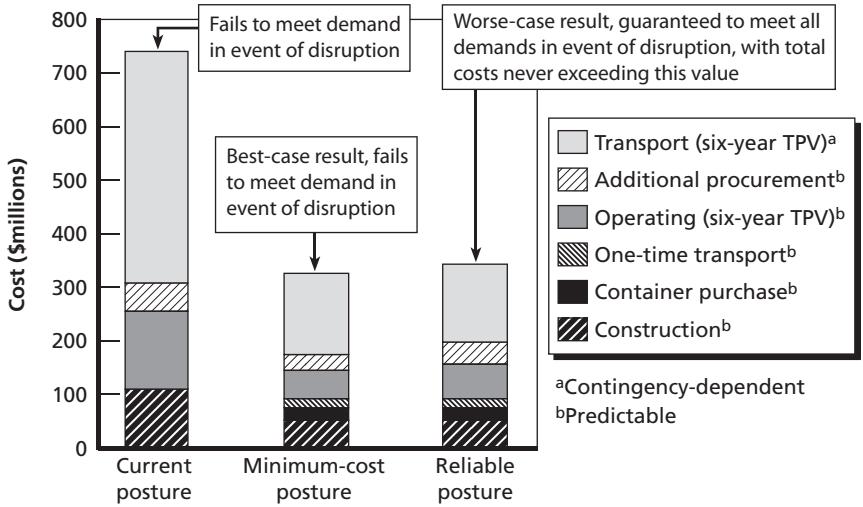
Focus first on the center bar, denoting the total system minimum-cost posture presented in Chapter Three, which cannot satisfy all demands in the event of disruption. The center bar can be thought of as a best-case result. That is, if access to all sites could be assured, it is possible to reduce costs to this level. However, recall that this minimum-cost posture fails to meet nearly 10 percent of deployment requirements in the event of disruption to a single FSL.

The rightmost bar denotes the BEAR posture that is reliable in the event of short-term loss of access to any FSL. It can be thought of as a worst-case result. That is to say, if such a posture is implemented, it is guaranteed to satisfy all demands for this set of deployments in the event of a disruption to any single FSL. Further, the model ensures that the total cost would never exceed the value presented on this bar. Even in the worst case, this posture would meet all demands at a cost that is only 6 percent greater than the best-case minimum cost. The leftmost bar in this figure presents the similar best-case cost of the current posture, which is very expensive and, as demonstrated above, fails to fully meet demands in the event of disruption.

There are other options for building a level of reliability in the event of disruption into the prepositioning posture. For example, some attention has been given to the potential storage of assets on an afloat prepositioning ship. Our prior analysis suggests that this is not a cost-effective strategy.[7] In fact, we note that the six-year TPV cost to operate a single afloat prepositioning fleet (APF) ship is on the order of $60 million, equal to roughly 20 percent of the total reliable optimization cost, and that such a ship could hold only about 10 percent of the total amount of inventory presented in Figure 5.7. Afloat storage is expensive because the Air Force is essentially paying for continuous transport of WRM assets regardless of whether the assets are being moved in support of an actual deployment. The Virtual Afloat concept, which is used in this reliable posture for a relatively small amount of assets (an amount comparable to the capacity of a single APF ship), allows many of the benefits of afloat storage to be realized without incurring the APF's large costs during periods in which assets are not being transported in support of deployments. Other drawbacks to afloat storage that were noted in our earlier monograph include the relatively large size of the ships that were considered, requiring access to deepwater ports, which may necessitate a long road march from the deepwater seaport to the FOL, along with potential difficulties in getting access to afloat-stored assets for maintenance.

[7] Amouzegar et al., 2006.

Figure 5.7
Effect of Reliability on Cost



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Strategies Used in a Reliable Posture

Let us briefly consider the mechanisms that are available to networks that allow them to deal with disruptions, in an attempt to understand how the reliable network can achieve such strong performance in the face of disruption. The primary strategies for coping with disruptions are building redundancy into the system or redistributing risk across facilities. Three techniques that use these strategies are procuring additional inventory, opening additional facilities, and distributing inventory more evenly across facilities.

In what circumstances would we expect each of these techniques to be most beneficial? Procuring excess inventory should be desirable when procurement costs are low relative to other cost categories and when the operating and maintenance costs for assets are low relative to

the other costs.[8] The technique of opening additional facilities should be desirable when construction costs are low relative to other costs or when the transport throughput constraints associated with movement of assets out of storage locations are relatively tight. The third strategy of more equitable distribution of inventory across facilities should be desirable when transportation costs are low, allowing more assets to be stored at sites that are not necessarily the closest to the locations where they would be used, or if strong economies of scale are not present. Note that this analysis assumes that there were no economies of scale associated with the storage and PMI operations for WRM assets.

Returning now to the reliable posture identified by the optimization model, we can evaluate to what extent this posture uses each of these techniques. The reliable posture procures only one additional 550i housekeeping set beyond the minimum-cost posture. Recall that the set procurement costs here are in the range of $6 million to $10 million, with the exception of the FO set, which is about $1 million. Contrast these procurement costs with the reliable posture's total system cost of approximately $300 million, over six years. Thus, even though procurement costs are not particularly high in this example, the reliable posture procures only slightly more inventory than does the minimum-cost posture. Both the fault-tolerant posture and the minimum-cost posture have an equal number of facilities and, with one exception, use the same locations. Thus, the reliable posture achieves fault tolerance without opening large numbers of additional facilities. Finally, the reliable posture has a somewhat more evenly distributed inventory than does the minimum-cost posture, with the standard deviation of the number of assets stored across facilities being about 4 percent less than for the reliable posture. The reliable posture thus does not make extensive use of this technique, either. However, it is the combination of these effects that allows the reliable posture to guarantee that all demands can be met in the case of loss of access to an FSL, at a very small cost increase over the minimum-cost alternative.

[8] This technique would also be beneficial if procurement lead times are particularly long.

CHAPTER SIX

Conclusions and Potential Extensions to Research

This monograph has extended RAND's analytic framework for Air Force WRM prepositioning to include a number of factors not addressed in previous work, such as alternative packaging configurations for assets and networked maintenance concepts for WRM. It has also advanced the mathematical models that lie at the heart of this framework, by developing two optimization models addressing uncertainty—one that addresses robustness to uncertain future demands and the other addressing reliability in the event of disruption at the FSLs used for WRM storage. This analytic framework was applied to a review of prepositioning strategies for two classes of WRM assets: BEAR and WRMV.

Conclusions

A geographically dispersed set of a large number of WRM FSLs is attractive when one considers the balance between predictable and contingency-dependent costs. The traditional approach to identifying prepositioning postures is to select a set of locations that satisfies MCO delivery requirements while minimizing a set of predictable costs, such as facility construction, operations and maintenance, asset procurement, and the one-time movement of assets to their new storage sites. The contingency-dependent transportation costs associated with moving the assets from FSLs to FOLs have not traditionally been considered in such analyses, because the costs associated with executing MCOs would be funded through a supplemental request,

outside the set of programmable costs used to develop the capabilities, such as prepositioning postures, needed to support MCOs. However, recent OSD guidance directs that the Armed Forces should plan for a security environment requiring continuous engagement in multiple small deployments around the globe, while maintaining the ability to execute MCOs. Although MCO execution costs would remain outside the programmed budget and supported through supplemental budget authorizations, because many of these lesser contingencies will likely require the use of WRM, it is unclear to what extent the costs associated with these smaller deployments, many of which may be exercises, should be included in the services' programmed budgets as opposed to supplemental budget requests.

The ability to satisfy time-phased WRM delivery requirements remains the primary consideration; thus, throughout our analysis, all prepositioning postures that are presented satisfy the deployment effectiveness constraints. Each alternative posture can then be evaluated with respect to its level of cost and risk.[1] We used our optimization model to find minimum-cost postures that meet all deployment requirements (both steady-state and MCO) but minimize only predictable costs and found that the model identified postures that were concentrated into a small number of FSLs and that heavily used existing WRM prepositioning sites. We then allowed the optimization model to identify postures that minimized the total system costs (i.e., the sum of predictable and contingency-dependent costs, excluding MCO transportation costs) and observed that the model suggested postures that were geographically dispersed into a large number of FSL sites, often at new locations.

There are significant cost implications associated with these very different WRM prepositioning strategies. Because the strategy that focuses on predictable costs only does not include contingency-dependent transportation costs in its decisions, it can be subject to extremely high transportation costs for non-MCO operations in future environments as defined by the DoD SPG. The strategy that considers

[1] Thus, the analysis presented in this monograph can be viewed as a constant-effectiveness, variable-cost, and variable-risk analysis.

total system costs can accept additional investment in predictable costs (for BEAR assets in one of the potential futures that we examined, the total system cost posture required an investment of $176 million in TPV over six years for predictable costs, compared with $118 million TPV for the posture optimized against predictable costs only), because these cost increases are more than offset by significantly reduced non-MCO transportation costs ($152 million for the total system cost optimization and $470 million for the predictable cost-only optimization). The finding that a dispersed set of WRM FSLs could accept a relatively small increase in predictable costs that would be offset by much larger reductions in contingency-dependent costs was consistent across all of the sets of scenarios that were examined for both BEAR and WRMV, including scenarios in which the non-MCO deployment demands were reduced significantly.

