Optimizing a Portfolio Approach to Improve Condition Index and Sustain Critical U.S. Coast Guard Facilities

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Dedication

I dedicate this to my loving family whose unwavering support and encouragement have inspired me throughout this journey. To my wife Alaina, thank you for your patience, flexibility, and accommodations during this academic pursuit which impacted vacation schedules, social events, and consumed many nights and weekends.

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Abstract of Praxis

Optimizing a Portfolio Approach to Improve Condition Index and Sustain Critical U.S. Coast Guard Facilities

The United States Coast Guard manages and maintains a vast network of shore infrastructure assets, comprising 43,550 assets across 3,320 sites, with an estimated value of over $27 billion dollars. However, years of inadequate investments have produced a backlog of shore infrastructure projects in excess of $3 billion dollars. Based on historical funding appropriations, the Coast Guard said it would take approximately 395 years to address this backlog (GAO-19-82, 2019). One of the key issues contributing to this backlog has been not considering life cycle costing in infrastructure planning. Overall, operation and maintenance expenses comprise 60% to 80% of a facility's overall life cycle cost. Although significant progress has been made in this area, the Coast Guard still must address the billions of dollars in deferred backlogged projects. This capability gap exacerbates facility degradation, shortens service life, and increases future repair costs.

The U.S. Coast Guard lacks an optimized, data-driven approach prioritizing maintenance activities for critical shore infrastructure assets. Such an approach is crucial for combating the compounding effects of facility degradation, mitigating operational impact, and operating efficiently within resource constraints. In this environment, investments must be allocated based on need, as determined by facility key performance indicators (KPIs) like the condition index. Furthermore, due to the Coast Guard's crucial role in national security, these investments must consider KPIs reflecting the criticality of each asset concerning mission execution and operational readiness. This intersection of

mission essentiality, mission dependency, and facility needs is critical to operational readiness within a resource constrained environment.

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List of Acronyms

A	Alteration
API	Asset Priority Index
ASCE	American Society of Civil Engineers
AtoN	Aids to Navigation
BCA	Business Case Analysis
C	Code Compliance
CBA	Cost Benefit Analysis
CCI	Comprehensive Condition Index
CEM	Civil Engineering Manual
CEU	Civil Engineering Unit
CG-43	Office of Civil Engineering, United States Coast Guard
CG-TIMS	Coast Guard Technology Information Management System
CI	Condition Index
CMMS	Computerized Maintenance Management System
D	Demolition
DHS	Department of Homeland Security
DLM	Depot Level Maintenance

DLM&R	Depot Level Maintenance & Repair
DOD	Department of Defense
DOI	Department of Interior
DOT	Department of Transportation
EC&R	Environmental Compliance & Restoration
FCA	Facility Condition Assessment
FDCC	Facilities Design & Construction Center
FI	Functionality Index
FRMM	Financial Resource Management Manual
FRPC	Federal Real Property Council
FRPP	Federal Real Property Profile
FY	Fiscal Year
GAO	Government Accountability Office
HIDI	Highway Information Database Integration
I	Improvement
IGCE	Independent Government Cost Estimate
IIJA	Infrastructure Investment & Jobs Act
ILP	Integer Linear Programming

ISO	International Organization for Standardization
KPI	Key Performance Indicators
LCC	Life Cycle Costing
M	Maintenance
M&R	Maintenance & Repair
MACID	Maintenance, Alteration, Compliance, Improvement, Demolition
MAVT	Multi-Attribute Value Theory
MC	Minor Construction
MCDA	Multi-Criteria Decision Analysis
MDI	Mission Dependency Index
MDP	Markov Decision Process
MEI	Mission Essentiality Index
MILCON	Military Construction
MOO	Multi-Objective Optimization
NI	Needs Index
NRC	National Research Council
NSGA	Nondominated Sorting Genetic Algorithm
O&S	Operations & Support

OLM	Organizational Level Maintenance
OLM&R	Organizational Level Maintenance & Repair
OMB	Office of Management & Budget
ORI	Operational Readiness Index
PC&I	Procurement, Construction, and Improvement
PRV	Plant Replacement Value
RAMPSS	Rapid Asset Modeling of Pavement Sustainment Challenges
RBB	Requirements Based Budget
RIK	Replacement In Kind
ROM	Rough Order of Magnitude
SAMS	Shore Asset Management System
SI	Stewardship Index
SILC	Shore Infrastructure & Logistics Center
SIVA	Shore Infrastructure Vulnerability Index
SMDP	Semi-Markov Decision Process
SMS	Sustainment Management System
SUI	Space Utilization Index
TDOT	Texas Department of Transportation

