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Optimizing the capacity and operation of U.S. Army ammunition production facilities

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NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

OPTIMIZING THE CAPACITY AND OPERATION OF U.S. ARMY AMMUNITION PRODUCTION FACILITIES

by

Vedat Bayram

June 2002

Thesis Advisor: Gerald G. Brown
Second Reader: Robert F. Dell

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As the executive agent for ammunition, the Army manages the arsenals and plants that produce conventional ammunition for the Department of Defense. This industrial base must be able to manufacture a wide range of ammunition and ordnance items. In peacetime, the Army tests new rounds, makes training rounds, and manufactures rounds or components for war reserves, stockpile maintenance and upgrades. The Army must also manage and maintain capacity to replenish ammunition consumed by major theater wars without expanding the industrial base. The combined organic and inorganic industrial base can meet current requirements, but parts are becoming obsolete, and are expensive to operate. To improve efficiency and reduce per-unit costs while maintaining strategic control of this key defense capability, the Army is seeking to reconfigure facilities, and stabilize production rates. The Army realizes that the industrial base structure has to change. This thesis provides a prototypic decision support model that captures the essence of their problem by optimizing transition actions while satisfying complicated long-term constraints on resources, management, and capacity. The model suggests yearly decisions for a planning horizon of a decade or more, and is demonstrated with 16 organic installations, structures located therein, and process centers housed in those structures.

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OPTIMIZING THE CAPACITY AND OPERATION OF U.S. ARMY AMMUNITION PRODUCTION FACILITIES

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

As the executive agent for ammunition, the Army manages the arsenals and plants that produce conventional ammunition for the Department of Defense. This industrial base must be able to manufacture a wide range of ammunition and ordnance items. In peacetime, the Army tests new rounds, makes training rounds, and manufactures rounds or components for war reserves, stockpile maintenance and upgrades. The Army must also manage and maintain capacity to replenish ammunition consumed by major theater wars without expanding the industrial base. The combined organic and inorganic industrial base can meet current requirements, but parts are becoming obsolete, and are expensive to operate. To improve efficiency and reduce per-unit costs while maintaining strategic control of this key defense capability, the Army is seeking to reconfigure facilities, and stabilize production rates. The Army realizes that the industrial base structure has to change. This thesis provides a prototypic decision support model that captures the essence of their problem by optimizing transition actions while satisfying complicated long-term constraints on resources, management, and capacity. The model suggests yearly decisions for a planning horizon of a decade or more, and is demonstrated with 16 organic installations, structures located therein, and process centers housed in those structures.

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LIST OF ACRONYMS

AAP	Army Ammunition Plant
AMC	Army Materiel Command
ARDEC	Armaments Research, Development, and Engineering Center
ARMS	Armament Retooling and Manufacturing Support
BRAC	Base Realignment and Closure
BRACAS	Base Realignment and Closure Action Scheduler
CAA	Center for Army Analysis
COCO	Contractor Owned Contractor Operated
CRN	Crane Army Ammunition Plant
DOD	Department of Defense
DPG	Defense Planning Guidance
FGC	Federal Government Corporation
GAMS	General Algebraic Modeling System
GAO	General Accounting Office
GOCO	Government Owned Contractor Operated
GOGO	Government Owned Government Operated
HOLS	Holston Army Ammunition Plant
IOWA	Iowa Army Ammunition Plant
KANS	Kansas Army Ammunition Plant
LAKEC	Lake City Army Ammunition Plant
LAP	Load Assemble and Pack
LNST	Lone Star Army Ammunition Plant
LOUS	Louisiana Army Ammunition Plant
McA	McAlester Army Ammunition Plant
MIL	Milan Army Ammunition Plant
MISS	Mississippi Army Ammunition Plant
MTW	Major Theater of War
OSAF	Optimally Stationing Army Units to Bases
OSUB	Optimally Stationing Units to Bases
PBD	Program Budget Decision
PBLF	Pine Bluff Arsenal
PNNL	Pacific Northwest National Laboratory
PwC	Pricewaterhouse Coopers
RADF	Radford Army Ammunition Plant
RIA	Rock Island Arsenal
ROOM	Regionalization and Outsourcing Optimization Model
RVBNK	Riverbank Army Ammunition Plant
SCR	Scranton Army Ammunition Plant
TACOM	Tank-Automotive and Armaments Command
WVL	Watervliet Arsenal

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EXECUTIVE SUMMARY

The American government built its first Army ordnance facilities after the Revolutionary War. Congress allocated funds for arsenals to make the United States self-sufficient. These efforts resumed with the beginning of World War I, but even then U.S. forces still had to use ammunition manufactured outside the continental United States (CONUS). Although 32 ammunition plants had been constructed by the end of World War I, World War II brought even more massive expansion. Army arsenals and Army Ammunition Plants (AAPs) have served the United States well for over two hundred years, sustaining the readiness and responsiveness of its armed forces. Of facilities built after the Revolutionary War and during World Wars I and II, 16 are still open today.

As the DOD's executive agent for ammunition, it is the U.S. Army's responsibility to manage the conventional ammunition production base that meets peacetime demands of the armed services and maintains capacity to replenish wartime consumption. The Army's organic and inorganic production base capacity is far in excess of any anticipated requirement. This report examines part of the organic base.

Since the end of the Cold War, workload and employment at two remaining arsenals and surviving AAPs have declined substantially, and they currently operate at a fraction of capacity; per-unit costs have increased as fixed costs have been allocated among diminished production quantities. Personnel reductions have not kept pace with workload reductions.

The Army production base can continue to meet current requirements, but at what cost? Facing a limited budget, it is not likely that the Army will invest in advanced, flexible munitions manufacturing technology required for the production base, leading to further obsolescence of the base and increasing costs. The existing base is becoming obsolete, and is not cheap. The risk of not being able to meet replenishment requirements is also increasing.

So, the problem at hand is to reconfigure Army ammunition production facilities, stabilize production rates, and perhaps attract private investment in new technology.

Ammunition is critical to the military, and it has unique classes of commodity groups that are hazardous to manufacture. The structure of the ammunition industrial base includes a combination of Government Owned Government Operated (GOGO) plants; Government Owned Contractor Operated (GOCO) plants; and Contractor Owned Contractor Operated (COCO) plants. This combination of commercial (inorganic) and Army (organic) industrial base segments represents the National Technology and Industrial Base (NTIB) infrastructure and is the source of all materiel needed by the DOD to carry out its peacetime and replenishment responsibilities in support of the National Military Strategy (NMS). The Army-managed industrial base infrastructure is a resource to satisfy the materiel needs of all US forces in a timely manner, with reliable, maintainable, and affordable materiel.

The vision of the Army Chief of Staff for a flexible, light, responsive force and the need to fund this transformation has put increasing pressure on all commands, including Army Materiel Command (AMC), to reduce its operating costs. The Army cannot continue to afford the full operational capability of the AAPs and arsenals while maintaining significant amounts of underutilized capacity.

In peacetime, the industrial base must develop new rounds for testing; manufacture special training rounds; and make existing rounds or components for war reserves, stockpile maintenance or upgrades. Further, there must be capacity to make ammunition and ordnance items to replenish stocks consumed during major theater of wars (MTWs).

Changing the governance of the industrial base is a possible approach to improving the manufacture of ammunition and ordnance items and requires consideration of many complex issues.

Economics and politics constrain the options available to maintain, close, or change the management of GOGO, GOCO, and COCO facilities. Base realignments and closures incur significant relocation costs for both equipment and personnel; property and equipment transfers are costly and time consuming. These decisions are influenced by several factors, including the complexity and number of actions that the Army can implement at any one time, the cost of actions, including environmental remediation, and the degree of control the Army wants to exercise over the resulting ammunition infrastructure.

Prior studies share the common goal of reducing infrastructure cost of a set of installations. However, none of them has addressed Army arsenals and AAP installation types, or the subject of minimizing the unutilized capacity at these facilities.

The work reported in this thesis derives from a tasking that the Deputy Under Secretary of the Army for Operations Research gave the Center for Army Analysis (CAA) to review an ongoing study (PBD407) that examines the reorganization of the Army's ammunition production base. As part of CAA's review, they recommended to the PBD407 oversight, the Director of Force Development (Logistics), that this work be accomplished to augment PBD407. CAA is also tasked with the G3's Stationing of the Army for Transformation analysis, which this effort may also assist in.

We favor a prescriptive optimization model because the Army has a successful history of such models for base closing and realignment and other related issues. The Army understands and accepts the advantages of optimization. We want to learn the best way to deal with the management of the ammunition industrial base. Spreadsheet analysis is an option, but it is descriptive and requires that we suggest the alternate solutions to be evaluated in which case we never know whether there are better solutions left unexamined.

We develop a flexible decision support tool that schedules the way and the rate that actions should be carried out to transition government ammunition facilities between modes of operation while satisfying complicated long-term constraints on resources and oversight. This decision support tool minimizes fixed and variable possession and operating costs of Army arsenals and Army Ammunition Plants, meeting the replenishment requirements and the demand for peacetime production of ammunition and ordnance items.

We introduce a mixed integer programming model developed as an aggregated optimization-based decision support system that will suggest optimal yearly schedules of actions that satisfy exogenous constraints on budget, management, and capacity over a planning horizon of a decade or longer.

We consider reconfiguration of 16 different installations, of which, two are GOGO "hard iron" arsenals that manufacture ordnance items, three are GOGO AAPs, and 11 are GOCO AAPs. Of the GOCO AAPs, five are inactive. The rest of these installations are active.

We generate synthetic and thus unclassified data randomly but systematically for a proof prototype for a total of 16 different installations, 34 structures, 19 process centers, and nine process types for a 10-year horizon.

We plan by year because the DOD and the Army also budget and plan by year. We consider a 10-year planning horizon because the cost implications of near-term decisions extend at least that far into the future. We choose modes of operation in our model to reflect the current industrial base management modes and the alternatives at hand.

The lexicon we use to represent the industrial base includes a set of "installations", areas within these devoted to similar activities we call "structures", and these structures contain "process centers" that perform particular manufacturing tasks.

We demonstrate the model for two different scenarios, a full system optimization model and a more reasonable single-issue scenario. The full model suggests actions for every installation. The single-issue scenario examines the most problematic portion of ammunition installations: load, assemble, and pack (LAP) process centers and the installations housing them.

We seek year-by-year operating modes for each installation, structure and process center. A schedule that defines which installations, structures or process centers are running (in any mode of operation), which ones are disposed, and which process centers will be moved to which receiving structures and installations is specified for every year for a 10-year period of time.

For every planned year, we determine which open and working process center will have to work how many shifts to accomplish its part of the manufacturing of required materiel. We also determine the estimated costs to perform all these changes.