Alternative packaging configurations and maintenance concepts can allow such dispersed WRM prepositioning postures without incurring significant investments in infrastructure construction. A dispersed posture that achieves significant reduction in total system cost might still be undesirable to policymakers if it required a large investment in permanent infrastructure to be built at foreign locations. However, if BEAR assets, which are currently all stored in an airlift-friendly palletized configuration requiring inside warehouse storage, were to be packaged in shipping containers, much of this construction cost could be avoided. This is because steel shipping containers do not require inside storage; in effect, the container serves as the warehouse. Such a strategy was found to be attractive in all of the scenarios analyzed by our optimization models, with optimization solutions storing between 70 and 75 percent of BEAR assets in containers, of which 5 to 10 percent were stored at seaports, consistent with the Virtual Afloat concept. Storing assets in commercial containers also offers other qualitative benefits, such as allowing assets to blend in with the large number of nonmilitary containers moving through civilian supply chains, not noticeable to most observers as military cargo.

We also examined an alternative packaging configuration for WRMV, in which vehicles are shrink-wrapped in plastic and have pre-

servatives added that allow the vehicle to remain in a ready state without regular maintenance inspections for up to three years. This wrapping configuration can also allow vehicles to be stored outside in some environments. Even if inside storage is required for wrapped vehicles, our analysis suggests that a lease of commercial warehouse space would be cost-effective and not overly risky for such wrapped vehicles.

This analysis also considered alternative maintenance concepts for the PMIs performed on WRM. The traditional approach uses a permanent on-site maintenance capability collocated with the WRM storage site. For BEAR assets, we examined the traditional approach along with two alternative concepts: traveling maintenance teams, where a team of maintainers periodically travels from a site with permanent BEAR maintenance to storage sites lacking a permanent maintenance capability, and asset swap, wherein assets requiring maintenance are moved out of storage sites that do not have a permanent on-site maintenance capability and are replaced with serviceable assets sent from an FSL with permanent on-site maintenance. The cost-optimized postures produced by our models made significant use of these alternative maintenance concepts for BEAR. Although asset swap was not considered as an alternative for WRMV because of the frequency and short duration of WRMV inspections, the model again identified postures that make significant use of traveling maintenance teams. These alternative maintenance concepts can further reduce the facility and infrastructure required at new FSLs because of the reduced requirement for maintenance facilities and equipment at sites using these concepts.

Cross-AOR support can significantly reduce WRM requirements and cost. WRM assets are currently positioned on an AOR-specific basis, with a focus on support of MCOs within each AOR. Although there is currently some capability for cross-AOR support, wherein assets stored in one AOR are used to support operations in another, it requires that approval be granted quite high up the Air Force chain of command, which can cause such long delays that tight delivery time lines may not be met. We performed sensitivity analyses to examine the effect of an optimized global WRM management construct, where assets could potentially be moved from any FSL to any FOL without any additional delay for cross-AOR shipments, against

an alternative that was optimized but did not allow for any cross-AOR support (this alternative could also be interpreted as one in which cross-AOR support is allowed but requires a delay of 20 days for approval to move assets across regional boundaries, thus exceeding the delivery time lines assumed for these optimization runs).[2] The global management of WRM assets achieved very large cost reductions in such an environment, primarily because the shared global pool of WRM reduces the total requirements for WRM assets. Further, when considering that potential combat operations may occur near the boundary of multiple geographic commands (e.g., the Caucasus region near the boundary of CENTCOM and EUCOM), posturing WRM assets from a global perspective may enhance U.S. capabilities and responsiveness along such "fault lines."

A substantial level of robustness and reliability can be designed into WRM prepositioning postures at relatively little cost. A network of FSLs should be designed in such a way that it is not susceptible to poor performance if future conditions diverge from plans, be it due to unexpected contingencies varying from the planned deployment requirements or to loss of access to network facilities. This monograph analyzed network design with respect to both variability across the set of scenarios to be supported ("demand-side" uncertainty, termed *robustness*) and potential disruptions to the availability of network locations ("supply-size" uncertainty, termed *reliability*).

When a WRM posture is designed to support one set of future deployment requirements but a different set occurs, the WRM posture may not be able to satisfy the time-phased demands at all FOLs. We demonstrated this concept with an example that considered a set of three potential futures. When a WRM posture was optimized against a single future, it was shown to be unable to support the deployment requirements for either of the other two futures. Our modified "robust optimization" model was able to identify a single posture that was capable of meeting all deployment requirements across three alterna-

[2] One could envision another alternative, wherein a fraction of the assets allocated to each AOR (perhaps those associated with MCO support) are retained under AOR control, but all other assets are managed globally by a central manager.

tive futures derived from the SPG, with total costs that were only 4 to 8 percent more expensive than the nonrobust, minimum-cost alternative for each future.

An undesirable feature of cost-optimized network designs is that they often generate a relatively brittle posture that performs poorly in the event of disruption to the network. This occurs because a traditional cost-optimization approach usually depends heavily on a small number of very cost-effective nodes. Such a strategy can lead to demands not being satisfied in the event of disruptions, particularly when an adversary can target a network's most critical points. We demonstrated this concept with an application to BEAR prepositioning. For both the current BEAR posture and the minimum-cost posture previously identified by our model, a loss of access to an FSL for a 30-day period can cause nearly 10 percent of all time-phased demands at FOLs to be unsatisfied. We developed a "reliable optimization" model that was able to guarantee that all demands would be met in the event of such a disruption to any FSL, with the worst-case costs for this posture only 6 percent greater than the best-case costs for the nonreliable, minimum-cost optimization (whose worst-case performance involves over 9 percent of demands going unsatisfied).

Much of the robustness and reliability benefits achieved by these alternative WRM postures is due to the recommended dispersal of assets across a large number of sites. This dispersal appears to be both cost- and risk-effective, with geographic dispersal increasing the likelihood that assets are stored near unexpected deployment locations, and dispersal of assets reducing the risk associated with denial of access to FSLs.

Potential Extensions to Future Research

The extension of this research to other types of network disruptions, such as the loss of multiple facilities or the loss of specific transportation links, might provide additional insights into prepositioning strategies. It is also possible to envision extending this research to other types of logistics networks, such as networks of aircraft maintenance facili-

ties. Another concept for addressing reliability in the event of network disruptions is the hardening of critical network nodes. That is, instead of addressing the loss of access to a network site, in certain environments the Air Force may have alternatives for protecting such critical sites against potential disruptions. Mathematical modeling techniques could be used to develop approaches for identifying where a limited set of hardening resources should be concentrated to maximize the level of reliability. Finally, the scope of this analysis could be extended to include considerations of non–Air Force war reserve materiel, such as Joint WRM or Special Operations Command assets that the Air Force might be allocated early in a contingency to assist in the opening and maintenance of aerial lines of communication.

APPENDIX

Mathematical Model Details

This appendix presents the mathematical programming formulations used in this monograph to evaluate WRM prepositioning strategies. For background and a detailed discussion of previous versions of these RAND models, see Amouzegar et al. (2004, 2006). This model is a Mixed Integer Programming model, developed using the General Algebraic Modeling System.

This appendix first presents the model that considers *reliability in the event of facility disruption*. Following the complete description of this model, the appendix then describes the few modifications that are necessary to create a model that can address *robustness to uncertain future demands*.

Indices and Sets

$a \in \mathbf{A}$	commodity types
$b, b' \in \mathbf{B}$	FSLs
$c, c' \in \mathbf{C}$	FOLs
$d \in \mathbf{D}$	packaging configurations
$e \in \mathbf{E}$	transportation modes
$f \in \mathbf{F}$	facility types
$h, h', h'' \in \mathbf{H}$	"local" time periods (associated with each FOL)
$i \in \mathbf{I}$	"global" time periods

$j \in \mathbf{J}$	maintenance concepts
$k \in \mathbf{K}$	years within the modeled time horizon
$fe \in \mathbf{FE}$	failure events, where each element *fe* corresponds to a scenario entailing loss of access at one FSL.

The model accounts for temporal considerations through the use of two sets: a set of "global" time periods, denoted by elements $i \in \mathbf{I}$, and a set of "local" time periods that are associated with each FOL, denoted by elements $h \in \mathbf{H}$.

