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THESIS

THE UNITED STATES ARMY'S MULTI-PERIOD OPTIMAL READINESS ALLOCATION MODEL

by

Jay Persons

June 2011

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The U.S. Army has undergone unprecedented change in the last decade, completing an organizational transformation and redesigning its deployment policies. These changes and other factors have resulted in an increase of 107% in equipping requirements between 2003 and 2011, forcing the Army to update its equipping policies. We develop the "multi-period optimal readiness allocation model" (MPORAM) to maximize unit equipment readiness across the force over several years. MPORAM extends an earlier single-period model to account for the dynamic nature of unit priorities, budget, and other factors that vary over the planning horizon. Using a small test case, we observe that MPORAM distributes and/or transfers equipment in anticipation of future demand needs. For example, if one unit cannot improve its readiness in one time period, MPORAM focuses on improving other units' ratings, if possible, regardless of their priorities. Using two realistically-sized cases, we observe that the multi-period solution does not differ notably from the single-period solution. Thus, we cannot make any strong conclusions about the added value of MPORAM in these cases. However, these results are strongly influenced by a large gap between supply and demand, and we expect MPORAM to improve the single-period solution in more balanced cases.

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THE UNITED STATES ARMY'S MULTI-PERIOD OPTIMAL READINESS ALLOCATION MODEL

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LIST OF ACRONYMS AND ABBREVIATIONS

ARFORGEN	Army Force Generation
BCT	Brigade Combat Team
CPM	Capital Planning Model
ERC	Equipment Readiness Code
FY	Fiscal Year
G-8 FDA	Analysis Division of the Army G-8 Force Development Directorate
LIN	Line Item Number
MPORAM	Multi-Period Optimal Readiness Allocation Model
MTOE	Modified Table of Organization and Equipment
NPS	Naval Postgraduate School
ORAM	Optimal Readiness Allocation Model
POM	Program Objective Memorandum
SACS	Structure and Composition System
SSO	Systems Synchronization Officer
T/R	Train/Ready

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EXECUTIVE SUMMARY

The United States Army has undergone unprecedented change in the last decade. During that time the Army has completed an organizational transformation and redesigned its deployment policies. These changes, along with an increase of 107% in Army equipping requirements between 2003 and 2011 for operations in Iraq and Afghanistan, have forced the Army to update its equipping policies.

The Army's default equipping objective is to provide as much needed equipment as possible to units; however, due to the increased requirements, fiscal constraints and other factors, *the Army does not have enough equipment to fill all requirements, all of the time*.

In 2009, the Analysis division of Army G-8 Force Development Directorate (G-8 FDA) approached the Naval Postgraduate School's (NPS) Operations Research department for assistance in developing a model to optimize unit equipment readiness levels. NPS faculty developed the "optimal readiness allocation model" (ORAM) that prescribes an optimal, *near-term* redistribution plan to maximize overall readiness across the force.

ORAM is a single-period model, so equipping decisions lack any projections over time. The Army wishes to assess the impact of long-term equipment purchase decisions on unit readiness *and* to determine an equipment distribution plan to achieve readiness goals over several years. For this reason, G-8 FDA is seeking assistance to develop a multi-period ORAM (MPORAM). This thesis develops such a model. MPORAM accounts for the dynamic nature of unit priorities, budget, and other factors that vary over the planning horizon, and determines an equipment distribution plan that maximizes readiness across the force over the planning horizon.

We have used a small test case to verify MPORAM's ability to distribute and/or transfer equipment in anticipation of future demand needs. In particular, we observe that if one unit cannot improve its readiness in one time period, MPORAM focuses on

improving other units' ratings, if possible, regardless of their priorities. Also, assessing penalties for transferring equipment between units is critical to ensure MPORAM does not prescribe an unstable equipping policy.

We have also tested MPORAM on two realistically-sized cases provided by G-8 FDA. These cases have been solved for both the entire planning horizon (multi-period) and for the first period alone (single-period). By comparing each multi-period solution with its single-period version we observe that no significant differences exist in the readiness outputs at the unit level in any of the priorities. Thus, we cannot make any strong conclusions about the added value of MPORAM relative to ORAM.

This is particular to the cases provided by G-8 FDA: the results are strongly influenced by the large difference between the increasing demand for equipment and the projected supply of equipment purchased over the planning horizon. The increasing demand for equipment has been heavily influenced by transformation and current operations in Iraq and Afghanistan. At the same time, the current economic situation in the United States has constrained the Army's ability to purchase the equipment necessary to meet those demands.

With transformation complete and a decrease in the demand for deployed forces in future years, coupled with a stronger U.S. economy, the gap between demand and supply should decrease. In that scenario, the results observed in the small test case (where the contribution of MPORAM is significant) may be reproduced to a realistic case, and we expect MPORAM to determine a distribution plan that differs and improves readiness compared to the single-period solution. We recommend MPORAM to continue to be tested by NPS and G-8 FDA.

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I. INTRODUCTION

A. BACKGROUND

The U.S. Army has undergone unprecedented change in the last decade, completing an organizational transformation and redesigning its deployment policies. These changes and other factors have resulted in a dramatic increase in equipping requirements over the last decade, forcing the Army to update its equipping policies. We develop the "multi-period optimal readiness allocation model" (MPORAM) to maximize unit equipment readiness across the force over several years. MPORAM extends an earlier single-period model to account for the dynamic nature of unit priorities, budget, and other factors that vary over the planning horizon.

1. U.S. Army Organizational Transformation

Even though the United States has not faced a peer adversary since the fall of the Soviet Union in the late 1980s, its Army remained a force organized to conduct large-scale wars against a Soviet-type army throughout the 1990s. Divisions were the basic warfighting organization with corps as the primary headquarters units. Corps are commanded by a lieutenant general (three-star) and commands three to four divisions. Divisions are commanded by a major general (two-star) and have about 17,000 soldiers. A division usually includes three or four maneuver brigades, each with three maneuver battalions, an artillery brigade with three artillery battalions, an aviation (helicopter) brigade, a support brigade and other enabler units. There are two types of divisions, heavy and infantry. Heavy divisions are a mix of: (a) mechanized infantry units equipped with tracked armored personnel carriers to quickly bring infantry soldiers to the battle and, (b) armor units equipped with tanks to provide overwhelming firepower. The infantry soldier is the fighting force of infantry divisions. This structure was well-suited for defeating past adversaries, but did not fit the operational environment of the new millennium.

Beginning in the early 2000s, the Army began an organizational transformation from this rigid, division-based force, to a modular, brigade combat team (BCT) based force. Today, BCTs are the basic warfighting unit, with divisions as the primary headquarters unit. BCTs are commanded by a colonel and are the maneuver brigades of the past augmented with an artillery battalion, support element and other enabler units to equip them to conduct major combat operations. Additionally, a BCT can be augmented with different levels and types of other enabling units (military police, engineers, civil affairs, etc.) depending on their mission. There are three types of BCTs: the traditional infantry and heavy BCTs, and a new medium BCT. Medium BCTs were fielded beginning in the late 1990s as a force that provided more firepower and mobility than the infantry BCTs, but required less support than the heavy BCTs. The medium BCTs are equipped with a wheeled armored personnel carrier (Stryker) to move infantry personnel to the battle. The Army also includes additional enabler units: artillery, engineer, military police, aviation, and other supporting brigades that can be organized according to the mission requirements and deployed along with BCTs to conduct operations.

The Army executed this organizational transformation while simultaneously conducting operations against an unpredictable adversary in Iraq and Afghanistan. The enemy in those countries arises from ideological groups (as opposed to nations) that are opposed to the United States These ideological groups are supported by various elements, ranging from individual financiers to nations that provide arms and training, and operate within countries and localities that provide sanctuary or do not have the security forces to eliminate them. Al Qaeda is the most infamous example of these groups. They attack U.S. elements and their allies with small units and attempt to influence the population to oppose U.S. and allied operations. This type of war has forced the United States to alter its objectives. In addition to killing or capturing enemy forces, the United States began focusing on influencing the relevant populations to support the United States and its partners and developing security forces in nations so that they can reduce the ability of these groups to operate within their borders. The Army's force structure for operations in Iraq and Afghanistan reflects this new focus. Engineer, military police, civil affairs and other enabling units are key elements resident within every BCT and division deployed to Iraq and Afghanistan.

2. Army Force Generation Model

The increased requirements for forces in Iraq and Afghanistan necessitated that the Army also transform its deployment policies. From 2001 to 2005, most Army units were conducting six-month deployments to Iraq or Afghanistan. These deployments and the high demand for forces in both countries resulted in many units redeploying after only six months at home station. The "six month on, six month off" schedule did not provide the stability required for operations. During the six months of deployment, units were not able to establish the battle rhythm and connections with local leaders necessary to effectively achieve their objectives. During the six months at home, units were not able to recover their equipment, receive and train new personnel or train for the next deployment. In order to overcome these issues, the Army decided to employ a rotational readiness strategy, called the Army Force Generation (ARFORGEN) model [1]. Units transition through three force pools in this model: "reset," "train/ready," and "available," respectively.

ARFORGEN was developed to provide stability in deployment cycles during operations conducted over many years, like Iraq and Afghanistan. It is also intended to be generic enough to apply to future operations. "ARFORGEN is a cyclic training and readiness strategy that synchronizes strategic planning, prioritization and resourcing to generate trained and ready modular expeditionary forces tailored to joint mission requirements" [1].

Currently units spend two years at their home station (six months in the reset phase and 18 months in the train/ready phase) and potentially one year deployed as part of the available pool for a total of three years in the cycle. The reset phase is projected to include approximately 1/6 of the operating force. Units in reset are those that have just finished the available phase (potentially from a deployment). They focus on reconnecting with families, receiving new personnel, and fixing and maintaining equipment from the deployment. They conduct very limited individual training, such as basic marksmanship training.

After the reset phase, units enter the train/ready phase. This pool is projected to contain approximately half of the operating force. Units in the train/ready phase begin training on unit tactics and operations. They progress through squad-level training (e.g., room clearing operations), platoon- and company-level training (e.g., isolating and searching houses) and battalion- and brigade-level training (e.g., isolating and clearing a neighborhood or city). The train/ready phase normally culminates in a capstone training exercise conducted at a national training site like Fort Irwin, California, or Fort Polk, Louisiana, in order to verify that the unit is prepared to execute their mission before being assigned to the available pool.

During the train/ready phase, some units will be identified and scheduled for deployment to a theater of operations, such as Iraq or Afghanistan. Units scheduled to deploy are designated as part of the deployment expeditionary force and are placed under the operational control of the headquarters they will report to during their deployment. They train on the mission-essential tasks and are assigned a mission-essential equipment list specific to the deployment mission. For example, a BCT scheduled for deployment to Afghanistan will be assigned to a division headquarters in that country for reporting purposes, train on the tasks they will conduct, and receive the equipment they need for operations.

Units not scheduled for deployment are designated part of the contingency expeditionary force. They remain assigned to their administrative headquarters and train on their core, mission-essential tasks with their core equipment requirements.

Once units have completed the necessary training for scheduled or potential deployment, they enter the available pool of units. This pool is projected to include approximately 1/3 of the operating force. During this phase, forces in the deployment expeditionary force deploy in accordance with their deployment schedule. Units in the contingency expeditionary force remain prepared for immediate deployment on any emerging contingency to any theater where they are needed. Once released from the available pool, units return to the reset pool to begin the cycle again.