We have reviewed the model with LTC Bill Tarantino at the Center for Army Analysis. LTC Tarantino believes the model introduced here will potentially be used to support the Army's Industrial Base Review led by the Army Material Command, CAA's upcoming stationing analysis, and in the next series of Base Realignment and Closure analyses.

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I. INTRODUCTION

A. SHORT HISTORY OF U.S. ARMY AMMUNITION PRODUCTION BASE

It was not until after the Revolutionary War that the new American government built its first Army ordnance facilities to satisfy its own needs for munitions should the requirement arise again to mobilize. Congress allocated funds for arsenals to make the United States self-sufficient. These efforts resumed with the beginning of World War I, but even then U.S. forces still had to use ammunition manufactured outside the continental United States (CONUS). Although 32 ammunition plants had been constructed by the end of World War I, World War II brought massive expansion. Congress authorized the construction of 112 plants, 84 of which were subsequently built. In 1944, the peak production year, the U.S. produced more ammunition than all of its enemies and allies combined [Sawyer, 1993]. Army arsenals and Army Ammunition Plants (AAPs) have served the United States well for over 200 years, sustaining the readiness and responsiveness of its armed forces. Of facilities built after the Revolutionary War and during World Wars I and II, 16 are still open today (See Figure 1 for geographic locations and Table 2 for a list of installations).

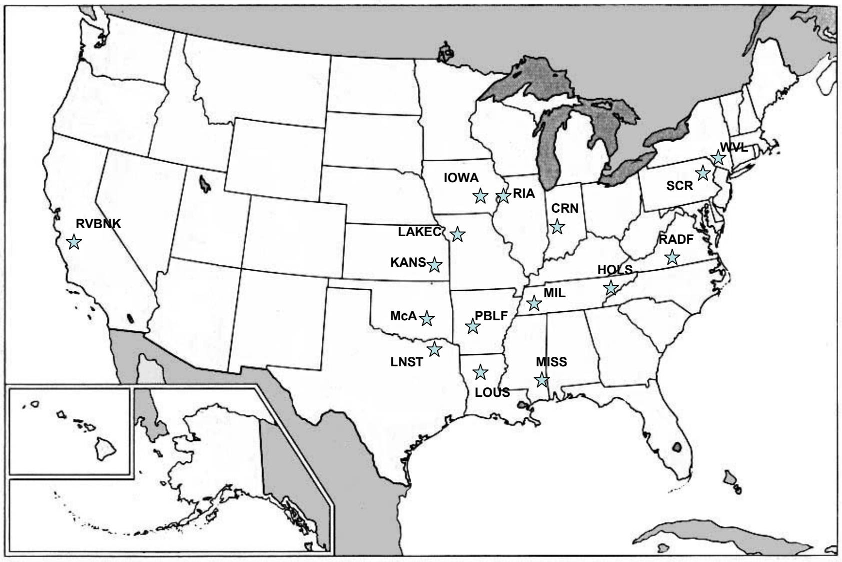

Figure 1. Geographic Locations of U.S. Army Arsenals and Ammunition Plants
This map shows the geographic locations of the 16 Army arsenals and ammunition plants studied by this thesis, which are spread throughout the continental United States. [Background map from University of Texas Library on Line, 2002]

In this thesis we use the terms "facility" and "installation" interchangeably for arsenals and AAPs. Each structure is constituted by a set of functionally related buildings and/or an area of land housed by an installation. Process centers within a structure manufacture ammunition and ordnance items of a specific type.

B. OPERATING THE AMMUNITION PRODUCTION BASE AT REDUCED LEVELS

The U.S. Army manages a conventional ammunition production base with dual missions: fill armed services peacetime demands for training and also maintain capacity to replenish war consumption [Doherty and Rhoads, 1998]. The Army's large current production base is far in excess of any anticipated requirement.

Since the end of the Cold War, workload and employment at two remaining arsenals and surviving AAPs have declined substantially, and they currently operate at a fraction of capacity; per-unit costs have increased as fixed costs have been allocated among diminished production quantities. Personnel reductions have not kept pace with workload reductions [GAO 1998, NSIAD-99-31, p. 56].

The Army has followed a "shrink in place" approach to reducing production to meet the needs expressed in the National Military Strategy [Doherty and Rhoads, 1998]. The Army has lacked time and resources to modernize or otherwise invest in more flexible, or in right-sized production lines, resulting in an increasing disparity between its production base and requirements for its capacity. Some equipment operates only at a designed production rate, and reducing this rate is not feasible.

Downsizing has shrunk management in place along with physical infrastructure [Doherty and Rhoads, 1998]. As a consequence, the organization, current processes, missions and functions are not well aligned and coordinated with current needs. Current management is compartmentalized, and this frustrates integration and coordination.

Budgets have not kept pace with large facility and maintenance costs, continued liabilities for environmental remediation within the United States and partnerships with other countries, and un-funded pension costs. With the ratio of fixed to variable costs becoming more and more unfavorable, it is clear that the Army's production base requires reconfiguration to improve cost effectiveness to remain economically viable.

The Department of Defense (DOD) defines ammunition replenishment capacity as the production capability to bring munitions stockpiles back to a pre-set level within a defined time interval after they have been depleted by a major military action [Systems Readiness Office, 1997]. Replenishment capacity requires production capacity in addition to that meeting everyday demands of the military for training and other purposes. The Army keeps reserve production capacity in the form of inactive industrial facilities and lay-away industrial facilities, and these are costly. Long lead times for bringing laid-away capacity back into production for replenishment is a significant concern [Doherty and Rhoads, 1998].

Utilities at ammunition plants are designed to support production at many times current volumes, and minimum feasible operating output from these utilities can be significantly greater than what the plants can consume. This wastes output. Utilities use raw materials (e.g., coal) at a level higher than necessary to maintain production and with higher labor cost [Systems Readiness Office, 1997].

Process equipment operating at its designed rate may produce faster than the plant needs. Most plants resort to shut-down and start-up cycles of such equipment. Such interruptions are hard on equipment, increase maintenance costs, and lead to poor production yields.

When customers buy from the Army production base, they pay a unit-price that includes a share of the operating cost (cost of production), and also the full cost of maintaining underutilized capacity [Doherty and Rhoads, 1998].

> "An arsenal official estimated that as of April 1998 Watervliet facility was using about 17 percent of its total manufacturing capacity—based on a single 8-hour shift, 5-day workweek—compared with about 46 percent 5 years ago and about 100 percent 10 years ago. Similarly, as of July 1998, officials at the Rock Island Arsenal estimated that the facility was utilizing about 24 percent of its total manufacturing capacity compared with about 70 percent 5 years ago and about 81 percent 10 years ago. [GAO/NSIAD-99-31, p. 57]"

Likewise, according to a survey made for some of the AAPs by Pacific Northwest National Laboratory (PNNL), as of 1998 the annual costs of underutilized capacity are shown in Table 1.

FACILITY	CAPACITY UTILIZATION (%)	ANNUAL COST OF UNDERUTILIZED CAPACITY ($M)
Crane AAP	15-20	4.9
Holston AAP	20-25	26.4
Iowa AAP	30-35	15.5
Kansas AAP	10-15	6.9
Lake City AAP	10-15	37
Lone Star AAP	1.5	20.1
McAlester AAP	30-35	6.5
Milan AAP	15-20	25.1
Pine Bluff Arsenal	15-20	13.5
Radford AAP	10-15	27
TOTAL	Avg. 15-20	182.9

Table 1. Capacity Utilization of Army Ammunition Plants

The table depicts the costs of underutilized capacity for some of the Army Ammunition Plants as of 1998. AAPs are not working at a full capacity, e.g., Crane AAP is only utilizing at most one fifth of its capacity and the annual cost of that underutilized capacity is $ 4.9 million. [From: Doherty and Rhoads, 1998]

The Army production base can meet current requirements, but at what cost? Development of advanced, flexible munitions manufacturing technology for the Army production base is not an anticipated fully budgeted investment for the government. The existing base is becoming obsolete, and is not cheap. The risk of not being able to meet replenishment requirements is increasing. Traditionally, such risks have been dealt with by directing workload to government-owned production facilities. This is no longer viable because the munitions market has been split, with an increasing portion of the basic munitions work being done by commercial suppliers via Program Manager (PM) managed acquisition programs [Doherty and Rhoads, 1998].

So, the problem at hand is to reconfigure Army facilities, stabilize production rates, and perhaps attract private investment in new technology. Something has to change.

C. IMPORTANCE OF THE PROBLEM AND THE ISSUES AT HAND

> "The military services have over 5 million tons of conventional ammunition, explosives, and missiles valued at about $80 billion as of September 30, 1994. This ammunition, if loaded onto railroad cars, would stretch over 800 miles—the distance from Washington, D.C., to Orlando, Florida. [GAO/NSIAD-96-129, p. 2]"

Ammunition is critical to the military, and it has unique classes of commodity groups that are hazardous to manufacture. The structure of the ammunition industrial base is also unique. It is a combination of Government Owned Government Operated (GOGO) plants; Government Owned Contractor Operated (GOCO) plants; and Contractor Owned Contractor Operated (COCO) plants. Ammunition production also requires some unique raw materials: There are very few sources for the critical energetic materials and components necessary for production of high-quality ammunition [Whitfield II, 1993].

The vision of the Army Chief of Staff for a flexible, light, responsive force and the need to fund this has put increasing pressure on all commands, including the Army Materiel Command (AMC) to reduce its operating costs. The Army cannot afford the full operational capability of the AAPs and arsenals, with tremendous amounts of underutilized capacity. Retention costs of inactive plants could be eliminated if the Army determines that these plants are unneeded and declares them excess [GAO/NSIAD-97-56]. "The assistant Chief of Staff for Installation Management at the 13 January 2001 Senior Installation Leaders' Conference made it clear that the Army must think again about how its installations are funded and operated. He considers it unlikely that the Army's future budgets will provide the level of investment required to maintain the Army's real estate in its current condition, let alone (outside a few specific programs) provide the investment funds required to improve the conditions of its installations." [PwC, 2001b]

The Congress, Department of Defense, and the Army need to answer the following questions:

- What manufacturing technology will be needed to meet current and future ammunition requirements, which skills need to be retained, and how much of the production capacity should be kept?

- Does the current Army and commercial industrial base meet the requirements? How well?
- Is it reasonable for the government to continue to own industrial facilities?
- What is the best way to meet requirements and find capacity when it is needed?
- What is the best way for the government to manage industrial base and ammunition production?