The time period notations can be explained as follows. Suppose that a 365-day period was to be modeled, with each individual time period equal to one day. Then set **I** would have 365 elements. Now, suppose that in our planning scenario, FOL *c* was "active" only during a contingency period that begins on day 101 and ends on day 120. Then, for FOL *c*, set **H** would have 20 elements; there is no need to track activities at *c* (or consume computer memory) for the other 345 days.[1]

The model captures reliability in the event of FSL disruption considerations through the use of a set of "failure events," denoted by $fe \in \mathbf{FE}$, with one element *fe* for every FSL, corresponding to a potential loss of access at each FSL, along with an additional *fe* element corresponding to the case where no FSL fails. The failure events that are modeled here should be viewed as short-term disruptions that prevent access to prepositioned materiel for a relatively brief period and that would not allow the user enough time to reposition WRM assets in response to emerging contingencies.

We need to specify an interval over which the loss of access to an FSL occurs, using parameters *FailTime* to denote the start of this interval and *FailDuration* to denote the length of this interval. Thus, during

[1] We assume that each FOL *c* corresponds to exactly one period of continuous activity at one location. For example, if the planning scenario under consideration requires deployment activity at FOL *c* between days 101 and 120, and then no activity at that location until another period of activity at FOL *c* between days 171 and 185, we would define a unique element in set **C** for each of these two periods, to allow for savings in computer memory requirements.

the global time periods i_1, i_2, . . . , *FailTime*, access is assumed to be guaranteed to all FSLs; the model then assumes that during global time periods, *FailTime* + 1, . . . , *FailTime* + *FailDuration,* loss of access to an FSL could potentially occur at any FSL. Finally, during global time periods *FailTime* + *FailDuration* + 1, . . . , i_{max}, it is again assumed that access is guaranteed to all FSLs.

The model should not be structured in such a way that it identifies one set of actions in advance of a loss of access to FSL b_1 and another set of actions in advance of a loss of access to FSL b_2. Recall that the aim of this analysis is to identify an FSL posture that retains flexibility for the decisionmaker in the event of an unexpected loss of access to any FSL. If the model were focused on the loss of access to a specific FSL and was allowed to have knowledge about the time and specific location at which the loss of access occurs, it could "look ahead" and take such actions as minimizing the inventory at the affected FSL in advance of the loss of access to mitigate these effects.

Instead, our model generates a single set of decisions for time periods i_1, i_2, . . . , *FailTime*, allowing the posture to retain the necessary flexibility at *FailTime* to satisfy all future demands regardless of the FSL to which access is lost. Note that our approach allows the model foresight with respect to the time of failure but not to any specific location of failure. Then, following *FailTime*, a separate set of decisions needs to be tracked in the event of each possible FSL failure. Thus, the model needs to include two versions of all variables and constraints that have a temporal dimension: one for time periods before *FailTime*, for which a single set of decisions needs to be tracked to identify the status of the overall system at *FailTime*, and a second version for time periods following *FailTime*, for which the status of the system must be independently tracked for each potential FSL failure.

Because each FOL in set **C** has a temporal aspect, associated with its period of deployment activity, we specify two subsets of **C**:[2]

[2] An alternative, and perhaps more intuitive, description is that subset $\mathbf{C_A}$ contains all FOLs such that the contingency in which they are involved starts before *FailTime*, whereas subset $\mathbf{C_B}$ contains all FOLs such that the contingency in which they are involved ends after *FailTime*.

$c_a \in \mathbf{C_A} \subseteq \mathbf{C}$	subset of FOLs, such that the contingency in which they are involved (a) ends before *FailTime* or (b) starts before *FailTime* and ends after *FailTime*
$c_b \in \mathbf{C_B} \subseteq \mathbf{C}$	subset of FOLs, such that the contingency in which they are involved (a) starts before *FailTime* and ends after *FailTime* or (b) starts at or after *FailTime.*

For each FSL $b \in \mathbf{B}$, we identify a primary storage site, which is generally assumed to be located at an airfield. Because one of the primary research tasks to be addressed in this project was an evaluation of the Virtual Afloat concept, in which some fraction of the assets is stored at a seaport, for each FSL we identified the nearest seaport and included an option for assets to be stored there, as well as at the FSL's primary airfield location.

Several sets are used to model policy options. A detailed explanation of the use of such sets follows:

- $d \in \mathbf{D}$: d_1 denotes palletized (for BEAR) or wrapped (for WRMV) assets stored at the FSL's airfield, d_2 denotes containerized (for BEAR) or unwrapped (for WRMV) assets stored at the FSL's airfield, d_3 denotes containerized (for BEAR) or wrapped (for WRMV) assets stored at the FSL's nearest seaport
- $e \in \mathbf{E}$: e_1 denotes airlift, e_2 denotes truck, and e_3 denotes sealift
- $f \in \mathbf{F}$: f_1 denotes inside storage space at the FSL's airfield, f_2 denotes outside storage space at the FSL's airfield, f_3 denotes inside storage space at the FSL's nearest seaport, f_4 denotes outside storage space at the FSL's nearest seaport, and f_5 denotes maintenance space at the FSL's airfield
- $j \in \mathbf{J}$: j_1 denotes asset swap, j_2 denotes on-site maintenance (whether by a permanent on-site maintenance team or by a traveling maintenance team)

Data Elements

Cost Coefficients

$\Delta_{b,j}$	fixed cost to open a storage facility at FSL b under PMI maintenance concept j
$\Pi_{b,f}$	cost per unit of type f facility capacity expansion at FSL b
$\Lambda_{a,b,b',d,j}$	operating and maintenance cost per unit of commodity a authorized for storage at FSL b in configuration d receiving its PMI from FSL b' using maintenance concept j (including container purchase and PMI transport as necessary)
$\Upsilon_{a,b,c,d,e}$	transport cost per unit of commodity a transported from FSL b to FOL c in configuration d via transport mode e (including setup costs such as additional trucking and container rental-packing as necessary)
$\Omega_{e,k}$	cost of procuring an additional mode e transport vehicle beyond the initial allotment of such vehicles in year k
Ψ_a	cost of procuring an additional unit of a beyond the current total authorization level.

Other Parameters

FailTime	global time when the failure event begins
FailDuration	duration (in global time periods) of the failure event
δ_a	current total authorization level for commodity a
ι	minimum number of total assets required to be authorized for storage at any FSL used

κ_c	global time associated with the start of the contingency at FOL *c;* note that this allows for translation between local time h and global time i as follows: $i = \kappa_c + h - 1$
ω_c	local time associated with the stop of the contingency at FOL c
υ_c	transport time via truck from FOL c's seaport to the FOL including truck loading time
ψ_c	indicates whether FOL c is within 5 nm of a seaport (1 if *not within 5 miles;* 0 otherwise)
μ_d	time to prepare and load one truck containing commodities packaged in configuration d
ζ_b	maximum throughput per time unit at FSL b's seaport for trucks
η_c	unique scenario associated with FOL c
Ξ_i	year associated with global time period i
$\kappa^2_{c,fe}$	earliest time after *FailTime* that collocated material can be sourced for FOL c from the FSL which fails under failure event *fe*
$\alpha_{a,d,f}$	type f facility requirement per unit of commodity a packed in configuration d
$\beta_{b,f}$	existing type f facility capacity at FSL b
$\gamma_{b,f}$	maximum potential type f facility capacity expansion at FSL b
$\varepsilon_{a,b,b',j}$	units of commodity a required for PMI transit pipeline per unit of a stored at FSL b receiving PMI via maintenance concept j from FSL b'

$\aleph_{c,a}$	global time of reconstitution and return for all commodity a used at FOL c
$\theta_{a,d,e}$	number of mode e vehicles required to transport one unit of commodity a in configuration d
$\lambda_{b,d}$	time to prepare and load one aircraft at FSL b containing commodities packaged in configuration d including time necessary to transport the load from the storage location to FSL b's airfield
$\rho_{b,c,e}$	transport time from FSL b to FOL c via mode e, where $\rho_{b,c,e_2} = 0$ implies that FSL b and FOL c are collocated
$\chi_{b,d}$	time to prepare, load, and transport one truckload containing commodities packaged in configuration d from FSL b's storage location to its seaport and then load these commodities onto a ship
$\xi_{b,e}$	throughput per time unit at FSL b for transport mode e
$\pi_{c,e}$	throughput per time unit at FOL c for transport mode e
$\sigma_{e,k}$	initial fleet size for transport mode e during year k
$\phi_{a,c,h}$	demand at FOL c for commodity a at local time h.

Variables

All variables are assumed to be nonnegative.

Binary Variables

$P_{b,b',j}$ indicates if FSL b is used, with all commodities stored at b receiving their PMI from FSL b' using maintenance concept j.

Integer Variables

$Q_{a,b,b',d,j}$ units of commodity a authorized for storage at FSL b in configuration d receiving PMI from FSL b' using maintenance concept j.

