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THESIS

ALLOCATION OF NAVY REAL PROPERTY MAINTENANCE FUNDING

by

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March 1997

Thesis Advisor: Robert F. Dell

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The Office of the Chief of Naval Operations (OPNAV) allocates roughly $900 million annually from its operations and maintenance (O&M) appropriation for facilities maintenance and repair. Annual reports of facility condition, plant value, and maintenance and repair costs provide the basis for apportionment of these funds to each of 15 major Naval organizations (major claimants). Funding shortfalls have contributed to a chronic deferral of maintenance and repair projects. The resulting backlog of critical unfunded requirements for facilities maintained by the O&M appropriation totaled $2 billion at the end of fiscal year 1995. OPNAV's objective is to stabilize or reduce this backlog over time while providing maintenance and repair funding for the major claimants consistent with readiness objectives. This thesis develops a multiobjective, infinite horizon linear program to determine multi-year maintenance and repair funding levels for the major claimants while adhering to annual budget constraints and a standard Navy facility priority system linked to operational readiness. The model produces funding recommendations that are managerially and administratively feasible, and it shows an improved capacity to apportion funding consistently with the existing priority system.

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ALLOCATION OF NAVY REAL PROPERTY MAINTENANCE FUNDING

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requirements for the degree of

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ABSTRACT

The Office of the Chief of Naval Operations (OPNAV) allocates roughly \$900 million annually from its operations and maintenance (O&M) appropriation for facilities maintenance and repair. Annual reports of facility condition, plant value, and maintenance and repair costs provide the basis for apportionment of these funds to each of 15 major Naval organizations (major claimants). Funding shortfalls have contributed to a chronic deferral of maintenance and repair projects. The resulting backlog of critical unfunded requirements for facilities maintained by the O&M appropriation totaled \$2 billion at the end of fiscal year 1995. OPNAV's objective is to stabilize or reduce this backlog over time while providing maintenance and repair funding for the major claimants consistent with readiness objectives. This thesis develops a multiobjective, infinite horizon linear program to determine multi-year maintenance and repair funding levels for the major claimants while adhering to annual budget constraints and a standard Navy facility priority system linked to operational readiness. The model produces funding recommendations that are managerially and administratively feasible, and it shows an improved capacity to apportion funding consistently with the existing priority system.

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EXECUTIVE SUMMARY

The Office of the Chief of Naval Operations (OPNAV) allocates roughly $900 million annually from its operations and maintenance (O&M) appropriation for facilities maintenance and repair. Annual reports of facility condition, plant value, and maintenance and repair (M&R) costs provide the basis for apportionment of these funds to each of 15 major Naval organizations (major claimants). Funding shortfalls have contributed to a chronic deferral of maintenance and repair projects. The resulting backlog of critical unfunded requirements for facilities maintained by the O&M appropriation totaled $2 billion at the end of fiscal year 1995. OPNAV's objective is to stabilize or reduce this backlog over time while providing maintenance and repair funding for the major claimants consistent with readiness objectives. This thesis develops a multiobjective, infinite horizon linear program called OMAR (Optimization of Maintenance and Repair) to determine multi-year maintenance and repair funding levels for the major claimants consistent with readiness objectives.

In the planning process the Director, Assessment Division (N81) is responsible for analyzing how all Navy programs, under alternative multi-year funding levels, contribute to the Navy's operational readiness. This analysis is complicated by yearly maintenance and repair budgets committing more money to the program but achieving less backlog reductions than another budget sequence. OMAR's design allows N81 to investigate the effects of borrowing additional funds from other O&M programs in order to accomplish more work on time and avoid real cost increases associated with deferring maintenance and repair.

The Deputy Chief of Naval Operations (Logistics), N4, is responsible for allocating multi-year maintenance and repair budgets to each of the major claimants. When total annual budgets are fixed, OMAR helps N4 determine how to allocate each year's budget in order to give Navy-wide funding priority to maintenance and repair projects for facilities most important to operational readiness.

Computational studies indicate that planners should borrow funds when: (1) the decisionmaker indicates a quantifiable willingness to exceed the budget; (2) target backlog levels are not being met; and (3) lower long term net costs would result from borrowing. A comparison of critical backlog achieved by funding levels established in Program Objective Memorandum 98 with those achieved by an optimal allocation restricted by the same fixed annual budgets shows that more high priority work—that most relevant to operational needs—is accomplished Navy-wide with an optimal allocation. Explicit modeling of total noncritical project costs (deferrable backlog), not previously accomplished, shows that early identification and reporting of noncritical M&R projects leads to better decisions regarding multi-year total budget levels and claimant funding allocations.

I. MAINTENANCE AND REPAIR OF NAVY FACILITIES

A. INTRODUCTION

The Navy is embroiled in a growing internal debate about how it should allocate scarce budget dollars between its force structure (e.g., procurement and sustainment of ships, aircraft, and weapons systems) and its infrastructure (e.g., operations and maintenance of airfields, piers, repair facilities, hospitals, and utilities) [Struble 1996]. The Navy's principal concern is to provide infrastructure for the support of its operating forces at the smallest possible cost. Long term factors affecting its ability include:

- mission definition and new mission requirements,
- decisions to change the size or structure of operating forces and their supporting commands,
- decisions to outsource or privatize certain infrastructure functions,
- decisions to expand, realign, or close bases, and
- decisions to build or demolish existing facilities.

In the short term, however, infrastructure represents fixed capital and incurs sizeable expenses for its operation, maintenance, and repair. In 1995, the Department of the Navy (DoN) owned a physical plant valued at $137 billion. The Navy's 1995 budget for base support under the Operations and Maintenance, Navy (O&M,N) appropriation totaled $3.4 billion, including $899 million authorized for real property maintenance (RPM)—such as routine maintenance, major repairs, design, and minor construction. At the end of the year, unfunded, critical maintenance and repair requirements for the same facilities totaled $2 billion, or 222% of available funding [N44 1995].

A number of organizations on the Navy staff (Figure 1.1), primarily N4 (logistics), determine maintenance and repair funding levels. The processes examine apportionment of RPM funding in four major dimensions:

- major claimants (maintaining organizations);
- investment categories (functions performed by the facilities);
- priorities (relative importance of various facilities to the Navy's operational mission); and
- years in which maintenance and repair projects are to be performed.

B. THESIS ORGANIZATION

This thesis addresses the problem of allocating multi-year maintenance and repair funds from the O&M,N appropriation to each of 11 major claimants. It presents a multiobjective, infinite horizon linear programming model to help OPNAV recommend multi-year funding levels for the major claimants subject to annual budget constraints. The model considers each of the above dimensions in determining how to reduce or stabilize maintenance backlog while conforming to a standard Navy facilities priority system.

The remainder of this chapter describes the decision framework on which the model is based. Chapter II reviews Operations Research literature pertinent to the problem and investigates a number of infrastructure models designed to solve similar problems. Chapter III describes the model's basic assumptions and then develops it in detail, defining all of the data elements and their sources. Chapter IV identifies specific difficulties in the inspection and reporting systems, and proposes an alteration to the model to work with the data currently available; it further summarizes computational experience with the Navy's 1995 annual inventory, reports, and budgets for years 1996-2003. Chapter V presents conclusions and recommendations for further work. Appendix A describes and implements a standard method of constructing a linear composite scale for preference analyses; Appendix B formulates two finite horizon approximations used to solve the infinite horizon linear program; Appendix C provides a list of acronyms; and Appendix D contains facility condition report summaries, inventory data, and maintenance and repair funding levels from 1995 to 2003.

C. MANAGEMENT SYSTEMS AND PROCESSES

1. Planning and Programming

The Navy establishes budgets through its Planning, Programming, and Budgeting System (PPBS). As a part of the planning process the Director, Assessment Division (N81) has two principal responsibilities relating to facilities management. In the Investment Balance Review (IBR), N81 acts as the Navy's "honest broker" by helping to balance the competing requirements of mission and support areas for funding. It performs qualitative and quantitative analyses of various program requirements and weighs the projected outcomes of alternative funding options. As the assessment sponsor for the Navy's Readiness Support Area (SA), N81 examines how various programs contribute to the Navy's operational readiness. As a part of both responsibilities, installation analysts require the ability to analyze proposed RPM funding levels in light of long term goals, operational readiness, competing requirements for funding, and facility condition.

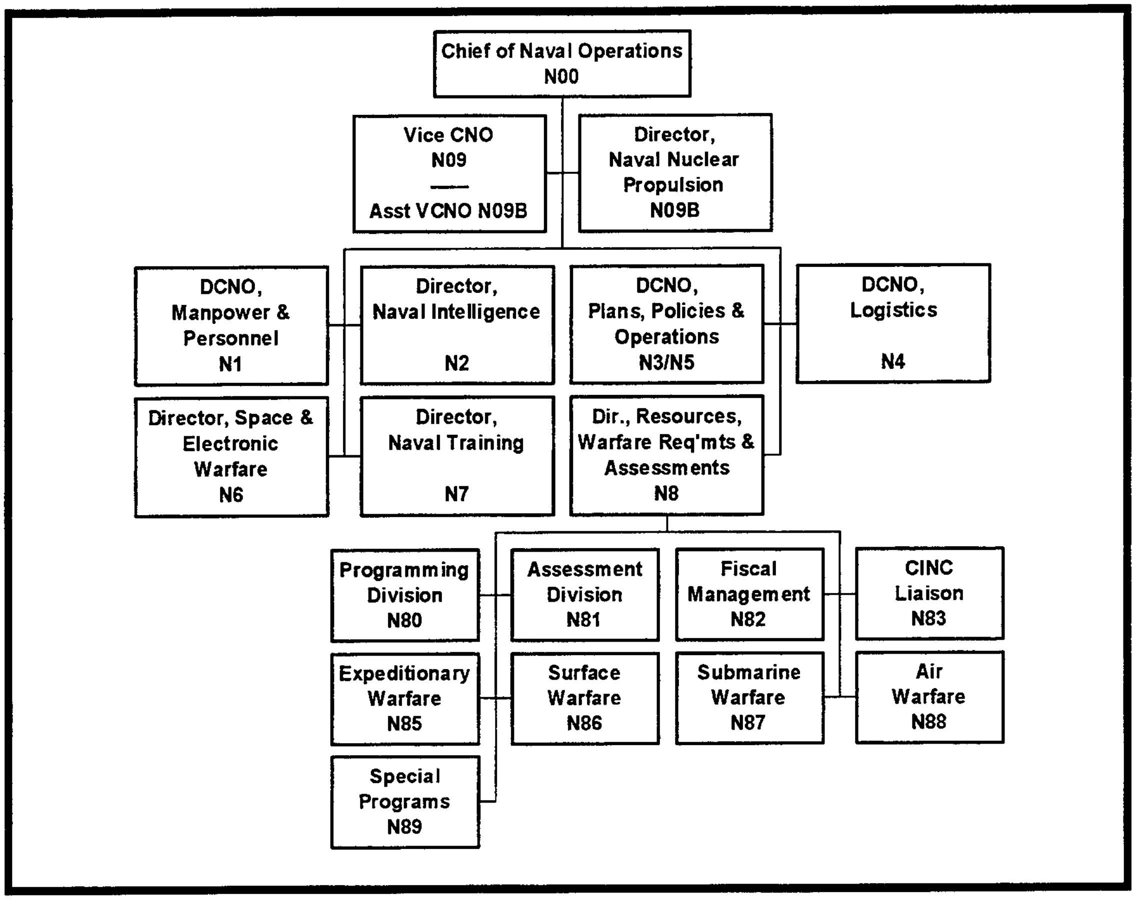

Figure 1.1. Organizational chart of the Office of the Chief of Naval Operations (OPNAV). Source: Larson and Palmer [1994], page 54. The chart illustrates the naming conventions. Specific divisions are shown only for N8; they are titled by adding a digit (e.g., Assessment Division, N81). Subdivisions of N81 would be labeled N811, N812, etc. Notice that Headquarters, US Marine Corps (HQMC) is not part of this staff; OPNAV and HQMC are the two major staff organizations that manage the Department of the Navy.

Based on the results of the IBR and guidance from the Office of the Secretary of Defense and the Secretary of the Navy, the Director, Programming Division (N80) divides the Navy's budget among the resource sponsors, who are responsible for managing DoN programs and their requirements. The Deputy Chief of Naval Operations (Logistics), N4, is the resource sponsor for Support and Infrastructure (S&I) funding. As a part of the programming process, N4 is responsible for developing the *Sponsor Program Proposal* (SPP) for S&I, which allocates the S&I funding among its constituent programs including RPM—in turn apportioned among the major claimants.

The Navy has a number of tools at its disposal to manage its real property maintenance program: a coherent organizational structure for facilities management; a detailed inventory management system; inspection and condition reporting systems; and a comprehensive priority system that ranks maintenance and repair projects in order of their perceived impact on operational readiness.

2. Facilities Management Organization

The Navy's facilities management organization has two main hierarchies, one acting in support of the other (Figure 1.2). The first hierarchy consists of the Navy organizations directly responsible for funding, managing and executing RPM funds. It mirrors the overall sponsor/claimant structure of the Navy's programming and budgeting system; see, for example, Larson and Palmer [1994]. The second hierarchy is the Naval Facilities Engineering Command (NAVFAC) and its subordinate activities, which provide professional engineering support and data management. The following sections describe this organizational structure from the top down, discussing the primary and supporting functions at each level.

a. Top Management

N4 is most directly accountable for the status of the Navy's shore installations. Other divisions within OPNAV exercise primary control over particular installations or facility types and work with N4 in the management of S&I programs; these divisions include N1, N09B, and various divisions under N8 (see Figure 1.1).

Headquarters, Naval Facilities Engineering Command (NAVFAC) is OPNAV's primary supporting organization for RPM decisions. NAVFAC works directly with N4, collecting and maintaining inventory, engineering, and cost data to support OPNAV decisions. Additional data come from annual reports (described later in the chapter) and budget submittals from the major claimants and the NAVFAC engineering field divisions.

b. Mid-Level Management

OPNAV coordinates the activities of 20 major claimants (the subset receiving facilities funding from O&M,N appears in Table 1.1). NAVFAC provides facilities engineering support by geographic region (Figure 1.3), and designates one engineering field division (EFD) or engineering field activity (EFA) to coordinate facilities engineering needs of the major claimants located within each region.

c. Installation Management

Staff civil engineers at the major claimants coordinate the overall facilities management for subordinate installations. Navy Public Works Centers (PWC) or Public

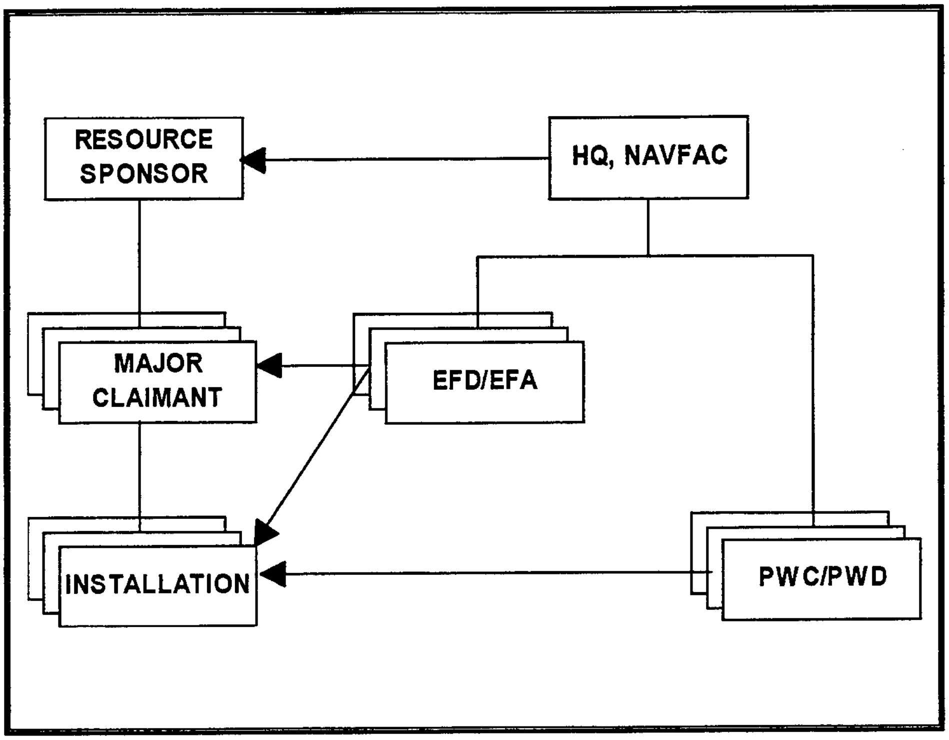

Figure 1.2. Simplified schematic of the Navy facilities management organization. Reports of facility condition flow up the solid lines to parent organizations; funding flows from the top down. The arrows indicate NAVFAC engineering and decisionmaking support. The diagram is simplified because each of several activities jointly occupying an installation may report to a different major claimant; similarly, each major claimant may report different sets of facilities to different resource sponsors.

Works Detachments (PWD), each supporting one or more installations, perform or contract all facility inspection, maintenance, and repair [Worcester 1996]. PWCs work with installations' staff civil engineer offices; in addition to routine maintenance work and contracting, they may also provide information systems support or assist in preparation of periodic facilities reports [Merritt 1996; Stump 1996]. The Defense Business Operating Fund (DBOF) pays their overhead expenses; service fees charged to the supported activities cover the remainder.

3. Inventory Management

The quantity, value, size, features, age, and status of each building or structure in the Navy's shore facilities inventory is kept in the Naval Facilities Assets Database (NFADB), managed by NAVFAC [NAVFAC 1995]. Updated annually as facilities are built, destroyed,

Major Claimants (O&M, N)	
BUPERS*	Bureau of Naval Personnel
CNO (N09B)	Assistant Vice CNO
CNET	Chief of Naval Education & Training
LANTFLT	CINC, US Atlantic Fleet
METOC	Commander, Naval Meteorology and Oceanography Command
NAVAIR	Commander, Naval Air Systems Command
NAVEUR	CINC, US Naval Forces Europe
NAVFAC	Commander, Naval Facilities Engineering Command
NAVSEA	Commander, Naval Sea Systems Command
NAVSUP	Commander, Naval Supply Systems Command
NCTC	Commander, Naval Computers and Telecommunications Command
PACFLT	CINC, US Pacific Fleet
SECGRU	Commander, Naval Security Group
SPAWAR	Commander, Space and Naval Warfare Systems Command
SSP	Director, Strategic Systems Program

Table 1.1. Major claimants receiving RPM funding from the Operations and Maintenance, Navy (O&M,N) appropriation. Source: N44 [1995b]. Others receive their RPM funding from other sources such as DBOF or FH,N; this thesis does not address specifically the apportionment of appropriations other than O&M,N. The Navy has created a new administrative fund source under which BUPERS and some other assets fall, but BUPERS still received O&M,N funding in 1996 and 1997. Major claimants allocate this funding to subordinate activities and installations for actual performance of maintenance and repair.

renovated, or transferred between maintaining organizations or appropriations, the NFADB helps installation managers determine what facilities and associated equipment they are responsible to maintain.

The NFADB incorporates several distinct measures of facility worth. *Current plant value* (CPV) represents a facility's estimated current purchase price; it incorporates any replacement, modernization, or major equipment installation performed. A facility's *plant replacement value* (PRV) represents an estimate of what it would cost to replace a facility using modern construction materials and techniques [Giorgione 1994]. Appraised values also appear, but are not typically used in budgeting calculations. Hereafter we refer to plant value in terms of CPV.