UFC	Unified Facilities Code
USACE	United States Army Corps of Engineers
USCG	United States Coast Guard
VUCA	Volatile, Uncertain, Chaotic, Ambiguous
WF	Worst First

List of Symbols

AL_m	added life
β_{pm}	added life for treatment option
$C_{c,p}$	current cost of project *p*
C_m	repair costs
$C_{o,p}$	original cost of project *p*
CAL_m	ratio of repair cost to added life
CCI_i	comprehensive condition index for asset *i*
CI_i	condition index for asset *i*
CS_b	condition score prior to repair
CS_{net}	threshold condition score (e.g. 70)
CS_{pm}	estimated condition score post repair
DM_i	deferred maintenance, expressed in dollars, associated with asset *i*
$DM_{ALT,i}$	deferred alterations, expressed in dollars, associated with asset *i*
$DM_{CC,i}$	deferred code compliance, expressed in dollars, associated with asset *i*
$DM_{ENV,i}$	deferred environmental work, expressed in dollars, associated with asset *i*

$DM_{IMP,i}$	deferred improvements, expressed in dollars, associated with asset *i*
$DM_{MISC,i}$	deferred miscellaneous needs, expressed in dollars, associated with asset *i*
$DM_{MR,i}$	deferred maintenance and repair, expressed in dollars, associated with asset *i*
e_{im}	pavement condition improvement *i* for treatment *m*
i	asset
L_1	length of pavement (miles) in pavement section *i*
$MD_{b,i}$	mission inter-dependency associated with asset *i*
$MDI_{AVG,i}$	final mission dependency index for asset *i*
MDI_i	mission dependency index for asset *i*
$MDI_{O,i}$	operational mission dependency index for asset *i*
$MDI_{S,i}$	strategic mission dependency index for asset *i*
$MDI_{T,i}$	tactical mission dependency index for asset *i*
$MD_{w,i}$	mission intra-dependency associated with asset *i*
n	number of mission interdependencies associated with asset *i*
n	number of attributes

n	compounding period (years)
N_1	# of lanes in pavement section *i*
p_{pm}	curve parameters for traffic level
PB_{2017}	completed projects between start of FY 2018 and end of FY 2022
PB_{FY18}	project backlog starting in fiscal year 2018 (October 1, 2017)
PB_{FY22}	project backlog at conclusion of fiscal year 2022 (September 20, 2022)
PRV_i	plant replacement value, expressed in dollars, for asset *i*
r	rate of inflation (Consumer Price Index 10 year average of 2.49%)
SA_i	space allocated for asset *i*
SR_i	space required for asset *i*
SUI_i	space utilization index for asset *i*
$v(x)$	MAVT function
v_i	normalized value for asset *i*
$v_i(x_i)$	normalized single attribute value function of x_i
$v_{CC,i}$	normalized core capabilities for asset *i*
$v_{HC,i}$	normalized hazard condition for asset *i*
$v_{MDI,i}$	normalized mission dependency index for asset *i*

$v_{MU,i}$	normalized mission uniqueness for asset *i*
w_i	attribute (x_i) weight
$x_{CCF,i}$	area cost factor for asset *i*
$x_{CF,i}$	contingency factor (typically 1.05) for asset *i*
$x_{FQ,i}$	facility quantity (i.e. square feet) for asset *i*
$x_{HF,i}$	historical factor (typically 1.05) for asset *i*
x_{imt}	binary decision (0 or 1) to associate a treatment *m* for pavement section *i*
$x_{INF,i}$	inflation for asset *i*
$x_{LF,i}$	locality factor for asset *i*
$x_{PDF,i}$	planning and design factor (typically 1.09) for asset *i*
$x_{SIOH,i}$	supervision, inspection, and overhead (typically 1.057) for asset *i*
Z_1	condition score improvement for pavement section *i*

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Chapter 1: Introduction

1.1 Background

Operating and maintaining shore facilities, to include buildings and structures, constitute 60–80% of a facility's life-cycle cost (National Academies of Sciences, 1998). As shore facilities age, subsystems within these facilities reach their life expectancies and require recapitalization. At this point, core building components require improvements to remain functional, and building spaces quickly become antiquated and require renovation and upgrades to remain productive and habitable. These costs account for an additional 10-20% of the facility's overall life cycle cost. When combined with the costs of building operation and maintenance, recapitalization and improvement efforts contribute to a total of 70-90% of the facility's life cycle expenses. This clearly demonstrates that the majority of costs associated with shore facilities occur after the initial acquisition and construction phases.