Continuous Variables[3]

$CommonCost$ total system costs incurred before $FailTime$

$FutureCost_{fe}$ total system costs incurred after $FailTime$ under failure event fe

$MaxFutureCost$ maximum $FutureCost_{fe}$ across all failure events

$X^1_{b,c_a,h}$ number of sea vehicles departing at time $\kappa_{c_a} + h - 1 < FailTime$ from FSL b's seaport bound for FOL c_a

$X^2_{b,c_b,h,fe}$ number of sea vehicles departing at time $\kappa_{c_b} + h - 1 \geq FailTime$ from FSL b's seaport bound for FOL c_b under failure event fe

$V^1_{b,c_a,h}$ number of air vehicles departing at time $\kappa_{c_a} + h - 1 < FailTime$ from FSL b's airfield, bound for FOL c_a

[3] Note that this model was initially built using integer variables to constrain the number of air and sea vehicles used for transport of WRM assets. No such integer assumption was placed on trucks used to transport WRM, because such trucks were assumed to be plentiful. These integer variables were later relaxed to the continuous variables presented above, to allow the model to obtain solutions more quickly.

$V^2_{b,c_b,h,fe}$	number of air vehicles departing at time $\kappa_{c_b} + h - 1 \geq FailTime$ from FSL b's airfield, bound for FOL c_b under failure event fe
$XX^1_{a,b,d,i}$	inventory level of commodity a at FSL b in configuration d at global time $i \leq FailTime$
$XX^2_{a,b,d,i,fe}$	inventory level of commodity a at FSL b in configuration d at global time $i > FailTime$ under failure event fe
$R^1_{a,b,c,d}$	units of commodity a in configuration d sourced for FOL c from collocated FSL b at time $\kappa_c \leq FailTime$
$R^2_{a,b,c,d,fe}$	units of commodity a in configuration d sourced for FOL c from collocated FSL b at time $\kappa_c > FailTime$ under failure event fe
$S_{b,f}$	amount of type f facility used at FSL b
$N_{b,f}$	amount of capacity expansion for type f facility at FSL b
$T^1_{a,b,c_a,d,e,h}$	units of commodity a transported from FSL b to FOL c_a in configuration d via transportation mode e departing the storage location at time $\kappa_{c_a} + h - 1 < FailTime$
$T^2_{a,b,c_b,d,e,h,fe}$	units of commodity a transported from FSL b to FOL c_b in configuration d via transportation mode e departing the storage location at time $\kappa_{c_b} + h - 1 \geq FailTime$ under failure event fe
$W^1_{a,b,c_a,h,h'}$	number of sea vehicle loads of commodity a loaded onto the ship at FSL b's seaport at local time h, departing the seaport at time $h' \geq h$ bound for FOL c_a, such that $\kappa_{c_a} + h' - 1 < FailTime$

$W^2_{a,b,c_b h,h',fe}$	number of sea vehicle loads of commodity a loaded onto the ship at FSL b's seaport at local time h, departing the seaport at time $h' \geq h$ bound for FOL c_b, such that $\kappa_{c_b} + h' - 1 \geq FailTime$ under failure event fe
$O^1_{a,b,c_a,h,h'}$	number of sea vehicle loads of commodity a departing FSL b's seaport at time $\kappa_{c_a} + h - 1 < FailTime$, transported via truck from FOL c_a's seaport to the FOL with the truck departing FOL c_a's seaport at time $h' \geq h + \rho_{b,c_b,e_3}$ $h' \geq h + \rho_{b,c_a,e_3}$
$O^2_{a,b,c_b,h,h',fe}$	number of sea vehicle loads of commodity a departing FSL b's seaport at time $\kappa_{c_b} + h - 1 \geq FailTime$, transported via truck from FOL c_b's seaport to the FOL with the truck departing FOL c_b's seaport at time $h' \geq h + \rho_{b,c_b,e_3}$ under failure event fe
$Y^1_{e,k}$	number of additional mode e vehicles procured in year k occurring before *FailTime*
$Y^2_{e,k,fe}$	number of additional mode e vehicles procured in year k occurring after *FailTime* under failure event fe
Z_a	additional units of commodity a procured, beyond the current total authorization level.

Variables $R^1_{a,b,c,d}$ and $R^2_{a,b,c,d,fe}$ are introduced to allow the model to not consume transportation resources when an FOL sources WRM from a collocated FSL.

A description of how the decision variables act upon the time periods follows:

- All transportation movements (i.e., $T^1_{a,b,c_a,d,e,h}$, $T^2_{a,b,c_b,d,e,h,fe}$, and related variables) are assumed to depart at the end of a time period.

- Collocated FSL/FOL deliveries are assumed to be sourced from the FSL inventory at the *beginning* of the FOL's first local time period *h*.
- FSL inventory ($XX^1_{a,b,d,i}$, $XX^2_{a,b,d,i,fe}$) is defined as the amount in storage at the *beginning* of time period *i*, following the removal of any demands from collocated FOLs.
- Failure events are assumed to occur in the *middle* of a time period.
- It is assumed that at time $i = FailTime$, all materiel en route (i.e., materiel that has already left an FSL bound for an FOL) continues its trip as planned.
- Under a failure event in which access is lost to FSL *b*, if there is an FOL collocated at FSL *b*, we assume that the collocated FOL is still operational, but that it cannot source supplies from FSL *b* during the failure interval.

Equations

Objective Function

$$\min \; CommonCost + MaxFutureCost \tag{A.0}$$

$$\begin{aligned} CommonCost = & \sum_{b} \left(\sum_{b',j} \Delta_{b,j} P_{b,b',j} + \sum_{f} \Pi_{b,f} N_{b,f} \right) \\ & + \sum_{a,b,d} \left(\begin{array}{l} \sum_{b',j} \Lambda_{a,b,b',d,j} Q_{a,b,b',d,j} \\ + \sum_{c_a,e,h} \Upsilon_{a,b,c_a,d,e} T^1_{a,b,c_a,d,e,h} \end{array} \right) \\ & + \sum_{e,k} \Omega_{e,k} Y^1_{e,k} + \sum_{a} \Psi_a Z_a \end{aligned} \tag{A.1}$$

$$FutureCost_{fe} = \sum_{a,b,c_b,d,e,h} \Upsilon_{a,b,c_b,d,e} T^2_{a,b,c_b,d,e,h,fe} + \sum_{e,k} \Omega_{e,k} Y^2_{e,k,fe} \quad \forall fe \tag{A.2}$$

$$MaxFutureCost \geq FutureCost_{fe} \quad \forall fe \tag{A.3}$$

The model minimizes the total system costs of building a WRM prepositioning posture and conducting exercises and supporting lesser contingencies, while constraining the solution set to have an infrastructure capable of supporting MCO requirements if deterrence should fail. As discussed above, because the costs associated with conducting these MCOs cannot be programmed for, we include the constraints associated with satisfying MCO demands but do not include their transportation costs in the optimization objective function. The model has been extended beyond the traditional minimum-cost formulation to identify a reliable prepositioning posture that can satisfy delivery time lines even in the event of loss of access to any prepositioning facility.

However, because this model addresses a prepositioning posture's performance across multiple potential FSL failure events, the meaning of an objective function that minimizes cost is somewhat ambiguous, depending on a decisionmaker's level of risk tolerance and the relative weighting associated with each potential FSL failure event (note that the model has assured that all demands will be satisfied in the event of loss of access to any single FSL, thus the risk considered here is the risk associated with increased total system cost). Constraint A.1 computes *CommonCost*, the total system cost components that are common across all potential failure events, including the FSL opening cost, the facility expansion cost, the operations and maintenance cost assessed against the stored commodities, and the procurement cost for additional assets; also included are the deployment transportation cost and the additional transport vehicle procurement cost for the global time periods occurring before *FailTime*. Constraint A.2 then captures $FutureCost_{fe}$, the total system costs that are unique to

each potential FSL failure event *fe*, consisting of the deployment transportation cost and additional transport vehicle procurement cost for those global time periods following *FailTime*. Constraint A.3 ensures that the variable *MaxFutureCost* is at least as large as the largest potential $FutureCost_{fe}$.

The objective function can then be defined as a function of these cost variables. The mathematical formulation presented above uses a *minimax* approach in objective A.0, minimizing the maximum cost incurred across all potential failure events, a highly risk-averse position. Other alternative objective functions could be considered, such as the following:

$$\min \; CommonCost + \frac{\sum_{fe} FutureCost_{fe}}{\|\mathbf{FE}\|} \qquad \text{(A.0-alt)}$$

Objective A.0-alt minimizes the average cost across all potential FSL failure events. Objective A.0-alt could be modified to include some sort of weighting system, where alternative failure events are weighted according to, e.g., their relative likelihood of occurrence.