The Department of Defense has directed the Army to prepare a report on the "rightsizing" of the industrial facilities and to determine how they can be consolidated to reduce the unutilized capacity. In Program Budget Decision (PBD) 407 for Fiscal Year (FY) 2000, the Department of Defense expresses particular concern about the cost efficiency of the arsenal system [Albright, 2000]. This document states:

> "It is obvious from the data that the long-term financial stability of the Ordnance activities is in jeopardy. The mobilization requirements are determined by the National Defense Strategy. Notwithstanding the need to support wartime requirements, it must be recognized that having this much capacity idle year after year is very costly….Accordingly, the alternative provides for the Army to lead a study, with participation from the OSD Comptroller, PA&E, AT&L, and the Joint Staff, to look at the proper sizing of the ordnance activities. The study recommendations should address the rightsizing of all the ordnance activities until unutilized capacity at any one facility is no higher than 25%. [Albright, 2000]"

D. RELATED ARMY STUDIES OF THE PROBLEM

The Army has commissioned several analyses of these issues.

1. AMMO FAST 21 [Whitfield II, 1993]

U.S. Army Armament Munitions and Chemical Command (AMCCOM) has proposed a strategy to reshape the munitions industrial base. This strategy's main goal is to minimize the operating costs of the arsenals and AAPs by reducing the total number of these facilities, declaring some excess, converting some to caretaker status, and encouraging the commercial use of those facilities and the equipment they have. Some of these proposals were enabled by the Armament Retooling and Manufacturing Support Act that was approved by Congress in 1992 [10 U.S.C. 4553].

2. Footprint Reduction

The second phase of PBD 407 [RAND, 2002] requires the Army to assess the excess space and equipment at Watervliet and Rock Island Arsenal and to devise a footprint reduction plan. The proper sizing of the arsenal's buildings, equipment and tooling is to be determined by means of capacity analysis. This capacity analysis is driven by requirements, including current needs, Program Objective Memorandum (POM) for the next five years, and replenishment requirements that are now to replace one or two Major Theater Wars' worth of consumed ammunition.

3. Privatization-in-Place

Privatization-in-place is a concept in which the functions or process centers of an installation that was once managed and operated by the government are taken over by a commercial sector. To date, privatization-in-place has been used by DOD for transferring industrial work to the commercial sector, associated with base closures.

> "As a general rule, privatization-in-place has not optimized reductions in excess capacity and operating costs in the infrastructure owned and operated by DOD—a major base realignment and closure objective. Rather than closing facilities and transferring defense work to other underutilized defense facilities in the public or private sector to reduce excess capacity, privatization-in-place allows work to remain at the original sites to be performed by the private sector. [GAO/NSIAD-00-23]"

The infrastructure is no longer owned by DOD; however, it is still funded by DOD for contract work performed at those facilities. As a result, although indirectly, the DOD continues to pay for unutilized capacity and the goal of eliminating excess capacity cannot be realized.

4. Parcelization

Parceling divides an installation (e.g., an ammunition plant) with excess area into smaller partitions and then conveys these parcels to third parties. Operations Support Command (OSC) has endeavored to cut down the cost of retention of the excess facilities through renting out the facilities and land to third parties while executing the parcelization disposal process. PricewaterhouseCoopers (PwC) was commissioned by Operations Support Command to conduct a business case analysis that would include a cost-benefit analysis to quantify the financial impact of parceling excess Army real property [PwC, 2001b]. The PwC study finds that parcelization is a poor method of disposing of a real property that increases the disposal time and the facility's net operations, maintenance and disposal costs along with some other setbacks for the Army.

5. Cost of Ownership Study

Commissioned by the Operations Support Command, PwC conducted this data analysis study of ownership costs focusing on those costs required to maintain a facility in an inactive or lay-away status. The study included arsenals, ammunition plants, and ammunition depots. [PwC, 2001a]

6. The Totally Integrated Munitions Enterprise (TIME) Program [ARDEC, TACOM; 1997]

Initiated in 1997, the objective of TIME was to update the Army's munitions manufacturing capability. "The high level vision of TIME is that it will provide the DOD with a cost-effective, flexible manufacturing capability to meet U.S. munitions needs in the 21st century. This vision of TIME attempts to address munitions manufacturing as a total system, integrating all aspects of the enterprise, including the definition of munitions requirements, the design of products and processes, scale-up, production, supply chain, logistics, product support, and even the eventual demilitarization of unused munitions." [National Research Council, 2002]

TIME has supported the Army as the single manager for conventional ammunition for all of the armed services, to fulfill its responsibilities defined by DOD's current and future munitions manufacturing and replenishment policy.

E. CURRENT INDUSTRIAL BASE

The Army Industrial base is a part of the National Technology and Industrial Base. It is defined as a combination of GOGO, GOCO, and COCO industrial capacity available for development, manufacture, maintenance, modification, overhaul, storage, testing, and research of ammunition and ordnance items required by the United States and selected allies in support of the National Security Strategy (NSS), the Defense Planning Guidance (DPG), and the National Military Strategy. Overall, the commercial and Army industrial base segments represent the National Technology and Industrial Base infrastructure and are the source of all materiel needed by the Army to carry out its peacetime and replenishment responsibilities in support of the National Military Strategy. The Army industrial base infrastructure is a resource to satisfy the materiel needs of Army forces in a timely manner, with reliable, maintainable, and affordable materiel.

Of the installations built after the Revolutionary War and during World Wars I and II to manufacture ammunition, 16 are still open today. These 16 installations are categorized into five classes of production:

- "Ordnance items, such as gun tubes and gun mounts are manufactured at GOGO Rock Island Arsenal, IL; and Watervliet Arsenal, NY;
- Metal parts are manufactured at the GOCO Louisiana AAP, LA; Mississippi AAP, MS; Riverbank AAP, CA; and Scranton AAP, PA;
- Load Assemble and Pack (LAP) operations of a special nature are conducted at the GOGO Crane Army Ammunition Activity, IN.; McAlester AAP, OK.; and Pine Bluff Arsenal, AR.;
- Other GOCO LAP operations are conducted at Iowa AAP, IA; Kansas AAP, MO.; and Milan, Lake City, Lone Star, Louisiana AAPs also manufacture metal parts and conduct LAP operations; and
- Propellants and explosives are manufactured at the GOCO Radford AAP, VA.; and Holston AAP, TN." [Tarantino, 2001]

In summary, of the 16 facilities under review (See Table 2), two are GOGO "hard iron" arsenals that manufacture ordnance items, three are GOGO AAPs, and 11 are GOCO AAPs.

In addition to the installations named, 11 other ammunition plants have been declared excess, 10 outside of the Base Realignment and Closure (BRAC) process, and one as a part of this process [Tarantino, 2001]. These installations are still in the disposal process.

INSTALLATION	Mission	Management	Developed Square Footage	Number of Buildings
Watervliet Arsenal	Cannon Mfg.	Active GOGO	1.2M	91
Rock Island Arsenal	Manufacturing	Active GOGO	6.5M	197
Iowa AAP	LAP	Active GOCO	4.3M	1148
Lake City AAP	LAP	Active GOCO	3.2M	490
Louisiana	Metal Parts	Inactive GOCO	2.8M	731
Mississippi AAP	Metal Parts	Inactive GOCO	229K	131
Lone Star AAP	LAP	Active GOCO	2.2M	858
McAlester AAP	Bomb Fill	Active GOGO	9.5M	2226
Crane AAP	LAP/Bomb Fill	Active GOGO	5.6M	209
Pine Bluff Arsenal	LAP/Chemical	Active GOGO	3.5M	947
Holston AAP	RDX/HMX, Explos.	Active GOCO	2.5M	475
Milan AAP	LAP	Active GOCO	3.9M	1457
Radford AAP	Propellant Mfg.	Active GOCO	3.7M	1038
Riverbank AAP	Metal Parts	Inactive GOCO	800K	184
Scranton AAP	Metal Parts	Inactive GOCO	500K	4
Kansas AAP	LAP	Inactive GOCO	2.2M	555

Table 2. Basic Facts About the Arsenals and Army Ammunition Plants Studied by this Thesis

Arsenals and AAPs with different missions and management modes range in size from McAlester AAP with 2,226 buildings in 9.5 million square feet of development, to Scranton AAP with only four buildings in 500 thousand square feet. [From: PwC, 2001a]

The Armament Retooling and Manufacturing Support (ARMS) Act of 1992 [10 U.S.C. 4553], authorizes a program under which funds are appropriated to permit infrastructure investments to attract commercial tenants. If the Army elects to consolidate its ammunition production base, required capabilities and capacities can be moved onto a smaller number of installations rendering others excess. The need for a process center that today happens to be located in a structure housed by an installation should not be confused with the need for the structure or installation itself. Process centers can be moved, and as a consequence installations and structures can be rendered excess, and eventually disposed. For that reason, it seems appropriate initially to determine the optimal assignment of capabilities and capacities to installations before changing the ARMS program's improvements and encumbering installations with long-term contracts and tenants.

The commercial sector cannot currently provide all the capabilities and capacity needed to meet peacetime and replenishment requirements for ammunition production [Doherty and Rhoads, 1998]. Capabilities in the government-owned base are needed to meet these requirements. This is primarily due to the way ammunition production has been managed by the government. The government has chosen to retain ownership of installations with capabilities to manufacture propellants and explosives, to load, assemble and pack (LAP) large caliber ammunition and bombs, pyrotechnics, large quantities of small caliber ammunition, and to manufacture large quantities of specialized metal parts (See Figure 2) [Doherty and Rhoads, 1998]. Work is directed to these government installations so that the skills can be maintained and as much of the base as possible can be kept ready to meet replenishment requirements.

Figure 2. Ammunition Metal Parts Manufacturing
Ammunition metal parts manufacturing can be categorized into artillery shell manufacturing, deep-drawn cartridge case manufacturing, and grenade manufacturing. Artillery shell and deep-drawn cartridge case manufacturing require special capability and equipment. [From: Tarantino, 2002b]

F. REQUIREMENTS

The Army is DOD's single manager for the military services' conventional ammunition and is responsible for ensuring that an adequate industrial base is maintained to meet the services' ammunition requirements [GAO/NSIAD-96-133]. The industrial base must have the capability and capacity for the manufacture of a wide range of ammunition and ordnance items. Ordnance materiel is needed for two basic reasons. In peacetime, the base must develop new rounds for testing; and manufacture special training rounds; and existing rounds or components for war reserves, stockpile maintenance or upgrades. Current policy assumes MTWs are fought and won without relying on expansion of the industrial base; no surge is assumed [Tarantino, 2001]. Further, ammunition and ordnance items are needed to replenish stocks consumed during major MTWs. Current policy requires capacity to be maintained to manufacture one MTW's worth of replenishment materiel generally within three years after the completion of a two MTW scenario [Tarantino, 2001]. After an MTW, the base must be able to rapidly replenish inventories depleted during the conflict. The peacetime and replenishment requirements therefore provide the design basis for the production base that must be available to comply with the Defense Planning Guidance [Doherty and Rhoads, 1998].

1. Peacetime Requirements

Peacetime requirements represent the services' planned procurement of conventional ammunition (and Single Manager for Conventional Ammunition [SMCM] related components) under the current Future Years Defense Plan (FYDP 96-03) [Doherty and Rhoads, 1998]. The procurement is aimed to satisfy Future Year Defense Plan training, testing and current operation requirements—on top of stockpiling the war reserves in anticipation of a two MTW scenario, while complying with federal budgetary constraints.