The U.S. Coast Guard resembles every other agency in the federal government and military sector regarding funding gaps for facility sustainment needs. Facility sustainment budgets are routinely underfunded and historically underestimated, increasing deferred maintenance backlogs over time. Although current investment decisions incorporate life-cycle costs and assessment (cradle-to-grave analysis), thousands of facilities predate these considerations, so budgets for sustaining these facilities must compete against budgets for new initiatives and efforts across the federal government. Furthermore, many facilities have exceeded their design lives but continue to be utilized, necessitating more capital to remain operational and habitable.

This challenge has been the topic of significant research by industries and the government to optimally use limited funding within a portfolio of competing assets. Each of the latter has varying levels of operational, maintenance, recapitalization, and modernization needs. To this end, numerous methodologies have been tested to improve investment decisions, with numerous indices used to measure performance based on varying parameters of a facility's importance, condition, and sustainability needs. Therefore, this literature review highlights these various methodologies and indices, as well as the budgetary policies and regulations that govern project funding and execution.

1.2 Problem Statement

The U.S. Coast Guard lacks an optimized, data-driven approach that prioritizes maintenance activities associated with critical facility management to combat facility degradation, mitigate operational impact, and optimally operate in a resource-constrained environment.

The U.S. Coast Guard needs a data-driven approach to optimally prioritize maintenance activities associated with critical facility management. Selecting optimal activities within a resource constrained environment could prevent future costly replacement (vice repair) projects, maximize a facility's condition index, and reduce the growth rate of the corrective maintenance backlog (Weeks & Leite, 2021).

1.3 Thesis Statement

A mathematical optimization model to rank order maintenance and repair activities would improve condition indices for critical U.S. Coast Guard facilities.

Failure to execute critical maintenance and repair activities results in long-term compounding failures, associated increased costs of repair, and diminished facility lifespans impedes the U.S. Coast Guard's operational mission, creating enterprise gaps from inconsistent, unequal investment (Synovec & Howard, 2021). Thus, ranking maintenance and repair activities (projects) facilitates optimal budget allocation based on existing approved projects associated with existing critical facilities.

1.4 Research Objectives

- *Generate an asset priority hierarchy based on asset criticality.*
- *Generate a prioritized listing of projects based on asset criticality.*
- *Construct a built model that is transparent, repeatable, and trustworthy.*
- *Analyze the Depot-Level Maintenance and Repair (DLM&R) backlog and identify trends.*
- *Focus on the condition index but analyze other indicators and their importance to facility asset management.*
- *Gain expert knowledge of existing prioritization techniques.*

1.5 Research Scope

In this study, all data is taken from the U.S. Coast Guard's computerized maintenance management system (CMMS) for shore facilities, referred to as the Shore Asset Management System (SAMS) and was masked and scrubbed entirely. These SAMS datasets include the depot-level maintenance and repair (DLM&R) project backlog and the Coast Guard's location portfolio dataset. The scope includes significant data analysis through data wrangling techniques to merge, sort, and associate features of

each dataset, necessary before creating the optimization model and applying constraints and thresholds.

1.6 Research Assumptions and Bounds

This research assumes accuracy of SAMS data for DLM&R projects and locations. Policy interpretations are described in the publicly available U.S. Coast Guard Financial Resource Management Manual (FRMM) and Civil Engineering Manual (CEM) formed the basis of constraints utilized in the optimization model.

This research examines prioritizing DLM&R projects associated with critical facilities. Condition index calculations and analysis are based on 9,936 projects valued at $2.204B that constituted the DLM&R backlog as of September 30, 2022. Organizational Level Maintenance and Repair (OLM&R) and Procurement, Construction, and Improvement (PC&I) projects are not considered in this research since each category of projects has separate funding streams, funds authorities, and oversight. Additionally, DLM&R constitutes the majority of the deferred maintenance backlog concerning costs and project quantity.