Constraints

$$\sum_{b',j} P_{b,b',j} \leq 1 \quad \forall b \qquad \text{(A.4)}$$

$$\sum_{b',j} P_{b',b,j} \leq \|\mathbf{B}\| P_{b,b,j_2} \quad \forall b \qquad \text{(A.5)}$$

$$\sum_{a,d} Q_{a,b,b',d,j} \leq P_{b,b'j} * \sum_{a} (100\delta_a) \quad \forall b,b',j \qquad \text{(A.6)}$$

$$\sum_{a,b',d,j} Q_{a,b,b',d,j} \geq \iota \sum_{b',j} P_{b,b',j} \quad \forall b \tag{A.7}$$

$$\sum_{b,b',d,j} (1+\varepsilon_{a,b,b',j}) Q_{a,b,b',d,j} = \delta_a + Z_a \quad \forall a \tag{A.8}$$

Constraint A.4 is an assignment constraint, assigning each potential storage site to at most one unique "maintenance site and maintenance concept." Constraint A.5 ensures that no FSL b' can receive maintenance at an FSL b if FSL b is not providing its own on-site maintenance. Constraint A.6 ensures that WRM assets are authorized for storage only at opened FSLs. Constraint A.7 ensures that every opened FSL has assigned to it at least some minimal amount of WRM assets. Constraint A.8 enforces that the total number of authorized commodity a assets is equal to the current total authorizations for asset a plus the additional procurement for asset a (setting aside some pipeline of assets $\varepsilon_{a,b,b',j}$ if assets are maintained via a maintenance concept that calls for unserviceable assets to be transported between their storage and maintenance locations).

$$\sum_{a,b',j} \left(\alpha_{a,d_1,f_1} Q_{a,b,b',d_1,j} + \alpha_{a,d_2,f_1} Q_{a,b,b,d_2,j} \right) = S_{b,f_1} \quad \forall b \tag{A.9}$$

$$\sum_{a,b',j} \left(\alpha_{a,d_1,f_2} Q_{a,b,b',d_1,j} + \alpha_{a,d_2,f_2} Q_{a,b,b',d_2,j} \right) = S_{b,f_2} \quad \forall b \tag{A.10}$$

$$\sum_{a,b',j} \alpha_{a,d_3,f_3} Q_{a,b,b',d_3,j} = S_{b,f_3} \quad \forall b \tag{A.11}$$

$$\sum_{a,b',j} \alpha_{a,d_3,f_4} Q_{a,b,b',d_3,j} = S_{b,f_4} \quad \forall b \tag{A.12}$$

$$\sum_{a,b',d} \alpha_{a,d,f_5} \left(Q_{a,b',b,d,j_1} + Q_{a,b,b',d,j_2} \right) = S_{b,f_5} \quad \forall b \tag{A.13}$$

Constraints A.9–A.13 determine an intermediate variable, $S_{b,f}$, equal to the amount of type *f* facility space used at FSL *b*.

$$S_{b,f_1} + S_{b,f_2} + S_{b,f_5} \leq \beta_{b,f_1} + \beta_{b,f_2} + \beta_{b,f_5} + \gamma_{b,f_2} \quad \forall b \tag{A.14}$$

$$S_{b,f_3} + S_{b,f_4} \leq \beta_{b,f_3} + \beta_{b,f_4} + \gamma_{b,f_4} \quad \forall b \tag{A.15}$$

$$S_{b,f_1} \leq \beta_{b,f_1} + N_{b,f_1} + \beta_{b,f_5} + N_{b,f_5} - S_{b,f_5} \quad \forall b \tag{A.16}$$

$$S_{b,f_2} \leq \beta_{b,f_2} + N_{b,f_2} + \beta_{b,f_1} + N_{b,f_1} + \beta_{b,f_5} + N_{b,f_5} - S_{b,f_1} - S_{b,f_5} \quad \forall b \tag{A.17}$$

$$S_{b,f_3} \leq \beta_{b,f_3} + N_{b,f_3} \quad \forall b \tag{A.18}$$

$$S_{b,f_4} \leq \beta_{b,f_4} + N_{b,f_4} \quad \forall b \tag{A.19}$$

$$S_{b,f_5} \leq \beta_{b,f_5} + N_{b,f_5} \quad \forall b \tag{A.20}$$

Variable S_{bf} is then constrained to be less than both the maximum amount of storage space possible (Constraints A.14–A.15) and the amount of storage space obtained (Constraints A.16–A.20) for type f facilities at FSL b. Note that we have assumed that a single $\gamma_{b,f}$ term is defined for potential expansion at each FSL's airfield (γ_{b,f_2}) and each FSL's nearest seaport (γ_{b,f_4}); the total expansion summed across inside storage, outside storage, and maintenance space must be less than this single term. Further, we assume that at each FSL's airfield, excess existing maintenance space can be used for inside storage or outside storage requirements at no cost, and that excess existing inside storage space can be used for outside storage requirements at no cost. This assumption is not applied to each FSL's nearest seaport (specifically, to Constraint A.19), because there was no existing seaport storage at the time of this research.

$$XX^1_{a,b,d,i_1} = \sum_{b',j} Q_{a,b,b',d,j} - \sum_{c \ni \kappa_c = 1} R^1_{a,b,c,d} \quad \forall a,b,d \tag{A.21}$$

$$\begin{aligned} XX^1_{a,b,d,i} = XX^1_{a,b,d,i-1} &- \sum_{\substack{c_a,e \\ h \ni \kappa_{c_a} \\ +h-1=i-1}} T^1_{a,b,c_a,d,e,h} \\ &- \sum_{c \ni \kappa_c = i} R^1_{a,b,c,d} + \sum_{\substack{e,h \\ c_a \ni \aleph_{c_a,a} = i}} T^1_{a,b,c_a,d,e,h} \\ &+ \sum_{c \ni \aleph_{c,a} = i} R^1_{a,b,c,d} \quad \forall a,b,d, 1 < i \le FailTime \end{aligned} \tag{A.22}$$

$$XX^{2}_{a,b,d,i,fe} = XX^{1}_{a,b,d,i-1} - \sum_{\substack{c_b,e \\ h \ni \kappa_{c_b} \\ +h-1=i-1}} T^{2}_{a,b,c_b,d,e,h,fe} - \sum_{c \ni \kappa^{2}_{c,fe}=i} R^{2}_{a,b,c,d,fe} + \sum_{\substack{e,h \\ c_a \ni \aleph_{c_a,a}=i}} T^{1}_{a,b,c_a,d,e,h} + \sum_{\substack{e,h \\ c_b \ni \aleph_{c_b,a}=i}} T^{2}_{a,b,c_b,d,e,h,fe} + \sum_{c \ni \aleph_{c,a}=i} \left(R^{1}_{a,b,c,d} + R^{2}_{a,b,c,d,fe} \right)$$
$$\forall a,b,d,fe,i = FailTime + 1 \tag{A.23}$$

$$XX^{2}_{a,b,d,i,fe} = XX^{2}_{a,b,d,i-1,fe} - \sum_{\substack{c_b,e \\ h \ni \kappa_{c_b} \\ +h-1=i-1}} T^{2}_{a,b,c_b,d,e,h,fe} - \sum_{c \ni \kappa^{2}_{c,fe}=i} R^{2}_{a,b,c,d,fe} + \sum_{\substack{e,h \\ c_a \ni \aleph_{c_a,a}=i}} T^{1}_{a,b,c_a,d,e,h} + \sum_{\substack{e,h \\ c_b \ni \aleph_{c_b,a}=i}} T^{2}_{a,b,c_b,d,e,h,fe} + \sum_{c \ni \aleph_{c,a}=i} \left(R^{1}_{a,b,c,d} + R^{2}_{a,b,c,d,fe} \right)$$
$$\forall a,b,d,fe,i \geq FailTime + 2 \tag{A.24}$$

Constraints A.21–A.24 use a recursive inventory equation to track the available inventory level of commodity *a* at FSL *b* in configuration *d* at global time *i*.

$$\sum_{\substack{c_a,e \\ h \ni \kappa_{c_a}+h-1=i}} T^1_{a,b,c_a,d,e,h} \le XX^1_{a,b,d,i} \quad \forall a,b,d,i < FailTime \tag{A.25}$$

$$\sum_{\substack{c_b,e \\ h \ni \kappa_{c_b}+h-1=i}} T^2_{a,b,c_b,d,e,h,fe} \le XX^1_{a,b,d,i}$$
$$\forall a,b,d,fe,i = FailTime \tag{A.26}$$

$$\sum_{\substack{cb,e \\ h \ni \kappa_{cb}+h-1=i}} T^2_{a,b,cb,d,e,h,fe} \le XX^2_{a,b,d,i,fe}$$
$$\forall a,b,d,fe,i > FailTime \tag{A.27}$$

Constraints A.25–A.27 then ensure that the number of assets shipped out of an FSL at time i does not exceed the FSL's available inventory at time i.