Officially declared in 1995, and still undergoing revision, the DOD's Capabilities-Based Munitions Requirements (CBMR) determines requirements. The basis for this is to give general guidance for all the branches of service to determine the total munitions requirements (TMR). Not constrained by the budget, the Total Munitions Requirements is broken down into two categories. These categories are war reserve munitions and training, testing, and current operational requirements.

The war reserve munitions can be separated into the following four categories: combat requirements, residual readiness requirements, strategic readiness requirements, and special operations forces requirements. The combat requirements are those ammunitions required to defeat the threat and maintain operational flexibility during two MTWs.

The Army defines "operational flexibility" as the munitions required to support the initial readiness of combat troops committed to the MTWs, plus the munitions in the "sustainability pipeline" [Doherty and Rhoads, 1998]. A combat load is the mix and number of munitions a weapon platform or system would be required to carry into combat. Initial readiness states that all weapon platforms or systems are issued with one combat load of munitions at the very beginning of the MTW. The sustainability pipeline is composed of those munitions staged intra-theater to sustain the initial war fight until the inter-theater (strategic) logistics takes its place.

The readiness reserve requirements and strategic reserve requirements are the munitions required after the completion of the MTW. For those Army forces committed to the MTW, the residual readiness requirement is generally one combat load, and is required to enable the Army to take care of any unforeseen contingencies to sustain operational flexibility. The strategic readiness requirement pertains to uncommitted forces and is currently fixed at one combat load [Doherty and Rhoads, 1998].

Training munitions can be categorized into training-standard and training-unique munitions. The maximum training requirements are determined from the prescribed (mandatory) training standards for individual and weapons systems and from the programs of instruction requirements for the training base [Doherty and Rhoads, 1998].

The requirement for annual training is calculated from historical records of actual training expenditures. The highest execution within the last three years is adjusted to accommodate force structure changes, weapons fielding plans, and changes in training strategies [Doherty and Rhoads, 1998].

Testing munitions can be classified as research, development, and test and evaluation (RDTE) and life-cycle maintenance and upgrade munitions. The total required for peacekeeping missions is represented by current operational requirements.

2. Replenishment Requirements

Replenishment requirements represent the munitions and components that need to be rapidly replenished after the two MTWs have occurred-in anticipation of a third MTW [Doherty and Rhoads, 1998]. The 2001 Quadrennial Defense Review states:

> "The United States will continue to meet its commitments around the world, including in Southwest and Northeast Asia, by maintaining the ability to defeat aggression in two critical areas in overlapping time frames. The United States is not abandoning planning for two conflicts to plan for fewer than two. On the contrary, DOD is changing the concept all together by planning for victory across the spectrum of possible conflict. …U.S. forces will remain capable of swiftly defeating attacks against U.S. allies and friends in any two theaters of operation in overlapping timeframes. … U.S. forces will be capable of decisively defeating an adversary in one of the two theaters in which U.S. forces are conducting major combat operations. [QDR, 2001]"

From this, we conclude that planning for munitions production must ensure adequate reserves for at least one major theater war, with provision for timely production of replacement munitions concurrent with their expenditure in that war and/or adequate reserves for a second major theater war.

The process for determining the replenishment requirements is implemented in five basic steps. First, the DPG provides the principal planning assumptions on the scope, duration, and intensity of anticipated MTWs and the general objectives for industrial base to support the Army prior to and after wars. The second step is to estimate how many of what items, such as tanks, mortars and artillery pieces, are destroyed and how many spare parts and how much of what kind of ammunition will possibly be consumed or required during an MTW. Step three determines how to restore the Army. The fourth step is to choose where this materiel will be manufactured, i.e. commercial firms (whether COCO or GOCO), government factories. Finally, the decision is made as to which capacities or resources need to be retained at government factories.

G. OPTIONS FOR CHANGE

Changing the governance of the industrial base is a possible approach of great significance to improving the manufacture of ammunition and ordnance items and requires consideration of many and complex issues (See Figure 3).

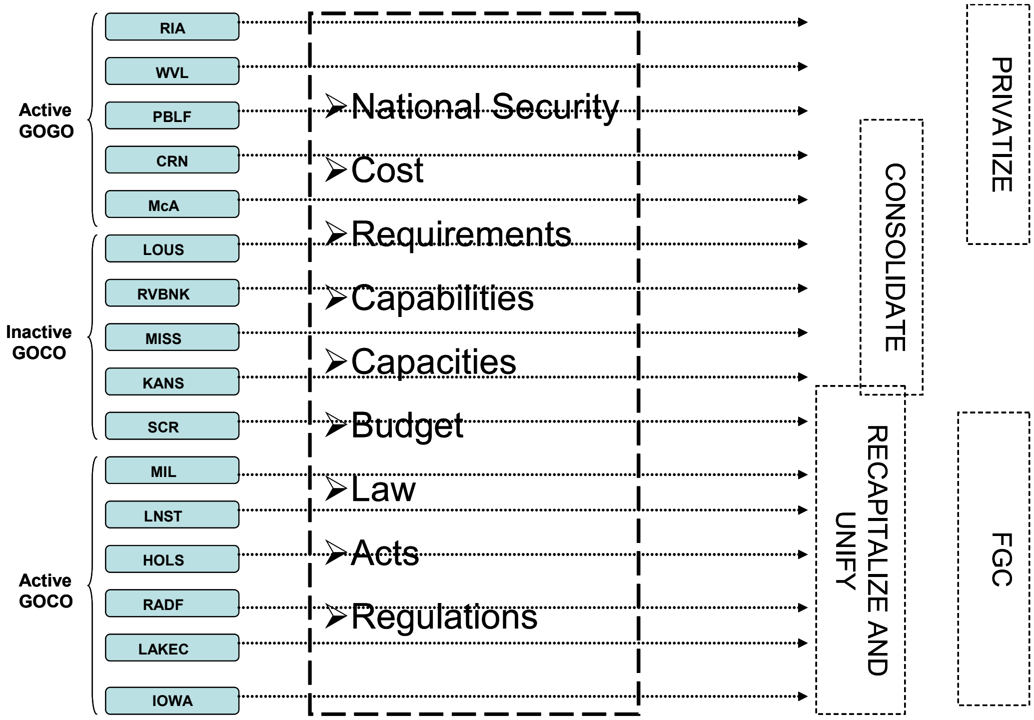

Figure 3. Options to Reconfigure the Ammunition Industrial Base
Reconfiguration of the current ammunition industrial base is challenged by some factors such as national security and cost. Depending on these factors, the status quo of an installation can be changed by any of the four options–consolidating, recapitalizing and unifying, creating a Federal Government Corporation (FGC), privatizing or a mix of them. [From: RAND, 2002]

In addition to the status quo, the Army is considering four basic options [Tarantino, 2001]:

1. Privatize

Privatizing simply means divesting an installation of the means of manufacture and procuring all the necessary ammunition and ordnance items from commercial sector. With that option the Army gets rid of what some refer to as a peripheral function, manufacturing. However, this option minimizes the Army's control over the land, buildings, and equipment and manufacture, as well as introduces cost risk, which is a concern to the Army.

2. Create an FGC

This option requires transferring of all the manufacturing assets from the Army to a congressionally chartered Federal Government Corporation (FGC). Creating an FGC is compatible with the view that the government must retain control of ordnance facilities and manufacturing of the required materiel while leaving the management of manufacturing to an organization whose main function is manufacturing.

3. Consolidate

Consolidating attempts to relocate functions to as few of the current properties as possible. Once this option is implemented, excess facilities are returned to the public and private institutions for other uses. The implementation phase of this option would incur some costs for the transfers of functions from one installation to another.

4. Recapitalize and Unify

With recapitalization manufacturing moves from today's single-function ammunition installations to installations that serve other purposes as well.

H. SCOPE OF THIS THESIS

The objective of this thesis is to develop a flexible decision support tool that can suggest the way and the rate that actions should be carried out to transition government ammunition facilities between modes of operation while satisfying complicated long-term constraints on resources and oversight. This decision support tool will minimize fixed and variable possession and operating costs of Army arsenals and Army Ammunition Plants (AAPs), meeting the replenishment requirements and the demand for peacetime production of ammunition and ordnance items.

Decisions to maintain, close, or change the management of government-owned and operated (GOGO) facilities, government-owned, contractor operated (GOCO) facilities, and completely privatized facilities (COCO) are governed by a number of economic and political constraints. Base closing and realignment incurs significant relocation costs for both equipment and personnel, and property and equipment transfers are costly and time consuming. Other factors bear on these decisions, including the sheer complexity and number of actions that the Army can manage at any one time, the cost of actions, including environmental remediation, and the degree of control the Army wants to exercise over the resulting ammunition infrastructure.

The work reported in this thesis derives from a tasking that the Deputy Under Secretary of Army for Operations Research gave the Center for Army Analysis to review ongoing study (PBD407 study) that examines the reorganization of the Army's ammunition production base. As part of CAA's review, they recommended to the lead of PBD407, the Director of Force Development (Logistics), that this work be accomplished. CAA is also tasked with the G3's Stationing of the Army for Transformation analysis, which this effort may also assist in. [Tarantino, 2002a]"

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II. LITERATURE REVIEW AND CURRENT REGULATIONS

A. LITERATURE REVIEW

Army is not foreign to the idea of using optimization to reduce and reshape its infrastructure. Prior studies share the common goal of reducing the infrastructure cost and minimizing the unutilized capacity of a variety of Army Installations. However, none of these studies has directly addressed the ammunition industrial base requirements while minimizing the unutilized capacity at the arsenals and AAPs.

1. Base Realignment and Closure Action Scheduler (BRACAS) [Wong, 1995]

Rather than just calculating cost estimates for the alternatives at hand, Free [1994] developed a BRAC optimization model as a scheduler for the Army base realignment and closure actions. Following that, and as an improvement to the Cost of Base Realignment Actions (COBRA) [Richardson and Kirmse, 1994] and Free's model, a mixed-integer linear program BRACAS was developed. BRACAS suggests timetables for BRAC actions that both satisfy yearly budget constraints and maximize net present value. [Dell, 1998]

BRACAS determines when to allocate the necessary one-time costs of installation closure and realignment actions to obtain the maximum net present value of the savings less the one-time costs while satisfying yearly budgets. [Wong, 1995]

2. Modeling Closure of Army Materiel Command (AMC) Installations [Tarantino, 1992]

Tarantino developed a bi-criteria mixed integer programming model with the objectives of minimizing infrastructure and operating costs and maximizing military value to generate alternate realignment solutions for AMC. The model considers realignment of depot maintenance, research and development, test and evaluation, and administrative functions on 32 different AMC installations.