1.7 Research Questions and Hypotheses

1.7.1 Hypothesis 1 (Thesis) and Results

By what percentage will an optimization model improve the condition index against fiscal year (FY) 2018 baseline conditions?

Hypothesis: The optimization model will improve the condition index by at least 10% from the FY 2018 baseline conditions.

1.7.2 Hypothesis 2 and Results

By what percentage will an optimization model improve the condition index against actual FY 2022 conditions?

Hypothesis: The optimization model will improve the condition index by at least 5% from the actual FY 2022 conditions.

1.7.3 Hypothesis 3 and Results

What is the percent variance in project count between the optimized project selection and the actual project selection between the start of FY 2018 and the conclusion of FY 2022?

Hypothesis: The percent variance between an optimized and actual selection of projects between the beginning of FY 2018 and the conclusion of FY 2022 will be 10%.

1.7.4 Hypothesis 4 and Results

What is the regional variance between an optimized selection of projects and the actual selection of projects from the beginning of FY 2018 to the conclusion of FY 2022?

Hypothesis: The regional variance between an optimized selection of projects and the actual selection of projects will be within 25% by area and 15% by region from the beginning of FY 2018 to the conclusion of FY 2022.

1.7.5 Hypothesis 5 and Results

What is the regional execution impact for an optimized selection of projects compared to the actual selection of projects between the start of FY 2018 and the conclusion of FY 2022?

Hypothesis: The regional execution impact for an optimized selection of projects compared to the actual selection of projects between the start of FY 2018 and the conclusion of FY 2022 is within 20% for each Civil Engineering Unit.

1.8 Research Motivation

Overall, U.S. Coast Guard decision-makers need a data-driven technique that is complex enough to account for the various business rules and policy requirements of the federal government but transparent enough for these decision-makers to gain trust in the process. Otherwise, a capability gap will continue to exist within the management of critical shore infrastructure, incurring significant costs and impacting future operations. The Coast Guard continues innovating and evaluating its business processes, but the nature of the organizational capability trap inhibits progress, necessitating an alternate approach that can be defended and readily adopted, yielding immediate results. Thus, the model's outcome must be practical and transparent.

1.9 Praxis Overview

This praxis comprises five chapters, beginning with the Introduction in Chapter 1. Each chapter focuses on a specific research phase to reach the study objectives and the research questions.

Next, Chapter 2 explores a literature review on facility asset management, particularly evaluating challenges of the United States federal government and policies and procedures that dictate shore infrastructure investments for the United States Coast Guard. Chapter 2 also explores government and industry key performance indicators used to measure performance and define asset criticality hierarchy, and highlights literature

specific to decision-making methodologies used to prioritize assets and projects, drive investment decisions, and categorize shore infrastructure assets.

Chapter 3 examines the methodology used to gather, process, and analyze data for a mathematical multi-objective optimization model. This section summarizes the U.S. Coast Guard's shore infrastructure data, categorizing it by location and project features, including a baseline analysis of the Coast Guard's shore facility portfolio used to benchmark against the optimized approach. Beyond this, Chapter 3 describes the mathematical optimization model formulation to include the objective function, decision variables, constraints, and various asset and location characteristics, as well as the optimization construction using the R programming language.

Chapter 4 summarizes the results and analysis of the mathematical optimization model constructed in R Studio and compares the results derived from the model to those of the baseline conditions described in Chapter 3. Additionally, Chapter 4 analyzes the results of the five research questions from Chapter 1, as well as their associated hypotheses, and systematically describes the procedures used to validate the optimization model and perform a sensitivity analysis.

Chapter 5 concludes the praxis report by summarizing the results and conclusions obtained from the research and the contributions to the field of knowledge within the engineering management discipline. Lastly, Chapter 5 offers future research opportunities based on the results of this praxis that should be explored for both the U.S. Coast Guard and the engineering management discipline of study at large.

Chapter 2: Literature Review

2.1 Introduction

This section explores the extensive research in the field of engineering management on the resource gaps in the federal facility portfolio that have created capability gaps for U.S. infrastructure. Additionally, this study examines the governing federal investment policies and resourcing business rules dictating federal asset management, emphasizing the U.S. Coast Guard, and existing methodologies and research used to prioritize assets and projects.