In making and assessing budget decisions, OPNAV organizations classify NFADB CPV data several ways—investment categories (IC) are one of the most important classifications for budgeting purposes. ICs (see Table 1.2) represent either broad classifications of

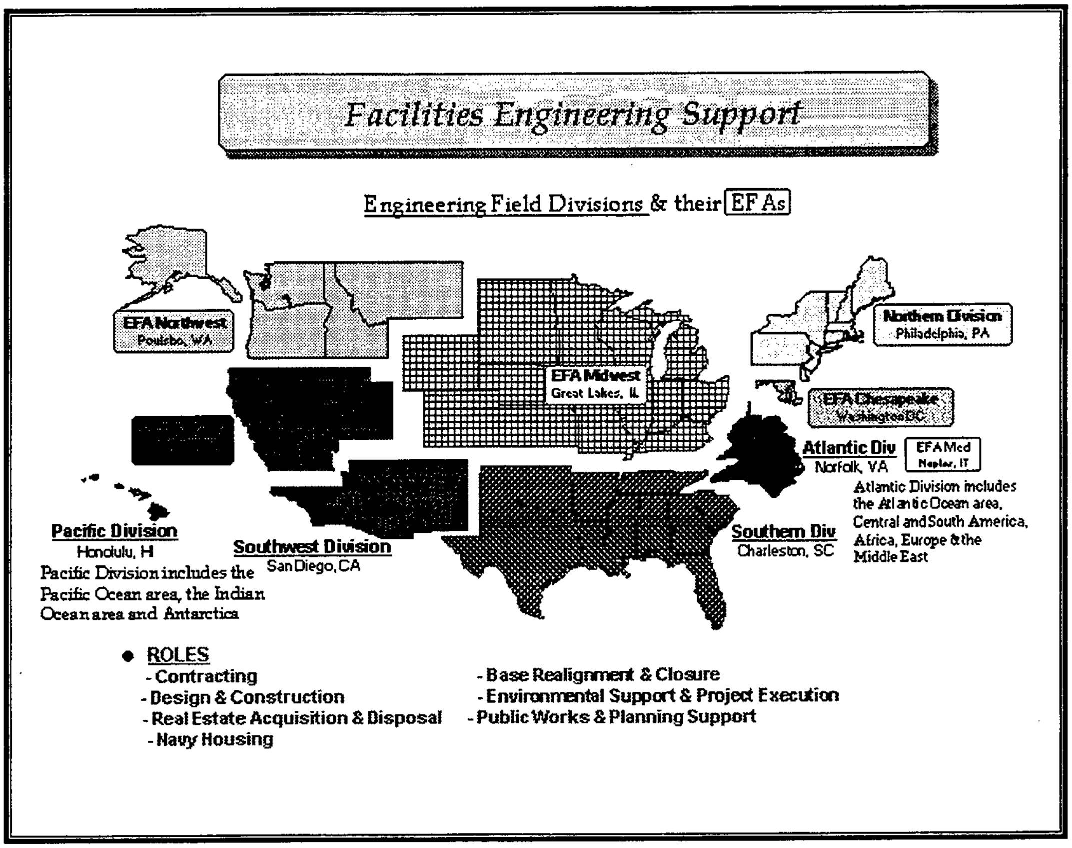

Figure 1.3. NAVFAC Engineering Field Divisions and Engineering Field Activities. Source: NAVFAC [1997]. In their public works and planning support role, EFDs and EFAs assist major claimants by analyzing annual installation reports and performing some of the facility control and safety inspections at the installations themselves (see Figure 1.2).

facilities by their designated purpose (e.g., berthing facilities) or common types of facilities expenditures, such as grounds maintenance.

Facilities are also classified by the fund source (appropriation) paying for their maintenance and repair; see Figure 1.4. The largest proportion of CPV, and the majority of funding, falls in the O&M,N (Operations and Maintenance, Navy) appropriation.

Classification of facilities by using organization and maintaining organization is often critical to decisions regarding budgeting, demolition or new construction. For each property record, the NFADB lists the using organization, the organization with maintenance responsibility (these organizations are not always the same), and the major claimant responsible for providing maintenance funds.

	Facility Investment Categories
01	Aviation operational facilities
02	Communication facilities
03	Waterfront operational facilities
04	Other operational facilities
05	Training facilities
06	Aviation maintenance production
07	Shipyard maintenance production
08	Other maintenance production
09	RDT&E
10	POL supply & storage
11	Ammunition supply & storage
12	Other supply & storage
13	Medical facilities
14	Administrative facilities
15	Troop housing & messing
16	Other personnel support services
17	Utilities
18	Real estate & ground structures
OTHER	Emergency service work; grounds maintenance; non-Navy real property

Table 1.2. Source: CNO [1987b]. Investment categories (ICs) group facilities based on the functions they perform. They are a principal categorization used annually by OPNAV to report plant value and maintenance backlog. ICs can be further divided into cost accounts; there are approximately 110 RPM cost accounts. Cost accounts themselves represent a number of facility category codes, most precisely describing the type and function of the facility.

4. Facility Inspection and Cost Estimation

A standard inspection program, administered uniformly by NAVFAC and OPNAV, is in place at each installation. Facility inspectors regularly examine building and facility components to determine their serviceability. The results, along with projected costs to correct any deficiencies and an estimate of the year by when the deficiency must be corrected, are kept in a local database either at the installation's staff civil engineer's office or at the supporting PWC or PWD. Maintenance activities use the databases to write job orders, submit reports to the major claimant, provide updates to the NFADB, and construct annual and long-range maintenance plans extending roughly five years into the future. The Long Range Maintenance Planning system (LRMP) [Balke and Kruzicki 1990] is a good example of Navy installation-level inspection and cost estimation information systems.

In the LRMP operations manuals, Balke and Kruzicki [1990] delineate the facilities maintenance cost estimation procedures followed by PWC Norfolk; we summarize them here as a representative implementation of Navy-wide policy and procedures.

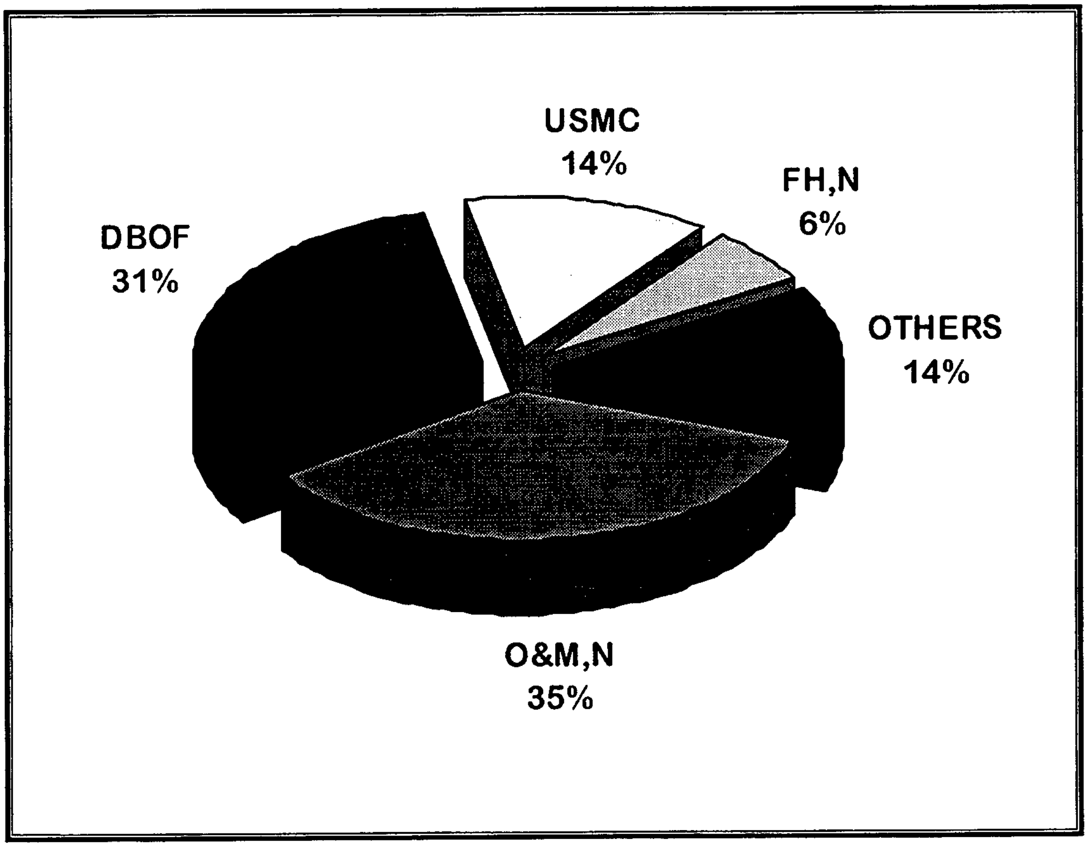

Figure 1.4. Department of the Navy (DoN) 1995 current plant value (CPV) by fund source. The diagram shows the percentage of total DoN CPV maintained by funds from the indicated appropriation. The largest four are Operations and Maintenance, Navy (O&M,N); Defense Business Operating Fund (DBOF); Operations & Maintenance, Marine Corps (O&MMC); and Family Housing, Navy (FH,N). The total CPV depicted is $137 billion. Source: N44 [1995a].

Inspections are performed by knowledgeable facilities maintenance personnel familiar with structural, mechanical, or electrical systems maintenance and repair. The inspector identifies new facility deficiencies and re-evaluates known, uncorrected deficiencies from earlier inspections. For each deficiency identified, the inspector prepares an estimate that identifies the scope of the project. The estimate specifies a complete work breakdown structure (Figure 1.5) and provides a bottom-up engineering cost estimate for each task identified during the inspection. Total cost for completing a task is specified in terms of equipment, labor, and materials. The LRMP system at PWC Norfolk incorporates a cost estimation software package that determines the cost of completing a task based on equipment and materials requirements and labor rates. The inspector further considers special equipment or accessibility measures required to complete each task, and includes these considerations in the estimate. If the installation or PWC determines that the project must be contracted, it adds contract costs to the estimate (as percentages of the estimate subtotal); for projects without an open-end contract, additional fees may be required for contractor bonds or engineering work.

NAVFAC [1997] describes a standard DoD facilities cost estimation package called the Construction Criteria Base (CCB), published by the National Institute of Building Sciences, capable of providing automated engineering cost estimates based on detailed data regarding a particular maintenance or repair project. It is available, though not currently in use. It includes the Commercial Unit Price Book (CUPB), which contains detailed equipment, labor, and materials prices in various portions of the continental US.

Maintenance plans schedule projects based on their relative criticality. Therefore, projects may not be completed in the same year as their estimates. The scheduled "accomplishment year" reflects the inspectors' or engineers' assessment of the remaining life of the system or component. For example, maintenance activities generally complete work on systems or components currently in a state of total failure or imminent failure (six months after inspection) in the current year. A component whose estimated lifetime is 25 years may function but manifest rapid deterioration when 23 years old; the schedule may dictate its repair or replacement in its 24th or 25th year at the discretion of the inspection team or PWC engineering department. Less pressing deficiencies may be scheduled for the third or fourth year following the inspection. The maintenance plan depicts then-year project completion costs, requiring that a cost estimate be revised for inflation of labor and materials costs if the project is not completed on time. PWC Norfolk schedules projects on a five-year cycle and applies an annual inflation factor of approximately 3% to labor and materials costs [Balke and Kruzicki 1990].

5. Condition Reporting Systems

The Shore Base Readiness Report (BASEREP) and the Annual Inspection Summary (AIS) are the two major reports filed by installation commanders. These reports are complementary. The BASEREP provides qualitative information on the status of an installation's facilities; its intent is to gain the installation commander's perspective on how well the shore facilities contribute to the installation's mission readiness [CNO 1987c]. The AIS, a quantitative listing of outstanding facility deficiencies, provides the results of ongoing facilities evaluations and inspections and the costs to correct the deficiencies in a particular year [CNO 1987a]. Major claimants collate and analyze installations' reports for consistency and accuracy before forwarding them to OPNAV.

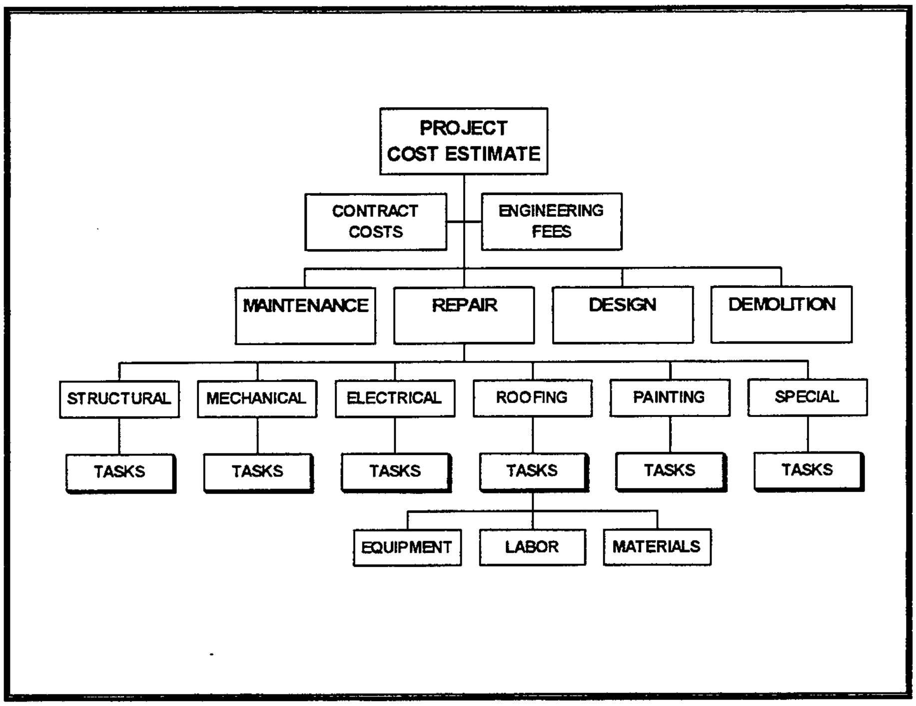

Figure 1.5. Work breakdown structure for project cost estimates. "Special" projects may include work on major installed equipment such as elevators or roof cranes. An additional project type, "Other", may be used to represent projects that do not fall into any of the types listed. An installation's annual inspection summary (AIS) is a comprehensive list of unfunded projects remaining as a firm requirement at the end of the year; corresponding total outstanding costs are obtained by summing the projects' cost estimates computed as shown in the figure. The AIS is one of the two annual reports used to support RPM budget requests and, therefore, a principal component of the S&I SPP. Source: Balke and Kruzicki [1990].

The AIS only represents a portion of M&R projects. In order to be reported on the AIS, a deficiency must cause one of the following conditions if it is not corrected [CNO 1987b]:

- A catastrophic environmental condition.
- A significant safety hazard.
- An unacceptable quality-of-life condition for those living or working at or near the facility.
- An inability to perform the facility's assigned mission.

These conditions are called *deficiency types*; exactly one deficiency type is associated with each maintenance or repair project. A deficiency type may denote either an existing problem or one projected to occur by a particular time; the Navy distinguishes these by identifying "critical" and "deferrable" maintenance projects. If the condition exists or is imminent (projected to exist within six months of the inspection [Balke and Kruzicki 1990]), the inspector classifies the project as "critical" and schedules it for accomplishment in the current fiscal year. If the condition is not imminent, the inspector classifies the project as "deferrable" and it is scheduled for accomplishment in a later year, as previously described. If a deferrable deficiency remains uncorrected at the end of the year identified in the maintenance plan, it becomes critical with the associated deficiency type, meaning that it should be corrected immediately. All uncorrected, critical deficiencies at the end of the year appear on the AIS as "critical backlog" of maintenance and repair (BMAR). "Deferrable backlog" represents the total present worth of all deferrable project costs. The detailed portions of the AIS (the *Maintenance and Repair of Real Property (MRRP) Deficiency List* and the *Cost Account Summary*), not submitted to OPNAV but maintained and used by the major claimants, list specific project costs and totals by cost account, respectively [CNO 1987a]. The Navy reports its critical backlog annually to Congress as a measure of facility status and management efficiency.

Some legitimate maintenance and repair costs are not reportable through the AIS. These include emergency work, service calls, and maintenance and repair of base construction equipment; they appear largely in IC "OTHER". Managers must predict these requirements since they largely cannot identify them in the inspection process. Each installation (or its public works center or detachment) tracks these costs and reports aggregate figures to the installation and claimant comptrollers. The amount of these expenses varies considerably by installation depending on the size, usage rates, serviceability of facilities, staff organization, and method of accomplishing work. At the installation level, managers view these expenses as "nondiscretionary" because this work is absolutely necessary in order to continue normal daily operations [Shepard and Lord 1996]. Therefore, this category of M&R work largely cannot be deferred until later years. Deficiencies anticipated to be funded from special appropriations such as DoD environmental cleanup funds are not listed on the AIS, because they do not have to compete for funding from the installations' budgets. Some major claimants do not submit an AIS at all; OPNAV provides M&R funding largely based on historical budgets [Worcester 1996].

6. Priority Systems

In 1989, the CNO published the *Shore Facility Life Extension Program* (Shore FLEP) [CNO 1989]. It is based on the premise that shore facilities, like other Navy capital investments, are costly and represent a considerable maintenance and repair commitment to maintain or extend their useful life. It also acknowledges that the Navy cannot afford to maintain its entire shore infrastructure properly. It therefore places a value on facilities according to the functions they perform: higher priority facilities contribute more to the Navy's overall operational readiness than lower priority facilities. Commanders and facilities managers place higher priority on M&R requirements for facilities in higher priority Shore FLEP categories. The categorization appears in Table 1.3.

Facility Purpose	Investment Categories	Examples
High Priority:		
Aviation Operations	01	Air traffic control, ground electronics
Fleet Communication Operations	02, 04	Microwave links, AUTODIN switching
Port Operations	03, 04	Berthing, pier-side services
Training Services	05	Formal instruction facilities
Bachelor Housing Services	15	Personnel accommodations
Messing Services	15, 16	Dining facilities
Utility Operations	17	Power, steam, water, sewage
Security Services	04, 16, 17, 18	Law enforcement, physical security
Medium Priority:		
Aircraft Maintenance	06, 08	Maintenance facilities
Ship Repair Services	07	Shore Intermediate Maintenance Activities
POL Products/Services	04, 10	Fuel storage and distribution
Ordnance Services	04, 08, 11	Weapons and ammunition storage
Medical Services	08, 13	Hospitals, clinics, sanitation
Dental Services	08, 13	Dental clinics
Personal Services	04, 16	Personnel administration; chapels
Family Housing Services	16, 20	Family housing; housing referral
Low Priority:		
Special Base Operations	02, 04, 08	Oceanography, intelligence
Operational Systems Engineering	08	Calibration services, in-service testing
RDT&E	09	Research facilities
Supply Services	04, 08, 10, 12	Supply administration & storage
Corrections	15, 16	Brigs, secure detention facilities
Administrative Services	14	Legal services, postal facilities
Information Services	04, 14	Automated data processing
Public Works Services	04, 08, 10, 17, 18	Inspection & repair; grounds maintenance; hazardous materials services
Fire Protection	16	Fire stations
Base Transportation	04, 08, 18	Roads, rail networks, motor pools
Base Communications	02	Base telephone services

Table 1.3. Shore Facility Life Extension Program priorities. Source: CNO [1989]. Investment categories may appear in more than one priority category because they are specified here in terms of their subordinate cost accounts and facility category codes. Facility inspection data and maintenance costs are available at this level of detail in the *MRRP Deficiency Lists* submitted annually to the major claimants.

II. RELATED RESEARCH

A. OPTIMIZING CAPITAL BUDGETING DECISIONS

Organizations frequently must decide how to allocate funds, over time, among a number of competing requirements. When the requirements can be sufficiently characterized in terms of their respective cash flows, and any mutual dependencies clearly defined, a wide range of proven optimization techniques can be applied. The typical objective is to maximize the net present value (NPV) of returns accruing from a portfolio of investments or projects, subject to budget constraints and various other restrictions. Optimization techniques have been developed also to handle cases in which multiple objectives exist or even those in which an objective can only be defined implicitly [Rosenthal 1985]. Interpretation of "target" resource levels as absolute requirements may, in a particular instance of an optimization model, either preclude a feasible solution or limit the quality of the solution attained in an undesirable way. Implementation of "elastic" constraints (e.g., Brown, Clemence, Teufert, and Wood [1991]) helps resolve these difficulties in a consistent manner.