3. Optimally Stationing Units to Bases (OSUB) [Dell, Fletcher, Parry, and Rosenthal; 1994]

OSUB was developed to help the Army with its 1995 BRAC decisions for maneuver and training bases. It is a bi-criterion integer linear programming model that generates solutions such as realignment and closure recommendations for Army maneuver and training bases by minimizing operating cost while maximizing military value.

4. The Regionalization and Outsourcing Optimization Model (ROOM) [Kerman, Brown, and Dell; 1998]

ROOM reduces planned infrastructure costs using a personnel assignment model subject to some additional constraints. It suggests an optimal combination of regionalization and outsourcing for a Navy shore installation with personnel numbers altered by homebasing.

5. Optimal Stationing of Army Forces (OSAF) [CAA-R-01-42, 2001]

The objective of OSAF is to systematically examine possible alternatives for Army stationing and determine an optimal Army stationing policy for a given set of installations, force structure, available budget, and stationing restrictions. The installation types OSAF addresses in the continental United States are maneuver, command and control, professional schools, major training areas, and training schools along with a number of leased facilities.

B. REGULATIONS

Reconfiguration of Army ammunition industrial base is restricted by different regulations. These regulations basically specify the rules of reconfiguring the industrial base.

1. ARMS Act [10 U.S.C. 4553]

Created by Public Law 102-484, the Armament Retooling and Manufacturing Support (ARMS) Act of 1992, authorizes a program under which funds are appropriated to permit infrastructure investments to attract commercial tenants.

2. Arsenal Act [10 U.S.C. 4532]

In 1920, Congress enacted the Arsenal Act, which provides that the Army is to have its supplies made in U.S. factories or arsenals on condition that they can do so on an economical basis. In its current version, this Act states:

> “The Secretary of the Army shall have supplies needed for the Department of the Army made in factories or arsenals owned by the United States, so far as those factories or arsenals can make those supplies on an economical basis. The Secretary may abolish any United States arsenal that he considers unnecessary. [Albright, 2000]”

When making decisions based on the Arsenal Act, the Army compares public and private sector manufacturing costs to determine whether supplies can be economically obtained from government owned facilities---a process referred to as “make or buy”. [GAO 1998, NSIAD-99-31, p. 58]

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III. MODEL DEVELOPMENT

A. INTRODUCTION

There are many economic and political constraints that restrict the decisions to maintain, close, or change the management of GOGO, GOCO, and COCO facilities. Base realignment and closure operations incur significant relocation costs for both equipment and personnel, and property and equipment transfers are costly and time consuming. These decisions are influenced by other factors, including the complexity and number of actions that the Army can handle at any one time, the cost of actions including environmental remediation, and the degree of control the Army wants to exercise over the resulting ammunition infrastructure.

The model introduced here is an aggregated, optimization-based decision support tool that will suggest optimal schedules of actions that satisfy exogenous constraints on money, management, and capacity over the long term.

The model considers reconfiguration of 16 different installations, of which, two are GOGO "hard iron" arsenals that manufacture ordnance items, three are GOGO AAPs, and 11 GOCO AAPs. Of the AAPs that are in GOCO mode of operation, five are in inactive status. The rest of these installations are in active status.

The model suggests year-by-year operating modes for each installation, structure and process center. A schedule of which installations, structures or process centers are running (in any mode of operation), which ones are disposed, and which process centers will be moved to which receiving structures and installations is specified for every year for a 10-year planning horizon. The model ensures that the replenishment requirements and the demand for peacetime production of ammunition and ordnance items are met and some additional constraints are satisfied.

For every year, we determine which open and working process center will have to work how many shifts to accomplish its part of the manufacturing of required materiel.

The model will also determine the costs incurred to perform the operations stated above. Those costs include:

- The fixed cost to operate an installation, structure, and process center;
- The multi-year costs of any mode transition for each installation, structure and process center;
- The variable cost of operating a process center; and
- The cost of moving process centers between installations and structures.

1. Model Objective

The objective function of the model evaluates the fixed and variable possession and operating costs of Army arsenals and Army Ammunition Plants (AAPs), the cost of changing modes of operation for each installation, structure and process center, and the cost of moving process centers between installations or structures.

2. Modeling Assumptions

Each installation considered by the model has structures that house process centers of certain types, such as LAP, metal parts manufacturing, canon manufacturing, and explosives manufacturing. These installations, the structures inside them and the process centers housed in those structures are allowed to change modes of operation over time, in our case a 10-year planning horizon (See Figure 4). We only allow change of operating modes where admissible. For instance, if an installation is in an active GOGO state the alternate new modes of operation for that installation for the next year would be active GOGO, active GOCO, active COCO, active FGC, inactive GOGO, and finally the state of being disposed. Likewise, all of the other admissible transitions are specified one-by-one by the model. Further, because of the current regulations and restrictive legislation, or because the Army might want to limit the degree of changes permitted, for some installations certain mode transitions may be forced, while others may be prohibited.

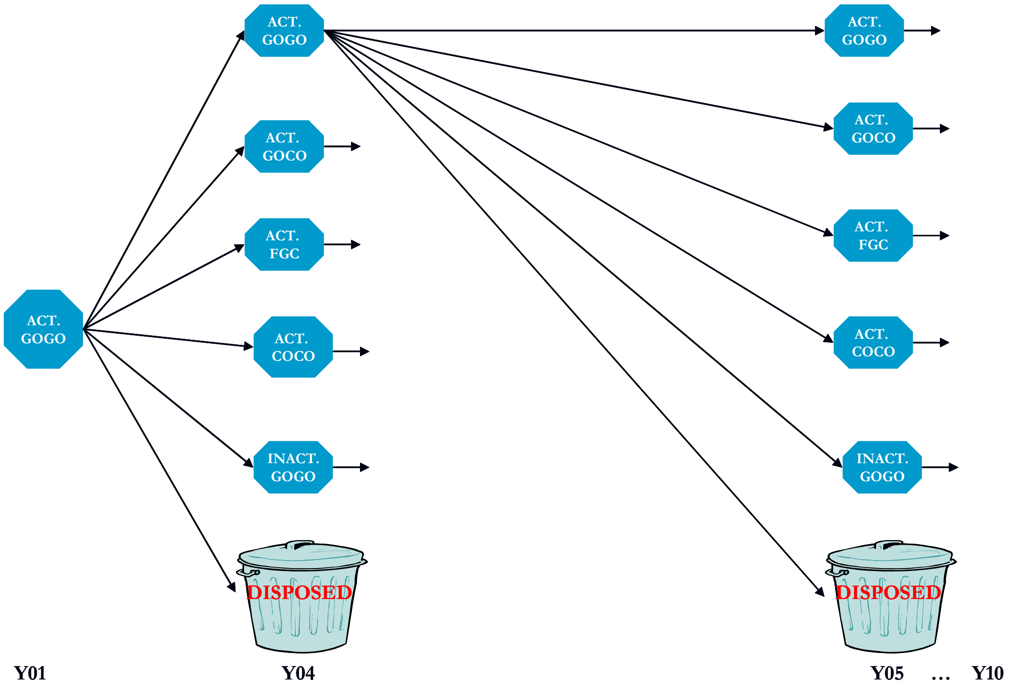

Figure 4. Change of Management Modes of Installations, Structures, and/or Process Centers over Time

This figure represents the alternate change of modes over time for any installation, structure or process center. Because decisions in years “y01” through “y03” are already committed, the first set of discretionary solutions appears in year “y04”.

The model is an aggregate one, that is, we do not consider the operation or movement of machines individually. Rather, the finest resolution we consider in the model is the process center (See Figure 5).

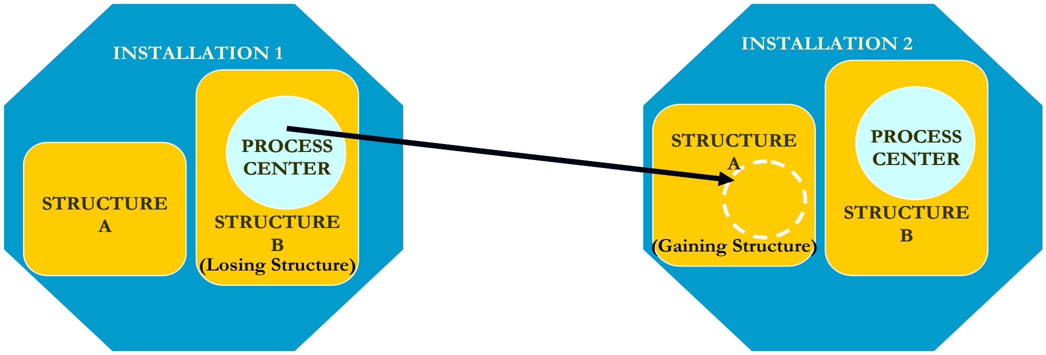

Figure 5. Moving Process Centers

The figure is a representation of potential movement of process centers from a losing structure (in Installation 1) to a gaining structure (in Installation 2). Gaining structures can be either in the same or in another installation.

By using elastic constraints [Brown, et. al., 1997] we permit yearly peacetime requirements and yearly and/or cumulative replenishment requirements to be violated at a penalty cost for each ton of violation. This permits us to deal with grossly infeasible scenarios, a real concern.

The model represents the year of action, rather than the year that the action is adopted. If there is a lag between decision and action, that lag is exogenous. Here, we use the first three years as “frozen”, so this lag is implicitly taken to be three years.

The various costs of implementing a particular decision starting in a particular year may be incurred by the Army over the entire planning horizon, rather than all at once.

The space a process center needs when it is in inactive status is assumed to be negligible compared to the space required for it when it is in active status.