For potential peace-time environments in the future that do not require high levels of deployed forces, the available pool includes a set of units identified as the first responders to emerging conflicts. They are designated the "mission" force and consist of one corps and five division headquarters, 20 BCTs, and 90,000 support soldiers [2].

For potential, extremely-high force demand environments the train/ready pool includes a "surge" force in case the demand exceeds the force assigned to the available pool. The surge force consists of one corps and three division headquarters, 10 BCTs, and 41,000 support soldiers [2].

3. Equipping Strategy

Organizational transformation, implementation of the ARFORGEN model and equipment requirements for units in Iraq and Afghanistan have resulted in an increase of 107% in Army equipping requirements between 2003 and 2011 [3]. Additionally, there are nations that have the economic, technologic and manpower to raise an army to challenge the Army in a large-scale war in the future. Even though the focus of operations and policies for the last decade has been operations in Iraq and Afghanistan, the Army must ensure future strategies and policies account for these potential large-scale wars against peer adversaries. One of the strategies that needed revision based on current operations and the projected future operational environment was the Army's equipping strategy. The Army Deputy Chief of Staff, G-8, addressed this requirement in 2009 with the publication of the fiscal year 2010 (FY10) equipping strategy. This document prescribed a transition from a cold-war, tiered-equipping readiness strategy into one that facilitates equipping soldiers and units according to their position in the ARFORGEN cycle, enabling them to accomplish their assigned mission [3]. The Army continues to procure the equipment necessary to complete the conversion to a BCT-based force. However, even with larger budgets, the Army continues to have equipment shortages due to the ongoing wars in Iraq and Afghanistan. Fiscal constraints dictate the Army be creative in managing the assignment of equipment needed for its operating forces.

The Army's equipping goal is to ensure soldiers and units have the equipment they need, when they need it [3]. The Army's default objective is to provide as much needed equipment as possible to units; however, *the Army does not have enough equipment to fill all requirements, all of the time*. A number of collective factors cause the Army's inability to maintain all units at high equipment readiness ratings. (See the next section for a summary of the Army's unit equipment readiness calculation procedures.) The recently published FY11 equipping strategy describes the Army's plan to mediate these shortages and equip units according to their position in the ARFORGEN cycle by allowing lower-priority units (i.e., reset units) to transfer some equipment to higher-priority units (i.e., units in the train/ready or available pools). Additionally, some equipment from reset units will be identified for national-level maintenance, modernization, or rebuild.

4. Equipment Readiness Calculation

The Army determines a unit's on-hand equipment readiness based on a number of factors. Items in the Army inventory are identified by an alpha-numeric code called the line item number (LIN). Every unit has a documented requirement for a specific number of LINs and the number of items they require for each of those LINs. This document is called the modified table of organization and equipment (MTOE). Each LIN assigned to each unit is further identified by an equipment readiness code (ERC) of "A" or "P." ERC P items are referred to as "pacing" items and "are those major weapon systems, aircraft, and other equipment items that are central to the organization's ability to accomplish/provide core functions/designed capabilities" [4]. They are mission-essential equipment. All other items are assigned ERC A. ERC A items do not completely preclude the unit from accomplishing its designed mission if they are missing.

For every LIN in every unit, a single LIN S-rating is assigned based on the percentage of the required amount of that LIN on hand in that unit: S-1 if the unit has at least 90% of the required amount, S-2 if the unit has at least 80%, S-3 if the unit has at least 65%, and S-4 if the unit has less than 65% [4].

Once all of a unit's LIN S-ratings are calculated, a unit S-rating is assigned. However, this rating cannot be higher than that of the lowest ERC P LIN S-rating. A unit is assigned S-rating S-1 if all of its ERC P LINs are S-1 and at least 90% of its ERC A LINs are S-1; S-2 if all of its ERC P LINs are S-1 or S-2 and at least 85% of its ERC A and P LINs are S-1 or S-2; S-3 if none of its ERC P LINs are S-4 and at least 80% of its ERC A and P LINs are S-1, S-2 or S-3; and, S-4 if any of its ERC P LINs are S-4 or greater than 20% of its ERC A and P LINs are S-4.

	Unit A				**Unit B**			
LIN	**ERC**	**On-Hand**	**Required**	**LIN S-rating**	**ERC**	**On-Hand**	**Required**	**LIN S-rating**
L1000	A	91	100	**S-1**	-	-	0	-
L1001	P	191	200	**S-1**	A	57	60	**S-1**
L1002	A	40	50	**S-2**	P	84	100	**S-2**
L1003	A	12	40	**S-4**	-	-	0	-
L1004	A	88	100	**S-2**	-	-	0	-
L1005	A	77	90	**S-2**	A	77	80	**S-1**
L1006	A	56	80	**S-3**	-	-	0	-
L1007	A	83	100	**S-2**	-	-	0	-
L1008	P	143	150	**S-1**	-	-	0	-
L1009	A	137	140	**S-1**	-	-	0	-
L1010	A	256	300	**S-2**	-	-	0	-
L2000	-	-	0	-	P	37	40	**S-1**
L2003	-	-	0	-	A	143	150	**S-1**
L2004	-	-	0	-	A	191	200	**S-1**

Table 1. Two fictional units MTOE and equipment on-hand data, and resulting LIN S-ratings. Unit A's S-rating is determined by its ERC A LINs with only 82% of its LINs being S-2 or better and 92% of its LINs being S-3 or better, resulting in an S-3 rating. Unit B's S-rating is determined by one of its ERC P LINs being S-2 and all of its LINs being S-2 or better, resulting in an S-2 rating.

Table 1 shows two fictional units' MTOE and equipment on-hand data, with the resulting LIN and unit S-ratings. Unit A's S-rating is S-3 because all of its P LINs are S-1 but only nine of its eleven (82%) assigned LINs are S-2 or better and 92% of its LINs are S-3 or better. Unit B is S-2 because one of its P LINs is S-2 and all of its assigned LINs are S-2 or better. This simple example also illustrates that ERC assignment is unit-specific: both units have a requirement for L1002, but in unit B it has ERC P, whereas in unit A it is considered an ERC A LIN. For a detailed discussion of S-ratings see [4], chapter 9, section 3.

5. Current Equipment Distribution Process

Despite the shortage of equipment, the Army's process for determining an equipment distribution plan has been focused on filling units to 100% of their requirements. Systems synchronization officers (SSOs) within the Army G-8 Force Development Directorate are responsible for determining a distribution plan for each item to each unit by month in an attempt to achieve this goal.

SSOs work with the Department of the Army systems coordinators in the office of the Assistant Secretary of the Army for Acquisition, Logistics and Technology, and the systems integrators within the Army G-3/5/7. The Department of the Army systems coordinators provides the acquisition and production plan for each item. The systems integrators provide the current on-hand and required amounts for each item by unit. They also provide the unit priorities, according to their position in the ARFORGEN cycle and the needs of other units in the same ARFORGEN pool. There are 81 SSOs organized under nine divisions within the G-8 Force Development Directorate Director of Materiel division. They are loosely aligned with the Army war fighting functions (movement and maneuver, fires, intelligence, sustainment, command and control and protection).

Each SSO manages a subset of similar items (e.g., all helicopters). SSOs attempt to determine the best distribution plan by focusing on distributing equipment coming out of production, "reset" equipment, and excess unit equipment (units with equipment over 100% of requirements). Several factors complicate the SSOs task of determining a distribution plan: changing unit priorities from the systems integrators, deviations from previous planned unit allocations, delays or changes to the production schedule, changes to on-hand amounts due to battle loss or "reset" requirements, and many others. See Figure 1 for a depiction of this process. SSOs work independently of other SSOs as they distribute the items under their control. Therefore, they attempt to maximize units' LIN S-ratings, but do not have complete visibility of items and how they affect each unit's overall rating.

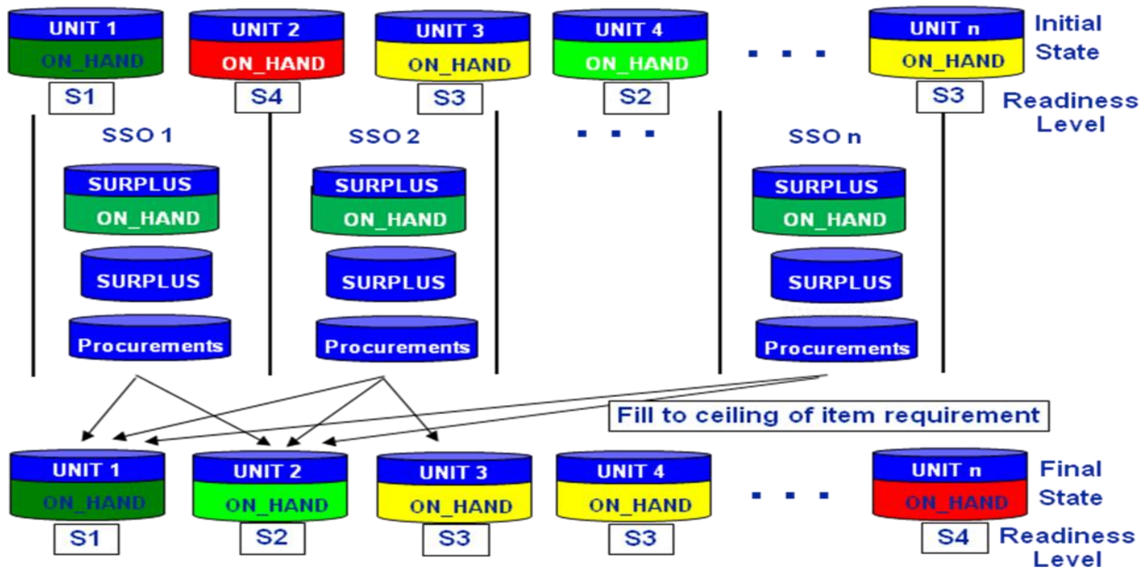

Figure 1. Graphic of the current equipment distribution process where SSOs work independently to improve the unit-LIN S-ratings of the LINs they control. After [5].

6. Equipping Goals

The FY11 equipping strategy describes the Army's new equipment distribution process to align the equipping process with ARFORGEN priorities. It designates specific equipping points, called "aim points," in the ARFORGEN cycle to ensure operating force units have what they need when they need it. Aim points provide the Army with a means to distribute equipment to units in order to achieve a prescribed state of readiness at predetermined points in the ARFORGEN cycle. This, in turn, allows Army leadership to make decisions geared to mitigate that risk related to unit equipping. Figure 2 shows how the current aim point goals align with the ARFORGEN cycle for the active and reserve components. For the active component, "Aim Point 1" is the day a unit enters the train/ready pool and "Aim Point 2" is six months after "Aim Point 1," that is, when the unit is expected to begin training on unit tactics and operations. The Chief of Staff of the

Army directed that active component units be equipped to S-3 at aim point one and S-2 at aim point two. Additionally, units will be equipped to S-1 prior to entering the available pool or assuming the surge force mission, and units in the reset pool will be equipped to facilitate the conduct of individual and institutional training [3]. Similar aim points and goals are established for the reserve component and Army National Guard units.