Weingartner [1963] is a standard reference for the formulation of capital budgeting problems using linear and integer programming. Clark, Hindelang, and Pritchard [1989] define several generic capital budgeting problems and examine the application of linear, integer, and goal programming techniques to their solution. These texts explain in detail most of the techniques used in the models we describe in the remainder of this section.

Bradley [1986] formulates a large-scale, mixed integer linear program to determine an optimal portfolio of investments for GTE. The model, termed the Capital Program Management System (CPMS) optimizer, evaluates candidate project cash flows to determine optimal levels of investment in projects over time. Several key design features are prototypical of this class of models and apply directly to the Navy RPM problem. The CPMS optimizer relieves managers from tedious quantitative evaluation of many alternatives so that they can apply their time and judgement to non-quantifiable tasks such as long range planning and restructuring, development of alternatives, and other key aspects of the broader decision context. The model considers short-term restrictions and long-term objectives simultaneously, often making minor modifications to the former in order to achieve significant improvement—otherwise impossible—in the latter. This tradeoff can be justified based on the economic principle of marginal cost [Rosenthal 1985; Bradley 1986], and is a feature common to the other optimization models discussed below. As a result of implementing the model, GTE's management has much greater visibility of the investment decisions made at subordinate telephone operating companies by gathering more information at top management levels. This enables GTE to evaluate investment alternatives and examine specific tradeoffs relatively quickly [Bradley 1986].

Brown, Clemence, Teufert, and Wood [1991] formulate an optimization model to modernize Army helicopter assets. The model, PHOENIX, considers both procurement costs as well as support, operating, and retirement costs in determining what assets to buy, upgrade, or retire, and when each such action should be taken. Constraining factors include program budgets, production schedules, and required mixes of aircraft types. The primary characteristic of PHOENIX useful in the context of the real property maintenance budgeting problem is its ability to recommend modifications to the annual program budgets to achieve economically sensible budget targets over time, accomplished with elastic constraints. PHOENIX, however, models a problem largely unlike facilities maintenance and repair. It is a mixed integer linear program that makes "buy or don't buy" decisions regarding single investment projects with enormous individual costs; its procurement decisions assume full commitment of operations and support costs; and it models specific industrial processes (e.g., production lines) not specifically encountered in facilities maintenance management.

Two mixed integer linear programs developed at the Naval Postgraduate School provide useful insights for capital budgeting optimization models. Free [1994] develops a model to schedule Army base realignment and closure (BRAC) actions based on projected costs and resultant savings. It is similar to PHOENIX and CPMS in that its decisions incur large, indivisible expenses at different points in time, and it incorporates elastic budget constraints to allow a sensible tradeoff between short-term budgets and long-term savings from the BRAC process. It is especially relevant in the context of this thesis because it demonstrates the successful application of capital budgeting optimization models to DoD infrastructure decisions: In 1994, its proposed schedule achieved a 34% higher BRAC savings ($223 million) than the original manual schedule submitted to the BRAC commission [Free 1994].

Carr [1996] formulates a model to help the Ballistic Missile Defense Office develop an annual procurement strategy for theater missile defense systems. In modeling the characteristics of an optimal multi-year procurement plan, Carr develops the concept of a "continued debt penalty" that balances the long-term gain realized from exceeding a particular budget to a dollar equivalent borrowing cost, and carries over indebtedness from year to year [Carr 1996]. This concept is important to the development of the Navy RPM model described here.

Each of these models recommends specific actions to be taken at different future times, and spends future budget dollars based on past, present, and future actions and requirements. As a result, each relies strongly on cost estimation and projection. Clark et al. [1989] devote a chapter to emphasizing the need for forecasting future requirements and understanding the assumptions inherent in the forecasting methods. The CPMS optimizer's success as a planning tool for GTE depended on the meticulate analysis of alternatives and careful prediction of available budgets [Bradley 1986]. The PHOENIX modelers divided themselves into a modeling team and a data development team; the latter devoted their efforts largely to accurate determination and categorization of the numerous costs incurred in helicopter procurement and overhaul [Brown, Clemence, Teufert and Wood 1991, pp. 43-45]. Free [1994] used the Cost of Base Realignment Actions (COBRA) cost estimation model to provide input to the optimization model; Carr [1996] used fundamental parametric cost estimation procedures to determine and apply production learning effects, cost overruns, and schedule overruns. The Navy faces a similar cost projection problem in managing its RPM budget because its inspection program cannot identify all of the requirements that accrue over the time horizon considered, and because not all of the major claimants receiving RPM funds submit inspection results.

B. MODELS FOR FACILITIES MAINTENANCE AND REPAIR

Models developed specifically for public sector facilities M&R also rely on some mechanism to project either future costs or future facility condition [Neely, Neathammer and Stirn 1991; Golabi, Kulkarni and Way 1982; Madanat, Karlaftis and McCarthy 1997; Lind 1995; Falk and McCormick 1983]. Many also incorporate optimization techniques to minimize a measure of net cost [Golabi, Kulkarni and Way 1982], maximize a subjectively derived benefit function [Lind 1995], or maximize a measure of asset value [Falk and McCormick 1983]. Models used as facilities M&R budgeting decision tools typically address a timeline of several years and integrate dynamically the effects of successive decisions on total work requirements, facility condition, and budget requirements [Golabi, Kulkarni and Way 1982; Falk and McCormick 1983]. This section describes several such models, their forecasting techniques, and an appraisal of their suitability for the Navy RPM budgeting problem.

1. US Army Models

The US Army Construction Engineering Research Laboratory developed a budgeting decision aid called the Maintenance Resource Prediction Model (MRPM) [Neely, Neathammer and Stirn 1991]. The model consists of an extensive cost database and a series of database access programs designed to help Army organizations predict M&R costs for a specific set of facilities. The costs reflect the M&R tasks the research team determined should be performed for a particular facility based on its type of construction, components, installed equipment, age, and other specifications, in order to keep the facility in a satisfactory condition. The MRPM calculates costs for performance of each task from the specific material and labor requirements corresponding to the task, and from time and cost factors maintained by the Army. The model assumes that the maintaining organization covers equipment costs, e.g., trucks, ladders, etc., separately. If properly maintained and managed, the MRPM could be an effective tool in the accurate determination of operating and support costs corresponding to candidate projects in the military construction program. However, the MRPM data reflect the construction technology, equipment, and materials in use at Army installations in the 1980s and would require constant updating for effective use. Further, the basic research concludes that condition assessment programs are too expensive. Since the data assume that the facilities being maintained are always kept in a satisfactory condition, the MRPM cannot assess the deferred costs of failing to provide required funding.

The Army currently uses a facilities condition reporting system called the Installation Status Report (ISR) [United States Military Academy 1993]. It is a distributed information management system designed to provide Army-wide visibility of facility quantity and quality relative to uniformly established standards. The reports group facilities into five ISR areas and approximately 200 facility category groups (FCGs). The condition ("quality") of facilities in each of the ISR areas and FCGs are rated as either "green" (meets standards), "amber" (fails to meet standards but is operational), or "red" (fails to meet standards and poses hazards or obstacles to proper utilization). The quantity of facilities is measured as a percentage of the total size (physical area) requirement. Quality and quantity assessments are combined to rate facilities on a scale of C1 (best) to C4 (worst), with non-evaluated facilities falling into an administrative category (C5). The ISR software identifies three possible remedial actions (sustainment, renovation, and new construction) to correct for deficiencies in quality and quantity, and computes the cost of remedial actions on a per-unit-area basis. The resulting costs are shown as a requirement of the installation or Major Army Command (MACOM; roughly equivalent to a Navy major claimant) over a period of five years.

The ISR provides only information, and currently does not incorporate an allocation methodology. Lind [1995] proposes a method for making budget decisions regarding facilities at the installation, MACOM, and Headquarters, Department of the Army levels based on the ISR and associated costs. The method determines the decisionmakers' goals for their organizations, and explains how to relate ISR areas and FCGs to goals by estimating the relative importance of each type of facilities to the achievement of each goal. A set of linear programs allocate M&R funds at each level of the hierarchy to maximize a measure of benefit derived from the facility weights.

The Army's approach to installation M&R funding is not suitable for direct application to the Navy. While the Army directly ties discrete levels of facility quantity and condition to costs required to upgrade the facilities to C1 status, the Navy does not. BASEREP shows similar discrete levels of facility quantity and condition (C1-C4), but does not contain cost data. The Navy does not consider construction requirements (facility quantity) to be pertinent to M&R needs, so it addresses quantity deficiencies and costs separately through the MILCON process. Finally, the Army does not have a standard priority system linking facility condition with operational readiness similar to Shore FLEP. Lind's model would elicit equivalent information from decisionmakers separately at each level of the management hierarchy.

2. Probabilistic Infrastructure Deterioration Models

Another class of models (e.g., Madanat, Karlaftis, and McCarthy [1997]) deals with discrete facility condition ratings and is relatively well developed in the literature. Perhaps the best known of these models is a decision support system developed for the Arizona Department of Transportation [Golabi, Kulkarni and Way 1982; Wang and Zaniewski 1996]. This model, called the Network Optimization System (NOS), provides the least cost annual M&R recommendations to keep the Arizona road network in a satisfactory condition. In the model's first year, when Arizona maintained a road network with a PRV in excess of $6 billion, it saved over $14 million in M&R costs. The initial version of the model identified 120 distinct road conditions and 17 alternative maintenance actions, and used regression analysis with Arizona's extensive historical condition data to determine the probability of a road segment deteriorating from one condition to another one year after the application of one (or none) of the seventeen maintenance actions. The prediction part of the model uses these transition probabilities to construct a discrete-time Markov chain (e.g., Feller [1957] and Ross [1993]) with a one-year time step; the optimization part is a linear program that minimizes total discounted costs corresponding to maintenance actions over a finite time horizon.

Two successful outcomes of implementing NOS were: (1) The state legislature became more receptive to budget requests, because NOS not only developed minimal-cost maintenance programs, but it also provided expected road conditions corresponding to different budget levels [Golabi, Kulkarni and Way 1982, pp. 17-18]; and (2) Arizona Department of Transportation headquarters gained a greater degree of control over the condition of roads statewide. Prior to the implementation of NOS, district managers submitted their own budget requests regardless of needs elsewhere in the state. With the ability to prioritize and balance requirements on a statewide basis, the Arizona Department of Transportation was able to select specific maintenance actions that, though not necessarily the best for each individual road segment, ensured a least-cost maintenance policy for the entire highway system by "considering the costs versus benefits of *all* actions in the context of short-term and long-term standards, and current road conditions" [Golabi, Kulkarni and Way 1982, p. 17].

Implementation or modification of NOS for Navy RPM funding allocation is not currently feasible. Navy facilities include not only roads but numerous other types of buildings and structures requiring many different types of corrective actions. Though the BASEREP does provide discrete condition ratings (C1 through C4, like the Army system), they are largely qualitative in nature and are not explicitly linked to M&R actions or costs. Another concern raised by Madanat, Karlaftis and McCarthy [1997] is that the assumptions required to implement Markov deterioration models do not hold for certain types of facilities (their research examined bridge decks), and other prediction methods are required.

3. Maintenance and Repair Optimization

Falk and McCormick [1983] present an optimization model that maximizes a measure of capital asset value by applying manpower and M&R budgets over time. The model is dynamic; i.e., it relates maintenance backlog and asset value in one period, t, to their values in the previous period, $t-1$, modified by the resources applied in period t (these constraints typically are called inventory balance relationships). These types of constraints are useful and appear in current Navy RPM models (discussed in the next section) as well as the model developed in this thesis (presented in the next chapter). The model assumes that annual M&R requirements are proportional to the previous year's asset value. It also introduces several premises that do not hold for the Navy. Foremost, the model's budget levels increase over time. Assets can be purchased in any period, and a fixed proportion are retired in each period; total assets decrease over time if the maintenance requirements generally exceed available funding. A single budget funds asset procurement and M&R. Further, the asset value being maximized does not depend on asset condition: M&R requirements only exist to consume a portion of the budget, and lack of funding does not affect the performance of assets on hand. The model represents a single organization's decisions and does not require the apportionment of M&R funds among subordinate organizations or specific projects. Finally, it considers a finite horizon, which may or may not lead to an optimal set of decisions. For example, it is not clear that the model's decisions over a four year horizon would also be optimal for the first four years of a five year horizon. This phenomenon is known as "end effects" (e.g., Walker and Dell [1995]).

C. NAVY REAL PROPERTY MAINTENANCE MODELS

Giorgione [1994], expanding on the results of a Department of Defense (DoD) report to Congress [DoD 1989], surveys numerous public and private organizations with facilities M&R programs in place, and distills three common methods of determining facilities' M&R requirements and budgeting for them. Based on the relative advantages and disadvantages of each, he recommends a method for the Navy to use (which it currently does).

- *Historical budgeting* adjusts the current year's budget for inflation, and perhaps other, subjective factors, and recommends it again for the following year. These methods perpetuate program funding inequities, produce budgets unrelated to actual requirements, and cannot be applied in a stable or decreasing budget environment.

- *Formula budgeting* refers to a family of models that use one or more explanatory ("driver") variables to determine M&R costs statistically. These variables may include PRV or CPV, number of personnel supported, physical area of the facilities, energy consumption rates, average facility age, and types or functions of facilities. The primary advantages of these methods are simplicity of calculation and flexibility in selection of the type and number of cost drivers. The disadvantages are that the resulting budgets do not depend directly on actual facility condition, and that the models must be updated to reflect changing construction technologies, facility inventories, and M&R techniques.

- *Zero-based budgeting* refers to bottom-up requirements determination, as opposed to top-down requirements estimation. Development of a zero-based budget starts with determination of management's goals and then proceeds to prioritize requirements relative to the goals in order to determine an itemized budget. The advantages of this method are that it links budget actions to organizational goals, and produces a budget that directly addresses specific requirements. Giorgione concludes that this procedure is not feasible for the Navy, because it would require excessive manpower and time to gather data and analyze it properly.

Giorgione recommends that a formula method be used to predict outyear M&R requirements, but that base year requirements be established at the level of reported BMAR.

This approach suggests the form of the model should resemble an inventory balance relationship, where BMAR in successive years depends on its value in previous years and on budgets and requirements in the intervening years. Mathtech [1991] and Ackerman, Choi, and Weis [1995] develop two such models, which can be implemented in a spreadsheet for fast "what-if" analyses of M&R budgets at the OPNAV level. Several other organizations including NAVFAC have developed very similar models; a collection of them are currently in use at N4.

These models have several shortcomings. They do not provide the ability to allocate funding, based on the Shore FLEP or any priority system, to the major claimants. It is not possible to perform manual tradeoff analyses for different claimant budget levels, because model coefficients corresponding to each major claimant do not exist. Additionally, these models do not incorporate an optimization technique, so they cannot weigh one subordinate organization's requirements against another in attempting to reach a Service-wide goal. The model developed in this thesis can address these shortcomings.

III. A MODEL FOR NAVY RPM BUDGET ALLOCATION

The primary function missing from the RPM budgeting models currently used by OPNAV is allocation. That is, these models predict BMAR over a number of years given total funding, but do not assist in determining how to apportion the funding among major claimants to best satisfy the Navy's priorities. This chapter presents a linear programming model, OMAR (Optimization of Maintenance and Repair), to determine multi-year funding levels for the major claimants receiving O&M,N funding for the maintenance and repair of real property, with the following objectives:

- Reduce both critical and deferrable backlog at each major claimant and in each priority category to specified annual levels.
- Minimize net present value (NPV) of total additional costs incurred by deferring projects.
- Prevent unmanageably large swings ("funding turbulence") in claimant budget levels from year to year.

These objectives can conflict with one another. Measures of funding turbulence and target levels of backlog are subjective and require specific management interpretation. Characterization of a solution as "optimal" in this setting is vague. For these reasons, we present OMAR as a tool to achieve solutions to the budgeting and allocation problem that, in some sense, "best satisfy" basic management goals.

A. SCOPE OF MODEL DECISIONS

OMAR allocates approximately 92% of major claimant O&M,N RPM funding (1995 figures). Minor construction projects constitute 7%; they do not contribute to BMAR nor specifically address the correction of maintenance or repair deficiencies reported in the AIS. Another 1% is earmarked for the major claimants who maintain relatively small physical plants and do not submit AIS reports.

B. THE TIME HORIZON

The decisionmaker's time horizon is a fixed input quantity—nominally the six years of the POM. OMAR considers years beyond the final year of the POM because the processes being modeled actually extend indefinitely, and optimization models can exploit an artificially-imposed finite horizon unrealistically. The formulation presented in this chapter has an infinite time horizon. Two finite horizon approximations (primal equilibrium and dual equilibrium) appear in Appendix B, and help produce solutions free of end effects in accordance with procedures developed by Walker [1995] and Walker and Dell [1995].

C. MODEL ASSUMPTIONS

The prospective use of the model at OPNAV, as well as the quantity and scale of the input data, require several simplifying assumptions.

- Any fraction of an individual project can be completed by providing an equivalent fraction of its cost.
- Major claimants apportion their funding to installations in order to complete projects, ultimately with the same net effect envisioned by the model. MRRP funding allocated by the model does not "migrate" to cover other O&M,N expenses nor is it augmented from other categories of O&M,N.
- Maintenance and repair requirements, except for those comprising the base year BMAR, are known a fixed number of years in advance through the inspection process.
- For each year a project is unfunded, its completion cost increases in real terms by a factor $0 \leq d < 1$.
- MRRP deficiency lists detail individual unfunded projects by investment category, cost account, and facility category code; separate critical and deferrable projects; and provide a scheduled accomplishment year. These data allow explicit funding prioritization by Shore FLEP priority level. Accomplishment year data are available at the installation level but are not normally collected by the major claimants, EFDs or EFAs. We therefore assume that OPNAV can obtain them in a data collection effort augmenting the annual reporting process.
- MRRP funding in excess of the prescribed annual budget is only available by taking it from other appropriations or O&M,N programs. This money is borrowed at a fixed nominal interest rate and compounded annually; any amount may be repaid in subsequent years.
- Major claimants and installations can predict or know in advance the "nondiscretionary" or "cost of ownership" costs associated with standing job orders, emergency work, and service calls.

D. ELEMENTS OF THE MODEL

This section defines requisite sets and indices, data elements, decision variables, and elastic variables, followed by the model formulation. Indices and data appear throughout in lower case; variables are in upper case.

1. Sets and Indices

- c major claimants directly receiving O&M,N funding (LANTFLT, PACFLT, NAVSEA, NCTC, ...);
- i investment category (IC) (01, 02, ..., 18; OTHER);
- p priority category (high, medium, low);
- t fiscal years $(1, 2, \ldots)$;
- x set of ICs pertaining to AIS-reportable deficiencies (01, 02, ..., 18); and
- y number of years in the future from the current year $(0, 1, 2, \ldots, k)$.

2. Data

- $budget_t$ total MRRP budget estimate for fiscal year t (FY t thousands of dollars);
- $cbwt_{cp}$ dollar-equivalent penalty for each dollar of priority p critical backlog remaining above the target level at claimant c;
- d rate annual project costs increase due to deterioration $(0 \leq d < 1)$;
- $dbwt_{cp}$ dollar-equivalent penalty for each dollar of priority p deferrable backlog remaining above the target level at claimant c;
- $defer_{cxpt}$ thousands of dollars of maintenance and repair at claimant c, deferrable in year zero, that become critical if uncorrected at the end of year t in IC x of priority p (year t thousands of dollars);
- $\Delta_{tt'}$ conversion factor from year t dollars to year t' dollars, where t and t' are both within the real planning horizon;
- $endc_{cpt}$ desired level of critical backlog at claimant c of priority p deficiencies at the end of fiscal year t (year t thousands of dollars);

- $endd_{cpt}$ desired level of deferrable backlog at claimant c of priority p deficiencies at the end of fiscal year t (year t thousands of dollars);
- γ approximation of $\Delta_{t,t-1}$ in years beyond the current planning horizon;
- $nondiscret_{ct}$ required funding for non-AIS-reportable deficiencies such as standing job orders, emergency work, and service calls at claimant c in fiscal year t (year t thousands of dollars);
- $nturwt_c$ dollar-equivalent penalty per dollar reduction in total MRRP funding of claimant c from one year to the next below desired lower bound of variation;
- $pturwt_c$ dollar-equivalent penalty per dollar increase in total MRRP funding of claimant c from one year to the next above desired upper bound of variation;
- r inflation-free annual interest rate to borrow funds in excess of established budget levels;
- $startblog_{cxp}$ critical backlog at the beginning of the first year of priority p deficiencies at claimant c in IC x (year zero thousands of dollars);
- $startfund_c$ year zero MRRP funding for claimant c (year zero thousands of dollars);
- T_0 final year of decision horizon; and
- $\underline{vary}, \overline{vary}$ lower and upper bounds for acceptable year-to-year variation in claimants' MRRP funding levels, expressed as a percentage of the recommended annual budget.