B. MODEL FORMULATION

1. Indices

$i \in I$	Installation (fenced dirt) ~16
$s, s' \in S$	Structure (shelter or shelter complex)
$i(s)$	Host installation for structure $s \in S$
$p \in P$	Process center (Hardware, e.g. {small metal fab., LAP, energetics,…})
s_p	Subset of structures $s \in S$ that can house process center p
$t \in T$	Process type {e.g., small metal fab., LAP, energetics,…}
$t(p)$	Process type of process center $p \in P$
$y^+ \in Y^+$	Calendar year =0,1,…,Y~10
lag	Years from decision to execution ~3
$y^\# \in Y^\#$	Frozen years {0,1,…,lag}

$y, y' \in Y$	Planning years = {*lag*+1, *lag*+2,…, *Y*}, $Y = Y^{+} - Y^{\#}$
$m^{+} \in M^{+}$	Mode of operation {ACTIVEGOGO, ACTIVEGOCO, ACTIVECOCO, ACTIVEFGC, INACTIVEGOGO, INACTIVEGOCO, INACTIVECOCO, INACTIVEFGC, disposed}
$m, m' \in M$	Modes of operation when entity is “kept”, $M = M^{+} \setminus \{disposed\}$
$m^{*} \in M^{*}$	“Open-and-working” modes of operation {ACTIVEGOGO, ACTIVEGOCO, ACTIVECOCO, ACTIVEFGC}
$m^{\#} \in M^{\#}$	“Closed” modes of operation {INACTIVEGOGO, INACTIVEGOCO, INACTIVECOCO, INACTIVEFGC}
$\{m, m^{+}\} \in MM$	Set of admissible transitions, from $m \in M$, to $m^{+} \in M^{+}$
$\{m^{*}, m^{+}\} \in MSM$	Set of admissible transitions from open $m^{*} \in M^{*}$ to $m^{+} \in M^{+}$
$\{m^{\#}, m^{+}\} \in MCM$	Set of admissible transitions from closed $m^{\#} \in M^{\#}$ to $m^{+} \in M^{+}$

2. Given Data

$replencap_{t,y}$	Replenishment capacity required in year *y* for process type *t* (tons)
$work2train_{t,y}$	Demand in year *y* for training rounds from process type *t* (tons)
$shiftyield_{p,y}$	Tons produced per shift by process center *p* (tons/shift)
$workmax_{p,y,m^{*}}$	Maximum work capacity of process center *p* in year *y* working in mode m^{*} (shifts)
$workmin_{p,y,m^{*}}$	Minimum work capacity of process center *p* in year *y* working in mode m^{*} (shifts)

$structspace_s$	Space capacity of structure s (space)
$procspace_p$	Space requirement of process center p (space)
$icost_{i,y,m,m^+,y'}$	Fixed cost(s) to keep installation i during year y in mode m, and transition to mode m^+ the next year, incurred in y' (\$)
$scost_{s,y,m,m^+,y'}$	Fixed cost(s) to keep structure s during year y in mode m, and transition to mode m^+ the next year, incurred in y' (\$)
$pcost_{p,y,m,m^+,y'}$	Fixed cost(s) to keep process center p during year y in mode m, and transition to mode m^+ the next year, incurred in y' (\$)
$mcost_{p,y,s,s',y'}$	Fixed cost(s) to move process center p during year y from structure s in installation $i(s)$ to structure s' in installation $i(s')$, incurred in y' (\$)
$pvcost_{p,y,m*}$	Variable cost of working process center p during year y in mode $m*$ (\$/shift)

3. Decision Variables

$OPERATE_{i,y^+,m,m^+}$	in year y, keep installation i in mode m, and transition to mode m^+ the next year (binary)
$HOUSE_{s,y^+,m,m^+}$	In year y, keep structure s in mode m, and transition to mode m^+ the next year (binary)
$KEEP_{p,y^+,m,m^+}$	In year y, keep process center p in mode m, and transition to mode m^+ the next year (binary)
$RUN_{p,y,s}$	Process center p housed in structure s in year y, and both are open-and-working (binary)

$MOVE_{p,y^+,s,s'}$	In year *y*, move process center *p* from structure *s* to *s*‘ (binary)
$WORK_{p,y,m^*}$	Operation of process center *p* in open-and-working mode *m** during year *y* (shifts)

4. Formulation

Minimize fixed and variable possession and operating costs

$$\text{Min} \quad \sum_{\substack{i\in I, y\in Y,\\ \{m,m^+\}\in MM, y'\in Y}} icost_{i,y,m,m^+,y'} OPERATE_{i,y,m,m^+}$$

$$+ \sum_{\substack{s\in S, y\in Y,\\ \{m,m^+\}\in MM, y'\in Y}} scost_{s,y,m,m^+,y'} HOUSE_{s,y,m,m^+}$$

$$+ \sum_{\substack{p\in P, y\in Y,\\ \{m,m^+\}\in MM, y'\in Y}} pcost_{p,y,m,m^+,y'} KEEP_{p,y,m,m^+}$$

$$+ \sum_{\substack{p\in P, y\in Y,\\ s\in S, s'\in S, y'\in Y}} mcost_{p,y,s,s',y'} MOVE_{p,y,s,s'}$$

$$+ \sum_{p\in P, y\notin Y, m^*\in M^*} pvcost_{p,y,m^*} WORK_{p,y,m^*}$$

s.t.

By end of each year, fill cumulative training demand

$$\sum_{\substack{p\in P|t=t(p),\\ y'\in Y|y'\leq y, m^*\in M^*}} shiftyield_{p,y'} WORK_{p,y',m^*} \overset{\circ}{\geq} \sum_{y'\in Y|y'\leq y} work2train_{t,y'} \qquad (1)$$

$$\forall t\in T, y\in Y$$

By end of each year, maintain cumulative replenishment capacity

$$\sum_{\substack{p \in P | t = t(p), \\ y' \in Y | y' \leq y, \\ \{m^*, m^+\} \in MSM}} shiftyield_{p,y'} workmax_{p,y',m^*} KEEP_{p,y',m^*,m^+} \overset{\circ}{\geq} \sum_{y' \in Y \leq y} replencap_{t,y'} \tag{2}$$

$$\forall t \in T, y \in Y$$

During each year, maintain yearly replenishment capacity

$$\sum_{\substack{p \in P | t = t(p), \\ \{m^*, m^+\} \in MSM}} shiftyield_{p,y} workmax_{p,y,m^*} KEEP_{p,y,m^*,m^+} \overset{\circ}{\geq} replencap_{t,y} \tag{3}$$

$$\forall t \in T, y \in Y$$

Respect open-and-working process center work capacities

$$WORK_{p,y,m^*} \leq workmax_{p,y,m^*} \sum_{\{m^*, m^+\} \in MSM} KEEP_{p,y,m^*,m^+} \tag{4}$$

$$\forall p \in P, y \in Y, m^* \in M^*$$

$$WORK_{p,y,m^*} \geq workmin_{p,y,m^*} \sum_{\{m^*, m^+\} \in MSM} KEEP_{p,y,m^*,m^+} \tag{5}$$

$$\forall p \in P, y \in Y, m^* \in M^*$$

Each kept process center p must be located in a kept host structure

$$\sum_{s' \in s_p} MOVE_{p,y,s,s'} \leq \sum_{\{m, m^+\} \in MM} HOUSE_{s,y,m,m^+} \qquad \forall p \in P, y \in Y, s \in s_p \tag{6}$$

Process center p and its host structure s are open-and-working

$$RUN_{p,y,s} \leq \sum_{s' \in s_p} MOVE_{p,y,s,s'} \qquad \forall p \in P, y \in Y, s \in s_p \tag{7}$$

$$RUN_{p,y,s} \leq \sum_{\{m^*, m^+\} \in MSM} KEEP_{p,y,m^*,m^+} \qquad \forall p \in P, y \in Y, s \in s_p \tag{8}$$

$$RUN_{p,y,s} \leq \sum_{\{m^*, m^+\} \in MSM} HOUSE_{s,y,m^*,m^+} \qquad \forall p \in P, y \in Y, s \in s_p \tag{9}$$

Process centers located in a structure must fit in the structure

$$\sum_{p\in P|s=s_p} procspace_p RUN_{p,y,s} \le strucspace_s \sum_{\{m,m^+\}\in MM} HOUSE_{s,y,m,m^+} \qquad (10)$$

$$\forall s\in S, y\in Y$$

Each open-and-working process center *p* must be located in an open-and-working host structure *s*, maybe in a different mode

$$\sum_{\{m^*,m^+\}\in MSM} KEEP_{p,y,m^*,m^+} \le \sum_{s\in s_p} RUN_{p,y,s} \qquad \forall p\in P, y\in Y \quad (11)$$

Each open-and-working structure must have an open-and-working host installation, maybe in a different mode

$$\sum_{\{m^*,m^+\}\in MSM} HOUSE_{s,y,m^*,m^+} \le \sum_{\{m^*,m^+\}\in MSM} OPERATE_{i(s),y,m^*,m^+} \qquad \forall s\in S, y\in Y \quad (12)$$

Each closed, but kept structure *s* must have a kept host installation, maybe in a different mode

$$\sum_{\{m^\#,m^+\}\in MCM} HOUSE_{s,y,m^\#,m^+} \le \sum_{\{m,m^+\}\in MM} OPERATE_{i(s),y,m,m^+} \qquad \forall s\in S, y\in Y \quad (13)$$

Year-to-year mode transitions for each installation

$$\sum_{\{m',m\}\in MM} OPERATE_{i,y^+-1,m',m} = \sum_{\{m,m^+\}\in MM} OPERATE_{i,y^+,m,m^+} \qquad (14)$$

$$\forall i\in I, y^+\in Y^+ > lag, m\in M$$

Each structure

$$\sum_{\{m',m\}\in MM} HOUSE_{s,y^+-1,m',m} = \sum_{\{m,m^+\}\in MM} HOUSE_{s,y^+,m,m^+} \qquad (15)$$

$$\forall s\in S, y^+\in Y^+ > lag, m\in M$$

Each process center

$$\sum_{\{m',m\}\in MM} KEEP_{p,y^+-1,m',m} = \sum_{\{m,m^+\}\in MM} KEEP_{p,y^+,m,m^+} \tag{16}$$

$$\forall p\in P, y^+\in Y^+ > lag, m\in M$$

Moving process centers

$$\sum_{s'\in S_p} MOVE_{p,y^+-1,s',s} = \sum_{s'\in S_p} MOVE_{p,y^+,s,s'} \qquad \forall p\in P, y^+\in Y^+ > lag, s\in S_p \tag{17}$$

Selection constraints to tighten continuous relaxation of model

$$\sum_{\{m,m^+\}\in MM} OPERATE_{i,y,m,m^+} \le 1 - \sum_{y'\in Y<y,m} OPERATE_{i,y',m,'disposed'} \quad \forall i\in I, y\in Y \tag{18}$$

$$\sum_{\{m,m^+\}\in MM} HOUSE_{s,y,m,m^+} \le 1 - \sum_{y'\in Y<y,m} HOUSE_{s,y',m,'disposed'} \qquad \forall s\in S, y\in Y \tag{19}$$

$$\sum_{\{m,m^+\}\in MM} KEEP_{p,y,m,m^+} \le 1 - \sum_{y'\in Y<y,m\in M} KEEP_{p,y',m,'disposed'} \qquad \forall p\in P, y\in Y \tag{20}$$

$$\sum_{s\in S_p, s'\in S_p} MOVE_{p,y,s,s'} \le 1 - \sum_{y'\in Y<y,m\in M} KEEP_{p,y',m,'disposed'} \qquad \forall p\in P, y\in Y \tag{21}$$

Initial conditions, frozen for lag years

$$OPERATE_{i,y^\#,m,m} = 1 \qquad \forall i\in I, y^\#\in Y^\#, \text{ initial } m \tag{22}$$

$$HOUSE_{s,y^\#,m,m} = 1 \qquad \forall s\in S, y^\#\in Y^\#, \text{ initial } m \tag{23}$$

$$KEEP_{p,y^\#,m,m} = 1 \qquad \forall p\in P, y^\#\in Y^\#, \text{ initial } m \tag{24}$$

$$MOVE_{p,y^\#,s,s} = 1 \qquad \forall p\in P, y^\#\in Y^\#, \text{ initial } s \tag{25}$$

Variable domains

$$OPERATE_{i,y,m,m^+} \in \{0,1\} \qquad \forall i\in I, y\in Y, \{m,m^+\}\in MM$$

$$HOUSE_{s,y,m,m^+} \in \{0,1\} \qquad \forall s\in S, y\in Y, \{m,m^+\}\in MM$$

$$KEEP_{p,y,m,m^+} \in \{0,1\} \qquad \forall p \in P, y \in Y, \{m, m^+\} \in MM$$

$$MOVE_{p,y,s,s'} \in \{0,1\} \qquad \forall p \in P, y \in Y, s, s' \in S$$

$$WORK_{p,y,m^*} \geq 0 \qquad \forall p \in P, y \in Y, m^* \in M^*$$

$$RUN_{p,y,s} \in \{0,1\} \qquad \forall p \in P, y \in Y, s \in S$$

5. Discussion

The objective function evaluates fixed and variable possession and operation costs of installations, structures and process centers, along with the cost of changing the modes of operation for each of those entities year-by-year and the costs incurred by moving process centers between structures.