$$V^1_{b,c_a,h} \ge \sum_a \theta_{a,d_1,e_1} \left(\sum_d T^1_{a,b,c_a,d,e_1,h-\lambda_{b,d}} \right)$$
$$\forall b,c_a,h \ni h \le \omega_{c_a} - \rho_{b,c_a,e_1}$$
$$\text{and } \kappa_{c_a} + h - 1 < FailTime \tag{A.28}$$

$$V^2_{b,c_b=c,h,fe} \geq \sum_a \theta_{a,d_1,e_1} \left(\begin{array}{l} \sum_d T^1_{a,b,c_a=c,d,e_1,h-\lambda_{b,d}} \\ +\sum_d T^2_{a,b,c_b=c,d,e_1,h-\lambda_{b,d},fe} \end{array} \right)$$
$$\forall b,c,h \ni h \leq \omega_c - \rho_{b,c,e_1}$$
$$\text{and } \kappa_c + h - 1 \geq \mathit{FailTime} \text{ and } \kappa_c < \mathit{FailTime}, fe \quad \text{(A.29)}$$

$$V^2_{b,c_b,h,fe} \geq \sum_a \theta_{a,d_1,e_1} \left(\sum_d T^2_{a,b,c_b,d,e_1,h-\lambda_{b,d},fe} \right)$$
$$\forall b,c_b,h \ni h \leq \omega_{c_a} - \rho_{b,c_b,e_1} \text{ and } \kappa_{c_b} + h - 1$$
$$\geq \mathit{FailTime} \text{ and } \kappa_{c_b} \geq \mathit{FailTime}, fe \quad \text{(A.30)}$$

$$\sum_{\substack{h' \ni h' \geq h \\ \text{and } h' \leq \omega_{c_a} - \rho_{b,c_a,e_3} - \nu_{c_a}}} W^1_{a,b,c_a,h,h'} = \theta_{a,d_2,e_3} \sum_d T^1_{a,b,c_a,d,e_3,h-\chi_{b,d}}$$
$$\forall a,b,c_a \ni \kappa_{c_a} + \omega_{c_a} - 1$$
$$< \mathit{FailTime}, h \ni h \leq \omega_{c_a} - \rho_{b,c_a,e_3} - \nu_{c_a} \quad \text{(A.31)}$$

$$\sum_{h' \ni h' \geq h \text{ and } h' \leq \omega_c - \rho_{b,c,e_3} - \nu_c} \begin{pmatrix} W^1_{a,b,c_a=c,h,h'} \\ +W^2_{a,b,c_b=c,h,h',fe} \end{pmatrix}$$

$$= \theta_{a,d_2,e_3} \sum_d \begin{pmatrix} T^1_{a,b,c_a=c,d,e_3,h-\chi_{b,d}} \\ +T^2_{a,b,c_b=c,d,e_3,h-\chi_{b,d},fe} \end{pmatrix}$$

$$\forall a,b,c, \ni \kappa_c + \omega_c - 1 \geq FailTime, h \ni h \leq \omega_c - \rho_{b,c,e_3} - \nu_c, fe \tag{A.32}$$

$$X^1_{b,c_a,h} \geq \sum_{a,h' \ni h' \leq h} W^1_{a,b,c_a,h',h}$$

$$\forall b,c_a,h \ni h \leq \omega_{c_a} - \rho_{b,c_a,e_3} - \nu_{c_a}$$

$$\text{and } \kappa_{c_a} + h - 1 < FailTime \tag{A.33}$$

$$X^2_{b,c_b,h,fe} \geq \sum_{a,h' \ni h' \leq h} (W^2_{a,b,c_b,h',h,fe})$$

$$\forall b,c_b,h \ni h \leq \omega_{c_b} - \rho_{b,c_b,e_3} - \nu_{c_b}$$

$$\text{and } \kappa_{c_b} + h - 1 \geq FailTime, fe \tag{A.34}$$

$$\sum_{h' \ni h' \geq h + \rho_{b,c_a,e_3} \text{ and } h' \leq \omega_{c_a} - \nu_{c_a}} O^1_{a,b,c_a,h,h'} = \psi_{c_a} \left(\sum_{h' \ni h' \leq h} W^1_{a,b,c_a,h',h} \right)$$
$$\forall a, b, c_a, h \ni h \leq \omega_{c_a} - \rho_{b,c_a,e_3} - \nu_{c_a}$$
$$\text{and } \kappa_{c_a} + h - 1 < FailTime \tag{A.35}$$

$$\sum_{h' \ni h' \geq h + \rho_{b,c_b,e_3} \text{ and } h' \leq \omega_{c_b} - \nu_{c_b}} O^2_{a,b,c_b,h,h',fe} = \psi_{c_b} \left(\sum_{h' \ni h' \leq h} W^2_{a,b,c_b,h',h,fe} \right)$$
$$\forall a, b, c_b, h \ni h \leq \omega_{c_b} - \rho_{b,c_b,e_3} - \nu_{c_b}$$
$$\text{and } \kappa_{c_b} + h - 1 \geq FailTime, fe \tag{A.36}$$

The model uses a large number of intermediate transportation variables to capture the number of air and sea vehicles traveling between FSL *b* and FOL *c* that depart the airfield/seaport/storage location at local time *h*;[4] other intermediate variables capture the fractional number of sea vehicle loads loaded onto the ship at each FSL's seaport at each point in time and the fractional number of sea vehicle loads departing each FOL's seaport at each point in time using truck transport en route to final delivery at the FOL. Constraints A.28–A.36 provide the translation between the movement variables and the intermediate vehicle variables, for air vehicles (Constraints A.28–A.30), sea vehicle loads loaded onto the ship at the FSL's seaport (Constraints

[4] No such constraints were created for trucks used to transport WRM because the number of trucks used was not assumed to be an integer variable, eliminating the need for such a "translation" constraint to an intermediate variable.

A.31–A.32), sea vehicles (Constraints A.33–A.34), and sea vehicle loads transported by truck from the FOL's seaport to the FOL (Constraints A.35–A.36).

$$\sum_{c_a, h \ni \kappa_{c_a} + h - 1 = i} V^1_{b,c_a,h} \leq \xi_{b,e_1} \quad \forall b, i < FailTime \tag{A.37}$$

$$\sum_{c_b, h \ni \kappa_{c_b} + h - 1 = i} V^2_{b,c_b,h,fe} \leq \xi_{b,e_1} \quad \forall b, i \geq FailTime, fe \tag{A.38}$$

$$\sum_{c_a, h \ni \kappa_{c_a} + h - 1 = i} X^1_{b,c_a,h} \leq \xi_{b,e_3} \quad \forall b, i < FailTime \tag{A.39}$$

$$\sum_{c_b, h \ni \kappa_{c_b} + h - 1 = i} X^2_{b,c_b,h,fe} \leq \xi_{b,e_3} \quad \forall b, i \geq FailTime, fe \tag{A.40}$$

$$\sum_{\substack{a, c_a, d \ni d \neq d_3 \\ h \ni \kappa_{c_a} + h - 1 = i}} \theta_{a,d,e_2} \left(T^1_{a,b,c_a,d,e_2,h-\mu_d} + T^1_{a,b,c_a,d,e_3,h-\mu_d} \right) \leq \xi_{b,e_2} \quad \forall b, i < FailTime \tag{A.41}$$

$$\sum_{\substack{a,c_a \ni \kappa_{c_a} < FailTime, d \ni d \neq d_3 \\ h \ni \kappa_{c_a} + h - 1 = i}} \theta_{a,d,e_2} \begin{pmatrix} T^1_{a,b,c_a,d,e_2,h-\mu_d} \\ + T^1_{a,b,c_a,d,e_3,h-\mu_d} \end{pmatrix}$$

$$+ \sum_{\substack{a,c_b,d \ni d \neq d_3 \\ h \ni \kappa_{c_b} + h - 1 = i}} \theta_{a,d,e_2} \begin{pmatrix} T^2_{a,b,c_b,d,e_2,h-\mu_d,fe} \\ + T^2_{a,b,c_b,d,e_3,h-\mu_d,fe} \end{pmatrix} \leq \xi_{b,e_2}$$

$$\forall b, i \geq FailTime, fe \tag{A.42}$$

Constraints A.37–A.42 limit the throughput of mode *e* vehicles at FSL *b* to be less than the maximum such throughput for every global time period *i*, limiting the total number of vehicles that can be simultaneously processed at any location per time period.