3. Decision Variables

- $BMAR_{cxpt}$ value of priority p critical backlog at claimant c, IC x at the end of year t (year t thousands of dollars);
- DW_{cxypt} value in year t of all remaining priority p deferrable work at claimant c, IC x becoming critical in exactly y years (year t thousands of dollars);
- FC_{cxpt} year t funding at claimant c for existing critical deficiencies in IC x, priority p (year t thousands of dollars); and
- FD_{ciypt} year t funding at claimant c for deficiencies in IC i and priority p applied to deferrable work becoming critical y years in the future (year t thousands of dollars).

4. Elastic Variables

- $CBDEV_{cpt}$ priority p critical backlog at claimant c at the end of fiscal year t in excess of $endc_{cpt}$ (year t thousands of dollars);
- $DBDEV_{cpt}$ priority p deferrable backlog at claimant c at the end of fiscal year t in excess of $endd_{cpt}$ (year t thousands of dollars);
- LB_t balance of "loan" from other appropriations or programs in year t (year t thousands of dollars);
- $NTURB_{ct}$ decrease in dollars allocated to claimant c in fiscal year t below $\underline{vary}$% of the previous year's funding (year t thousands of dollars); and
- $PTURB_{ct}$ increase in dollars allocated to claimant c in fiscal year t above $\overline{vary}$% of the previous year's funding (year t thousands of dollars).

5. Formulation

Minimize

$$\sum_{c,x,p}\sum_{t=1}^{T_0-1}\Delta_{t,0}d\left(BMAR_{cxpt}+\sum_{y=1}^{k}DW_{cxypt}\right)+\sum_{c,x,p}\sum_{t=T_0}^{\infty}\Delta_{T_0,0}\gamma^{t-T_0}d\left(BMAR_{cxpt}+\sum_{y=1}^{k}DW_{cxypt}\right)$$

$$+\sum_{c,p}\sum_{t=1}^{T_0-1}\Delta_{t,0}(cbwt_{cp}CBDEV_{cpt}+dbwt_{cp}DBDEV_{cpt})$$

$$+\sum_{c,p}\sum_{t=T_0}^{\infty}\Delta_{T_0,0}\gamma^{t-T_0}(cbwt_{cp}CBDEV_{cpt}+dbwt_{cp}DBDEV_{cpt})$$

$$+\sum_{c}\sum_{t=1}^{T_0-1}\Delta_{t,0}(pturwt_cPTURB_{ct}+nturwt_cNTURB_{ct})$$

$$+\sum_{c}\sum_{t=T_0}^{\infty}\Delta_{T_0,0}\gamma^{t-T_0}(pturwt_cPTURB_{ct}+nturwt_cNTURB_{ct})$$

$$+\sum_{t=1}^{T_0-1}\Delta_{t,0}rLB_t+\Delta_{T_0,0}\sum_{t=T_0}^{\infty}\gamma^{t-T_0}rLB_t \qquad (3.1)$$

Subject to:

$$\begin{aligned} BMAR_{cxp0} &= startblog_{cxp} \quad \forall\, c,\, x,\, p; \\ LB_0 &= 0. \end{aligned} \qquad (3.2)$$

$$BMAR_{cxpt}=\Delta_{t-1,t}(1+d)BMAR_{cxp\,t-1}+DW_{cx0pt}-FC_{cxpt} \quad \forall\, c,\, x,\, p;\ t\le T_0; \qquad (3.3)$$

$$BMAR_{cxpt} = \gamma^{-1}(1+d)BMAR_{cxp\,t-1} + DW_{cx0pt} - FC_{cxpt} \quad \forall\, c,\, x,\, p;\, t > T_0. \tag{3.4}$$

$$\sum_x BMAR_{cxpt} \leq endc_{cpt} + CBDEV_{cpt} \quad \forall\, c,\, p,\, t. \tag{3.5}$$

$$\sum_x \sum_{y=1}^{k} DW_{cxypt} \leq endd_{cpt} + DBDEV_{cpt} \quad \forall\, c,\, p,\, t. \tag{3.6}$$

$$DW_{cxypt} = \Delta_{y+t,t} defer_{cxp\,(y+t)} - FD_{cxypt}$$
$$\forall\, c,\, x,\, p;\, \{y, t:\ (y = k \cup t = 1) \cap y + t \leq T_0\}; \tag{3.7}$$

$$DW_{cxypt} = \gamma^{y+t-T_0} \Delta_{T_0,t} defer_{cxp\,(y+t)} - FD_{cxypt}$$
$$\forall\, c,\, x,\, p;\, \{y, t:\ (y = k \cup t = 1) \cap T_0 - y < t \leq T_0\}; \tag{3.8}$$

$$DW_{cxypt} = \Delta_{t-1,t}(1+d)DW_{cx\,y+1\,p\,t-1} - FD_{cxypt} \quad \forall\, c,\, x,\, p;\, y \leq k-1,\, t \leq T_0; \tag{3.9}$$

$$DW_{cxypt} = \gamma^{-1}(1+d)DW_{cx\,y+1\,p\,t-1} - FD_{cxypt} \quad \forall\, c,\, x,\, p;\, y \leq k-1,\, t > T_0; \tag{3.10}$$

$$DW_{cxypt} = \gamma^{y} defer_{cxp\,(y+t)} - FD_{cxypt} \quad \forall\, c,\, x,\, p;\, y = k,\, t > T_0. \tag{3.11}$$

$$\sum_{c,i,y,p} FD_{ciypt} + \sum_{c,x,p} FC_{cxpt} + (1+r)\Delta_{t-1,t} LB_{t-1} \leq budget_t + LB_t \quad t \leq T_0; \tag{3.12}$$

$$\sum_{c,i,y,p} FD_{ciypt} + \sum_{c,x,p} FC_{cxpt} + (1+r)\gamma^{-1} LB_{t-1} \leq budget_t + LB_t \quad t > T_0. \tag{3.13}$$

$$FD_{ciypt} = 0 \quad \forall\, c,\ i = \text{OTHER};\, y > 0,\, p,\, t. \tag{3.14}$$

$$FD_{ciypt} \geq nondiscret_{ct} \quad \forall\, c;\, i = \text{OTHER};\, y = 0,\, p,\, t. \tag{3.15}$$

$$\Delta_{0,1}\underline{vary} \cdot startfund_c - NTURB_{c1} \leq \sum_{i,y,p} FD_{ciyp1} + \sum_{x,p} FC_{cxp1}$$
$$\leq \Delta_{0,1}\overline{vary} \cdot startfund_c + PTURB_{c1} \quad \forall\, c. \tag{3.16}$$

$$\Delta_{t-1,t}\underline{vary}\left(\sum_{i,y,p} FD_{ciyp\,t-1} + \sum_{x,p} FC_{cxp\,t-1}\right) - NTURB_{ct} \leq \sum_{i,y,p} FD_{ciypt} + \sum_{x,p} FC_{cxpt}$$
$$\leq \Delta_{t-1,t}\overline{vary}\left(\sum_{i,y,p} FD_{ciyp\,t-1} + \sum_{x,p} FC_{cxp\,t-1}\right) + PTURB_{ct} \forall\, c,\ t \leq T_0; \tag{3.17}$$

$$\gamma^{-1}\underline{vary}\left(\sum_{i,y,p} FD_{ciyp\,t-1} + \sum_{x,p} FC_{cxp\,t-1}\right) - NTURB_{ct} \leq \sum_{i,y,p} FD_{ciypt} + \sum_{x,p} FC_{cxpt}$$
$$\leq \gamma^{-1}\overline{vary}\left(\sum_{i,y,p} FD_{ciyp\,t-1} + \sum_{x,p} FC_{cxp\,t-1}\right) + PTURB_{ct} \forall\, c,\ t > T_0. \tag{3.18}$$

Constraints (3.2) set initial BMAR to levels reported in the AIS, and start the initial loan balance at zero.

Constraints (3.3) and (3.4) are inventory balance constraints for BMAR, as discussed in Chapter II. They require BMAR in year t equal BMAR in year $t-1$, plus proportional costs associated with deterioration and inflation, plus deferrable backlog scheduled to be accomplished by the end of year t but not yet funded, less funding applied in year t to correct critical deficiencies.

Constraints (3.5) and (3.6) prescribe annual target levels for BMAR and deferrable backlog, respectively, for each claimant and priority category. The variables $CBDEV_{cpt}$ and $DBDEV_{cpt}$ allow backlog to exceed the target levels at linear cost.

Constraints (3.7–3.11) are inventory balance constraints for deferrable backlog, categorized by claimant, IC, accomplishment year, and priority category. The model aggregates all projects in the deferrable backlog sharing this categorization and may pay portions of their cost at any time prior to their accomplishment year. Unpaid portions are augmented annually by inflation and by deterioration costs. The portion unpaid at the end of the accomplishment year is added to BMAR as part of constraints (3.3) and (3.4).

Constraints (3.12) and (3.13) are annual MRRP budget constraints. They show the implementation of Carr's "continued debt penalty" (see §IIA). If year t expenditures exceed the prescribed budget, the excess adds to year t's loan balance accruing interest annually at rate r. Conversely, if year t expenditures are below the prescribed budget, the excess goes toward any loan balance. The objective function, (3.1), discourages borrowing. The rate r is an "inflation-free" annual interest rate [Thuesen and Fabrycky 1988]; by contrast, a market interest rate expresses the escalation of a cash flow from the effects of interest and inflation in a single rate. The two rates provide equivalent methods of comparing cash flows over time: "actual-dollar" analysis requires use of the market interest rate; "constant-dollar" analysis requires the inflation-free rate. For example, \$1 at the beginning of year t has value $\$(1+r)(1+i)$ at the beginning of year $t+1$ when the inflation-free annual interest rate is r and the inflation rate is i. An equivalent market interest rate i' would compute the value in year $t+1$ to be $\$(1+i')$; in other words, $i' = r + i + ri$. The inflation-free rate is convenient for OMAR, because OPNAV frequently uses the O&M,N inflation factors to perform analyses in constant-dollar terms.

Constraints (3.14) specify that year t funding may not be used to fund "cost of ownership" activities, such as service calls or emergency work, in any year $t' > t$.

Constraints (3.15) require that funding allocated to claimant c in year t must meet or exceed projected costs of nonreportable, "nondiscretionary" M&R.

Constraints (3.16–3.18) prevent wide swings in claimant funding levels from year to year, limiting the total year t funding at claimant c to between $\underline{vary}$ percent and $\overline{vary}$ percent of the previous year's funding. The variables $NTURB_{ct}$ and $PTURB_{ct}$ allow variation in excess of the specified limits, at linear cost.

The objective function (3.1) minimizes the sum of: NPV of annual costs incurred by deferring critical and deferrable backlog; penalties for failing to meet annual goals for critical and deferrable backlog; penalties for year-to-year turbulence in claimant funding levels; and "interest" debts incurred by exceeding prescribed annual budgets. The cost of deferring projects is represented by modeling "deterioration" as a d-percent real annual increase in project cost.

E. SPECIFYING MANAGERIAL GOALS

During the development of the model, Worcester [1996] articulated a number of managerial concerns regarding the planning, programming and assessment of MRRP funding. The main objectives of the model, stated at the outset of the chapter, address most of these concerns. The planning and programming processes further require that the model possess two additional capabilities not present in the models currently used. The first of these is the ability to prioritize reduction of critical and deferrable backlog in consonance with the Navy's readiness concerns through the funding process. The second is the ability to examine the proposed funding levels and propose adjustments based on consistent and economically sound criteria. The preceding formulation incorporates these concerns by allowing measured violation of constraints such as annual backlog levels or annual budgets, commensurate with judgement regarding the type of projects that are deferred or funded as a result. The user must quantify this judgement by setting the parameters r, $cbwt_{cp}$, $dbwt_{cp}$, $pturb_c$, and $nturb_c$; there are many methods to do this. This section presents one systematic approach that ensures: (1) penalties incurred in the model represent concrete dollar-equivalent quantities, related in a sensible way; and (2) the model enforces consistent, rational tradeoffs based on the information provided.

1. Quantifying Shore FLEP Priorities

The model parameters $cbwt_{cp}$ and $dbwt_{cp}$ reflect the relative weight that OPNAV places on facility condition at each claimant, in each priority category. The relative importance of priority categories p does not change from claimant to claimant, because it is established by OPNAV directive [CNO 1989]. A typical way to model this relative importance is by assigning to each p a numeric weight $w_p \in (0, 1)$ such that $\sum_p w_p = 1$. Because the priority categories reflect, by definition, the relative importance of facilities in each category to the overall operational readiness of the Navy, a set of weights w_p represents a quantitative statement that category q is w_q/w_p times as important to operational readiness as category p. These kinds of statements are difficult to assess outright and a wealth of decision analytic methods (e.g., Srinivasan and Shocker [1973], Saaty [1980], Horsky and Rao [1984], Cook and Kress [1991], and Marshall and Oliver [1995]) have been developed to help make them. With only three attributes being compared, it would be feasible to select any set of weights w_p satisfying the requirements above and adjust them until reasonable model output resulted. The LINPAC (linear programming of preference comparisons) method of Horsky and Rao [1984] appears in Appendix A as a more structured approach.

2. Quantifying the Desire to Reduce Backlog

OPNAV desires to set annual target levels of critical and deferrable backlog. These targets appear in constraints (3.5) and (3.6). When year t funding is unable to achieve the target levels of backlog, the variables $CBDEV_{cpt}$ and $DBDEV_{cpt}$ represent the gap. An increase in year t funding, effectively by "borrowing" the money from other programs, is required to close this gap. A reasonable way to measure the relative importance of critical and deferrable backlog is to equate their reduction with the cost of borrowing the amount required. The interest rate r represents a notional inflation-free annual interest rate charged for these additional funds. A loan obtained in this way can be repaid in full at the end of m years with a repayment of $\$(1+r)^m$ per dollar borrowed; the total interest paid is $\$(1+r)^m - 1$ per dollar. This cost is explicitly minimized in the objective function. However, using this \$1 to pay for critical backlog would improve the objective function by $d + cbwt_{cp}$, provided $CBDEV_{cpt} > 0$ (the target level for critical backlog at claimant c and priority category p is not being met). The tradeoff between borrowing additional funds and incurring a penalty for failing to meet backlog goals can be established by specifying a number of years m_C (m_D) over which a claimant c borrows to reduce critical (deferrable) backlog for facilities of priority p:

$$\begin{aligned} d + cbwt_{cp} &= (1+r)^{m_C} - 1; \\ d + dbwt_{cp} &= (1+r)^{m_D} - 1. \end{aligned} \tag{3.19}$$

If $|\mathcal{C}|$ and $|\mathcal{P}|$ represent the number of claimants and priority categories considered by the model, then a total of $|\mathcal{C}| \times |\mathcal{P}|$ borrowing periods would have to be specified. A simpler approach would be to assess an average proportion of claimant CPV in a given priority category, e.g., high, and weight priority categories as described above. Only two borrowing periods must then be specified, one each for critical and deferrable backlog associated with high priority facilities. This can be accomplished by requiring first that

$$\begin{aligned} d + \lambda_C \frac{w_H}{|\mathcal{C}|} \sum_c \frac{CPV_{cH}}{\sum_p CPV_{cp}} &= (1+r)^{m_C} - 1 \quad \text{and} \\ d + \lambda_D \frac{w_H}{|\mathcal{C}|} \sum_c \frac{CPV_{cH}}{\sum_p CPV_{cp}} &= (1+r)^{m_D} - 1, \end{aligned} \tag{3.20}$$

where the subscript H denotes high priority, $|\mathcal{C}|$ denotes the number of claimants, CPV_{cp} denotes current plant value at claimant c of priority p, and λ_C and λ_D are dimensionless constants to be determined from (3.20) based on choices of m_C and m_D for critical and deferrable backlog, respectively. Individual weights can then be determined from

$$\begin{aligned} cbwt_{cp} &= \lambda_C w_p \frac{CPV_{cH}}{\sum_p CPV_{cp}} \quad \text{and} \\ dbwt_{cp} &= \lambda_D w_p \frac{CPV_{cH}}{\sum_p CPV_{cp}}. \end{aligned} \tag{3.21}$$

Equations (3.21) cause the model to favor claimants with higher proportions of CPV in high priority facility categories, but only provided significant backlog exists for those facilities. They also ensure that willingness to borrow additional funds for particular kinds of backlogged projects is directly related to the relative importance OPNAV attaches to the projects' respective facility priority categories, represented by the weights w_p. It is possible that $cbwt_{c,\text{low}} > cbwt_{c',\text{high}}$ if claimant c has a much larger proportion of high priority facilities than claimant c', but this does not occur with current CPV data (see Appendix D, Table D.1) and the weights determined in Appendix A.

3. Quantifying the Desire to Avoid Funding Turbulence

Constraints (3.16–3.18) are included in the model for two primary reasons. First, large inflows or outflows of MRRP funding can be detrimental to a major claimant's ability to perform effective maintenance and maintenance planning. Second, without them, the linear program is free to recommend spending unusually large portions of annual funding at a small number of major claimants in one year, and elsewhere the next year. The resulting decisions satisfy the basic requirements but are unusual and largely infeasible from a management perspective.

The variables $NTURB_{ct}$ and $PTURB_{ct}$ measure violation of these constraints: they incur proportional costs via the per-unit penalties $pturwt_c$ and $nturwt_c$. Qualitatively, the costs incurred by an unduly large budget increase should be offset by the corresponding reduction in M&R backlog; conversely, the savings realized by a large budget decrease should be offset by the corresponding increase in unfunded M&R requirements. The exact values of the penalties are largely discretionary, because the assessment that a given set of funding levels demonstrates excessive turbulence is largely a subjective one. The penalties can be adjusted more easily than those already described in order to obtain satisfactory recommendations from the model; but reasonable initial values can be obtained directly. One method for determining them is to assess the relative importance of staying within reasonable funding limits with respect to the importance of reducing critical backlog associated with high priority facilities. Increasing or decreasing the claimant funding limits is nominally less important; the turbulence weights can be expressed as percentages P_+ and P_-, respectively, of the critical backlog weights:

$$\begin{aligned} pturwt_c &= P_+ cbwt_{cH}; \\ nturwt_c &= P_- cbwt_{cH}. \end{aligned} \tag{3.22}$$

This method penalizes under- or over-funding a claimant without regard to the claimant's total CPV or level of backlog. If these factors are important to the allowable funding turbulence, the user can adjust the allowable turbulence, $\overline{vary}$ and $\underline{vary}$, to compensate.

The next chapter presents an implementation of OMAR with the data the Navy used to develop POM 1998 RPM funding levels. It examines the sensitivity of the model's results to several key assumptions and parameter values, and compares the funding allocated to major claimants in the POM with the funding recommended by OMAR on the basis of additional cost incurred.

IV. COMPUTATIONAL EXPERIENCE

This chapter describes OMAR's allocation of MRRP funding over eight years, 1996 to 2003, based on total available funding and AIS reports provided by the Director, Facilities Engineering Division (N442) for model evaluation purposes. These data appear in Appendix D. The analyses here are not intended to address a specific planning, programming, or budgeting need, but instead to demonstrate the model's performance under a number of scenarios. Difficulties in collection of the data required by the model appearing in the previous chapter lead to minor changes in the formulation; the specific problems and resulting reformulation appear in the next section. We subsequently compare OMAR recommendations with the Navy's actual decisions on the bases of total annual MRRP funding and allocation of the POM budget to 11 major claimants who both receive O&M,N funding for MRRP and submit AIS reports. The chapter concludes with an examination of the model's sensitivity to the borrowing rate, outyear budgets, willingness to borrow, and claimant underreporting of requirements.