Constraints (1) through (3) maintain adequate capacity to meet cumulative training demand and yearly and cumulative replenishment requirements. These constraints contain elastic variables (implied by the distinctive inequality symbols $\overset{\circ}{\geq}$, but not shown explicitly) that permit each cumulative and/or annual constraint to be violated at a penalty cost for each ton of violation.

Constraints (4) and (5) restrict the operation of process centers to be bounded by minimum and maximum work capacities.

Constraints (6) ensure that each kept process center is located in a kept host structure.

Constraints (7) through (9) enforce that if process center p is open and working, then its host structure s is open and working.

Constraints (10) enforce space restrictions on the process centers, which state that the process centers located in a structure must fit in that structure. If it is assumed that the process centers take the same amount of space when they are in inactive status, the term $RUN_{p,y,s}$ can be replaced with the term $MOVE_{p,y,s,s'}$ in this constraint.

Constraints (11) put a restriction on each open and working process center forcing each of them to be located in an open and working host structure.

Constraints (12) apply the same restrictions on open and working structures forcing each to be located in an open and working host installation. Both constraints (11) and (12) permit process centers located in structures and structures located in an installation and the installation itself to operate in different modes.

Similarly, constraints (13) enforce that each closed, but kept structure *s* must have a kept host installation, albeit perhaps in a different mode.

Constraints (14) through (17) represent year-to-year mode transitions for each installation, each structure and each process center, and the movements of process centers.

Constraints (18) through (21) are selection constraints to tighten the continuous relaxation of model by ensuring that once an entity is disposed it is gone forever and cannot be regained.

Constraints (22) through (25) represent the initial conditions for the entities.

For each installation, structure and process center we permit more than one mode change over the planning horizon. The number of mode transitions can easily be controlled by adding "turbulence" constraints, e.g.; for at most one transition per entity:

$$\sum_{y,m^+,m\neq m^+} OPERATE_{i,y,m,m^+} \leq 1 \qquad \forall i \in I \qquad \text{(TI)}$$

$$\sum_{y,m^+,m\neq m^+} HOUSE_{s,y,m,m^+} \leq 1 \qquad \forall s \in S \qquad \text{(TS)}$$

$$\sum_{y,m^+,m\neq m^+} KEEP_{p,y,m,m^+} \leq 1 \qquad \forall p \in P \qquad \text{(TP)}$$

Similarly the number of relocations of each process center can be controlled. E.g.:

$$\sum_{y,s,s'\neq s} MOVE_{p,y,s,s'} \leq 1 \qquad \forall p \in P \qquad \text{(TM)}$$

There is a possibility that some installations, structures and/or process centers may get disposed after year ‘y10’. This is due to “end effects”, that is there is no demand after year ‘y10’ and disposing is the cheapest alternative. This minor issue can easily be dealt with by precluding the variables “$OPERATE_{i,'y10',m,'disposed'}$”, “$HOUSE_{s,'y10',m,'disposed'}$”, and “$KEEP_{p,'y10',m,'disposed'}$” from the model.

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IV. RATIONALE FOR THIS MODEL

We plan by year because the DOD and the Army also plan by year. We consider a 10-year planning horizon because the cost implications at near-term decisions extend at least that far into the future.

As a part of National Technology and Industrial Base, the Army industrial base is defined as a combination of GOGO, GOCO, and COCO industrial capacities. Those are the management modes of the facilities currently supporting the ammunition industrial base. Some of those facilities are in active and some are in inactive modes of operation. Other than these management modes, the new idea of creating an FGC has been proposed to DOD and Army officials. This new option requires transferring of all the manufacture assets by the Army to a congressionally chartered FGC. This new management mode permits an installation or its structures or process centers to be active or inactive. The model modes of operation reflect these alternatives.

Since the enactment of the ARMS Act, it has been admissable with the Congress and the Army to permit an installation in one mode of operation to contain structures or process centers in another mode of operation. There have been examples of this implemented since 1992. Based on this, the model permits structures in an installation and the process centers in each of those structures to operate in different modes. For instance, an installation and the structures in it may be in GOGO operation mode, but a housed process center may be operated as an FGC or a GOCO. This embellishment is easily restricted if it is not wanted.

Once suggestions for a 10-year planning horizon are made, the budget allocated to the Army in a fiscal year may not be sufficient to pay for all the costs incurred for the implementation of the decisions suggested for that fiscal year. The various costs of implementing a decision will be incurred by the Army over the planning horizon, rather than all at once. We allocate costs incurred by a decision over the remaining years of the planning horizon. Other approaches to distribute those costs would be easy to implement. And, in particular, we can add constraints that are yearly aspiration levels for expenditures to adhere to forecast budgets.

We could use spreadsheets if we just needed a descriptive model, and were willing and able to input a complete, feasible decision for analysis. However, we need a prescriptive model to suggest what actions to take, because we are trying to discover what to do.

Solving this model manually is essentially impossible. Single alternatives can be evaluated but there are billions of them. Manual analysis of any alternative takes a long time.

Decisions can be manually controlled. The number of actions can be limited, the per-year cost can be constrained, the admissible transitions restructured, and so forth. The idea is to equip the Army with a planning tool that can optimize to a “clean sheet” plan, or investigate carefully crafted excursions from favored existing plans.

V. COMPUTATIONAL EXPERIENCE

A. DATA

Synthetic, unclassified, representative data has been generated randomly for a proof prototype using the General Algebraic Modeling System (GAMS) [GAMS, 2002] for a total of 16 different installations, 34 structures, 19 process centers, nine process types for a 10 year period.

To avoid "too-random" costs that lead to "too-random" outcomes, we have built a simple cost model to generate synthetic, "systematic" rather than completely random costs. We seek costs that mimic the size of installations and that do not vary too much over time, and that induce reasonable, face-valid transitions in our prototypic experiments.

For each entity and mode, we specify a uniform base annual operating and possession cost. We use this seed cost as the active cost for all years, and we use 20 percent of this for inactive cost in all years.

For a transition from active to inactive, same management mode, we just add 10 percent of operating and possession costs. For transition from inactive to active, same management mode, we add 60 percent of operating and possession costs.

For transition from one management mode to another, we add 200 percent of the base cost of the losing mode.

Other costs such as process center variable costs and movement costs, peacetime and replenishment requirements for each process type, and the amount of ammunition or ordnance items manufactured by each process center are generated in a similar way.

The idea is to get costs with some rational pattern that can be seen, explained, and easily changed in case someone has some specific suggestions. We want to keep this simple because random costs can be too distracting, and are more difficult to deal with than systematic costs.

B. IMPLEMENTATION OF THE MATHEMATICAL MODEL

The ammunition industrial base rationalization model is prototypically implemented in the GAMS [GAMS, 2002], using the CPLEX mixed integer program (MIP) solver [ILOG, 2002].

1. Full Model

The full model has been run with all of the 16 installations, 34 structures, and 19 process centers with nine different process types. The synthetic data files created by our generator are imported into GAMS as tables by using the "include" function. The resulting model has 41,282 variables, 33,495 of which are binary, and a total of 12,615 constraints. We use an integrality tolerance of one percent. Using an IBM compatible personal computer with 1 Gigabyte of random access memory and a 2 Gigahertz Intel Pentium 4 processor, with the random data it can take between an hour to many hours to generate and solve the full model depending on how relaxed or tight the constraints become with the data created.

2. Single-Issue Scenario

The Army regards LAP process centers and the installations housing them as the facilities with the highest unutilized capacity. LAP process centers are on the Army and DOD priority list for rationalization. We have run the model for only LAP process centers, and the installations and structures housing them. In this case we are left with only seven installations, 14 structures, and seven process centers and of course only one type of process: LAP.

This example of focused analysis requires simply fixing each variable that does not relate to any kind of LAP operation to its current state. The process centers that are already open and working are forced to stay open and working with a specified number of operating shifts (See Table 3). It takes between 15 seconds to a few minutes to generate and solve this single-issue model depending on how relaxed or tight the constraints become with the data created. The model is solved to optimality in the relaxed case, and with less than one percent relative integrality gap (to within less than one percent of integer optimality) in the tight case.

Process C.	Op. Mode	y04	y05	y06	y07	y08	y09	y10
CRNbombfil	ACTGOGO	260	260	260	260	260	260	260
CRNLAP	**ACTFGC**		**1092**					
CRNLAP	**ACTGOGO**	**260**		**260**	**260**			
HOLSexplos	ACTGOCO	260	260	260	260	260	260	260
IOWALAP	**ACTCOCO**				**260**			
IOWALAP	**ACTFGC**		**260**	**1092**		**1092**		
IOWALAP	**ACTGOCO**	**625**						
KANSLAP	**ACTFGC**					**260**	**260**	**1092**
LAKECLAP	**ACTFGC**		**260**					
LAKECLAP	**ACTGOCO**	**260**						
LNSTLAP	**ACTFGC**		**1092**				**260**	**496**
LNSTLAP	**ACTGOCO**	**260**						
McAbombfil	ACTGOGO	260	260	260	260	260	260	260
MILLAP	**ACTFGC**		**369**	**1092**				**260**
MILLAP	**ACTGOCO**	**260**						
PBLFchemic	ACTGOGO	260	260	260	260	260	260	260
PBLFLAP	**ACTFGC**				**260**	**1092**	**1092**	
PBLFLAP	**ACTGOGO**	**260**						
RADFpropel	ACTGOCO	260	260	260	260	260	260	260
RADFTNT	ACTGOCO	260	260	260	260	260	260	260
RIAmanu	ACTGOGO	260	260	260	260	260	260	260
WVLcanmanu	ACTGOGO	260	260	260	260	260	260	260

Table 3. LAP Optimization Case: Process Centers Yearly Work Schedule

In this single-issue scenario, each non-LAP process center is fixed to its current mode of operation and each active one is forced to work at least a minimum number of shifts in a year. The model is solved for only LAP process centers. For each process center that is specified by the model to stay in any active mode of operation, the number of shifts it has to work in a year is also specified. For instance, LNSTLAP process center is scheduled by the model to work 260 shifts (minimum work capacity) in active GOCO mode of operation in year ‘y04’, 1092 shifts (maximum work capacity) in active FGC mode of operation in year ‘y05’. Because it is in inactive mode of operation it is not scheduled to work for the next three years (‘y06’ through ‘y08’). It is again scheduled to work 260 and 496 shifts in active FGC mode of operation in years ‘y09’ and ‘y10’ respectively.