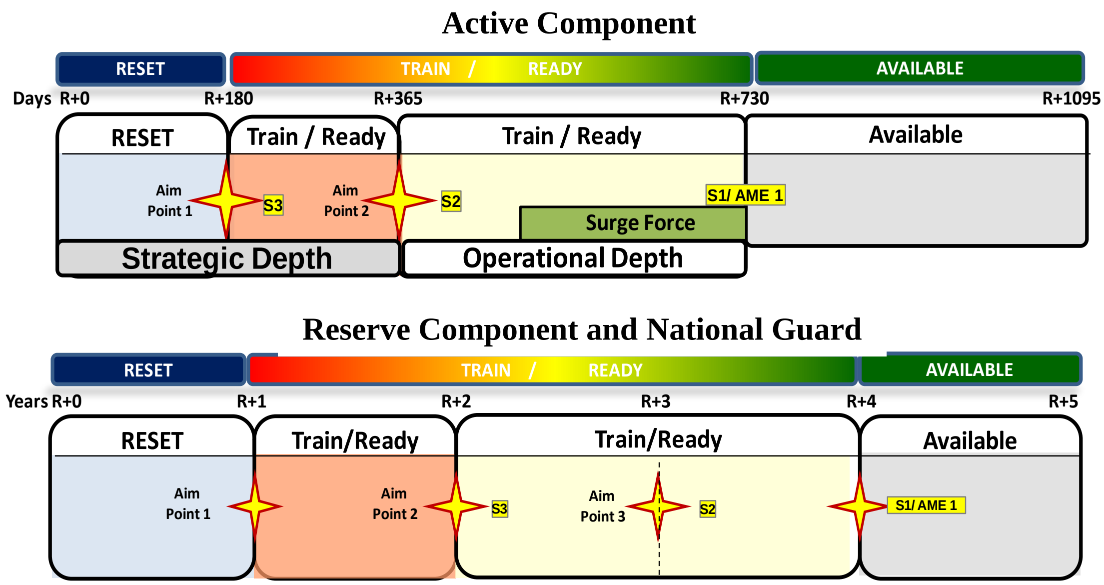

Figure 2. "Aim Point" and other equipping goals aligned with ARFORGEN cycle for the Army's active and reserve components. The goal is for units to progress from an S-3 rating to an S-2 rating during the train/ready cycle, and be equipped to S-1 prior to entering the available pool. From [3].

7. Program Objective Memorandum

The Army publishes a program objective memorandum (POM) in support of the Department of Defense's planning, programming, budgeting and execution system (See [1], chapter 9 for a detailed description.) This system allocates resources to ensure the services have the personnel and equipment necessary to achieve their missions. The POM is one of the key products of the system that describes in detail the Army's objectives for the programming phase and how it intends to allocate its resources over the next six years to achieve those objectives. For our purposes, the most important aspect of the POM is that it includes the number of each LIN planned for purchase in each year of the next six planning years.

8. Optimal Readiness Allocation Model

In 2009, the Analysis division of Army G-8 Force Development Directorate (G-8 FDA) approached the Naval Postgraduate School's (NPS) Operations Research department for assistance in developing a model to optimize unit S-ratings in the Army. NPS faculty developed the optimal readiness allocation model (ORAM) to "prescribe an optimal, *near-term* redistribution of equipment to Army units, in order to maximize overall readiness across the force" [6]. ORAM maximizes readiness "by determining the optimal near-term *redistribution* of on-hand LINs to other units within a selection of theater(s) based on the priority of the receiving unit (the unit's position in the ARFORGEN cycle) and the marginal increase in a unit's readiness" [6]. It calculates the LIN and unit S-ratings for each unit and uses these in the objective function to maximize a function of weighted S-ratings across all units.

Increasing unit S-ratings is given priority over LIN S-ratings. Because LIN S-ratings are also included in the objective function, the model increases LIN S-ratings within a unit, allowing it to improve its LIN S-ratings, even if the unit's S-rating does not improve.

ORAM first attempts to increase readiness by redistributing "planned" allocations (the allocation of equipment coming off the production line or out of reset), and optionally redistributing unit "excess" equipment, but without accounting for redistribution costs. ORAM is solved preemptively, that is, it determines a solution for units with highest priority first, and then fixes that solution and solves the model again for units in the next priority group, and so on.

There are factors used by the SSOs' equipment distribution plan that cannot be accounted for in ORAM. Thus, ORAM produces an optimistic solution (upper bound) on the level of readiness that can be actually achieved. However, by using a unit S-rating focus rather than a LIN S-rating focus, ORAM is able to achieve higher unit S-ratings than the current equipment distribution process. ORAM seeks to increase unit S-ratings by simultaneously considering all unit-LIN combinations in order to maximize unit readiness levels across the Army. Instead of attempting to fill to the LIN requirement and potentially increasing one unit's LIN S-rating at the expense of another unit's unit S-rating, ORAM "fills to the floor" of LIN S-rating requirements first, leaving more equipment available to increase other unit's S-ratings. Because a typical ORAM data set results in approximately 150,000 requirements (one for every ERC, LIN and unit combination), identifying an optimal solution is not trivial. Figure 3 depicts ORAM's equipment distribution process. All planned equipment allocations and excess equipment are identified as equipment available for (re)distribution (inventory) and distributed to units in order to maximize unit S-ratings across the force.

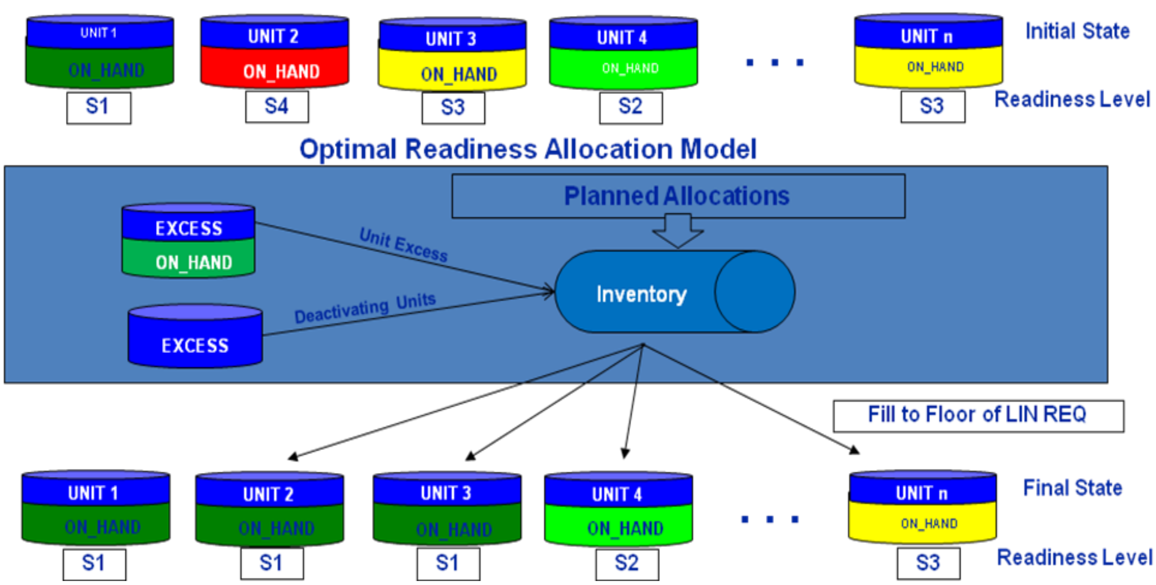

Figure 3. Graphic of the ORAM equipment distribution process that pools all planned allocations and excess equipment into one inventory and then distributes them to maximize unit readiness across all units. After [5].

ORAM provides leadership a readiness goal that the Army should be able to approach, even if it is not realistically achievable. It has been designed to answer the following questions for G-8 FDA and the Army [6]:

(1) What "level of readiness" can the Army achieve in the near-term with the on-hand LINs available for distribution?

(2) What allocation of LINs will achieve this maximum readiness?

(3) What is the minimal redistribution of LINs that will achieve this allocation?

In FY10, G-8 FDA used ORAM for several analyses to answer senior leader questions regarding the Army's equipping strategy. Of note, ORAM was used in the aim point analysis that the Chief of Staff of the Army used to develop the aim point goals for the FY11 equipping strategy.

B. LITERATURE REVIEW

Our problem falls in the well-known, general category of time-phased optimal resource allocation [7]. In these problems, one or several limited resources must be allocated among various competing needs or activities over time. In our case, we seek to allocate different LINs to several Army units over a pre-determined planning horizon in order to maximize the equipment on-hand readiness rating of the units.

Multiple applications of resource allocation models exist in the areas of facility expansion, portfolio management, project management, and production scheduling, among others [8]. However, we are not aware of any previous optimization-based approach to allocate equipment in the U.S. Army above the tactical unit level.

The RAND Corporation developed a systems engineering approach to analyze equipment serviceability readiness ratings [9]. This approach focuses on identifies supply issues that interfere with unit maintenance programs. For example, they analyze maintenance at the battalion level and aggregate the results to a division, but these results are not applicable to the Army as a whole.

Although not explicitly applied to equipment readiness, optimization has been applied to training readiness for an Army tank battalion [10] and a Navy "Prowler" squadron [11]. Both of these efforts focus on scheduling training events during a "peacetime" period in order to maximize training readiness for that period *and* minimize the days required to become fully trained when alerted for wartime deployment. Both models consist of two periods, a peacetime period that ranges from 30 days for the Prowler problem to 120 days for the tank problem, and a wartime period of undefined length. In both cases, only a single tactical unit is affected and Service-wide cases are not considered.

While these methodologies are informative, neither are applicable to a strategic, long-term, equipment on-hand readiness problem. The short-term focus of both methods is evident in the peacetime period of a few months followed by an undefined wartime period. By assigning training weights by period, the training models ignore the competing demands of different units and the dynamic effects of priorities, budget and other factors that change over several years. MPORAM assign weights by unit priority and readiness level in order maximize readiness across the entire Army, over several years. Period weighting could be implemented in MPORAM, but would not be significant when compared to the priority and readiness level weights, because they are more critical factors than time in the equipment on-hand readiness problem.

Finally, we are limited to the readiness metric defined by the Army [4]. However, for the optimization training models, the authors advocate using different metrics to assess readiness: specifically, they argue that readiness should be measured solely by time and dollars. For example, training readiness may be reported by the number of days for a unit to become fully-trained, and equipment on-hand readiness may be reported by the economic cost for a unit to achieve an S-1 rating. Our work does not propose using a new metric for readiness, but provides insight about different equipping policies effect on readiness levels, as they are currently defined.

C. THESIS OBJECTIVES AND ORGANIZATION

ORAM is a single-period model, so equipping decisions for units are static, lacking any projections over time. Distributions within a single year neglect effects on readiness in the upcoming years of the POM. The Army needs a method to assess the impact of POM equipment purchase decisions on unit S-ratings *and* to determine a long term equipment distribution plan to achieve unit S-rating goals as units rotate through the ARFORGEN cycle. For this reason, G-8 FDA is seeking assistance to expand ORAM into a multi-period model.

In this thesis, we develop a multi-period version of ORAM (MPORAM) in order to answer the following questions for G-8 FDA and the Army:

1. *Given six years of POM data, what distribution plan will maximize the level of readiness over the entire POM time horizon?*

2. *Given the resolution and uncertainties of the data and decisions in later years of the POM, how much does MPORAM improve ORAM?*

The remainder of this document is presented as follows. We develop our approach in Chapter II. This includes our limitations and assumptions, a generic description of the data, and the mathematical model formulation. In Chapter III, we describe the data sets used, the results obtained with MPORAM and the analysis of those results. We include an initial assessment on MPORAM's added value compared to ORAM. Chapter IV includes our conclusions and recommendations, as well as areas for further research and analysis.