$$\sum_{a,c_a,h \ni \kappa_{c_a} + h - 1 = i} \theta_{a,d_3,e_2} \begin{pmatrix} T^1_{a,b,c_a,d_3,e_1,h-\mu_{d_3}} \\ + T^1_{a,b,c_a,d_3,e_2,h-\mu_{d_3}} \end{pmatrix} \leq \zeta_b$$

$$\forall b, i < FailTime \tag{A.43}$$

$$\sum_{a,c_a \ni \kappa_{c_a} < FailTime, h \ni \kappa_{c_a} + h - 1 = i} \theta_{a,d_3,e_2} \begin{pmatrix} T^1_{a,b,c_a,d_3,e_1,h-\mu_{d_3}} \\ +T^1_{a,b,c_a,d_3,e_2,h-\mu_{d_3}} \end{pmatrix}$$

$$+ \sum_{a,c_b,h \ni \kappa_{c_b} + h - 1 = i} \theta_{a,d_3,e_2} \begin{pmatrix} T^2_{a,b,c_b,d_3,e_1,h-\mu_{d_3},fe} \\ +T^2_{a,b,c_b,d_3,e_2,h-\mu_{d_3},fe} \end{pmatrix} \leq \zeta_b$$

$$\forall b, i \geq FailTime, fe \tag{A.44}$$

Constraints A.43–A.44 limit the throughput of trucks at FSL *b*'s seaport for every global time period *i*.

$$\sum_b V^1_{b,c_a,h-\rho_{b,c_a,e_1}} \leq \pi_{c_a,e_1} \quad \forall c_a, h \ni h \leq \omega_{c_a}$$
$$\text{and } \kappa_{c_a} + h - 1 < FailTime \tag{A.45}$$

$$\sum_b \left(V^1_{b,c_a=c,h-\rho_{b,c,e_1}} + V^2_{b,c_b=c,h-\rho_{b,c,e_1},fe} \right) \leq \pi_{c,e_1}$$
$$\forall c, h, fe \ni h \leq \omega_c \text{ and } \kappa_c + h - 1$$
$$\geq FailTime \text{ and } \kappa_c < FailTime \tag{A.46}$$

$$\sum_b V^2_{b,c_b,h-\rho_{b,c_b,e_1},fe} \leq \pi_{c_b,e_1} \quad \forall c_b, h, fe \ni h \leq \omega_{c_b}$$
$$\text{and } \kappa_{c_b} \geq FailTime \tag{A.47}$$

$$\sum_b X^1_{b,c_a,h-\rho_{b,c_a,e_3}} \le \pi_{c_a,e_3} \quad \forall c_a, h \ni h \le \omega_{c_a} - \upsilon_{c_a}$$
$$\text{and } \kappa_{c_a} + h - 1 < \mathit{FailTime} \tag{A.48}$$

$$\sum_b \left(X^1_{b,c_a=c,h-\rho_{b,c,e_3}} + X^2_{b,c_b=c,h-\rho_{b,c,e_3},fe} \right) \le \pi_{c,e_3}$$
$$\forall c, h, fe \ni h \le \omega_c - \upsilon_c \text{ and } \kappa_c + h - 1$$
$$\ge \mathit{FailTime} \text{ and } \kappa_c < \mathit{FailTime} \tag{A.49}$$

$$\sum_b X^2_{b,c_b,h-\rho_{b,c_b,e_3},fe} \le \pi_{c_b,e_3}$$
$$\forall c_b, h, fe \ni h \le \omega_{c_b} - \upsilon_{c_b} \text{ and } \kappa_{c_b} \ge \mathit{FailTime} \tag{A.50}$$

$$\sum_{a,b} \left[\sum_d \left(\theta_{a,d,e_2} T^1_{a,b,c_a,d,e_2,h-\mu_d-\rho_{b,c_a,e_2}} \right) + \left(\sum_{h' \ni h' \le h-\rho_{b,c_a,e_3}-\upsilon_{c_a}} \left(\theta_{a,d_2,e_2} / \theta_{a,d_2,e_3} \right) O^1_{a,b,c_a,h',h-\nu_{c_a}} \right) \right]$$
$$\le \pi_{c_a,e_2} \quad \forall c_a, h \ni h \le \omega_{c_a} \text{ and } \kappa_{c_a} + h - 1 < \mathit{FailTime} \tag{A.51}$$

$$\sum_{a,b}\left[\sum_{d}\left(\theta_{a,d,e_2}T^{1}_{a,b,c_a=c,d,e_2,h-\mu_d-\rho_{b,c,e_2}}\right)\right.$$
$$\left.+\left(\sum_{h'\ni h'\le h-\rho_{b,c,e_3}-\upsilon_c}\left(\theta_{a,d_2,e_2}/\theta_{a,d_2,e_3}\right)O^{1}_{a,b,c_a=c,h',h-\nu_c}\right)\right]$$
$$+\sum_{a,b}\left[\sum_{d}\left(\theta_{a,d,e_2}T^{2}_{a,b,c_b=c,d,e_2,h-\mu_d-\rho_{b,c,e_2},fe}\right)\right.$$
$$\left.+\left(\sum_{h'\ni h'\le h-\rho_{b,c,e_3}-\upsilon_C}\left(\theta_{a,d_2,e_2}/\theta_{a,d_2,e_3}\right)O^{2}_{a,b,c_b=c,h',h-\nu_c,fe}\right)\right]$$
$$\le \pi_{c,e_2}\quad \forall c,h,fe \ni h\le \omega_c \text{ and } \kappa_c+h-1\ge FailTime$$
$$\text{and } \kappa_c < FailTime \tag{A.52}$$

$$\sum_{a,b}\left[\sum_{d}\theta_{a,d,e_2}T^{2}_{a,b,c_b,d,e_2,h-\mu_d-\rho_{b,c_b,e_2},fe}\right.$$
$$\left.+\sum_{h'\ni h'\le h-\rho_{b,c_b,e_3}-\upsilon_{c_b}}\left(\theta_{a,d_2,e_2}/\theta_{a,d_2,e_3}\right)O^{2}_{a,b,c_b,h',h-\nu_{c_b},fe}\right]$$
$$\le \pi_{c_b,e_2}\quad \forall c_b,h,fe \ni h\le \omega_{c_b} \text{ and } \kappa_{c_b}\ge FailTime \tag{A.53}$$

Constraints A.45–A.53 similarly limit throughput at the FOLs to be less than their maximum throughput, for every local time period *h*.

$$\sum_{b,c_a,h\ni\kappa_{c_a}+h-1=i} V^1_{b,c_a,h} \le \sum_{k\ni k=\Xi_i} (\sigma_{e_1,k} + Y^1_{e_1,k})$$
$$- \sum_{\substack{b,c_a \\ h\ni h\ge(i-\kappa_{c_a}-2\rho_{b,c_a,e_1}+2) \text{ and } h\le(i-\kappa_{c_a})}} V^1_{b,c_a,h}$$
$$\forall\ i\ < FailTime \tag{A.54}$$

$$\sum_{b,c_b,h\ni\kappa_{c_b}+h-1=i} V^2_{b,c_b,h,fe} \le \sum_{k\ni k=\Xi_i} (\sigma_{e_1,k} + Y^2_{e_1,k,fe})$$
$$- \sum_{\substack{b,c \\ h\ni h\ge(i-\kappa_c-2\rho_{b,c,e_1}+2) \text{ and } h\le(i-\kappa_c)}} \left(V^1_{b,c_a=c,h} + V^2_{b,c_b=c,h,fe}\right)$$
$$\forall\ i \ge FailTime, fe \tag{A.55}$$

$$\sum_{b,c_a,h\ni\kappa_{c_a}+h-1=i} X^1_{b,c_a,h} \le \sum_{k\ni k=\Xi_i} (\sigma_{e_3,k} + Y^1_{e_3,k})$$
$$- \sum_{\substack{b,c_a \\ h\ni h\ge(i-\kappa_{c_a}-2\rho_{b,c_a,e_3}+2) \text{ and } h\le(i-\kappa_{c_a})}} X^1_{b,c_a,h}$$
$$\forall\ i\ < FailTime \tag{A.56}$$

$$\sum_{b,c_b,h \ni \kappa_{c_b}+h-1=i} X^2_{b,c_b,h,fe} \le \sum_{k \ni k=\Xi_i} (\sigma_{e_3,k} + Y^2_{e_3,k,fe})$$

$$- \sum_{b,c \quad h \ni h \ge (i-\kappa_c-2\rho_{b,c,e_3}+2) \text{ and } h \le (i-\kappa_c)} \begin{pmatrix} X^1_{b,c_a=c,h} \\ +X^2_{b,c_b=c,h,fe} \end{pmatrix}$$

$$\forall\ i\ \ge FailTime, fe \tag{A.57}$$

Constraints A.54–A.57 ensure that the total number of mode *e* vehicles tasked with transporting assets at global time *i* does not exceed the inventory of mode *e* vehicles initially allocated to that time plus the additional mode *e* vehicles procured for that time period, for air and sea vehicles. Note that no such constraint was placed on the total number of trucks used to transport WRM, because of the assumption that such trucks were plentiful, although throughput constraints were imposed at the FSLs and FOLs limiting the number of trucks that could be processed per unit of time. It should be noted that this model makes a transportation asset unavailable for a period equal to the round-trip transportation time between each FSL and FOL, to allow for vehicle retrograde, but the retrograde movement itself is not tracked, unlike the earlier RAND models of Amouzegar et al. (2004, 2006), in which retrograde movements were explicitly modeled. The assumption here is that following this retrograde period of time, another vehicle is available to the system and appears on demand at any FSL to await loading.