A. DATA AVAILABILITY AND REFORMULATION

AIS reports forwarded to OPNAV do not contain individual project information; they contain critical and deferrable backlog data aggregated by investment category and claimant. Therefore, information about maintenance and repair requirements by priority category p is largely unavailable at OPNAV. The effects of this problem can be mitigated substantially, because most investment categories are dominated by facilities in a single priority category. It is possible to place an implicit value on high, medium, and low priority facilities maintained by each claimant by computing a weighted average of CPV by claimant and investment category using the original weights $cbwt_{cp}$ and $dbwt_{cp}$ described in Chapter III. OMAR can then weight both critical and deferrable backlog by claimant and investment category, instead of by claimant and facility priority:

$$cbwt_{cx} = \frac{\sum_p cbwt_{cp} CPV_{cxp}}{\sum_p CPV_{cxp}}; \text{and} \quad (4.1)$$

$$dbwt_{cx} = \frac{\sum_p dbwt_{cp} CPV_{cxp}}{\sum_p CPV_{cxp}} \quad (4.2)$$

Other parameters required to quantify judgment remain unchanged from those appearing in Chapter III. Removal of the priority category indices p throughout the remainder of the model produces the following reformulation; definitions of index sets, data elements, and variables follow from those given in Chapter III.

Formulation: Minimize

$$\sum_{c,x}\sum_{t=1}^{T_0-1}\Delta_{t,0}d\left(BMAR_{cxt}+\sum_{y=1}^{k}DW_{cxyt}\right)$$
$$+\sum_{c,x}\sum_{t=T_0}^{\infty}\Delta_{T_0,0}\gamma^{t-T_0}d\left(BMAR_{cxt}+\sum_{y=1}^{k}DW_{cxyt}\right)+\sum_{t=1}^{T_0-1}\Delta_{t,0}rLB_t+\sum_{t=T_0}^{\infty}\Delta_{T_0,0}\gamma^{T-T_0}rLB_t$$
$$+\sum_{c,x}cbwt_{cx}\left(\sum_{t=1}^{T_0-1}\Delta_{t,0}CBDEV_{cxt}+\sum_{t=T_0}^{\infty}\Delta_{T_0,0}\gamma^{t-T_0}CBDEV_{cxt}\right)$$
$$+\sum_{c,x}dbwt_{cx}\left(\sum_{t=1}^{T_0-1}\Delta_{t,0}DBDEV_{cxt}+\sum_{t=T_0}^{\infty}\Delta_{T_0,0}\gamma^{t-T_0}DBDEV_{cxt}\right)$$
$$+\sum_{c}pturwt_{c}\left(\sum_{t=1}^{T_0-1}\Delta_{t,0}PTURB_{ct}+\sum_{t=T_0}^{\infty}\Delta_{T_0,0}\gamma^{t-T_0}PTURB_{ct}\right)$$
$$+\sum_{c}nturwt_{c}\left(\sum_{t=1}^{T_0-1}\Delta_{t,0}NTURB_{ct}+\sum_{t=T_0}^{\infty}\Delta_{T_0,0}\gamma^{t-T_0}NTURB_{ct}\right) \tag{4.3}$$

Subject to:

$$\begin{aligned} BMAR_{cx0} &= startblog_{cx} \quad \forall\, c,\ x; \\ LB_0 &= 0. \end{aligned} \tag{4.4}$$

$$BMAR_{cxt}=\Delta_{t-1,t}(1+d)BMAR_{cx\,t-1}+DW_{cx0t}-FC_{cxt}\quad\forall\, c,\ x;\ t\le T_0; \tag{4.5}$$

$$BMAR_{cxt}=\gamma^{-1}(1+d)BMAR_{cx\,t-1}+DW_{cx0t}-FC_{cxt}\quad\forall\, c,\ x,\ t>T_0. \tag{4.6}$$

$$BMAR_{cxt}\le endc_{cxt}+CBDEV_{cxt}\quad\forall\, c,\ x,\ t. \tag{4.7}$$

$$\sum_{y=1}^{k}DW_{cxyt}\le endd_{cxt}+DBDEV_{cxt}\quad\forall\, c,\ x,\ t. \tag{4.8}$$

$$DW_{cxyt}=\Delta_{y+t,t}defer_{cx\,(y+t)}-FD_{cxyt}\quad\forall\ c,\ x;\ \{y,t:\ (y=k\ \cup\ t=1)\cap y+t\le T_0\}; \tag{4.9}$$

$$\begin{aligned} &DW_{cxyt}=\gamma^{y+t-T_0}\Delta_{T_0,t}defer_{cx\,(y+t)}-FD_{cxyt} \\ &\forall\ c,\ x;\ \{y,t:\ (y=k\ \cup\ t=1)\ \cap\ T_0-y<t\le T_0\}; \end{aligned} \tag{4.10}$$

$$DW_{cxyt}=\Delta_{t-1,t}(1+d)DW_{cx\ y+1\ t-1}-FD_{cxyt}\quad\forall\ c,\ x;\ y\le k-1,\ t\le T_0; \tag{4.11}$$

$$DW_{cxyt}=\gamma^{-1}(1+d)DW_{cx\ y+1\ t-1}-FD_{cxyt}\quad\forall\ c,\ x,\ y\le k-1,\ t>T_0. \tag{4.12}$$

$$DW_{cxyt}=\gamma^{y}defer_{cx\,(y+t)}-FD_{cxyt}\quad\forall\ c,\ x;\ y=k,\ t>T_0. \tag{4.13}$$

$$\sum_{c,i,y}FD_{ciyt}+\sum_{c,x}FC_{cxt}+(1+r)\Delta_{t-1,t}LB_{t-1}\le budget_t+LB_t\quad t\le T_0; \tag{4.14}$$

$$\sum_{c,i,y} FD_{ciyt} + \sum_{c,x} FC_{cxt} + (1+r)\gamma^{-1}LB_{t-1} \leq budget_t + LB_t \quad t > T_0. \tag{4.15}$$

$$FD_{ciyt} = 0 \quad \forall\, c,\ i = \text{OTHER},\ y > 0,\ t. \tag{4.16}$$

$$FD_{ciyt} \geq nondiscret_{ct} \quad \forall\, c,\ i = \text{OTHER},\ y = 0,\ t. \tag{4.17}$$

$$\Delta_{0,1}\underline{vary} \cdot startfund_c - NTURB_{c1} \leq \sum_{i,y} FD_{ciy1} + \sum_{x} FC_{cx1}$$

$$\leq \Delta_{0,1}\overline{vary} \cdot startfund_c + PTURB_{c1} \quad \forall\, c. \tag{4.18}$$

$$\Delta_{t-1,t}\underline{vary}\left(\sum_{i,y} FD_{ciy\,t-1} + \sum_{x} FC_{cx\,t-1}\right) - NTURB_{ct} \leq \sum_{i,y} FD_{ciyt} + \sum_{x} FC_{cxt}$$

$$\leq \ \Delta_{t-1,t}\overline{vary}\left(\sum_{i,y} FD_{ciy\,t-1} + \sum_{x} FC_{cx\,t-1}\right) + PTURB_{ct} \forall\, c,\ t \leq T_0; \tag{4.19}$$

$$\gamma^{-1}\underline{vary}\left(\sum_{i,y} FD_{ciy\,t-1} + \sum_{x} FC_{cx\,t-1}\right) - NTURB_{ct} \leq \sum_{i,y} FD_{ciyt} + \sum_{x} FC_{cxt}$$

$$\leq \ \gamma^{-1}\overline{vary}\left(\sum_{i,y} FD_{ciy\,t-1} + \sum_{x} FC_{cx\,t-1}\right) + PTURB_{ct} \forall\, c,\ t > T_0. \tag{4.20}$$

B. TOTAL FUNDING AND ALLOCATION: 1996-2003

1. Data Sources

The Director, Facilities and Engineering Division (N442) provided nine years of MRRP funding data for 16 major claimants (see Appendix D). The most recent AIS reports available were those corresponding to fiscal year 1995. Expenditure totals for IC OTHER, shown in the appendix by claimant, are used to represent a constant annual expense for each claimant in years 1996-2003.

Of the 16 major claimants the Navy funded from O&M,N in 1996-2003, those for whom AIS reports were not available (NAVSUP, SPAWAR, OTHER and NAVSECGRU) are not considered within OMAR and receive the MRRP annual budgets as they appear in Appendix D, Table D.6. BUPERS submitted a 1995 AIS but is not considered in the model because its primary fund source has changed; its allocation for 1996 and 1997 are not represented in the total budgets available to OMAR.

The model uses the O&M,N inflation factors through 2003 to convert year t dollars to year t' dollars. For years beyond 2003, they are approximated by an annual inflation rate of 2.19% ($\gamma = 1/1.0219 = 0.9786$).

2. Basic Assumptions

The following parameters reflect a baseline set of judgements used to determine the remainder of the data the model requires.

- Target levels of critical and deferrable backlog are annual 10% reductions of reported 1995 levels at each claimant in each IC through 2003.
- All unfunded projects increase in cost at a 3% rate annually.
- Funding levels for each major claimant can vary between 85% and 135% of the previous year's funding level. Penalties for real increases beyond 135% accrue at 55% of the penalty for exceeding annual critical backlog targets for high priority facilities; real decreases below 85% of the previous year's total are penalized at a rate of 45% of the same backlog penalty.
- Money may be borrowed from other O&M,N programs at an inflation-free annual interest rate of 4%. Considering the approximate 2.19% annual inflation rate, the equivalent market interest rate is 6.28%.
- Deferrable backlog appearing in Appendix D is not reported by year; the model considers that equal amounts at each claimant in each IC become critical if unfunded at the end of each year in a five year cycle.
- Relative weights for Shore FLEP high, medium, and low priority facilities are as computed in Appendix A.
- Chapter III provides a means to determine the backlog weights by specifying a maximum number of years m_c or m_d the decisionmaker is willing to exceed the budget in order to reduce critical or deferrable backlog in high priority facilities, respectively, by one objective function unit (thousands of base year dollars). For the base case calculations here, $m_c = 7$ and $m_d = 3$.
- The dual equilibrium approximation (a formulation appears in Appendix B) constraints are discounted at a rate $\alpha = 0.94$.

3. Results

The base case described above was implemented in the General Algebraic Modeling System (GAMS) [Brooke, Kendrick and Meeraus 1992] using the OSL [IBM Corporation 1991] solver, with a solution horizon of 20 years. The primal equilibrium approximation, from which optimal values of the decision variables were taken, had about 54,000 constraints, 98,000 variables, and 256,000 nonzero elements. Solution time was nine minutes on an IBM RS6000 Model 590 workstation. Except where noted, all variations from the base case used the same solution horizon, and the bounding techniques described in Walker [1995] guarantee that the resulting solutions were all within 1% of the infinite horizon optimal solutions.

Figure 4.1 shows total MRRP budgets, in constant FY96 millions of dollars, from 1995 to 2003. The figure demonstrates the adjustments the model recommends to the Navy's baseline figures based on willingness to borrow funds to avoid real cost increases

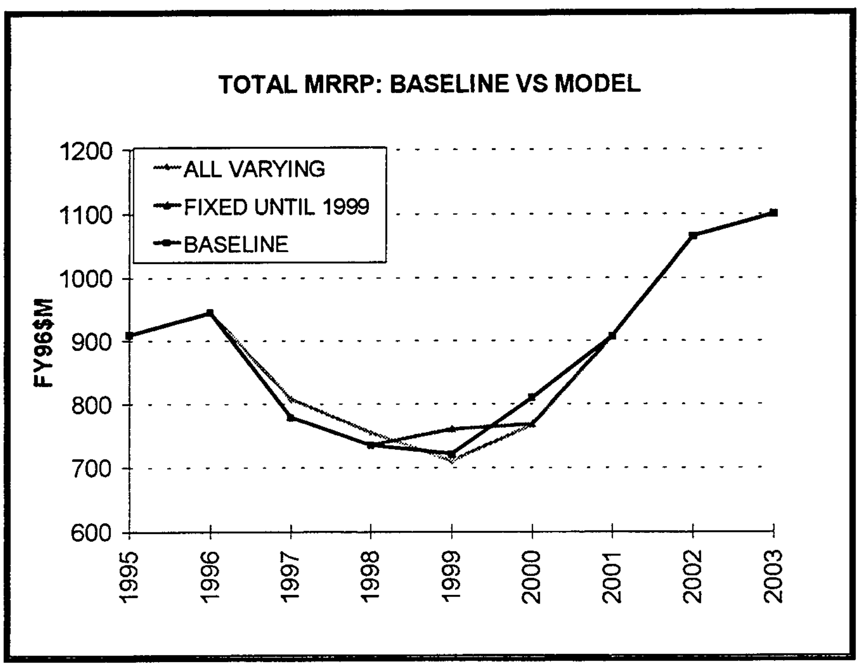

Figure 4.1. Total MRRP budgets in constant FY96 millions of dollars, from 1995 to 2003. The base case corresponds to the POM data provided by N442. The two alternatives are OMAR recommendations (1) when it is free to borrow funds from FY96-03; and (2) when it is only free to borrow funds from FY99-03. The model borrows in accordance with parameters set by the decisionmakers, in order to avoid real cost increases incurred by deferral of M&R projects. Having avoided long term cost increases, the model pays back with interest by coming in under budget in later years.

and meet backlog reduction targets in two cases: First, in all years 1996 to 2003; second, from 1999 to 2003 (useful for examining FY1999 alone). The model's decision to borrow funds in each case means that the borrowing reduces total multi-year program costs—by \$4.73 million in the first case and \$1.78 million in the second—because it is economically more sensible to pay for M&R projects sooner.

Figure 4.2 shows the model's recommended allocation of funding to the 11 major claimants considered in FY1999 when borrowing is not allowed—i.e., all annual budgets are fixed at the levels indicated by OPNAV and appearing in Figure 4.1. Totals for those claimants who receive O&M,N funding but do not appear in the allocation have already been subtracted from the annual total shown. The model's allocation is similar to that proposed by OPNAV, but it proposes allocating \$39.5 million less to PACFLT and \$49.5 million more to LANTFLT. The model expects that when the claimants have allocated their

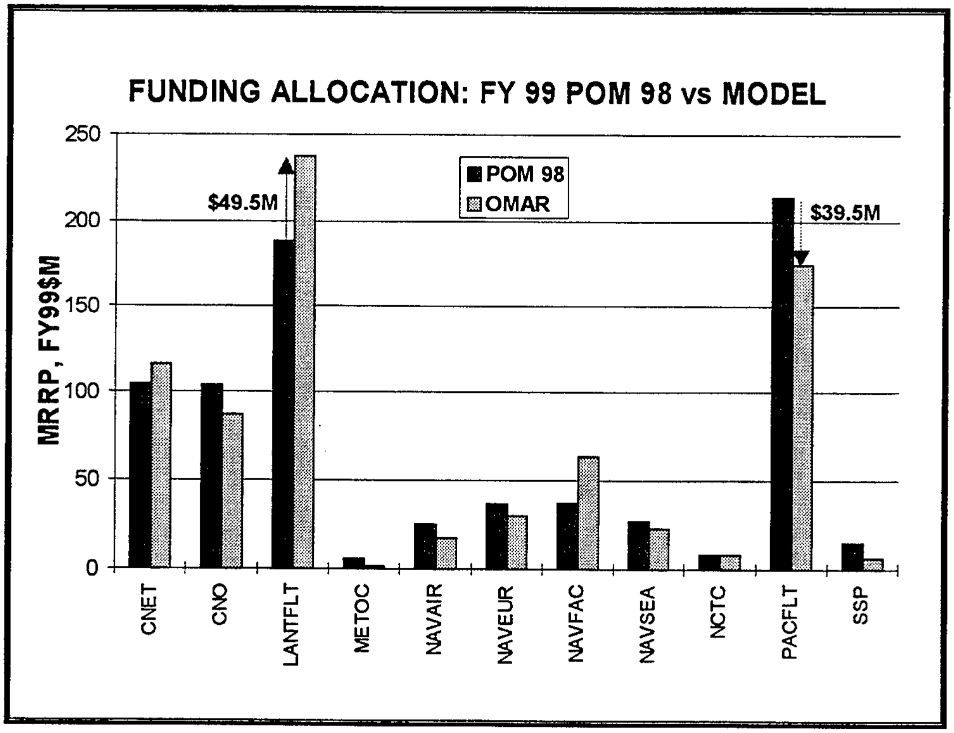

Figure 4.2. Allocation of FY99 MRRP funding among 11 major claimants, not including BUPERS, SPAWAR, SECGRU, NAVSUP, or OTHER. The amount allocated is \$879.2 million of the \$888.8 million total O&M,N MRRP, or 98.9%. OMAR was prevented from borrowing for comparison purposes, and critical and deferrable backlog targets were set at zero because OPNAV did not necessarily use the 10% annual reduction goals that the base case model runs assumed.

budgets for FY96, 97, and 98 among the projects in their long range maintenance plans, LANTFLT will have a larger backlog of high priority facilities.

Figures 4.3 and 4.4 provide a comparative measure of effectiveness for the model's allocation methods. The figures show the comparison of two model runs: in the first, claimant budget levels were fixed at the OPNAV totals shown in Appendix D; in the second, the model was free to allocate funding but was restricted to the same annual totals. The purpose for the comparison is to show that Navy-wide needs are better addressed by systematically ensuring that funding is allocated over time to the claimants who need them for M&R of facilities of most importance to operational readiness. Figure 4.3 shows FY2000 end-of-year critical backlog in ICs 01 (aviation operational facilities) and 05 (training facilities), both of which consist entirely of facilities in the high priority Shore FLEP category, as achieved by each model run. Figure 4.4 shows the same measure for ICs 12 (other supply and storage) and 14 (administrative facilities), which consist entirely of facilities in the low priority Shore FLEP category. When free to choose how to allocate the funding, the model achieves a lower end-of-year critical backlog in the high priority facilities, and balances that by deferring maintenance on the facilities of lower priority to operational readiness. This highlights the importance of proper allocation: if OPNAV apportions a fixed budget among the major claimants commensurate with their requirements, weighted by operational readiness priority, more high priority work can be accomplished Navy-wide than when allocations are not optimal, even when claimants spend their funding optimally in both cases.