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II. MPORAM METHODOLOGY AND DATA

A. LIMITATIONS

We identify the following limitations to the development of MPORAM:

- Forces modeled: The variation and scarcity of mission-essential equipping data for units in the train/ready and available pools limit MPORAM to modeling only contingency expeditionary forces.
- Planning horizon and time increment: MPORAM is designed to replicate the length of the POM (six years) and uses one-year time increments. This limits the ability to model monthly variations in the MTOE and equipment on-hand data and does not reflect the reset pool of the ARFORGEN cycle accurately. However, a one-year increment accurately reflects a budget year.
- Substitutions: MPORAM mirrors the initial version of ORAM and does not account for LIN substitution rules. Initial research with ORAM indicates that allowing for substitutions does not significantly impact results.
- Variability of distribution factors: There are several distribution factors that MPORAM cannot represent, such as changing unit priorities and equipment production schedules, equipment “reset” plans, battle loss or damage, etc. Therefore, MPORAM produces an optimistic solution, or “upper bound,” on the maximum readiness level achievable.

B. ASSUMPTIONS

The following assumptions are necessary for the development of MPORAM:

- Unit equipment requirements: We assume the MTOE accurately reflects the equipment needed for a unit to accomplish their designed mission. This assumption is realistic because unit MTOEs are continually modified to reflect modernization efforts that address identified capability gaps. The Army is conducting a major MTOE review in FY11 to ensure they accurately reflect requirements. This assumption is necessary because unit S-rating calculations are based on these requirements.
- Unit equipment on-hand: We assume unit equipment on-hand data in the structure and composition system (SACS) database is accurate. SACS is the primary database used by G-8 FDA. It includes current equipment on hand, projected MTOE requirements and programmed purchases, and position in the ARFORGEN cycle data for every unit in the Army over the

POM years. The assumption is valid because units report their equipment on-hand status monthly. The assumption is necessary because SACS is the database G-8 FDA uses to provide the input data for MPORAM.

- ARFORGEN assignment: We assume unit ARFORGEN assignment data is accurate and will not vary through the POM years. The assumption is valid because the ARFORGEN model is official Army policy. We use results of the ARFORGEN model to help determine unit priorities in MPORAM.
- Maintenance: All equipment on hand is assumed to be fully-mission capable. For the time increments modeled in MPORAM this assumption is valid because non-mission capable equipment does not stay with units for one year. The assumption is necessary because non-mission capable equipment on hand may decrease a unit's ability to perform its mission.

C. MODEL DESCRIPTION

MPORAM is a prototypic, mixed-integer linear program that addresses the Army's equipping challenges for the duration of the POM. It is an extension of ORAM that requires modifying the formulation to incorporate the dynamic nature of unit equipping priorities, budget, and other factors that vary over the POM years.

The objective of MPORAM is to maximize unit readiness by determining equipment (re)distribution plan for every year of the POM. There are many ways to measure unit readiness; for example, the number of units rated S-1, a weighted sum of unit S-ratings across all units, a weighted sum of unit S-ratings and LIN S-rating across all units, a weighted sum of LIN S-Ratings across all units, among others [6].

Like ORAM, MPORAM measures readiness as a weighted sum of unit S-ratings *and* LIN S-ratings across all units, but MPORAM expands it over the years of the planning horizon. Unit S-ratings weights are assigned based on the priority of the unit. A similar construct is used to assign each unit's LIN S-rating weights.

Solving the single-period ORAM preemptively by priority effectively assigns priority-1 units infinite more weight than priority-2 units, and priority-2 units infinite more weight than priority-3 units. With priorities accounted for by this preemption, weights in ORAM are then assigned to favor the highest S-ratings for units and LINs.

MPORAM also favors higher ratings but the preemptive scheme cannot be applied because ARFORGEN priorities change from one year to the next.

Table 2 provides the unit and LIN S-rating weights, respectively, used by MPORAM. Like ORAM, these weights reflect that increasing unit S-ratings is given priority over increasing LIN S-ratings in MPORAM. LIN S-ratings are included in the objective to give the model incentive to improve LIN S-ratings within a unit, even if its unit S-rating cannot improve. For now, these weights remain constant for the duration of the model, i.e., achieving S-rating S-1 for a priority-1 unit in the first year is the same as that in the last year.

	Priority		
Unit S-Rating	1	2	3
S-1	120	100	45
S-2	95	60	20
S-3	30	15	12
	Priority		
LIN S-Rating	1	2	3
S-1	12	10	4.5
S-2	9.5	6	2
S-3	3	1.5	1.2

Table 2. MPORAM weights by priority for achieving each unit and LIN S-rating, respectively. S-4 is the default rating and not explicitly modeled. Unit ratings are given priority over LIN ratings. Ratings are assumed constant for all time periods.

In order to discourage unnecessary redistribution, MPORAM includes a penalty in the objective function for redistributing equipment between units. A penalty is assessed for every item redistributed from a unit to another. (These penalties may also be used as a surrogate for redistribution costs.) In the current formulation, all penalties are equal, but these could be modified to better reflect Army preferences.

MPORAM determines an optimal (re)distribution of equipment to maximize unit readiness across the Army adhering to the following specifications:

- The allocation of each LIN in each time period is restricted to the total distributions available in that period, including purchases and transfers.

- Purchases in each period are limited by the budget for that period.
- LIN inventories in each unit and year must be represented.
- LIN and unit S-ratings must be calculated (including influence of ERC P LIN S-ratings on unit S-ratings).

See Section II.E for the complete formulation of the model.

D. DATA

G-8 FDA formats and provides all data for the model via the SACS database. First, they determine the set of units and the years they wish to analyze. For example, they may choose to analyze only active duty units stationed in the United States over the next six years. With the set of units and years established, they build a series of data files (see Table 3) that describe a complete problem.

For programmed purchases data, G-8 FDA may also use another optimization model developed by NPS called the capital planning model (CPM). CPM helps determine the portfolio of options to fund for the programmed budget in the POM years and was used by the Army staff to inform development of the POM in FY11. CPM recommends equipment to purchase over the POM years and other equipment funding decisions such as equipment modernization and reset [12]. Equipment in CPM is not modeled at the LIN level, but the solution can be mapped to a set of LINs to purchase for each year of the POM. This set of LINs can be used as the programmed purchase data for MPORAM. Since CPM does not determine the set of LINs to purchase (but an equipment strategy based on many other factors that affect equipment funding decisions), option values in CPM are not assigned by their effect on equipment readiness. For this reason, G-8 FDA may use MPORAM to determine the effect of CPM and other POM decisions on equipment readiness.

File	Description
Unit	the set of units
ARFORGEN	the set of unit priorities, typically priority-1 (available pool units), priority-2 (train/ready units), and priority-3 (reset units)
Period	the set of time periods (normally six years to reflect a POM cycle)
UnitCycle	each unit's priority by period
ERC	the set of ERCs (preloaded A and P)
Budget	the budget for each period
LIN	the set of LINs authorized by the units during the analysis years
Cost	the cost of each LIN (constant across all periods)
Readiness	the unit and LIN readiness ratings (preloaded S-1, S-2 and S-3. S-4 is the default and not explicitly modeled)
Delta	each unit's change, from the previous period, to LIN authorizations in the current period
Num	the unit S-rating metrics for every S-rating and unit in every period, by ERC
Per	the LIN S-rating metrics for every S-rating and unit-LIN combination in every period, by ERC
Avail	the number of each LIN programmed for purchase in each period
POM	the units that have authorizations for the LINs programmed for purchase in each period
Pt	the penalties for redistributing each LIN, by ERC
Req	each unit's initial authorization for all of its LINs
Oh	each unit's initial on-hand data for all its required LINs

Table 3. MPORAM input file names and description. These files describe a complete problem. Once the set of units and planning horizon (years) for analysis is determined, the rest of the data is drawn from the SACS database. Programmed purchases may also come from a CPM solution.

E. FORMUALTION

MPORAM's formulation is organized in standard mathematical programming format [13], adhering to the specifications and data described above in this chapter.

Indices

e	ERC category
l	LIN
s	S-rating (S-4 is the default and not explicitly represented in the model)
u	unit
t	time period (one year increments)
p	priority

Data [units]

val_{sp}	weight of having a unit with priority p at rating s [rating] (remains constant across all t)
$valL_{elsp}$	weight of having LIN l, category e, in a unit with priority p at rating s [rating] (remains constant across all t)
pt_{elu}	penalty for taking away LIN l, category e from unit u (set to 1.0 in all of our test cases)
$avail_{lt}$	number of LIN l available to distribute to units in period t [item]
$cost_l$	cost for each item l [$/item] (constant across all time periods)
$budget_t$	dollars available for purchases in period t [$]
oh_{elu}	initial number of LIN l, category e, assigned to unit u [item]

per_{elsut} number of LIN l, category e, required by unit u to achieve LIN S-rating s in period t [item]

num_{sut} number of LINs at LIN S-rating s required by unit u to achieve unit S-rating s in period t [item]

$auth_{elut}$ number of LIN l, category e authorized by unit u in period t [item]

Other Sets and Derived Sets

UTP subset of triplets (u, t, p) where unit u has priority p in period t

$ELUT$ derived subset of quadruplets (e, l, u, t) where unit u has a requirement for LIN l, category e in period t, i.e., if $auth_{elut} > 0$.

ELU derived subset of triplets (e, l, u) where unit u has a requirement for LIN l category e in some period

Decision Variables [units]

V_{sut} binary variable with value 1 if unit u is at rating s during period t (results of period t plan)

R_{elsut} binary variable with value 1 if LIN l, category e, for unit u is at rating s during period t (results of period t plan)

A_{elut} number of LIN l, category e to take away from unit u at the beginning of period t [item]

X_{elut} number of LIN l, category e, distributed to unit u at the beginning of period t [item]

B_{lt} number of LIN l to purchase at the beginning of period t [item]

I_{elut} inventory of LIN l, category e in unit u during period t [item]

Formulation

$$\text{Maximize} \sum_{\substack{s,u,t,p \mid \\ (u,t,p) \in \text{UTP}}} val_{sp} V_{sut} + \sum_{\substack{e,l,s,u,t,p \mid \\ (e,l,u,t) \in \text{ELUT}, \\ (u,t,p) \in \text{UTP}}} valL_{elsp} R_{elsut} - \sum_{\substack{e,l,u,t \mid \\ (e,l,u) \in \text{ELU}}} pt_{elu} A_{elut}$$

Subect to:

$$\sum_{e,u \mid (e,l,u,t) \in \text{ELU}} X_{elut} = avail_{lt} + B_{lt} + \sum_{e,u \mid (e,l,u,t) \in \text{ELU}} A_{elut} \qquad \forall l,t \qquad (1)$$

$$\sum_{l} cost_l B_{lt} \le budget_t \qquad \forall t \qquad (2)$$

$$I_{elut} = oh_{elu} + X_{elut} - A_{elut} \qquad \forall e,l,u,t \mid (e,l,u,t) \in \text{ELU},\ t = 1 \qquad (3)$$

$$I_{elut} = I_{elu(t-1)} + X_{elut} - A_{elut} \qquad \forall e,l,u,t \mid (e,l,u,t) \in \text{ELU},\ t > 1 \qquad (4)$$

$$per_{elsut} R_{elsut} \le I_{elut} \qquad \forall e,l,s,u,t \mid (e,l,u,t) \in \text{ELUT} \qquad (5)$$

$$\sum_{s} R_{elsut} \le 1 \qquad \forall e,l,u,t \mid (e,l,u,t) \in \text{ELUT} \qquad (6)$$

$$V_{sut} \le \sum_{s' \mid s' \le s} R_{els'ut} \qquad \forall e,l,s,u,t \mid (e,l,u,t) \in \text{ELUT},\ e = \text{P} \qquad (7)$$

$$num_{sut} V_{sut} \le \sum_{e,l,s' \mid s' \le s} R_{els'ut} \qquad \forall s,u,t \qquad (8)$$

$$\sum_{s} V_{sut} \le 1 \qquad \forall u,t \qquad (9)$$

$$\begin{aligned} & X_{elut}, A_{elut}, I_{elut} \ge 0 \quad \forall e,l,u,t \\ & B_{lt} \ge 0 \quad \forall l,t \\ & R_{elsut} \in \{0,1\} \quad \forall e,l,s,u,t \\ & V_{sut} \in \{0,1\} \quad \forall s,u,t \end{aligned} \qquad (10)$$

The model determines a unit distribution plan (X_t , B_t , and A_t) for all units, attempting to increase the unit S-rating for the current period *t* through an increase in the current inventory, I_t , while at the same time attempting not to penalize the unit S-rating for future periods. The unit readiness level at the beginning of t is based on a unit's inventory at the end of the previous period (I_{t-1}).