$$\sum_{b}\left[\sum_{d}\left(R^{1}_{a,b,c,d}+\sum_{h'\ni h'\le h-\lambda_{b,d}-\rho_{b,c,e_1}} T^{1}_{a,b,c_a=c,d,e_1,h'}\right.\right.$$

$$\left.+\sum_{h'\ni h'\le h-\mu_{d}-\rho_{b,c,e_2}} T^{1}_{a,b,c_a=c,d,e_2,h'}\right)+\left(\frac{1}{\theta_{a,d_2,e_3}}\right)$$

$$\sum_{h'\ni h'\le h-\rho_{b,c,e_3}-\upsilon_c}\left(\sum_{\substack{h''\ni h''\ge h'+\rho_{b,c,e_3}\\ \text{and } h''\le h-\upsilon_c}} O^{1}_{a,b,c_a=c,h',h''}\right.$$

$$\left.\left.+(1-\psi_c)\sum_{h''\ni h''\le h'} W^{1}_{a,b,c_a=c,h'',h'}\right)\right]\ge\sum_{h'\ni h'\le h}\phi_{a,c,h'}$$

$$\forall a,c,h\ni h\le\omega_c \text{ and } \kappa_c+h-1<FailTime \tag{A.58}$$

$$\sum_{b}\left[\sum_{d}\left(R^{1}_{a,b,c,d}+\sum_{h'\ni h'\le h-\lambda_{b,d}-\rho_{b,c,e_1}}\begin{pmatrix}T^{1}_{a,b,c_a=c,d,e_1,h'}\\+T^{2}_{a,b,c_b=c,d,e_1,h',fe}\end{pmatrix}\right.\right.$$

$$\left.\left.+\sum_{h'\ni h'\le h-\mu_{d}-\rho_{b,c,e_2}}\begin{pmatrix}T^{1}_{a,b,c_a=c,d,e_2,h'}\\+T^{2}_{a,b,c_b=c,d,e_2,h',fe}\end{pmatrix}\right)\right.$$

$$+\left(\frac{1}{\theta_{a,d_2,e_3}}\right)\sum_{h'\ni h'\le h-\rho_{b,c,e_3}-\upsilon_{c}}\left(\sum_{\substack{h''\ni h''\ge h'+\rho_{b,c,e_3}\\ and\quad h''\le h-\upsilon_{c}}}\begin{pmatrix}O^{1}_{a,b,c_a=c,h',h''}\\+O^{2}_{a,b,c_b=c,h',h'',fe}\end{pmatrix}\right.$$

$$\left.+\left(1-\psi_{c}\right)\sum_{h''\ni h''\le h'}\left(W^{1}_{a,b,c_a=c,h'',h'}+W^{2}_{a,b,c_b=c,h'',h',fe}\right)\right)\Bigg]$$

$$\ge\sum_{h'\ni h'\le h}\phi_{a,c,h'}\quad\forall a,c,h\ni h\le\omega_{c}\text{ and }\kappa_{c}+h-1=FailTime,fe \tag{A.59}$$

$$\sum_{b}\left[\sum_{d}\left(R^{1}_{a,b,c,d}+\sum_{c'\ni c=c' \text{ and } \kappa^{2}_{c',fe}\le\kappa_{c'}+h-1} R^{2}_{a,b,c',d,fe}\right.\right.$$

$$+\sum_{h'\ni h'\le h-\lambda_{b,d}-\rho_{b,c,e_1}}\left(T^{1}_{a,b,c_a=c,d,e_1,h'}+T^{2}_{a,b,c_b=c,d,e_1,h',fe}\right)$$

$$\left.+\sum_{h'\ni h'\le h-\mu_{d}-\rho_{b,c,e_2}}\left(T^{1}_{a,b,c_a=c,d,e_2,h'}+T^{2}_{a,b,c_b=c,d,e_2,h',fe}\right)\right)$$

$$+\left(\frac{1}{\theta_{a,d_2,e_3}}\right)_{h'\ni h'\le h-\rho_{b,c,e_3}-\upsilon_c}\left(\sum_{\substack{h''\ni h''\ge h'+\rho_{b,c,e_3}\\ \text{and } h''\le h-\upsilon_c}}\left(\begin{array}{l}O^{1}_{a,b,c_a=c,h',h''}\\ +O^{2}_{a,b,c_b=c,h',h'',fe}\end{array}\right)\right.$$

$$\left.\left.+(1-\psi_c)\sum_{h''\ni h''\le h'}\left(W^{1}_{a,b,c_a=c,h'',h'}+W^{2}_{a,b,c_b=c,h'',h',fe}\right)\right)\right]$$

$$\ge\sum_{h'\ni h'\le h}\phi_{a,c,h'}\quad\forall a,c,h\ni h\le\omega_c \text{ and } \kappa_c+h-1>FailTime,fe \tag{A.60}$$

Constraints A.58–A.60 ensure satisfaction of all demands at FOL c for commodity a required by local time period h. Note that this formulation does not assign any individual FOL's demand exclusively to one FSL. Instead, multiple FSLs may send commodities to an FOL, if the model finds that it would be cost-effective to do so.

$$T^2_{a,b,c_b,d,e,h,fe} = 0 \quad \forall a,b,c_b,d,e,h,fe \quad \ni \quad b = fe$$
$$\text{and } \kappa_{c_b} + h - 1 \geq FailTime$$
$$\text{and } \kappa_{c_b} + h - 1 < FailTime + FailDuration \tag{A.61}$$

$$P_{b,b,j_1} = 0 \quad \forall b, j_1 \tag{A.62}$$

$$Q_{a,b,b,d,j_1} = 0 \quad \forall a,b,d,j_1 \tag{A.63}$$

$$R^1_{a,b,c,d} = 0 \quad \forall a,b,c,d \quad \ni \quad \rho_{b,c,e_2} \neq 0 \tag{A.64}$$

$$R^2_{a,b,c,d,fe} = 0 \quad \forall a,b,c,d \quad \ni \quad \rho_{b,c,e_2} \neq 0 \tag{A.65}$$

Constraint A.61 enforces that no assets can be drawn from a failed FSL during the failure duration, for each FSL failure event. Constraints A.62–A.63 force any FSL that performs its own WRM maintenance to use an "on site" maintenance strategy. Constraints A.64–A.65 allow WRM assets to be sourced from a collocated FSL (and thus do not require the use of any transport vehicles) only if the distance between the FSL and FOL is zero.

With a few minor changes to this mathematical formulation, we can produce an optimization model that identifies a prepositioning posture that satisfies delivery time lines across multiple sets of future deployment requirements. This modified model identifies a robust posture that performs well across a set of envisioned futures, although

it does not accommodate loss of access to FSLs.[5] Thus, we eliminate Constraint (A.61) in this modified model.

To allow the model to account for multiple potential futures simultaneously, we replace set **FE** with a set of alternative future deployment scenarios, denoted $ds \in \mathbf{DS}$. We define new input parameter *ChangeTime*, such that during the global time periods $i_1, i_2, \ldots,$ *ChangeTime*, the demands at each FOL are identical across all futures (assuming that the near-term future is potentially less unpredictable); demands are then assumed to be different across different futures for global time periods *ChangeTime*, *ChangeTime*+1, . . . , i_{max}. We replace input parameter *FailTime* in the previous model with *ChangeTime*.

The intent of this model is to identify an FSL posture that retains flexibility for the decisionmaker across the range of alternative futures that are considered. In a manner similar to the reliability model, this robustness to an alternative future demand model generates a single set of decisions for time periods $i_1, i_2, \ldots,$ *ChangeTime*, allowing the posture to retain the necessary flexibility at *ChangeTime* to satisfy all demands across each future. Then, following *ChangeTime*, a separate set of decisions needs to be tracked for each alternative future. Thus, the model needs to develop two versions of all variables and constraints that have a temporal dimension to account for each future *ds*. For example, it is necessary to define variables

$$T^1_{a,b,c_a,d,e,h} \text{ and } T^2_{a,b,c_b,d,e,h,ds}$$

in a similar manner as was done for the reliability model.

Because this modified model needs to consider multiple sets of potential deployment requirements, we finally need to generate a demand constraint for each "commodity–FOL–time period–future" combination and need to add a *ds* subscript to the demand input parameter $\phi_{a,c,h,ds}$.

[5] It is possible to extend these concepts to build a model that could simultaneously address both reliability against disruption and robustness to uncertain future demands, but such a model would require many more variables and constraints than the models presented here, which are already so large as to approach the computational limits of current desktop computers.

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