4. Sensitivity Analyses

Four principal factors affecting the model's decisions are the interest rate at which funds are borrowed, changes to the outyear budgets, the decisionmakers' willingness to borrow to pay for M&R projects, and underreporting of requirements.

a. Borrowing Rate

With other base case factors constant, Figure 4.5 shows a comparison of annual total budgets from 1995 to 2003 when no borrowing is allowed, borrowing is allowed at 4% (6.27% market rate), and 7% (9.34% market rate). Predictably, amounts borrowed in total increase with decreasing rates; and funds are also borrowed sooner. Figure 4.6 shows the FY97 claimant budgets under each case; the model allocates the additional funding to

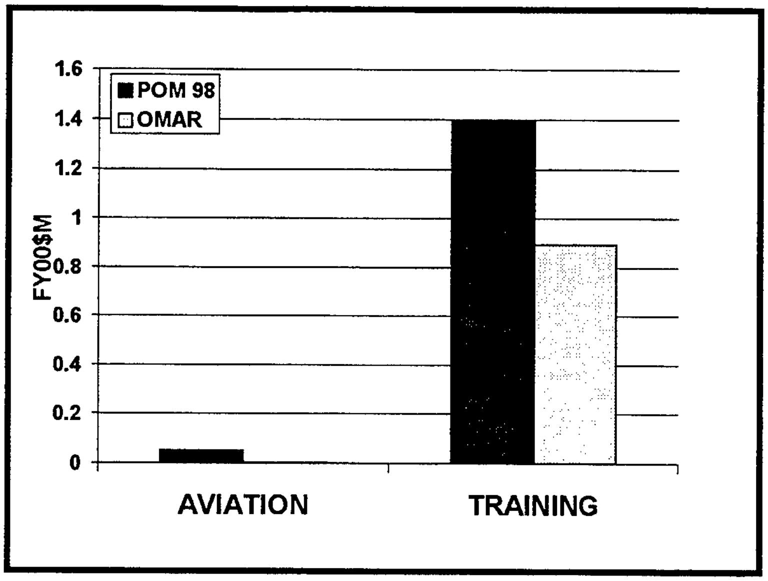

Figure 4.3. Comparison of FY2000 end of year critical backlog achieved for two high priority ICs (01 and 05) by the model when (1) claimant allocations are fixed at the levels in POM 98; and when (2) claimant allocations can vary. The figure demonstrates that funding can be systematically allocated over time to address particular M&R needs relative to overall Service-wide goals when those needs can be identified and tracked by claimant, IC, and year.

those with both higher total beginning-of-year requirements and with higher proportions of projects in higher priority facilities.

b. Outyear Budgets

Figure 4.7 shows the baseline OPNAV annual budgets and two alternatives for lower outyear budgets with no borrowing permitted. At the baseline totals, projects in the critical backlog as identified in 1995, plus those becoming critical in the intervening years, total only $16.4 million at the end of fiscal year 2003; this amount increases to $111.9 million and $532.7 million when the real increases projected to follow FY99 are cut in half or removed entirely, respectively. The relative size of this backlog in each Shore FLEP priority category is a better measure of the model's ability to allocate funding in a decreasing budget environment, because backlog totals are subject to reporting errors inherent in the data. Figure 4.8 shows that as outyear budgets decrease, facilities most important to operational readiness continue to receive most of the funding they require but lower priority facilities

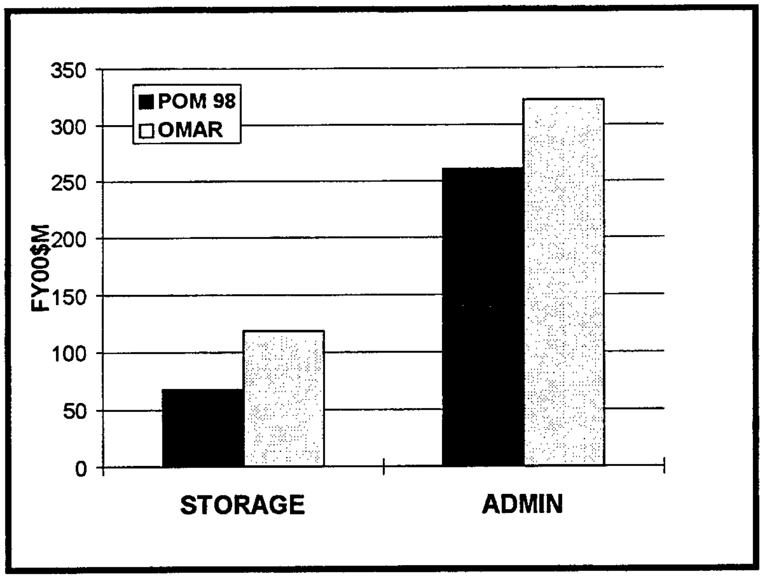

Figure 4.4. Comparison of FY2000 end of year critical backlog achieved for two low priority ICs (12 and 14) by the model when (1) claimant allocations are fixed at the levels in POM 98; and when (2) claimant allocations can vary. The larger totals shown for the varying case reflect compensation for the improvement in the high priority ICs, shown in Figure 4.3.

do not. The severity of the contrast observed in Figure 4.8 depends on the relative weights w_p that distinguish between the Shore FLEP categories.

c. Willingness to Borrow

The maximum number of years a decisionmaker is willing to exceed the budget in order to pay for backlog reduction has virtually no effect on the resulting allocations. It affects whether or not it is acceptable to borrow funds at all—an important distinction. Two separate OMAR runs provide comparisons with the base case ($m_c = 7$ and $m_d = 3$). In the first alternative, m_c and m_d were set at 9 and 5 respectively, indicating that the model should borrow if it could repay the loans in 9 and 5 years for reduction of critical and deferrable backlog toward their target (10% annual reduction) levels. The resulting total multi-year budget was exactly the same as the base case of 7 and 3 years. When m_c and m_d were set to 5 and 1, respectively, no borrowing occurred at all, and in all three cases the first year of claimant funding recommendations differed by no more than \$2.5 million; no more than 10% of any claimant's budget shifted (all but two were identical). The number of years m and the interest rate r together determine both backlog weights and funding turbulence weights; though changing m therefore changes many model coefficients, they change together in a way that keeps results consistent with the decisionmaker's preferences.

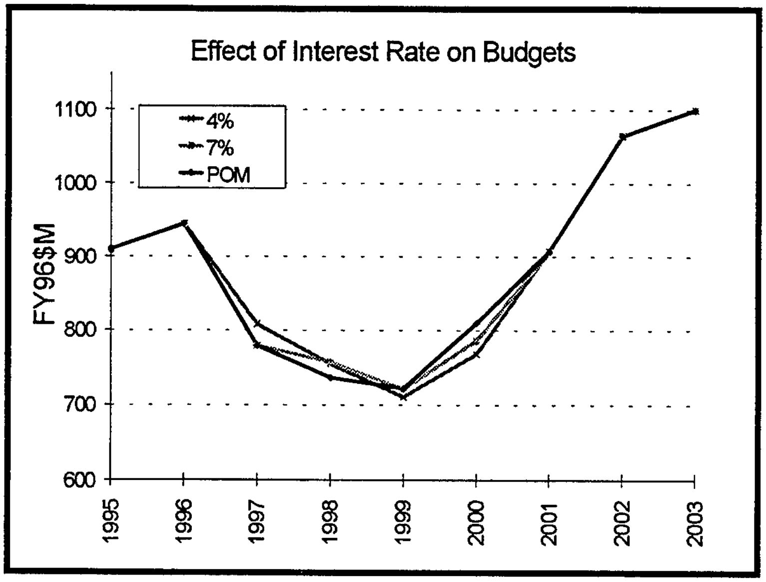

Figure 4.5. Total MRRP budgets from 1995 to 2003 when no borrowing is allowed, borrowing is allowed at an annual interest rate of 4% (6.27% market rate), and when it is allowed at 7% (9.34% market rate). More funding is borrowed earlier when interest rates are lower, as expected. The amount borrowed depends on the amount by which the end of year maintenance backlogs would exceed their targets without borrowing.

d. Underreporting of Requirements

Investigating the case where actual requirements far exceed reported requirements is important for two reasons. First, many believe the true M&R needs, those that would keep all facilities in satisfactory operating condition, to be as much as twice those reported or more [CNO 1986]. This would be consistent with actual conditions of insufficient funding for complete inspection and condition reporting programs and with the understandable failure of those programs to identify and predict all facility M&R requirements. Critical backlog is less likely than deferrable backlog to be underreported because it is, in most cases, a "show-stopper."

The effect of understated requirements was modeled by doubling the reported deferrable backlog. The base case assumptions change because they are unrealistic in the new scenario: A 4% inflation free interest rate for borrowing, 10% targets for annual reduction, and willingness to borrow for up to 7 and 3 years for critical and deferrable backlog combine to yield fantastic borrowing recommendations, topping a $1 billion loan balance by 1998. New assumptions are a reduced willingness to exceed the budget (no more than 3 years for critical and 1 year for deferrable deficiencies), an increased borrowing

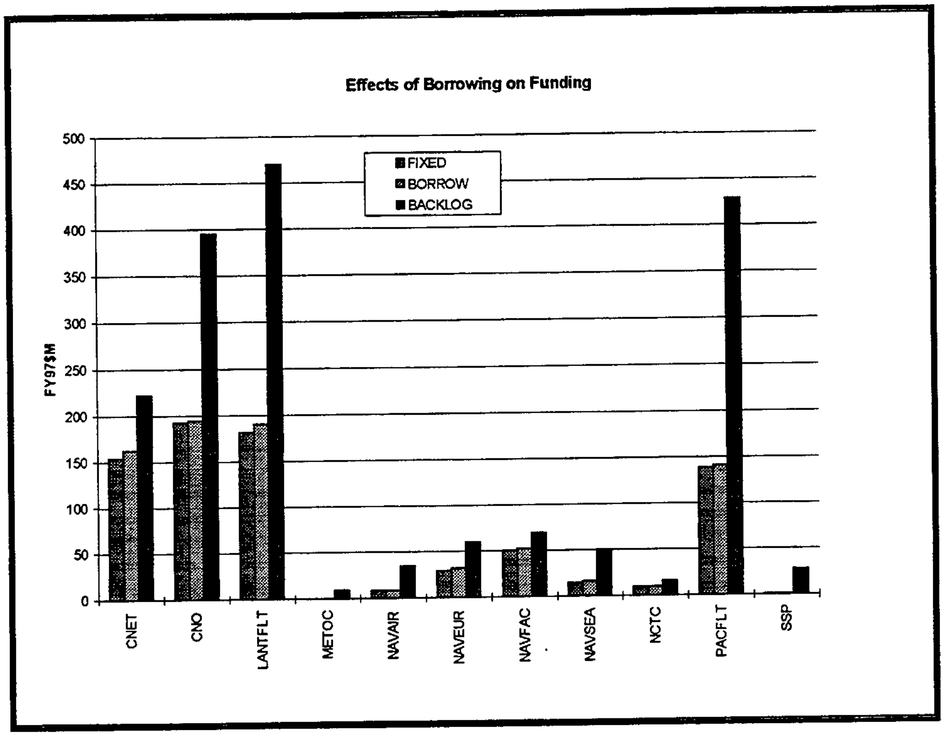

Figure 4.6. FY97 critical backlog at the beginning of the year, and claimant budgets under both no borrowing and borrowing at 4%. The model allocates the additional funding to those with both higher total beginning-of-year requirements and with higher proportions of projects in higher priority facilities.

interest rate (7% inflation free), and a 5% annual reduction target for critical backlog in real terms. With these restrictions, the solution horizon extended to 30 years provided convergence of primal and dual equilibrium approximations within a tolerance of 5.5% of the infinite horizon optimal solution. For the 11 major claimants modeled, the results of Figure 4.9 appear similar to those observed in previous years (a historical comparison of O&M,N backlog and funding appears in Figure 4.10).

A clear pattern appears in Figure 4.9. Given the option of when to pay for deferrable or critical backlog, the model reduces deferrable backlog each year in real terms which ultimately allows it to produce a drastic improvement in critical backlog levels (this effect is also dependent on increasing budgets in later years). A detailed view of the model's allocation of dollars between critical and deferrable backlog for the case of claimant underreporting by 50% appears in Figures 4.11 and 4.12. Both figures show a significant portion of annual MRRP funding being spent on noncritical M&R requirements, even when

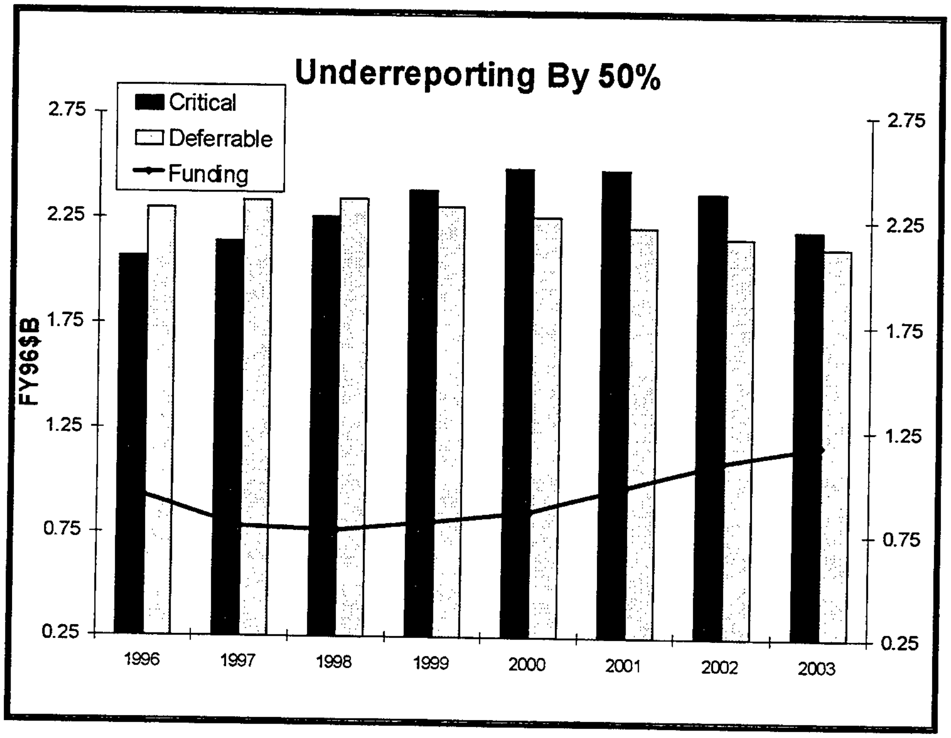

Figure 4.9. Total critical and deferrable backlog by year, in constant FY96 billions of dollars, and OMAR annual funding recommendations based on conservative decisionmaker judgment. Totals do not include claimants not submitting the AIS. The optimal solution shown "pays down" deferrable backlog early to reduce the projects becoming critical in later years. A moderate amount of borrowing ($41 million in addition to the budget of $766 million in constant 1996 dollars) occurs in FY1999, but otherwise the model follows the POM budget.

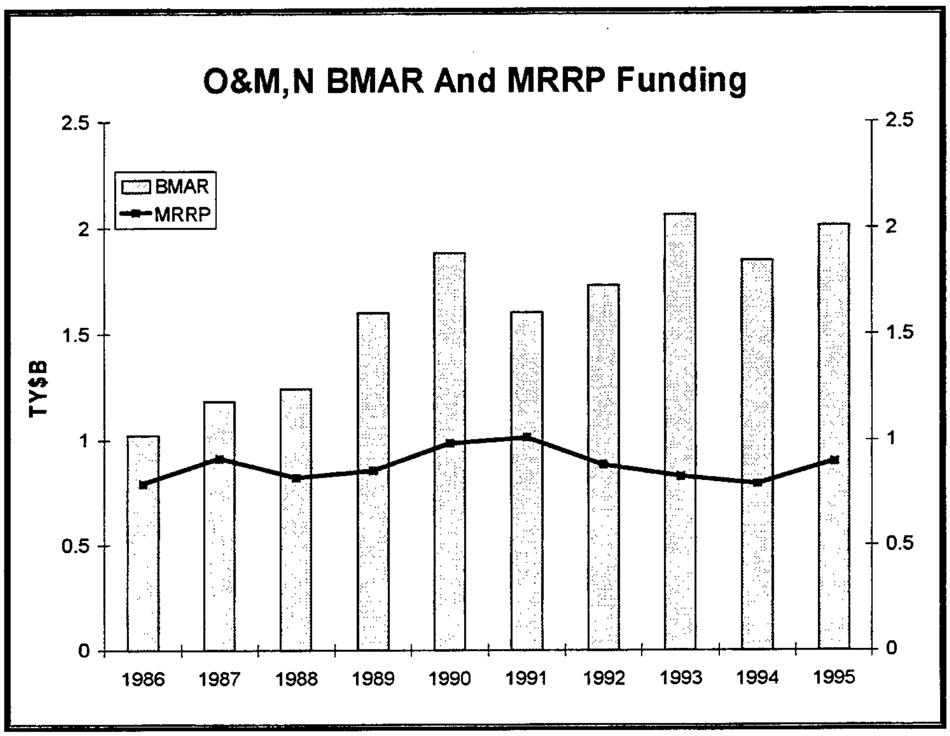

Figure 4.10. Historical O&M,N critical backlog and MRRP funding, in then-year billions of dollars. Figures do not include physical security projects; FY92-94 figures include demolition costs. Source: N44 [1995b].

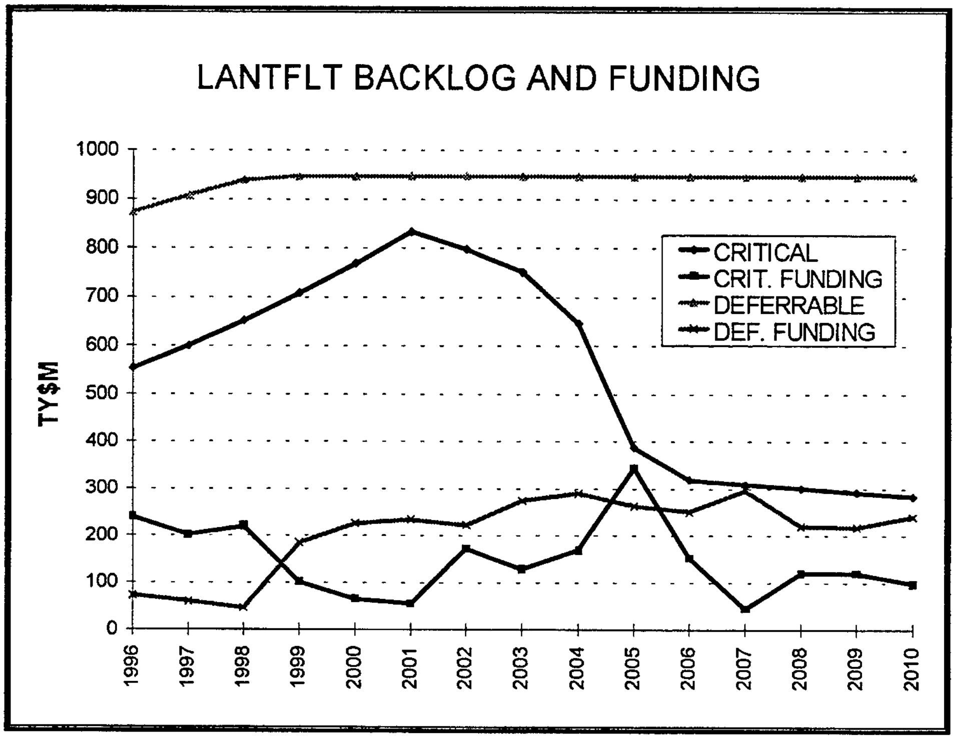

Figure 4.11. Total critical and deferrable backlog by year, in then-year millions of dollars, and OMAR annual funding recommendations for the US Atlantic Fleet based on the assumption that deferrable backlog is underreported by 50%. Even when targets for the reduction of critical backlog are not being met, and critical targets are weighted more heavily than deferrable targets, the optimal solution shown pays for deferrable work in order to minimize long term total costs. In this case, a larger amount of funding is required to pay for deferrable backlog than for critical backlog.

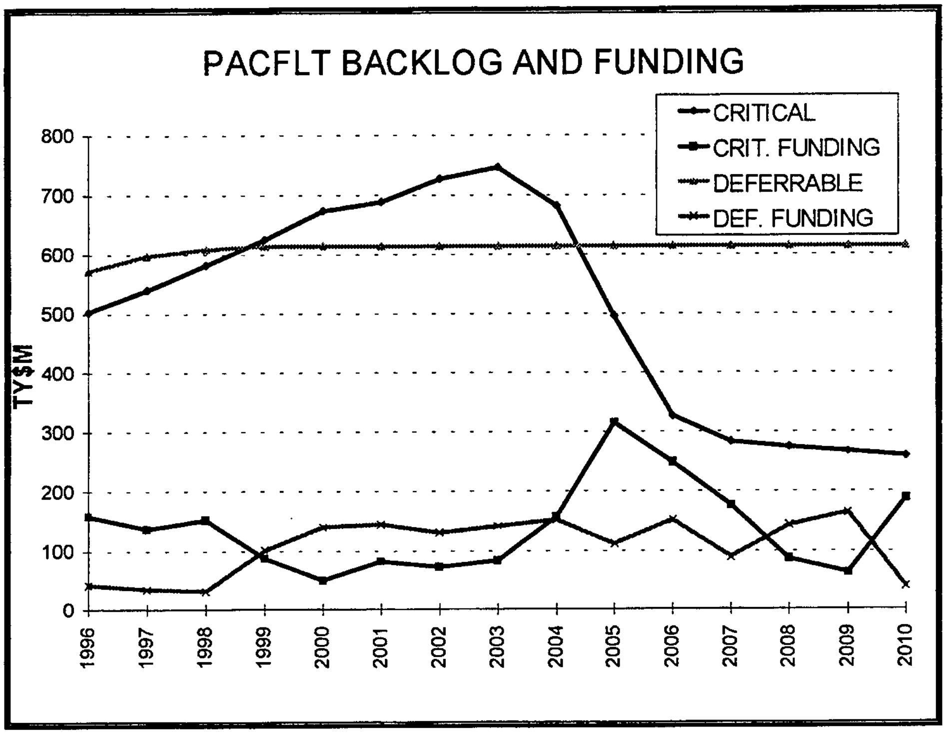

Figure 4.12. Total critical and deferrable backlog by year, in then-year millions of dollars, and OMAR annual funding recommendations for the US Pacific Fleet based on the assumption that deferrable backlog is underreported by 50%. Even when targets for the reduction of critical backlog are not being met, and critical targets are weighted more heavily than deferrable targets, the optimal solution shown pays for deferrable work in order to minimize long term total costs.