Constraint set (1) restricts the LIN allocation in each period to the total distributions available in that period, including purchases and transfers. Constraint set (2) limits purchases to the available budget in each period. Constraint sets (3) and (4) restrict the inventory of each unit-LIN combination to its inventory in the previous period plus the impact of the (re)distribution plan for the current period. Constraint set (5) restricts a unit-LIN rating based on the number of the LIN assigned to the unit in that period. Constraint set (6) allows at most one unit-LIN rating in each period. Constraint set (7) restricts a unit rating to be no better than a unit-LIN rating for pacing LINs in each period. Constraint set (8) restricts a unit rating based on the number of unit-LIN ratings in each period. Constraint set (9) allows at most on unit rating in each period. Constraint set (10) is used to bound variables.

F. MODEL VARIATIONS

Slight variations of MPORAM can be made in order to achieve various analytic objectives. Two MPORAM variations are implemented together for analysis in this thesis. They work together to isolate the effect of POM equipping policies on unit readiness. First, we prevent transferring equipment between units in MPORAM by fixing all $A_{elut} = 0$. Second, we create *LUT*, a derived subset of triplets (l, u, t) where unit u has an authorization in period t for LIN l programmed for purchase in period t. We then fix $X_{elut} = 0$ for each e and each $(l,u,t) \notin LUT$. This prevents MPORAM from allocating equipment to units that do not have an authorization for the LINs programmed for purchase every year. These two adjustments work together to allow analysis of the effect of distributing the LINs programmed for purchase in the POM.

These are just two examples of many potential variations that could be used to address specific objectives. Variations typically involve a restriction of the original problem and reduce computational time.

G. OUTPUT

MPORAM output recommends a (re)distribution plan to maximize unit readiness according to their priorities across all time periods. The amount of each LIN that each unit gains (X_{elut}) or transfers to another unit (A_{elut}) in every period, the LIN purchase plan (B_{lt}) for each period, and the resulting unit (V_{sut}) and unit-LIN S-ratings (R_{elsut}) are included in the output files. The impact of POM decisions on unit readiness are the key findings of interest to G-8 FDA so the results presented in Chapter III are focused on unit readiness ratings.

Table 4 lists the MPORAM output files and gives a description of each one.

File	**Description**
Gainers	the amount of each LIN that each unit gains (X_{elut}) or transfers (A_{elut}) in every period
LINSRate	the S-rating results of the solution for every unit-LIN combination in every period based on its inventory in that period (R_{elsut} and I_{elut})
Objective	the final objective function value of the model solution
Penalties	the amount of each LIN transferred from each unit in every period and the resulting penalty (product of A_{elut} and pt_{elu})
Purchases	the amount of each LIN purchased in each period and the budget for that period (B_{lt})
UnitSRate	the S-rating results of the solution for every unit in every period (V_{sut})
UnitSummary	summary file that includes unit data and results for each period: priority, count of ERC A and P LINs, worst ERC P LIN S-rating, count of LINs at each LIN S-rating and the resulting unit S-rating

Table 4. MPORAM output file names and descriptions. Every decision variable is included in the outputs. The UnitSummary file is used for presenting results and evaluating an equipping policy's readiness ratings. Other files can be used for detailed analysis of the solution.

H. SOFTWARE

MPORAM is implemented in the General Algebraic Modeling System and uses the CPLEX solver [14]. The typical full case instance (see Section III.A) includes 4.9 to

5.8 million constraints and 8.7 to 11.4 million variables (of which, between 2.9 and 3.4 million are binary.) CPLEX pre-solves the problem to drastically reduce the dimension to between 164,000 and 317,000 constraints and between 175,000 and 309,000 variables (of which, between 152,000 and 253,000 are binary.) Solve times (to within one percent of optimality) range from approximately one hour to three hours on a 3.2 giga-Hertz computer with 12.0 giga-bytes of random access memory.

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III. DATA SETS, RESULTS AND ANALYSIS

A. DATA SETS

We use a small test case and two full test cases to analyze MPORAM's ability to determine a multi-period distribution plan to maximize readiness over the POM years. The small test case has been developed by the author. It has allowed a detailed solution analysis with which to verify the implementation of the model formulation. G-8 FDA has provided the full test data sets to ensure MPORAM can be solved for a typical data set they may need to analyze.

1. Small Test Case

The small test case is a modified subset of the single-period ORAM data. We include data for subsequent periods to stress the model's ability to increase readiness. For this case, we assume two units and four assigned LINs. Both units require the same four LINs except that one unit has one ERC P requirement and three ERC A requirements, while the other unit has all ERC A requirements. Both units' authorizations for some of their LINs change after the third period, which allows us to test the model's ability to account for changes in future authorizations.

The initial unit S-rating for both units is S-4, with seven of the eight unit-LIN combinations rated S-4. We set these initial conditions in order to test MPORAM's ability to improve readiness over the planning horizon. In order to replicate the ARFORGEN cycle, we ensure that the two units have different priorities in every period and rotate through the priority levels during the planning horizon. To test MPORAM's ability to determine a distribution plan for programmed purchases, we vary the amount of each LIN available for distribution in each period (as the POM does). The small test case data set also includes a budget for each period to test the model's ability to determine a LIN purchase plan that improves readiness. The complete data set for this case can be found in the Appendix.

2. Full Test Cases

Two original full test cases have been provided by G-8 and include all of the 1,911 active duty units stationed in the continental United States and their 2,085 assigned LINs. The full test cases include data for each year of the upcoming POM, FY12 through FY17, including unit authorizations and priorities, LINs programmed for purchase, and the budget available. Subsequently, we create two other full cases restricted to the first year of data available.

The difference between the two original full test cases is the source of the programmed purchase data: the first one, "SACS," uses the SACS database, while the second, "CPM," uses a CPM solution. The SACS database includes programmed purchase data for every year, while CPM is designed to provide a solution for every year of the POM, except for the next year. For this reason, the SACS restricted full case uses FY12 data, while the CPM restricted full case uses FY13 data. Programmed purchase data represents the supply of equipment available to satisfy equipment demands.

An initial review of the SACS and CPM programmed purchase data files shows significant differences (see Table 5). These differences are expected: the CPM solution seeks to determine an equipping policy that maximizes the value of the policy for the entire POM, while the SACS data is focused on equipping the Army in the next year.

Unit authorizations represent equipment demands. These authorizations increase or decrease from year to year. We use the total change in unit-LIN authorizations as a metric for how equipment demands are changing over the POM years. Reviewing the unit authorizations data for the POM years reveals that, starting in FY13, the total change in items authorized increases every year by at least 396,000 items.

Table 5 shows the increase in items authorized (the demand) in the original full test cases, programmed purchases (the supply), and the difference between the demand and supply for each fiscal year. We see that in every year, except FY12, the demand exceeds the supply by between 274,000 and 406,000 items.

From this imbalance, we expect that MPORAM will not be able to identify a solution that results in high readiness ratings for all units across the POM. It should perform better in the first period of the SACS case because there is no increase in demand in FY12 in those data. We expect the readiness results to decrease every year for the rest of the POM because of the increasing difference between demand and supply for both data sets.

Year	FY12	FY13	FY14	FY15	FY16	FY17	Total
Change in Items Authorized	(baseline)	396,393	431,129	463,798	465,975	469,259	2,226,554
SACS Programmed Purchases	336,133	93,265	74,639	77,173	74,168	63,133	718,511
CPM Programmed Purchases	0	121,844	105,005	103,052	105,049	109,090	544,040
SACS Difference	(336,133)	303,128	356,490	386,625	391,807	406,126	1,508,043
CPM Difference	0	274,549	326,124	360,746	360,926	360,169	1,682,514

Table 5. Total change in items authorized in each year of the original full test cases, the number of items programmed for purchase in each year for the SACS and CPM data sets, and the difference between them for both data sets. Authorizations clearly exceed purchases for both data sets in every year except FY12. We expect this to affect MPORAM's ability to determine a solution that achieves high readiness ratings.

B. ANALYTIC APPROACH

First, we solve the small test case to verify MPORAMs ability to assess a POM equipping policy and to gather insights about how and why it determines a solution to maximize unit readiness.

Second, we use MPORAM to solve both original full test cases for the entire planning horizon (multi-period), and then for the restricted full test cases (single-period.) We compare the results of the first period of the multi-period results to the single-period results to gather insights about the value of MPORAM relative to ORAM. Using single-period input files, MPORAM replicates the formulation and modeling of ORAM with the one caveat discussed in Section II.C: due to the preemptive scheme applied in ORAM, weights are assigned by rating only, with higher priorities weighted infinitely more than any lower priority. Since, MPORAM cannot solve preemptively, weights are assigned by rating *and* priority.

The MPORAM weighting scheme is similar to ORAM's, but not identical. Still, we assume that the MPORAM results for a single period data set are an acceptable proxy for ORAM results for the same period. With this assumption, if we observe different results (in either of the full test cases) in the single-period version than the first period of the multi-period version, we can conclude that MPORAM is necessary to assess a POM equipping policy. (Note the converse is not necessarily true.)

C. RESULTS AND ANALYSIS

1. Results of the Small Test Case

The size of this test case allows detailed analysis and presentation of the MPORAM results. The complete unit readiness results for each period are shown in Table 6. It includes each unit's position in the ARFORGEN cycle, LIN counts (total and by ERC), worst ERC P S-rating, count of LINs at each rating, and resulting unit S-rating. Highlighted cells are periods when the units achieve an S-1 rating.

Because both units in the small test case have less than five LINs assigned in each period, the only unit ratings achievable are S-1 or S-4. For a unit to achieve S-1, all of its LINs must be rated S-1, otherwise it becomes S-4. This extreme characteristic, coupled with the other data being designed to stress the model, emphasizes how MPORAM decides between pairs of units to determine a solution to maximize unit readiness.

Unit	Period	ARFORGEN Cycle	Total LINs	# P LINs	# A LINs	Worst P LIN S-Rating	# LINs at Rating: S1	S2	S3	S4	Unit S-rating
U01842	1	Available	4	1	3	4	0	0	0	4	**4**
U01842	2	Reset	4	1	3	3	0	1	2	1	**4**
U01842	3	T/R	4	1	3	1	2	0	1	1	**4**
U01842	4	Available	3	1	2	1	3	0	0	0	**1**
U01842	5	Reset	3	1	2	1	3	0	0	0	**1**
U01842	6	T/R	3	1	2	1	3	0	0	0	**1**
U05386	1	T/R	4	0	4	1	4	0	0	0	**1**
U05386	2	Available	4	0	4	1	4	0	0	0	**1**
U05386	3	Reset	4	0	4	1	4	0	0	0	**1**
U05386	4	T/R	2	0	2	1	2	0	0	0	**1**
U05386	5	Available	2	0	2	1	2	0	0	0	**1**
U05386	6	Reset	2	0	2	1	2	0	0	0	**1**

Table 6. Small test case unit and unit-LIN data, unit-LIN readiness results and resulting unit readiness results for each period. Available units have the highest priority, followed by train/ready (T/R) and reset units, respectively. MPORAM uses the weights (by priority and readiness rating) from Table 2. All units achieve rating S-1 for the last three periods.