Our model generates an output log with all the detailed year-by-year information about the suggested operation modes of installations, structures, and process centers (See Table 4). In addition, all these results from GAMS are exported directly to Microsoft EXCEL [Microsoft Corp., 2000] files for numerical and graphical presentation. There are 10 data sheets (the original data created) and 13 results sheets that are automatically populated with solution details. E.g., installation history, installation cost, process center movement history, process center work, etc.

Process C.	y04	y05	y06	y07	y08	y09	y10
CRNLAP	ACTGOGO	ACTFGC	ACTGOGO	ACTGOGO	INACTGOGO	INACTGOGO	INACTGOGO
IOWALAP	ACTGOCO	ACTFGC	ACTFGC	ACTCOCO	ACTFGC	INACTFGC	INACTFGC
KANSLAP	INACTGOCO	INACTFGC	INACTFGC	INACTFGC	ACTFGC	ACTFGC	ACTFGC
LAKECLAP	ACTGOCO	ACTFGC	INACTFGC	INACTGOGO	INACTGOGO	INACTGOGO	INACTGOGO
LNSTLAP	ACTGOCO	ACTFGC	INACTFGC	INACTFGC	INACTFGC	ACTFGC	ACTFGC
MILLAP	ACTGOCO	ACTFGC	ACTFGC	INACTFGC	INACTFGC	INACTFGC	ACTFGC
PBLFLAP	ACTGOGO	INACTGOGO	INACTFGC	ACTFGC	ACTFGC	ACTFGC	INACTFGC

Table 4. LAP Process Centers Management Modes Optimized over Time

This table represents the management mode changes of LAP process centers in the "LAP" scenario. There are no restrictions on the number or frequency of mode transitions. The model makes these transitions to minimize the cost. In some cases it may be cheaper to transition state. For instance, CRNLAP is initially in ACTGOGO state, and because the variable cost of CRNLAP process center in ACTFGC mode is much less than it is in ACTGOGO mode, it changes to ACTFGC mode immediately for year 'y05'. Then in year 'y06' it becomes an ACTGOGO again. Going from ACTGOGO to INACTGOGO is much cheaper for CRNLAP than it is going from ACTFGC to INACTFGC, and being in INACTFGC or INACTGOGO for the rest of the horizon is the same price. Some of the process centers are disposed after year 'y10' because of "end effects" (i.e. this is the cheapest alternative and there is no following demand).

By using "turbulence" constraints (TI, TS, TP, and TM) we can restrict the number of mode changes of each installation, each structure and each process center to one (See Table 5) in our planning horizon.

Process C.	y04	y05	y06	y07	y08	y09	y10
CRNLAP	ACTGOGO	ACTGOGO	INACTGOGO	INACTGOGO	INACTGOGO	INACTGOGO	INACTGOGO
IOWALAP	ACTGOCO	ACTFGC	ACTFGC	ACTFGC	ACTFGC	ACTFGC	ACTFGC
KANSLAP	INACTGOCO	INACTGOCO	INACTGOCO	INACTGOCO	INACTGOCO	INACTGOCO	INACTGOCO
LAKECLAP	ACTGOCO	ACTFGC	ACTFGC	ACTFGC	ACTFGC	ACTFGC	ACTFGC
LNSTLAP	ACTGOCO	ACTFGC	ACTFGC	ACTFGC	ACTFGC	ACTFGC	ACTFGC
MILLAP	ACTGOCO	INACTGOCO	INACTGOCO	INACTGOCO	INACTGOCO	INACTGOCO	INACTGOCO
PBLFLAP	ACTGOGO	INACTGOGO	INACTGOGO	INACTGOGO	INACTGOGO	INACTGOGO	INACTGOGO

Table 5. LAP Process Centers Management Modes Optimized over Time with at most one Allowable Mode Transition

This table depicts the mode changes of LAP process centers over time when we restrict the number of mode changes of each installation, structure and process center to be no more than one. This more practical solution (a restriction of the prior scenario) only increases the optimal objective function value by four percent (synthetic).

Further, movement and operation (in shifts) of process centers, and any unavoidable peacetime and replenishment requirement shortages (See Table 6) are also specified. For each process type the report includes the costs (See Figure 6) associated with each one of these actions over a 10-year planning horizon.

Process Type	y04	y05	y06	y07	y08	y09	y10
bombfill	15	28	40	54	65	80	92
canmanu	14	32	47	61	76	90	105
chemic	14	31	47	63	78	92	106
explos	14	31	48	64	78	91	104
LAP	**4**	**10**	**14**	**19**	**26**	**33**	**40**
manu	17	30	46	64	80	98	115
metpart	17	32	48	66	85	101	120
propelman	17	33	46	62	75	90	105
TNT	14	27	42	56	72	88	106

Process Type	y04	y05	y06	y07	y08	y09	y10
bombfill	15	28	40	54	65	80	92
canmanu	14	32	47	61	76	90	105
chemic	14	31	47	63	78	92	106
explos	14	31	48	64	78	91	104
LAP	**0**	**0**	**0**	**0**	**0**	**0**	**0**
manu	17	30	46	64	80	98	115
metpart	17	32	48	66	85	101	120
propelman	17	33	46	62	75	90	105
TNT	14	27	42	56	72	88	106

Table 6. Cumulative Peacetime Requirement Shortages (K tons) of Process Types over Time

Initially, the model is solved fixing each installation, structure and process center to its current state. We assume that process centers are working one shift a day and five days a week--- a total of 260 shifts a year. Currently, none of the process type requirements can be met by the process centers. The table on the left represents the cumulative peacetime requirement shortages over time if every entity in the model is fixed to its current status. In the "LAP" scenario (the table on the right) the demands for peacetime load, assemble, and pack (LAP) of ammunition and ordnance items are met with the data used. Because non-LAP process centers are fixed, the model still shows the fixed, exogenous shortages for other process types.

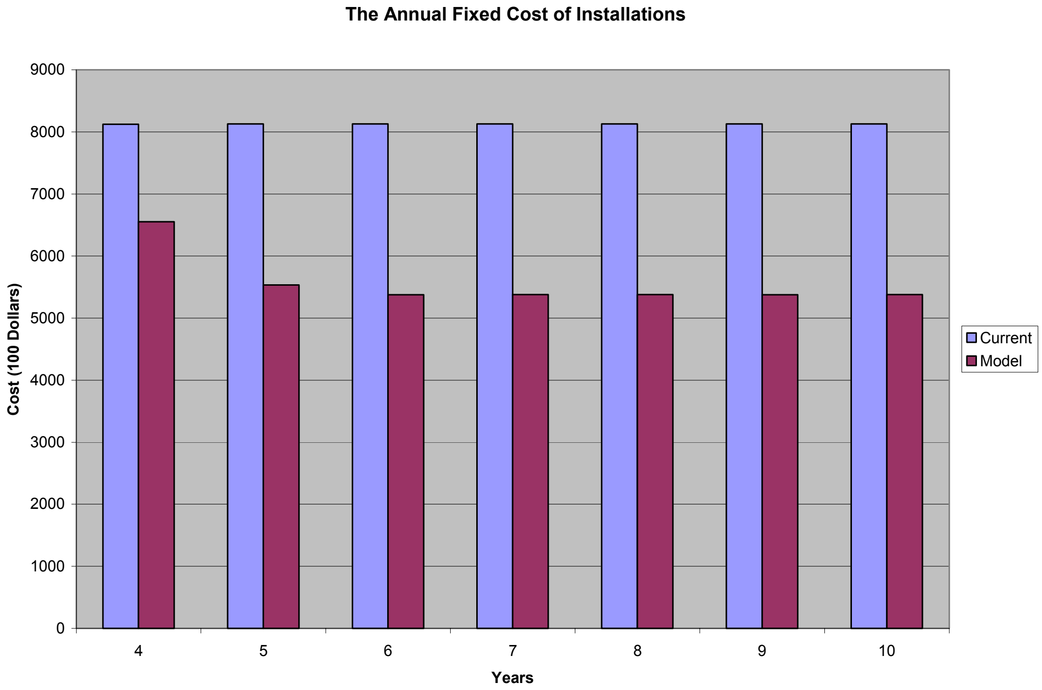

Figure 6. A Comparison of Current vs. Optimized Annual Fixed Costs of Installations This graph shows the annual fixed possession and operating costs of AAPs and arsenals if they are retained in their present state and if costs are minimized by changing state at most once per entity over the planning horizon. Here, the "end effects" of disposing all entities at the end of the planning horizon have been eliminated by precluding any last-period disposal. These costs include the cost of mode transitions and the movement cost of process centers.

In summary, we can see each action an installation, a structure, and/or a process center (See Table 7) takes.

CRNLAP	**y04**	**y05**	**y06**	**y07**	**y08**	**y09**	**y10**
Operation Mode	ACTGOGO	ACTFGC	ACTGOGO	ACTGOGO	INACTGOGO	INACTGOGO	INACTGOGO
Housing Structure	CRNSTRA	CRNSTRA	PBLFSTRA	PBLFSTRA	PBLFSTRA	PBLFSTRA	PBLFSTRA
Shifts	260	1092	260	260	0	0	0

Table 7. Example of an Optimized Ten-Year History of a Process Center Initially CRNLAP process center is in CRNSTRA (Crane AAP Structure A) and stays there for one more year. In year 'y06' it moves to PBLFSTRA (Pine Bluff Arsenal Structure A) and stays there for the rest of the planning horizon. The operation mode of CRNLAP and the number of shifts it is working each year can also be seen from the table.

VI. CONCLUSIONS

We think this model captures the essence of the Army’s problem. We recommend the Army try it.

CAA's LTC Bill Tarantino [2002a] says that “The model introduced here will potentially be used in the Army’s Industrial Base Review led by the Army Material Command, CAA's upcoming stationing analysis, and in the next series of BRAC analyses.”

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