V. CONCLUSIONS

A. SUMMARY

The model developed in this thesis, OMAR, addresses two separate but related decision problems OPNAV faces. In the planning process, N81 evaluates alternative multi-year budgets for the RPM program to improve shore installations' contribution to operational readiness. OMAR helps to balance the yearly funding needs of RPM with those of other programs by introducing the ability to borrow funds to minimize the cost of the RPM program over the infinite horizon. It does this while achieving user-specified annual target levels of maintenance and repair backlog, and observing a facility priority system linked to operational readiness. In the programming process, N4 allocates multi-year budgets to the major claimants; OMAR helps to develop budget allocations that address Navy-wide readiness priorities based on reported facility condition and plant value, putting scarce funding where it is most needed at the right time. No models currently in use by OPNAV provide these capabilities.

Computational results indicate that when model parameters are set according to the procedures developed in the thesis, OMAR suggests that planners borrow funds when economically sensible criteria are satisfied: (1) the decisionmaker indicates a willingness to exceed the budget; (2) target backlog levels are not being met; and (3) lower long term net costs result from borrowing. MRRP funding allocations provided by OMAR largely resemble those prepared by the Navy for POM 98, but generally provide greater funding than the POM to major claimants reporting larger amounts of high priority critical and deferrable backlog. A comparison of critical backlog achieved by MRRP funding levels established in POM 98 with those achieved by an optimal allocation restricted by the same fixed annual budgets shows that more high priority work—that most relevant to operational needs—is accomplished Navy-wide with an optimal OMAR allocation. In this way, OMAR forces M&R funding to address operational readiness.

Investigating the case where actual requirements exceed reported requirements produces multi-year funding and backlog data similar to that observed in previous years, suggesting that actual requirements are understated in annual reports. Explicit modeling of deferrable backlog, not previously accomplished, shows that early identification and reporting of noncritical M&R projects leads to better decisions regarding multi-year total budget levels and claimant funding allocations, and to better long term management of critical backlog.

B. RECOMMENDATIONS FOR FUTURE WORK

OMAR relies on AIS reports to depict facility condition accurately Navy-wide, but the implementation presented in Chapter IV does not use the detailed data available in the installations' long range maintenance plans. Availability of these data would allow explicit modeling of near-term (one to five years) M&R requirements to improve the model's recommendations.

Long range maintenance plans allow proper construction and justification of M&R budgets and major claimant allocations, but they do not predict future requirements accurately beyond two or three years. Data collection and analysis to support better predictions are necessary. Analysts, however, face a difficult task in that the Navy cannot afford to pay for proper upkeep of all facilities. Facility component lifetime data need to be based on condition and maintenance patterns over time, and not on engineering or maintenance standards that assume condition and maintenance are independent of funding adequacy. These studies would provide better projections of changes in long term facility condition resulting from funding decisions.

APPENDIX A. DETERMINATION OF FACILITY PRIORITY WEIGHTS

CNO [1989] relates facility condition to the Navy's operational readiness by defining high, medium, and low priority facility categories. Quantifying the priorities enables OMAR to allocate funding based on stated readiness needs. This appendix presents an implementation of the LINPAC method of Horsky and Rao [1984] to establish relative weights for Shore FLEP facility priorities. Terminology and notation are from their paper, except for using "alternatives" instead of "brands."

The method quantifies relative preferences among n alternatives that are characterized by m common attributes. It assumes that an additive multi-attribute value function (e.g., Rosenthal [1985] or Ringuest [1992]) adequately describes relative preferences for the alternatives based on the attributes. A decisionmaker examines all $\binom{n}{2}$ possible pairs of alternatives by comparing their relative scores with respect to the common attributes, and provides two pieces of information: (1) the preferred alternative; and (2) the difference in preference of the alternatives ("none," "small," "moderate," or "large"). Based on this information, a linear goal program determines a set of attribute weights that are most consistent with the stated preferences and preference differences.

Quantitative information needed consists of the scores of each alternative on each of the m attribute scales. Define:

x_j Ideal level of attribute j;

y_{ij} score of alternative i on attribute j; and

d_{ij} distance of alternative i from the ideal level of attribute j.

The objective in the current setting is to determine the relative degree facilities in each Shore FLEP priority category (high, medium, and low) contribute to Navy readiness by being in good condition. A natural qualitative measure of their contribution is the percent of CPV in a BASEREP C1 or C2 facility condition status (fully or substantially meets mission requirements, respectively). In the terminology of Horsky and Rao, the three attributes pertaining to each alternative evaluated are the percentages of CPV in C1 or C2 condition status for each of the three facility priority categories. Further, each alternative corresponds to a notional set of facilities listed by their BASEREP facility condition in each of the high, medium, and low priority categories. In other words, using the quantities defined above, denote

i alternatives;

j priority categories;

x_j 100% C1 or C2 facility condition;

y_{ij} percent of alternative i, priority j facilities in C1 or C2 facility condition;

and define $d_{ij} = (x_j - y_{ij})^2$ so that increasing values of y_{ij} produce decreasing marginal benefit.

The goal programming formulation of LINPAC appearing in Horsky and Rao [1984] is reproduced below along with a brief explanation.

Indices

p, q Alternatives, $1, 2, \ldots, n$;

r, s, t, u Indices aliasing p and q;

j Attributes, $1, 2, \ldots, m$; and

h, k Levels of preference, $k \in \{1, \ldots, 4\}$; $h \in \{1, 2, 3\}$ where 1 = none, 2 = small, 3 = moderate, 4 = large.

Data

$d_{q,j}$ Distance of alternative q from the ideal level of attribute j;

$\mathcal{S}$ Set of all ordered pairs (q, p) where the decisionmaker prefers alternative q to alternative p; and

$\mathcal{S}_k$ Set ($\mathcal{S}_k \subseteq \mathcal{S}$) of all ordered pairs (q, p) where the decisionmaker prefers alternative q to alternative p at level of preference k.

Variables

w_j Relative weight of attribute j, dimensionless;

$z_{q,p}$ Preference inconsistency between alternatives q, p measured in terms of weighted distance;

$v_{s,r,t,u}$ Degree-of-preference inconsistency between alternative pairings (s, r) and (t, u), measured in terms of weighted distance.

Formulation

$$\text{Minimize} \quad \sum_{q,p \in \mathcal{S}} z_{q,p} + \sum_{k:(s,r)\in\mathcal{S}_k} \; \sum_{h<k:(t,u)\in\mathcal{S}_h} v_{s,r,t,u}$$

Subject to:

$$\left\{ \sum_{j=1}^{m} w_j (d_{qj} - d_{pj}) \right\} + z_{q,p} \geq 0 \quad \forall (q,p) \in \mathcal{S}; \tag{A.1}$$

$$\left\{ \sum_{j=1}^{m} w_j (d_{s,j} - d_{r,j} - d_{t,j} + d_{u,j}) \right\} + v_{s,r,t,u} \geq 0 \quad \forall (s,r) \in \mathcal{S}_k;\ (t,u) \in \mathcal{S}_h,\ h < k \leq 4; \tag{A.2}$$

$$\sum_{j=1}^{m} w_j = 1; \tag{A.3}$$

$$\text{all} \quad w_j,\ z_{q,p},\ v_{s,r,t,u} \geq 0. \tag{A.4}$$

Constraints (A.1) measure inconsistency in the weighted distance differences between alternatives q and p where the decisionmaker has a preference for alternative q. Constraints (A.2) measure inconsistency in the stated degrees of preference for alternative pairs (s, r) and (t, u). For example, if s is preferred over r to a large degree but t is preferred to u to a small degree, and $V(q)$ is the value of alternative q determined by the weighted distances of its attributes from their ideal values, then $(V(s) - V(r)) - (V(t) - V(u)) > 0$. For the cases in which this difference is negative, the decisionmaker's judgement is inconsistent with the attribute weights, and $v_{s,r,t,u} > 0$.

Five sets of notional facility mix alternatives, for comparison on the basis of facility condition in each priority category, appear in Table A.1. A representative set of alternative preferences and preference differences, in Table A.2, provides the qualitative input for the LINPAC procedure.

For this example, LINPAC determines the optimal (most consistent) weights w_j^* to be 0.4895, 0.3125, and 0.1980 for high, medium, and low priority facilities respectively. In other words, for this decisionmaker, the readiness of low priority facilities is 40% as important as that of high priority facilities, and medium priority facilities are 64% as important.

	$y_{q,j} \times 100$			$d_{q,j}$		
Alternative q	High	Medium	Low	High	Medium	Low
1	95	67	53	0.0026	0.1093	0.2205
2	90	54	66	0.0101	0.2085	0.1136
3	72	82	53	0.0772	0.0334	0.2239
4	76	56	89	0.0586	0.1961	0.0131
5	85	70	80	0.0225	0.0900	0.0400

Table A.1. Five alternatives for comparison to determine quantitative weights for facility priorities. $y_{q,j}$ represent the percentage of facilities of priority j that are rated in C1 or C2 condition by BASEREP criteria; $d_{q,j} = (1 - y_{q,j})^2$ are the squared deviations from the ideal 100%. A response set of preferences and preference differences appears in Table A.2.

Alternative Pair	Preferred Alternative	Degree of Preference
(1,2)	1	small
(1,3)	1	moderate
(1,4)	1	moderate
(1,5)	5	none
(2,3)	2	small
(2,4)	2	large
(2,5)	5	moderate
(3,4)	3	small
(3,5)	5	moderate
(4,5)	5	small

Table A.2. Pairwise comparisons of alternatives given in Table A.1. The decisionmaker prefers alternative 1 to 4 with a "moderate" difference in preference; but he or she is indifferent between alternatives 1 and 5.

APPENDIX B. FINITE HORIZON APPROXIMATIONS

Versions of the linear programs in Chapters III and IV with finite horizons can produce unreasonable solutions. Walker [1995] describes a number of approximation methods for solving infinite horizon linear programs (truncation, salvage, fixed end conditions, and primal and dual equilibrium approximations), and provides a general algorithm for bounding infinite horizon linear and integer programs with the use of the primal and dual equilibrium approximations. For linear programs, formulation of primal and dual equilibrium approximations require an overlapping, "staircase" structure similar to that of the following problem (P) used by Walker [1995] (where $\alpha < 1$):

(P): Minimize

$$\sum_{t=0}^{\infty} \alpha^t \boldsymbol{c} \boldsymbol{x}_t \tag{B.1}$$

Subject to:

$$\boldsymbol{A}\boldsymbol{x}_0 \geq \boldsymbol{s}(0) \tag{B.2}$$

$$\boldsymbol{K}\boldsymbol{x}_t + \boldsymbol{A}\boldsymbol{x}_{t+1} \geq \boldsymbol{b}(t+1), \quad t = 0, 1, 2, \ldots \tag{B.3}$$

$$\boldsymbol{x}_t \geq \boldsymbol{0}, \quad t = 0, 1, 2, \ldots \tag{B.4}$$

The primal equilibrium approximation of (P) is a finite (T-period) formulation that places a restriction on the feasible region, typically by requiring that $\boldsymbol{x}_{t+1} = \boldsymbol{x}_t$ for $t \geq T$. The useful properties of this formulation are that its optimal objective function value is an upper bound to the optimal objective function value of (P); and that the optimal values of its decision variables, $\{\boldsymbol{x}_t^T;\ t = 0, 1, 2, \ldots T\}$, are feasible to (P).

The dual equilibrium approximation of (P) is a finite formulation that relaxes the feasible region, typically by aggregating constraints (B.3) for $t \geq T-1$ into a single set of constraints, discounting with factor α:

$$\begin{bmatrix} 1 & \boldsymbol{\alpha} & \boldsymbol{\alpha}^2 & \cdots \end{bmatrix} \begin{bmatrix} \boldsymbol{K} & \boldsymbol{A} & & \\ & \boldsymbol{K} & \boldsymbol{A} & \\ & & \boldsymbol{K} & \ddots \end{bmatrix} \begin{bmatrix} \boldsymbol{x}_{T-1} \\ \boldsymbol{x}_T \\ \vdots \end{bmatrix} \geq \begin{bmatrix} 1 & \boldsymbol{\alpha} & \boldsymbol{\alpha}^2 & \cdots \end{bmatrix} \begin{bmatrix} \boldsymbol{b}_T \\ \boldsymbol{b}_T \\ \vdots \end{bmatrix}$$

or

$$\boldsymbol{K}\boldsymbol{x}_{T-1} + (\alpha\boldsymbol{K} + \boldsymbol{A}) \sum_{t=T}^{\infty} \alpha^{t-T} \boldsymbol{x}_t \geq \frac{\boldsymbol{b}_T}{1-\alpha}, \tag{B.5}$$

where, for this problem, $\boldsymbol{x}_t$ have dimension $n \times 1$, $\boldsymbol{K}$ and $\boldsymbol{A}$ have dimension $m \times n$, $\boldsymbol{b}_T$ has dimension $m \times 1$, and the elements of the row vectors have dimension $1 \times m$. The constraints

(B.5) correspond to a single $n \times 1$ vector of decision variables $\boldsymbol{x}_\alpha = \sum_{t=T}^{\infty} \alpha^{t-T} \boldsymbol{x}_t$. The dual equilibrium formulation, provided it exists, always provides a lower bound on the optimal objective function of the infinite horizon minimization problem.

Walker [1995] uses the upper and lower bound properties of the primal and dual equilibrium reformulations together to bound the error associated with finite horizon approximations. The general algorithm iteratively increases the number of periods in the horizon until the difference between the objective function values of the primal and dual equilibrium reformulations is within a specified tolerance. The optimal values of the decision variables for the period(s) of interest are taken from the primal equilibrium solution, because they are guaranteed to be feasible to the infinite horizon problem.

The OMAR formulations appearing in Chapters III and IV have the overlapping structure indicated in the problem (P). The following sections provide primal and dual equilibrium reformulations of the model in Chapter IV, and demonstrate convergence of the approximations for that instance.

A. Primal Equilibrium Approximation

The objective function (4.3) is replaced with: Minimize

$$\begin{aligned}
&\sum_{c,x} \sum_{t=1}^{T_0-1} \Delta_{t,0} d \left(BMAR_{cxt} + \sum_{y=1}^{k} DW_{cxyt} \right) + \sum_{c,x} \sum_{t=T_0}^{T-1} \Delta_{T_0,0} \gamma^{t-T_0} d \left(BMAR_{cxt} + \sum_{y=1}^{k} DW_{cxyt} \right) \\
&+ \sum_{c,x} \Delta_{T_0,0} \frac{\gamma^{T-T_0}}{1-\gamma} d \left(BMAR_{cxT} + \sum_{y=1}^{k} DW_{cxyT} \right) \\
&+ \sum_{t=1}^{T_0-1} \Delta_{t,0} r LB_t + \sum_{t=T_0}^{T-1} \Delta_{T_0,0} \gamma^{t-T_0} r LB_t + \Delta_{T_0,0} \frac{\gamma^{T-T_0}}{1-\gamma} r LB_T \\
&+ \sum_{c,x} cbwt_{cx} \left(\sum_{t=1}^{T_0-1} \Delta_{t,0} CBDEV_{cxt} + \sum_{t=T_0}^{T-1} \Delta_{T_0,0} \gamma^{t-T_0} CBDEV_{cxt} + \Delta_{T_0,0} \frac{\gamma^{T-T_0}}{1-\gamma} CBDEV_{cxT} \right) \\
&+ \sum_{c,x} dbwt_{cx} \left(\sum_{t=1}^{T_0-1} \Delta_{t,0} DBDEV_{cxt} + \sum_{t=T_0}^{T-1} \Delta_{T_0,0} \gamma^{t-T_0} DBDEV_{cxt} + \Delta_{T_0,0} \frac{\gamma^{T-T_0}}{1-\gamma} DBDEV_{cxT} \right) \\
&+ \sum_{c} pturwt_{c} \left(\sum_{t=1}^{T_0-1} \Delta_{t,0} PTURB_{ct} + \sum_{t=T_0}^{T-1} \Delta_{T_0,0} \gamma^{t-T_0} PTURB_{ct} + \Delta_{T_0,0} \frac{\gamma^{T-T_0}}{1-\gamma} PTURB_{cT} \right) \\
&+ \sum_{c} nturwt_{c} \left(\sum_{t=1}^{T_0-1} \Delta_{t,0} NTURB_{ct} + \sum_{t=T_0}^{T-1} \Delta_{T_0,0} \gamma^{t-T_0} NTURB_{ct} + \Delta_{T_0,0} \frac{\gamma^{T-T_0}}{1-\gamma} NTURB_{cT} \right).
\end{aligned} \tag{B.6}$$

Constraints (4.4–4.20) are identical in the primal equilibrium approximation with fiscal years t limited to between 0 and T, the solution horizon. Additional constraints required so that $\boldsymbol{X}_{t+1} = \boldsymbol{X}_t$ for all variables $\boldsymbol{X}$ with $t \geq T$ are:

$$\left(1 - \frac{1+d}{\gamma}\right) BMAR_{cxT} = DW_{cx0T} - FC_{cxT} \quad \forall c,\ x; \tag{B.7}$$

$$DW_{cxyT} = \frac{1+d}{\gamma} DW_{cx\,y+1\,T} - FD_{cxyT} \quad \forall\, c,\, x;\ y \leq k-1; \quad \text{and} \tag{B.8}$$

$$\sum_{c,i,y} FD_{ciyT} + \sum_{c,x} FC_{cxT} + \frac{1+r}{\gamma} LB_T \leq budget_T + LB_T. \tag{B.9}$$

For all $t > T$, constraints (B.7) replace (4.6), (B.8) replace (4.12), and (B.9) replace (4.15).

B. Dual Equilibrium Approximation

This formulation changes the factor by which the objective function coefficients are discounted after year T from γ to $\alpha \leq \gamma$. The primal equilibrium approximation objective function discounts year $t < T$ terms at rate γ. To ensure that the two approximations can converge within an arbitrarily small ε at optimality, this formulation treats terms indexed with $t < T$ exactly as does the primal approximation. As in Walker [1995], define the additional variables $\boldsymbol{X}_\alpha = \sum_{t=T}^{\infty} \alpha^{t-T} \boldsymbol{X}_t$ for all variables $\boldsymbol{X}$.