The total amount of each LIN available for distribution in each period is shown in Table 7. Equipment available for distribution in each period is composed of the programmed purchase data input and part of the MPORAM solution: the purchase variable, B_{lt}, and the transfer variable, A_{elut}. LIN-period combinations not listed here have zero items available for distribution in that period.

LIN	PERIOD	Programmed Purchases	Budget Purchases	Transfers	Total
A20044	1	20	0	5	25
A20044	2	20	1	0	21
A20044	3	20	2	0	22
A20044	4	20	2	55	77
A20044	5	20	3	0	23
A20044	6	20	4	0	24
C68719	1	0	0	17	17
C68719	2	0	1	0	1
C68719	4	0	1	0	1
C68719	5	0	1	0	1
C68719	6	0	1	0	1
D02704	1	2	0	0	2
D02704	2	2	0	0	2
D02704	3	2	0	0	2
D02704	4	0	0	2	2
M12418	1	60	0	19	79
M12418	2	50	0	0	50
M12418	3	40	0	0	40
M12418	4	30	0	0	30
M12418	5	20	0	0	20
M12418	6	10	0	0	10

Table 7. Total amount of each LIN available for distribution in the small test case by programmed purchases, budget purchases, and transfers in each period. Programmed purchases are input data while budget purchases and transfers are determined by MPORAM decision variables, B_{lt} and A_{elut}, respectively. MPORAM determines a distribution plan (Table 8) for these items to achieve the results of Table 6.

2. Analysis of the Small Test Case

Analyzing these results, along with a detailed knowledge of the input data allows us to identify several characteristics of the MPORAM solution that is critical for our understanding before moving to the solution of the full test cases. MPORAM's unit (re)distribution plan for the small test case is presented in Table 8. It shows number of items by LIN that units receive (gain) or transfer (lose) in each period. MPORAM determines this distribution plan to achieve the readiness levels presented in Table 6.

Period	Unit	LIN	ERC	Change
1	U01842	A20044	A	-5
1	U05386	A20044	A	25
1	U01842	C68719	A	-17
1	U05386	C68719	A	17
1	U05386	D02704	A	2
1	U01842	M12418	A	-19
1	U05386	M12418	A	79
2	U01842	A20044	A	21
2	U05386	C68719	A	1
2	U01842	M12418	A	50
2	U01842	D02704	P	2
3	U01842	A20044	A	22
3	U01842	M12418	A	6
3	U05386	M12418	A	34
3	U01842	D02704	P	2
4	U01842	A20044	A	77
4	U05386	A20044	A	-55
4	U05386	C68719	A	1
4	U05386	D02704	A	-2
4	U05386	M12418	A	30
4	U01842	D02704	P	2
5	U01842	A20044	A	23
5	U05386	C68719	A	1
5	U05386	M12418	A	20
6	U01842	A20044	A	24
6	U05386	C68719	A	1
6	U05386	M12418	A	10

Table 8. Small test case LIN distribution plan for the items available for distribution (Table 7). The number of items each unit receives or transfers by LIN and period is displayed. This distribution plan produces the readiness results shown in Table 6.

We observe the following:

- First, <u>if one unit cannot improve its readiness in one time period, MPORAM focuses on improving the other unit's rating, if possible, regardless of priorities.</u> The results of Table 8 show this in the first period when the priority-1 unit, U01842, cannot achieve S-1 unit rating due to its ERC P LIN. MPORAM prescribes a distribution plan that achieves an S-1 rating for U05386, even though the unit has priority-2. As the detailed solution in Table 8 shows, U01842 does not receive any equipment in the first period: instead, the unit transfers some equipment to U05386, decreasing one of its LIN S-ratings to S-4, in order to facilitate improving U05386's S-rating.

- Second, MPORAM is accounting for future priorities. This is shown by the solution focusing on U05386 in the first period when it will become priority-1 in the next period. Then, again in the second period, the solution begins to allocate equipment to U01842 to facilitate it achieving S-1 rating in the next period when it will be priority-1 again (i.e., for the fourth period).

- Third, MPORAM is accounting for future authorizations. This is shown in Table 8 when U01842 does not receive LIN C68719 in the first three periods because the authorization becomes zero for the rest of the periods beginning in the fourth period. Then, again in the second period, the solution begins assigning D02704 to U01842 to account for its increase in authorizations, which occurs in the fourth period.

- Fourth, assessing penalties for transfers is critical to ensure MPORAM does not prescribe a turbulent equipping policy. Without these penalties the test solution unnecessarily moves the same equipment between units from one period to the next.

Figure 4 is the standard MPORAM results chart for the small test case. It shows the percentage of units in each ARFORGEN pool at each S-rating for each period of the model. For the small test case, the chart does not provide additional insights to those already discussed. But for the full test cases, similar charts display results that are not easily identified from the output files.

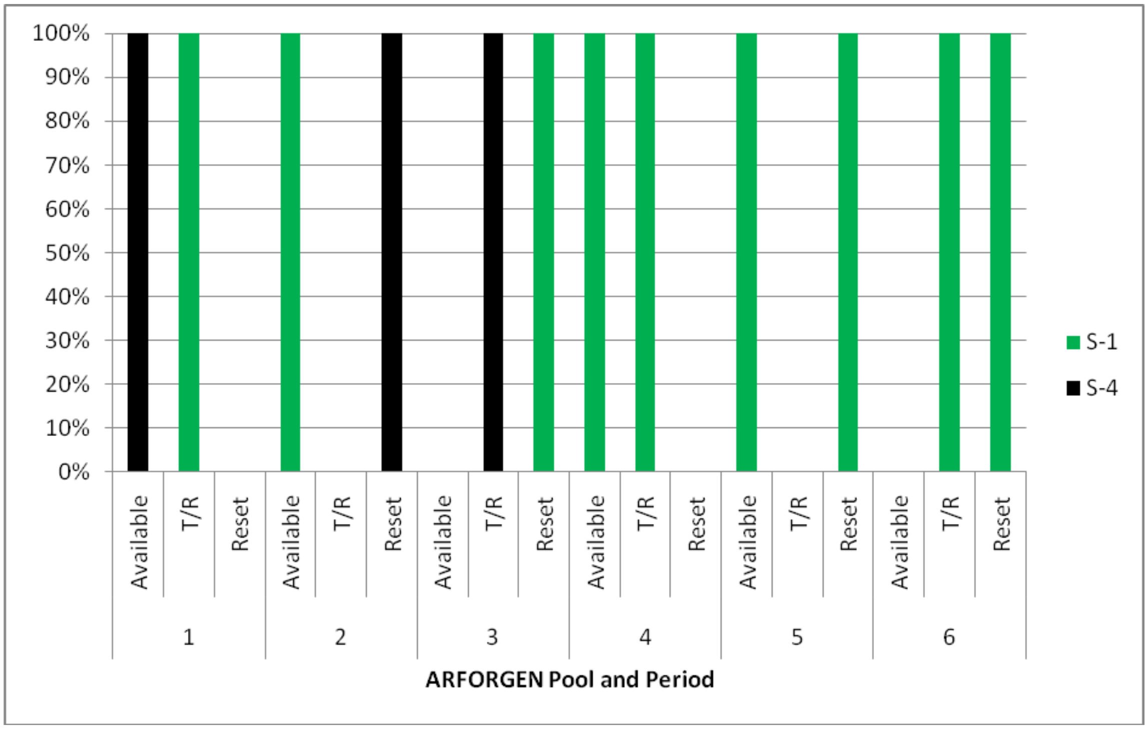

Figure 4. Small test case results chart with percentage of units in each ARFORGEN pool at each readiness level by period, with transfers. Due to inputs, units can only be rated S-1 or S-4. With MPORAM's prescribed (re)distribution plan both units achieve S-1 rating for the last three periods.

3. Results of Full Test Cases

The results of the full test cases are organized by the data set (SACS or CPM) and the planning horizon (single- or multi-period). To create the restricted, single-period data sets we have removed all data from the original multi-period cases except for the first period data.

G-8 FDAs primary purpose for MPORAM is to assess the effect of a POM programmed purchase plan on long-term unit readiness. For the full test cases, we implement the two model variations discussed in Section II.F, preventing unit transfers and allowing units to receive only the LINs they are authorized (and that are programmed for purchase) in each year.

The aggregated starting unit and unit-LIN readiness statistics are presented in Table 9. These statistics are the baseline for MPORAM: they illustrate the unit and unit-

LIN readiness levels prior to the distribution of items in a POM programmed purchase plan. They include the percentage of the total number of units and unit-LIN combinations at each readiness level. We note that high unit-LIN S-ratings (87% of the unit-LIN combinations rated S-1) do not result in high unit S-ratings (only 46% of the units rated S-1). This result illustrates the strong influence of ERC P LINs on unit readiness.

	S-1	S-2	S-3	S-4	Total #
% of Unit-LINS	87%	1%	1%	11%	170,752
% of Units	46%	25%	14%	16%	1,911

Table 9. Percentage of unit-LINs and units at each readiness level based on full test case inputs. These data are the baseline: the aggregated initial readiness ratings before execution of a POM programmed purchase plan.

a. Multi-Period SACS Results (FY12-FY17)

Figure 5 shows the multi-period results for the SACS data set. The chart shows that in the first period, FY12, the solution is better than it is for the rest of the POM. In FY12, 59% of the available units are S-1, but in FY13 this percentage drops significantly, to only 36%. At the same time, available units at S-4 increase from 10% to 21%. For the last five years, these percentages continue to worsen, finishing with 34% of the available units at S-1 and 31% at S-4 in FY17. The results are similar for the other ARFORGEN pools.

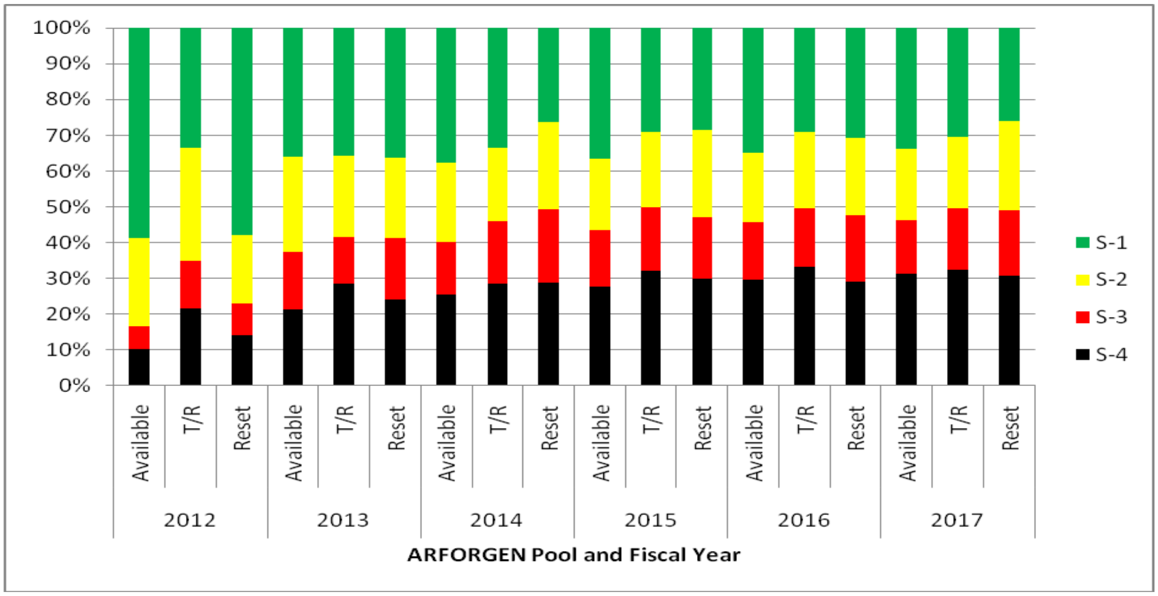

Figure 5. Multi-period (FY12-FY17) SACS results chart with percentage of units at each readiness level by ARFORGEN pool and (fiscal) year. FY12 results are better than for the other five years of the POM due a constant number of items authorized that year, and programmed purchases of over 200,000 more items in FY12 than in the rest of the years.