Section 2.2 describes the magnitude and condition of the federal government's shore infrastructure portfolio. Section 2.3 details the federal management policies and procedures governing investment strategies, including the U.S. Coast Guard's governance model for asset and project selection. Next, Section 2.4 clarifies the business rules that dictate U.S. Coast Guard decision-making for investment and project selection. Section 2.5 expounds on key performance indicators in the field of facility asset management used to measure infrastructure performance and criticality. Section 2.6 describes the decision-making methodologies used to prioritize assets and projects using key performance indicators and other metrics. Lastly, Section 2.7 concludes the literature review with a brief discussion on the field of facility asset management within the greater engineering management portfolio.

2.2 Federal Shore Infrastructure Portfolio

2.1.1 Asset Overview

The U.S. federal government's shore infrastructure portfolio consists of 911,000 assets, comprised of land, buildings, and structures (National Academies of Sciences,

2012). Nearly 60% of the federal government's shore infrastructure portfolio, or 550,000 assets, constitute Department of Defense assets valued at $1.3 trillion (United States Government Accountability Office (GAO), 2022). The last 50 years have produced a steady decline in infrastructure investment in the United States, from what was valued at 5% of the total Gross Domestic Product (GDP) in the 1960s, decreased to 2.5% in the 1990s, and current data suggests 2% investment levels today (Arif, Bayraktar, & Chowdhury, 2016). This lack of investment has exacerbated the likelihood of failure, increased future costs of maintenance and repair, and yielded a burdensome portfolio of failing infrastructure to manage, while competing for limited resources to restore capabilities (Arif, Bayraktar, & Chowdhury, 2016).

In 2021, the American Society of Civil Engineers' (ASCE) issued an Infrastructure Report Card characterizing the state of U.S. infrastructure as a C-, saying that the United States must invest $4.59 trillion dollars in infrastructure by 2025 to prevent further degradation (Mouio, 2017). This grade encompasses condition assessments and remaining service lives of roads, bridges, and utility infrastructure.

		FY 2016			
		Owned	Leased	Otherwise Managed**	Total
Buildings	Total Number	232,419	19,404	15,304	267,127
	Total Square Feet	2,368,129,721	280,103,254	122,135,363	2,770,368,339
	Total Annual Operating Costs	$11,507,899,223	$7,284,160,244	$514,369,635	$19,306,429,102
Structures	Total Number	415,146	3,449	77,579	496,174
	Total Annual Operating Costs	$6,230,950,083	$59,135,377	$95,998,804	$6,386,084,265
Land* **	Total Acres	19,602,337	1,328,020	21,413,159	42,343,516
	Total Annual Operating Costs	$124,878,776	$50,728,233	$180,546	$175,787,555
AOC** **	Total Annual Operating Costs (Buildings, Structures, Land)	$17,863,728,082	$7,394,023,854	$610,548,985	$25,868,300,921

Table 2.1 - Federal Government Annual Operating Costs

(Office of Government-wide Policy)

Operating costs include the funding necessary for utility services, maintenance and repair, and janitorial services (National Academies of Sciences, 2023). In 2016, the U.S. government spent $26B to operate its shore portfolio, as indicated in Table 2.1 and obtained through open-sourced Government Accountability Office (GAO) data. The U.S. federal government averages $38B annually for major construction and recapitalization efforts. This number includes all congressionally appropriated budgetary line items for shore infrastructure, such as Department of Defense (DoD) Military Construction (MILCON) and Procurement, Improvement, and Construction (PC&I) funding utilized by the U.S. Coast Guard.

2.1.2 Asset Condition

The estimated plant replacement value of the DoD's shore infrastructure portfolio is $1.3T. As of 2020, 30% of all DoD facilities had exceeded their lifespans, with an incurred deferred maintenance backlog in excess of $137B dollars, a 36% increase to the DoD's 2016 backlog valued at $100B (United States Government Accountability Office (GAO), 2022).

Similarly, in 2020, the Department of Transportation reported that 18.7% of all roads, 7.3% of all bridges, and 58% of all train stations were in unsatisfactory condition (U.S. Bureau of Transportation Statistics, 2022) and the Department of the Interior reported a $16.4B deferred maintenance backlog across its $300B shore infrastructure portfolio, constituting 20% of all land in the United States. (Department of the Interior, 2019).