The objective function (4.3), in the dual equilibrium approximation, becomes:

Minimize

$$\sum_{c,x} \sum_{t=1}^{T_0-1} \Delta_{t,0} d \left(BMAR_{cxt} + \sum_{y=1}^{k} DW_{cxyt} \right) + \sum_{c,x} \sum_{t=T_0}^{T-1} \Delta_{T_0,0} \gamma^{t-T_0} d \left(BMAR_{cxt} + \sum_{y=1}^{k} DW_{cxyt} \right)$$

$$+ \sum_{c,x} \Delta_{T_0,0} \gamma^{T-T_0} d \left(BMAR_{cx\alpha} + \sum_{y=1}^{k} DW_{cxy\alpha} \right)$$

$$+ \sum_{t=1}^{T_0-1} \Delta_{t,0} r LB_t + \sum_{t=T_0}^{T-1} \Delta_{T_0,0} \gamma^{t-T_0} r LB_t + \Delta_{T_0,0} \gamma^{T-T_0} r LB_\alpha$$

$$+ \sum_{c,x} cbwt_{cx} \left(\sum_{t=1}^{T_0-1} \Delta_{t,0} CBDEV_{cxt} + \sum_{t=T_0}^{T-1} \Delta_{T_0,0} \gamma^{t-T_0} CBDEV_{cxt} + \Delta_{T_0,0} \gamma^{T-T_0} CBDEV_{cx\alpha} \right)$$

$$+ \sum_{c,x} dbwt_{cx} \left(\sum_{t=1}^{T_0-1} \Delta_{t,0} DBDEV_{cxt} + \sum_{t=T_0}^{T-1} \Delta_{T_0,0} \gamma^{t-T_0} DBDEV_{cxt} + \Delta_{T_0,0} \gamma^{T-T_0} DBDEV_{cx\alpha} \right)$$

$$+ \sum_{c} pturwt_c \left(\sum_{t=1}^{T_0-1} \Delta_{t,0} PTURB_{ct} + \sum_{t=T_0}^{T-1} \Delta_{T_0,0} \gamma^{t-T_0} PTURB_{ct} + \Delta_{T_0,0} \gamma^{T-T_0} PTURB_{c\alpha} \right)$$

$$+\sum_c nturwt_c \left(\sum_{t=1}^{T_0-1} \Delta_{t,0} NTURB_{ct} + \sum_{t=T_0}^{T-1} \Delta_{T_0,0}\gamma^{t-T_0} NTURB_{ct} + \Delta_{T_0,0}\gamma^{T-T_0} NTURB_{c\alpha} \right) \tag{B.10}$$

Constraints (4.4–4.20) remain in force but only for $t \leq T-1$. Aggregating the remaining constraints with discounting, as in (B.5), produces the following additional constraints:

$$\left(1-(1+d)\frac{\alpha}{\gamma}\right) BMAR_{cx\alpha} = \frac{1+d}{\gamma} BMAR_{cx\,T-1} + DW_{cx0\alpha} - FC_{cx\alpha} \quad \forall\, c,\, x. \tag{B.11}$$

$$BMAR_{cx\alpha} \leq \frac{endc_{cxT}}{1-\alpha} + CBDEV_{cx\alpha} \quad \forall\, c,\, x. \tag{B.12}$$

$$\sum_{y=1}^{k} DW_{cxy\alpha} \leq \frac{endd_{cxT}}{1-\alpha} + DBDEV_{cx\alpha} \quad \forall\, c,\, x. \tag{B.13}$$

$$\frac{1+d}{\gamma} DW_{cx\,y+1\,T-1} + (1+d)\frac{\alpha}{\gamma} DW_{cx\,y+1\,\alpha} = DW_{cxy\alpha} + FD_{cx\alpha} \quad \forall\, c,\, x,\, y \leq k-1; \tag{B.14}$$

$$DW_{cxy\alpha} = \frac{\gamma^y}{1-\alpha} defer_{cx\,y+T} - FD_{cxy\alpha} \quad \forall\, c,\, x;\, y = k. \tag{B.15}$$

$$\sum_{c,i,y} FD_{ciy\alpha} + \sum_{c,x} FC_{cx\alpha} + \frac{1+r}{\gamma} LB_{T-1} \leq \frac{budget_T}{1-\alpha} + \left(1-(1+r)\frac{\alpha}{\gamma}\right) LB_{\alpha}. \tag{B.16}$$

$$FD_{ciy\alpha} = 0 \quad \forall\, c,\, i = \text{OTHER},\, y > 0. \tag{B.17}$$

$$FD_{ciy\alpha} \geq \frac{nondiscret_{cT}}{1-\alpha} \quad \forall\, c\, i = \text{OTHER},\, y = 0. \tag{B.18}$$

$$\begin{aligned} &\gamma^{-1}\underline{vary}\left(\sum_{i,y} FD_{ciy\,T-1}\right) - NTURB_{c\alpha} \\ &\leq (1-\frac{\alpha}{\gamma}\underline{vary})\left(\sum_{i,y} FD_{ciy\alpha} + \sum_x FC_{cx\alpha}\right) \quad \forall\, c; \end{aligned} \tag{B.19}$$

$$\begin{aligned} &(1-\frac{\alpha}{\gamma}\overline{vary})\left(\sum_{i,y} FD_{ciy\alpha} + \sum_x FC_{cx\alpha}\right) \\ &\leq \gamma^{-1}\overline{vary}\left(\sum_{i,y} FD_{ciy\,T-1} + \sum_x FC_{cx\,T-1}\right) + PTURB_{c\alpha} \quad \forall\, c. \end{aligned} \tag{B.20}$$

Differences between the objective function (B.10) and that appearing in the infinite horizon formulation follow directly from the substitution of variables $\boldsymbol{X}_\alpha$ for $\{\boldsymbol{X}_T, \boldsymbol{X}_{T+1}, \ldots\}$.

C. CONVERGENCE FOR POM-98 DATA

Applying the preceding formulations to the data the Navy used in preparing the 1998-2003 POM shows that the primal and dual equilibrium optimal objective function

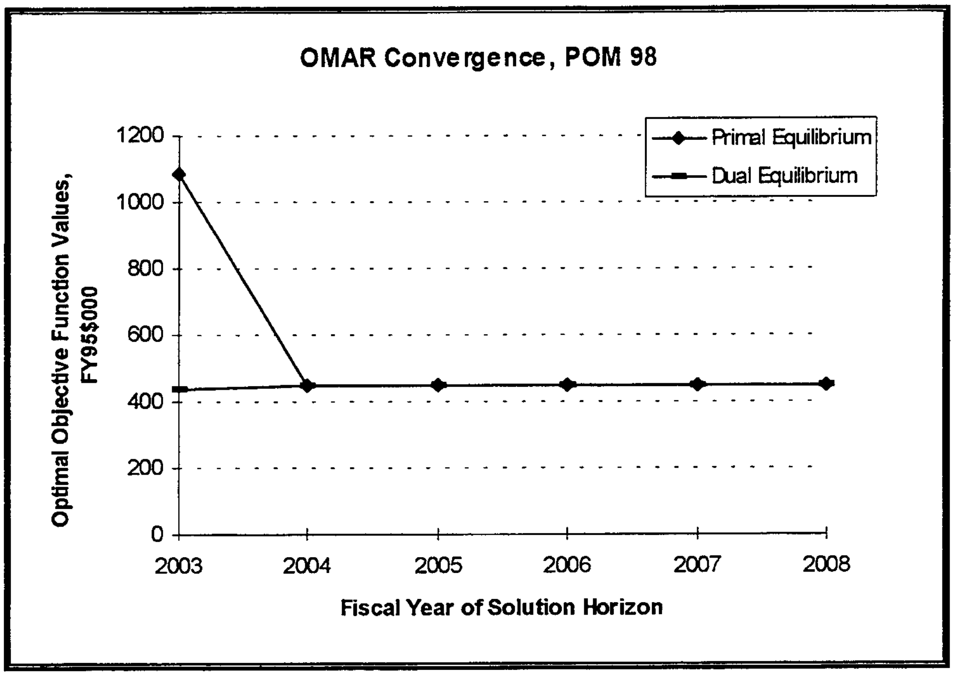

Figure B.1. Performance of OMAR primal and dual equilibrium approximations for the 1998 POM data set. In this instance, the two objective functions converge to the same value only one year beyond the end of the decision horizon.

values converge for solution horizons T in excess of nine years (ending in 2004), only one year beyond the desired length of the decision horizon. These objective function values appear in Figure B.1. While extending the solution horizon beyond the point of convergence of primal and dual equilibrium approximations yields the same optimal objective function value, the funding recommendations for the final two or three years continue to change. In practice, we discover that the alternate optima corresponding to longer solution horizons tend to produce more reasonable funding recommendations.

APPENDIX C. LIST OF ACRONYMS

AIS	Annual Inspection Summary
BASEREP	Shore Base Readiness Report
BMAR	Backlog of Maintenance and Repair
BRAC	Base Realignment and Closure
BUPERS	Bureau of Naval Personnel
CCB	Construction Criteria Base
CEC	Civil Engineer Corps
CNET	Chief of Naval Education and Training
CNO	Chief of Naval Operations
COBRA	Cost of Base Realignment Actions
CPMS	Capital Program Management System
CPV	Current Plant Value
CUPB	Commercial Unit Price Book
DBOF	Defense Business Operating Fund
DoD	Department of Defense
DoN	Department of the Navy
EFA	Engineering Field Activity
EFD	Engineering Field Division
FCG	Facility Category Group
FH,N	Family Housing, Navy
FLEP	Facilities Life Extension Program
GAMS	General Algebraic Modeling System
HQMC	Headquarters, United States Marine Corps
IBR	Investment Balance Review
IC	Investment Category
ISR	Installation Status Report
LANTFLT	US Atlantic Fleet
LINPAC	Linear programming for alternative comparison
LRMP	Long Range Maintenance Plan(ning)
M&R	Maintenance and Repair
MACOM	Major Army Command
METOC	Naval Meteorology and Oceanography Command
MRPM	Maintenance Resource Prediction Model
MRRP	Maintenance and Repair of Real Property
NAVAIR	Naval Air Systems Command
NAVEUR	US Naval Forces Europe
NAVINTEL	Naval Intelligence Command
NAVFAC	Naval Facilities Engineering Command
NAVSEA	Naval Sea Systems Command
NAVSUP	Naval Supply Systems Command
NCTC	Naval Computers and Telecommunications Command
NFADB	Naval Facilities Assets Database

NOS	Network Optimization System
O&M,MC	Operations and Maintenance, Marine Corps
O&M,N	Operations and Maintenance, Navy
OPNAV	Office of the Chief of Naval Operations
PACFLT	US Pacific Fleet
PHOENIX	Army helicopter fleet optimization model
POL	Petroleum, Oil, and Lubricants
POM	Program Objective Memorandum
PPBS	Planning, Programming, and Budgeting System
PRV	Plant Replacement Value
PWC	Navy Public Works Center
PWD	Navy Public Works Detachment
RDT&E	Research, Development, Testing, and Evaluation
RPM	Real Property Maintenance
SA	Support Area
S&I	Support & Infrastructure
SECGRU	Naval Security Group
SPAWAR	Naval Space and Warfare Systems Command
SPP	Sponsor Program Proposal
SSP	Strategic Systems Program
USMA	United States Military Academy
WBS	Work Breakdown Structure

APPENDIX D. BACKLOG, FUNDING, AND CPV DATA

This appendix contains the data used to produce the results presented in Chapter IV. It was provided by N44 and Headquarters, NAVFAC.

		CPV by Shore FLEP Priority, 1995$M					
Claimant	Total CPV	High	Percent	Medium	Percent	Low	Percent
CNET	7,392.0	4,636.6	63.7	1,070.6	14.5	1,687.8	23.8
CNO	4,069.6	2,867.8	70.5	446.2	11.0	756.5	19.6
LANTFLT	11,924.2	6,705.8	56.2	2,562.4	21.5	2,657.0	22.3
METOC	67.5	20.0	30.0	0.5	1.7	46.0	69.2
NAVAIR	884.7	352.4	40.9	331.0	37.4	200.4	23.7
NAVEUR	850.3	517.3	61.8	236.1	28.8	97.8	11.4
NAVFAC	970.1	442.6	46.5	88.5	9.0	441.9	45.5
NAVSEA	2,897.8	1,238.1	43.7	959.7	33.1	700.0	24.2
NCTC	1,296.9	919.4	71.9	45.2	3.5	331.3	26.6
PACFLT	13,681.8	7,488.6	55.7	3,189.7	23.3	3,004.5	22.0
SSP	584.1	171.5	29.2	281.7	48.1	133.8	23.7
TOTAL	44,613.0	25,354.3	57.8	9,207.6	21.6	10,052.1	23.5

Table D.1. 1995 O&M,N CPV by major claimant and Shore FLEP priority, taken from the 1995 Naval Facilities Assets Database with guidance from HQ, NAVFAC. Subtotals shown do not include property the NFADB indicated was non-Navy real property, because these properties are not reported in ICs 1–18 on the AIS. They do, however, include properties with excess codes 1-3, meaning the property could have been declared excess and therefore not be reportable on the AIS as requiring critical M&R. The differences in the proportions shown are not significant.

Year	Index
1995	1.00000
1996	1.02393
1997	1.04947
1998	1.07571
1999	1.09998
2000	1.12411
2001	1.14889
2002	1.17400
2003	1.19967

Table D.2. Inflation indices for the O&M,N appropriation with base year 1995. Source: N44.

Claimant	01	02	03	04	05	06	
			Investment Category				
CNET	12,390	40	7,004	1,485	35,198	15,857	
CNO	4,219	3,719	10,185	1,095	55,922	0	
LANTFLT	50,016	4,160	53,100	12,281	13,898	71,534	
METOC	3	0	0	0	1,020	0	
NAVAIR	141	5	747	10	2,246	3,660	
NAVEUR	6,393	823	1,032	2,629	663	4,342	
NAVFAC	34	6	1,785	208	240	0	
NAVSEA	0	5	19,015	456	1	0	
NCTC	0	5,254	2,501	102	0	0	
PACFLT	26,084	1,540	99,685	13,796	8,596	24,208	
SSP	0	25	3,169	169	0	0	
Total	99,280	15,577	198,223	32,231	117,784	119,601	
Claimant	07	08	09	10	11	12	
CNET	82	1,306	0	107	1	1,844	
CNO	152	7,478	0	90	24	2,882	
LANTFLT	8,161	10,008	818	1,004	2,558	11,643	
METOC	0	9	2,290	164	0	2	
NAVAIR	0	26	237	110	0	223	
NAVEUR	0	4,646	0	146	554	1,823	
NAVFAC	392	3,888	68	22	0	5,006	
NAVSEA	1,102	3,913	5	250	2	3,751	
NCTC	0	481	0	134	16	698	
PACFLT	8,009	12,359	448	14	13,387	12,251	
SSP	0	1,686	914	0	562	102	
Total	17,898	45,800	4,780	2,041	17,104	40,225	
Claimant	13	14	15	16	17	18	Total
CNET	1,669	32,649	135,365	17,668	10,219	13,301	286,185
CNO	3,501	58,811	175,786	29,503	65,354	38,214	456,935
LANTFLT	3,468	35,018	92,038	47,565	74,232	33,650	525,152
METOC	0	2,920	68	6	796	750	8,028
NAVAIR	138	2,262	7,675	5,568	473	378	23,899
NAVEUR	517	6,788	21,518	8,524	12,416	2,722	75,536
NAVFAC	32	3,758	3,942	3,397	12,006	22,108	56,892
NAVSEA	46	3,597	15,938	2,687	270	40	51,078
NCTC	103	435	2,410	2,159	7,433	2,605	24,331
PACFLT	3,461	17,082	127,529	59,138	27,058	25,591	480,236
SSP	0	13,362	442	474	663	2,466	24,034
Total	12,935	176,682	582,711	176,689	210,920	141,825	2,012,306

Table D.3. O&M,N critical backlog in FY1995 thousands of dollars by major claimant and investment category. Source: N44 [1995b].

Claimant	01	02	03	04	05	06	
	Investment Category						
CNET	9,898	276	6,953	2,042	16,393	17,935	
CNO	267	184	8,717	2,437	28,312	182	
LANTFLT	40,084	2,882	39,211	13,317	21,507	22,710	
METOC	0	0	0	0	0	0	
NAVAIR	2,517	77	4,797	155	4,027	5,928	
NAVEUR	3,672	172	598	838	101	437	
NAVFAC	6	27	1,110	293	877	0	
NAVSEA	0	8	2,026	301	2,568	1	
NCTC	0	2,969	512	110	37	0	
PACFLT	23,583	1,448	56,926	7,839	7,480	16,159	
SSP	0	172	5,097	794	0	0	
Total	80,027	8,215	125,947	28,126	81,302	63,352	
Claimant	07	08	09	10	11	12	
CNET	93	7,113	8	367	243	7,984	
CNO	197	1,356	0	0	2	1,799	
LANTFLT	11,643	16,462	1,447	1,820	3,676	20,376	
METOC	0	0	0	0	0	0	
NAVAIR	0	481	435	0	435	774	
NAVEUR	0	1,466	0	2,524	165	2,837	
NAVFAC	70	1,402	2	6	22	1,552	
NAVSEA	427	1,839	371	272	209	2,828	
NCTC	0	696	15	29	0	313	
PACFLT	7,108	12,714	650	351	18,190	14,733	
SSP	230	1,191	1,452	0	40	318	
Total	19,768	44,720	4,380	5,369	22,982	53,514	
Claimant	13	14	15	16	17	18	Total
CNET	749	13,629	129,076	24,681	6,427	27,797	271,664
CNO	2	21,312	4,716	10,815	13,640	7,442	101,380
LANTFLT	10,885	29,931	199,209	68,918	31,326	33,741	569,145
METOC	0	813	55	0	5	713	1,586
NAVAIR	705	2,527	5,067	5,178	5,520	3,425	42,048
NAVEUR	59	9,880	13,670	5,715	3,800	1,535	47,469
NAVFAC	105	8,382	1,870	2,656	1,919	8,839	29,138
NAVSEA	508	2,640	6,760	10,654	1,253	1,958	34,623
NCTC	10	348	1,124	1,558	5,546	4,476	17,743
PACFLT	995	12,815	80,166	40,645	21,307	45,838	368,947
SSP	0	374	0	682	236	211	10,797
Total	14,018	102,651	441,713	171,502	90,979	135,975	1,494,540

Table D.4. Deferrable backlog in FY1995 thousands of dollars by major claimant and investment category. Source: AIS reports provided by N44. Calculations in Chapter IV assume that these totals represent present worth of all deferrable project costs over a five year span, and that equal amounts occur in each year.

Claimant	IC OTHER
CNET	21,529
CNO	11,634
LANTFLT	45,639
METOC	333
NAVAIR	5,154
NAVEUR	10,251
NAVFAC	49,955
NAVSEA	8,113
NCTC	997
PACFLT	31,193
SSP	999

Table D.5. MRRP claimant execution totals for IC OTHER in fiscal year 1995 thousands of dollars. Source: N44. These figures were used in Chapter IV computations as annual "nondiscretionary" amounts required by each claimant, adjusting for inflation, in each of the subsequent years.

Major	Fiscal Year								
Claimant	1995	1996	1997	1998	1999	2000	2001	2002	2003
CNET	122,648	124,032	92,982	93,415	104,471	134,896	139,577	157,259	169,500
CNO	83,464	95,537	89,643	98,432	103,583	81,035	77,670	84,700	76,482
LANTFLT	243,927	221,955	219,673	186,002	188,197	244,558	263,141	299,041	331,321
METOC	3,967	6,402	4,925	5,030	5,905	6,056	6,913	6,827	6,531
NAVAIR	29,319	28,724	24,222	26,585	25,208	26,141	29,245	33,741	37,223
NAVEUR	31,412	56,839	41,355	43,301	36,823	49,396	51,334	54,716	55,885
NAVFAC	54,747	35,968	24,729	33,677	37,296	38,293	45,046	68,231	75,855
NAVSEA	35,440	34,541	27,120	24,042	27,020	26,292	25,981	32,197	35,284
NCTC	11,563	23,120	11,189	9,670	8,287	7,655	9,988	7,723	6,095
PACFLT	252,674	282,779	229,219	231,157	214,151	249,590	337,569	339,064	369,877
SSP	11,292	16,491	14,547	13,783	14,790	15,381	15,682	16,003	16,358
Subtotal	880,453	926,388	779,604	765,094	765,731	879,293	1,002,146	1,099,502	1,180,411
BUPERS	0	8,747	9,377	0	0	0	0	0	0
NAVSUP	1,065	5,821	4,916	5,459	6,314	6,705	7,043	7,194	7,346
SPAWAR	1,138	1,243	1,035	996	1,252	1,389	1,700	1,739	1,782
SECGRU	5,283	2,307	3,609	1,520	1,441	1,457	1,502	1,533	1,566
OTHER	0	0	0	0	0	0	5,500	111,100	97,700
Total	887,939	944,506	798,541	773,069	774,738	888,844	1,017,891	1,221,068	1,288,805

Table D.6. MRRP totals by major claimant and fiscal year, in then-year thousands of dollars. Source: N44. Subtotals indicate the major claimants and annual budgets used in the calculations of Chapter IV.

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