These results are expected, due to the two characteristics of the input data discussed in Section III.A.2: the decrease of over 200,000 items available for distribution from FY12 to FY13 and the yearly increase of almost 400,000 items authorized that begins in FY13. However, they show that MPORAM cannot allocate some of the equipment available for distribution in FY12 to other units in order to achieve readiness levels that do not vary so much from year to year across the POM years. An alternate solution could have sacrificed some readiness in FY12 to achieve higher readiness levels in the last five years. The prescribed distribution plan does result in readiness levels that do not vary much over the last five years of the POM. This could be a result of the less volatile programmed purchase data over the last five years (a decrease of only 30,000 items purchased from FY13 to FY17 versus the decrease of over 200,000 items between FY12 and FY13). The higher readiness levels in FY12 could also be influenced by the lack of an increase in authorizations that year. For the rest of the POM years authorizations increase by at least 396,000 items every year.

b. *Single-Period SACS Results (FY12)*

Single-period SACSs results for FY12 are presented in Figure 6. The results show high ratings for available pool units with almost 85% achieving S-1 or S-2. In Section III.C.4.a, we compare the single-period results to the multi-period results presented in the previous section.

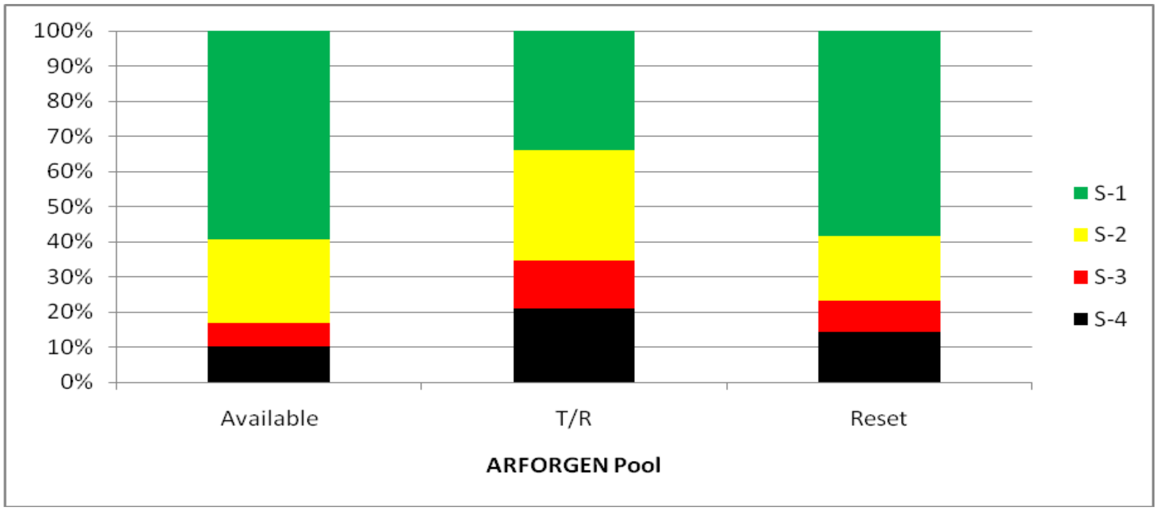

Figure 6. Single-period (FY12) SACS results chart with percentage of units at each readiness level by ARFOGREN pool. These results are nearly identical to the multi-period results for FY12. (See Section III.C.4.a.)

c. *Multi-Period CPM Results (FY13-FY17)*

Figure 7 shows the multi-period results for the CPM data set. The chart shows that the solution achieves readiness levels that do not vary much over the five-year planning horizon. The results are slightly worse in the first period, FY13, than for the rest of the POM. In FY13, 21% of the available units are S-1 and in FY14 this percentage rises to 31%. Then, it decreases to 25% in FY16 and finishes at 27% in FY17. At the same time the percent of available units at S-4 rises each year, starting at 25% in FY13 and finishing at 34% in FY17. The results are similar for the other ARFORGEN pools.

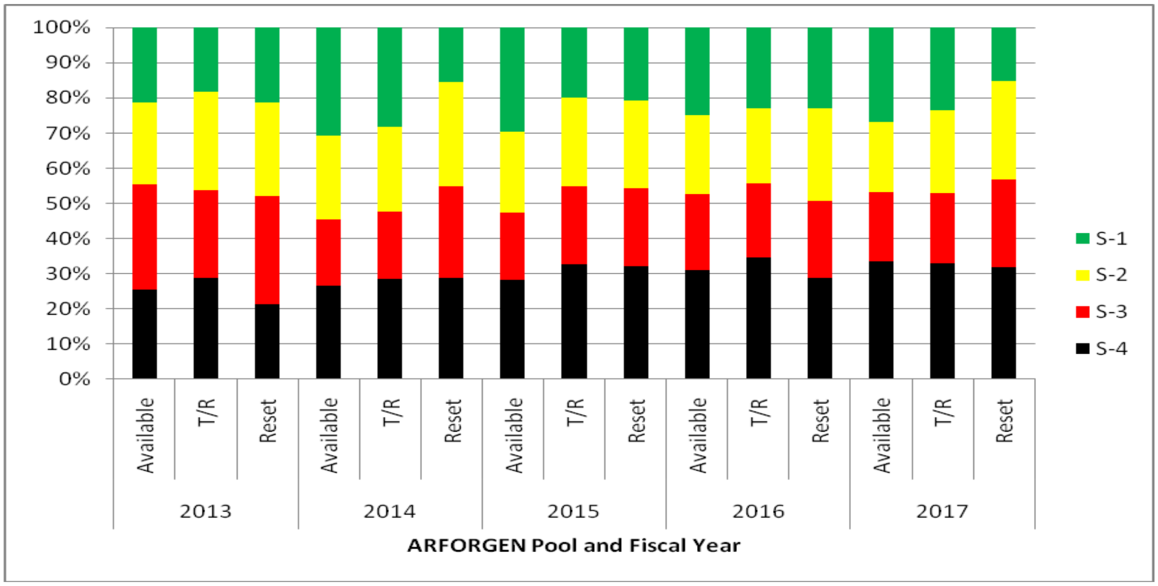

Figure 7. Multi-period (FY13-FY17) CPM results chart with percentage of units at each readiness level by ARFORGEN pool and year. Readiness ratings do not vary significantly from year to year, except FY13.

Since CPM has been designed to develop an equipping policy that maximizes value across the entire POM, the relative lack of variation in readiness levels from year to year is expected. The worse overall unit rating in the first period, FY13, could be due to an increase in items authorized of over 396,000 items in FY13 compared to programmed purchases of only 121,000 items in FY13.

d. Single-Period CPM Results (FY13)

Single-period CPM results are presented in Figure 8. The results show average ratings, with less than 50% of the available pool units achieving S-1 or S-2. In Section III.C.4.b, we compare the single-period results to the multi-period results presented in the previous section.

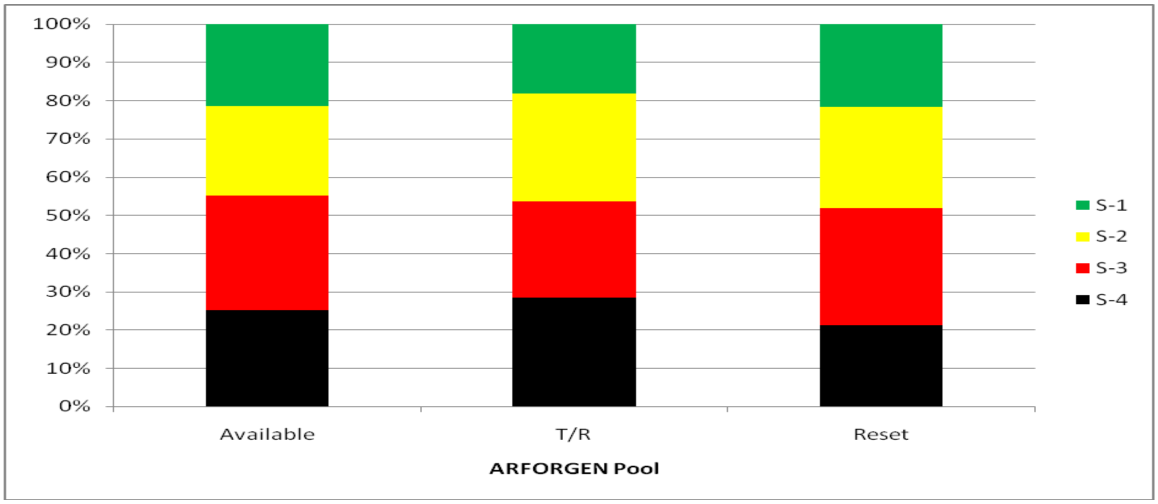

Figure 8. Single-period (FY13) CPM results chart with percentage of units at each readiness level by ARFOGREN pool. These results are nearly identical to the multi-period results for FY13. (See Section III.C.4.b.)

4. Comparison of Full Test Cases

Below we compare the single-period results for the first period to the multi-period results for the same period in both the SACS and CPM data sets. This comparison gives us insights about whether MPORAM provides a significantly different solution than single-period ORAM.

a. SACS Multi-Period Versus Single-Period (FY12)

Comparing the SACS multi-period results for FY12 to the single-period results for FY12 shows no significant differences. There are slight differences in a few of the ARFORGEN pool-readiness combinations but never for more than four units. None of these minor deviations results in a change of more than 1% of the total units in that ARFORGEN pool-readiness level combination. Table 10 shows these results by the percentage of units in each ARFORGEN pool at each readiness level. The highlighted cells indicate a higher percentage than the alternative. None of these differences are significant. Thus, no definitive conclusion about the advantage of MPORAM versus ORAM can be drawn from this comparison.

SACS Single Period Results (FY12)					
		Readiness			
Period	Priority	S-1	S-2	S-3	S-4
FY12	Available	59%	24%	7%	10%
	T/R	34%	31%	14%	21%
	Reset	58%	18%	9%	14%
SACS Multi-Period Results (FY12)					
		Readiness			
Period	Priority	S-1	S-2	S-3	S-4
FY12	Available	59%	24%	6%	10%
	T/R	33%	32%	13%	22%
	Reset	58%	19%	9%	14%

Table 10. Percentage of each ARFORGEN pool units at each readiness level for the single-period and multi-period SACS results in FY12. Highlighted cells indicate a higher percentage than the alternative.

b. CPM Multi-Period Versus Single-Period (FY13)

Comparing the CPM multi-period results for FY13 to the single-period results for FY13 also shows no significant differences. There are differences of at most two units in a few of the ARFORGEN pool-readiness level combinations but none of these minor differences results in a in a change in the percentage of the total units in that ARFORGEN pool-readiness level combination. Table 11 shows these results by the percentage of units in each ARFORGEN pool at each readiness level. As in the SACS comparison, the lack of differences does not allow us to draw a conclusion about the benefit of using MPORAM.

CPM Single- and Multi-Period Results (FY13)					
		Readiness			
Period	Priority	S-1	S-2	S-3	S-4
FY13	Available	21%	23%	30%	25%
	T/R	18%	28%	25%	29%
	Reset	21%	26%	31%	21%

Table 11. Percentage of each ARFORGEN pool units at each readiness level for the single-period and multi-period CPM results in FY13. (There are no differences.)

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IV. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

This thesis has developed MPORAM to address the Army's need for a method to assess the impact of POM equipment purchase decisions on unit S-ratings *and* to determine a long term equipment distribution plan to achieve unit S-rating goals as units rotate through the ARFORGEN cycle.

Based on the results and analysis presented in Chapter III, we describe our conclusions about MPORAM's ability to assess a POM equipping policy and its value relative to ORAM.

1. Ability to Assess a POM Equipping Policy

The results of the small test case show that MPORAM determines an optimal distribution plan that maximizes unit readiness over a six-year planning horizon while adhering to the model specifications.

Solving the small test case has allowed us to identify four key insights about the MPORAM solution: first, when one unit's readiness rating cannot improve, MPORAM attempts to improve another unit's readiness rating, regardless of priorities. The solution prescribed may even sacrifice LIN readiness ratings in a higher priority unit to achieve higher unit readiness ratings in a lower priority unit; second, MPORAM is accounting for future priorities; third, MPORAM is accounting for future authorizations; and fourth, penalties for transferring equipment between units are critical to avoid turbulent distribution plans.

Solving MPORAM for the full test cases ensures that it is capable of determining an optimal solution for a typical data set G-8 FDA would analyze. Since detailed analysis of the output files is very difficult, it is important to investigate overall output statistics with an understanding of the input in order to establish some conclusions. The input file statistics calculated for this research include: first, the change in items authorized by year (the demand), the number of items programmed for purchase by year (the supply), and the difference between the demand and supply by fiscal year (Table 5); and second, the initial percentage of unit-LIN combinations, and units at each readiness level (Table 9). The first set of statistics allows us to identify some potential causes of the readiness results achieved by MPORAM. The second set provide a baseline: the aggregated initial readiness ratings before distribution of the items in a POM programmed purchase plan.

2. Value Relative to ORAM

With no significant difference between the results of the single-period solution and the multi-period solution, we cannot make any strong conclusions about the added value of MPORAM relative to ORAM. This is particular to the cases provided by G-8 FDA: the results are strongly influenced by the large difference between the increasing demand for equipment (due to current operations in Iraq and Afghanistan) and the projected supply of equipment purchased.

B. RECOMMENDATIONS

The recommendations include the potential uses for MPORAM and the areas for further research.

1. Potential Uses

MPORAM should be used by G-8 FDA as a tool to evaluate the readiness ratings achieved by a CPM solution. As CPM continues to be used as a key tool to inform POM development in G-8, MPORAM can provide the readiness ratings achieved by a CPM solution as one metric of the utility of CPM. MPORAM can also serve as a tool for "what-if analysis" for a variety of questions that senior Army leadership may pose about a POM equipping strategy. Two examples of these questions are described in the next section.

There may be situations where MPORAM is necessary to evaluate a POM equipping policy. Even though this does not prove to be the case with the SACS or CPM data used in this thesis, with Army transformation complete and a decrease in the demand for deployed forces in future years, coupled with a stronger U.S. economy, the gap between demand and supply should decrease. In that scenario, the results observed in the small test case (where the contribution of MPORAM is significant) may be reproduced to a realistic case, and we expect MPORAM to determine a distribution plan that differs and improves readiness compared to the single-period solution. We recommend MPORAM to continue to be tested by NPS and G-8 FDA.

2. Areas for Further Research

Two main areas for further research involve a relaxation of MPORAM used in this thesis by allowing every unit to receive every LIN in each period rather than only allowing distribution of the LINs programmed for purchase to the units authorized those LINs, i.e., allowing X_{elut} to vary instead of fixing $X_{elut} = 0$ for each e and each $(l,u,t) \notin \text{LUT}$. This increases the size of the model and may exceed the ability of a typical computer to solve the problem. It may be possible to tighten the current formulation for these relaxations or it may require the development of a heuristic and/or decomposition scheme.

The first area for further research involves allowing MPORAM to delay distribution of equipment purchased in one year of the POM to a later year. This should result in more consistent readiness results across the POM and higher overall readiness ratings. To achieve this, a "warehouse" entity would need to be created that holds equipment not distributed during a given year. The warehouse input data would need to be developed with careful consideration. This area also requires the model to allow equipment transfers from the warehouse in subsequent periods without penalty. A discount on readiness rating weights in later periods is also needed to prevent the model prescribing a policy that delays most of the distributions to later periods to achieve higher readiness ratings for all high priority units.

The second area for further research involves allowing MPORAM to determine an optimal LIN purchase plan for each year to maximize readiness across the POM.

Instead of providing programmed purchase data and a limited budget for additional purchases each year, G-8 FDA could input full budget data for each year of the POM and allow MPORAM to recommend those purchases. This solution would provide the upper bound on readiness ratings achievable for the allocated budget. It also gives another metric for measuring the quality of a CPM solution or other equipping policy. This would require official budget data from the G-8 Program Analysis and Evaluation Directorate.

APPENDIX: SMALL TEST CASE DATA

This appendix provides the data required by MPORAM (see Section II.D) and create the input files described in Table 3 for the small test case discussed in Section III.A.1.

Table 12 provides the initial on-hand, authorized and resulting LIN S-rating for both units. This provides data for the "Oh" and "Req" files, and the first period of the "Delta" input file. Seven of the eight unit-LIN combinations are rated S-4, resulting in both units rated S-4. These initial conditions test MPORAM's ability to improve readiness over the planning horizon.

Unit	LIN	ERC	Authorized	On-Hand	S-rating
U01842	A20044	A	460	299	S-3
U01842	C68719	A	115	74	S-4
U01842	D02704	P	3	0	S-4
U01842	M12418	A	144	93	S-4
U05386	A20044	A	97	63	S-4
U05386	C68719	A	65	42	S-4
U05386	D02704	A	2	0	S-4
U05386	M12418	A	314	204	S-4

Table 12. Initial LIN authorizations and on hand data with the resulting LIN S-ratings for both units of the small test case. Seven of the eight LINs are S-4 resulting in both units rated S-4.

The planning horizon (input file "Period") is composed of periods 1 through 6. Table 13 shows the unit data for the entire planning horizon. This provides data for development of the "Unit," "UnitCycle," "LIN," "ARFORGEN," "ERC," and "Delta" files. It illustrates how the units' priorities change from period to period and how their authorizations change during the planning horizon. Highlighted cells indicate unit-LIN authorizations that change from the previous period. Building the "Num" and "Per" input files requires applying the unit and LIN S-rating metrics, respectively, of Section I.A.4, to the units and unit-LIN authorizations in each period shown in Table 13.

UNIT	Period	Priority	LIN	ERC	Authorization
U01842	1	Available	A20044	A	460
U01842	1	Available	C68719	A	115
U01842	1	Available	D02704	P	3
U01842	1	Available	M12418	A	144
U01842	2	Reset	A20044	A	460
U01842	2	Reset	C68719	A	115
U01842	2	Reset	D02704	P	3
U01842	2	Reset	M12418	A	144
U01842	3	T/R	A20044	A	460
U01842	3	T/R	C68719	A	115
U01842	3	T/R	D02704	P	3
U01842	3	T/R	M12418	A	144
U01842	4	Available	A20044	A	460
U01842	4	Available	C68719	A	0
U01842	4	Available	D02704	P	6
U01842	4	Available	M12418	A	144
U01842	5	Reset	A20044	A	460
U01842	5	Reset	C68719	A	0
U01842	5	Reset	D02704	P	6
U01842	5	Reset	M12418	A	144
U01842	6	T/R	A20044	A	460
U01842	6	T/R	C68719	A	0
U01842	6	T/R	D02704	P	6
U01842	6	T/R	M12418	A	144
U05386	1	T/R	A20044	A	97
U05386	1	T/R	C68719	A	65
U05386	1	T/R	D02704	A	2
U05386	1	T/R	M12418	A	314
U05386	2	Available	A20044	A	97
U05386	2	Available	C68719	A	65
U05386	2	Available	D02704	A	2
U05386	2	Available	M12418	A	314
U05386	3	Reset	A20044	A	97
U05386	3	Reset	C68719	A	65
U05386	3	Reset	D02704	A	2
U05386	3	Reset	M12418	A	314
U05386	4	T/R	A20044	A	0

UNIT	Period	Priority	LIN	ERC	Authorization
U05386	4	T/R	C68719	A	65
U05386	4	T/R	D02704	A	0
U05386	4	T/R	M12418	A	314
U05386	5	Available	A20044	A	0
U05386	5	Available	C68719	A	65
U05386	5	Available	D02704	A	0
U05386	5	Available	M12418	A	314
U05386	6	Reset	A20044	A	0
U05386	6	Reset	C68719	A	65
U05386	6	Reset	D02704	A	0
U05386	6	Reset	M12418	A	314

Table 13. Unit-LIN authorizations and ARFORGEN cycle data for the small test case. Units rotate priorities every period to replicate the ARFORGEN cycle and unit authorizations for selected LINs change during the planning horizon to replicate changing MTOE authorizations over the POM years.

Tables 14 and 15 provide the cost for each LIN (constant for all periods) and budget by period, respectively. This provides data for building the “Cost” and “Budget” input files. These data work together to test MPORAM’s ability to determine a LIN purchase plan to improve readiness.

LIN	Cost
A20044	269
C68719	125
D02704	1,997,000
M12418	256

Table 14. LIN costs for the small test case (constant for all periods.)

Period	Budget
1	0
2	500
3	600
4	750
5	1,000
6	1,250

Table 15. Budget by period for the small test case.

Table 16 shows the programmed purchase data for each LIN in each period and whether each unit has an authorization for that LIN in that period. If the unit has an authorization for the LIN in that period, a one is recorded in the unit column, otherwise a zero is recorded. This provides data for development of the "Avail" and "POM" input files. This tests MPORAM's ability to determine a distribution plan for programmed purchases.

			Authorized LIN?	
LIN	**Period**	**Programmed Purchases**	**Unit U01842**	**Unit U05386**
A20044	1	20	1	1
A20044	2	20	1	1
A20044	3	20	1	1
A20044	4	20	1	0
A20044	5	20	1	0
A20044	6	20	1	0
D02704	1	2	1	1
D02704	2	2	1	1
D02704	3	2	1	1
M12418	1	60	1	1
M12418	2	50	1	1
M12418	3	40	1	1
M12418	4	30	1	1
M12418	5	20	1	1
M12418	6	10	1	1

Table 16. Programmed purchase data by period, and whether each unit has an authorization for a LIN programmed for purchase in each period (1) or not (0) for the small test case.

Finally, for the "Pt" file, all the penalties for LIN transferring among units have been set to 1.0.

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