The Department of the Air Force reported a $33B deferred maintenance backlog across its $280B shore infrastructure portfolio. The Honorable John Henderson, current

Assistant Secretary of the Air Force for Installations, Environment, and Energy, testified to the U.S. House of Representatives Armed Services Committee on the need to "*embrace a cost-effective infrastructure investment approach, to save billions of dollars over the next 30 years through targeted infrastructure investments, and reinvest these savings to buy-down maintenance backlog and improve installation resilience*." (Henderson, 2019).

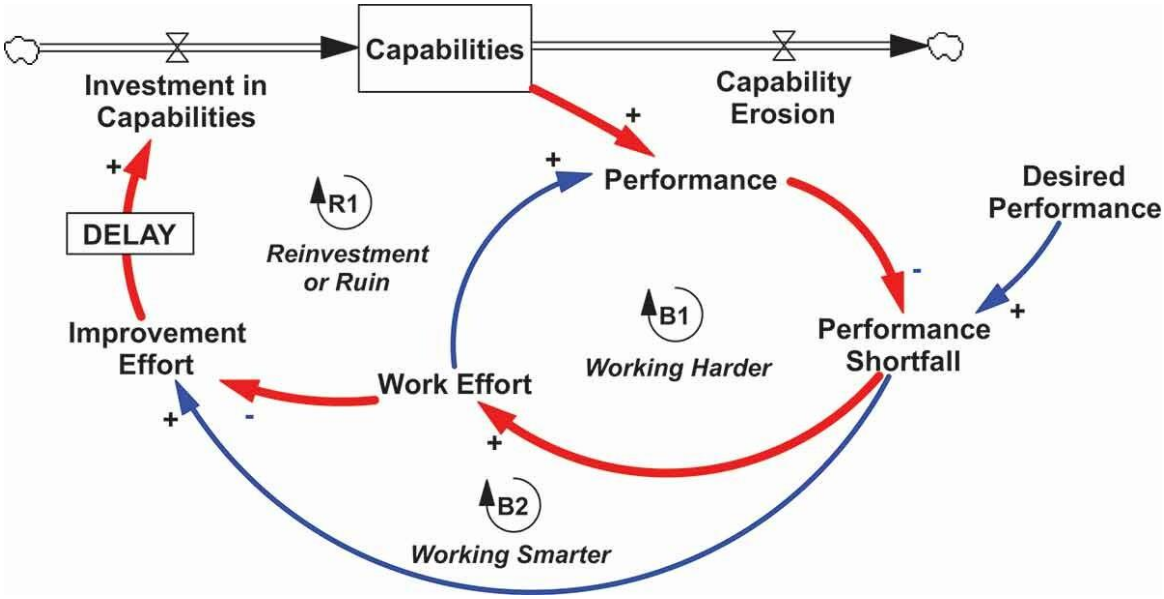

Figure 2.1 - Performance and Feedback Capability

(Repenning & Sterman, 2001)

The Air Force expects its deferred maintenance backlog to triple between 2019 and 2049 unless investment and resource allocation strategies improve (Synovec & Howard, 2021). Figure 2.1 above, obtained with the author's permission, speaks to the challenges faced by the U.S. Air Force and other federal entities, and depicts the investment gaps prevalent in organizations while highlighting the organizational ramifications that arise from delayed investments. These consequences not only affect

current capabilities and performance, but also diminish the likelihood of achieving future desired capabilities and performance objectives.

2.3 Facility Management

2.3.1 Federal Policy and Regulation

In 2004, the Federal Real Property Council (FRPC) was established under Executive Order 13327 to provide agency direction on real property asset management pertaining to planning, budgeting, prioritizing, and accounting for real property assets (Executive Order 13327 , 2004). Specifically, this agency direction was achieved by creating a Federal Real Property Profile Management System (FRPP MS) to track numerous facility metrics, including replacement value, repair needs, annualized operations, and maintenance costs. However, the FRPP MS did not provide agency guidance pertaining to investment decisions (Federal Real Property Council, 2022).

In 2016, the FRPC was codified into federal law under the Federal Property Management Reform Act (Public Law 114-318) to guide federal agencies through strategic real property management procedures, opportunities to reduce operating and maintenance costs, and opportunities to better manage federal real property assets (Public Law 114–318, 2016). The Office of Management and Budget stipulates the desired outcomes of facility asset management, but does not define what constitutes, nor how to property execute, facility asset management (National Academies of Sciences, 2023).

Federal policy does not stipulate tactical methods of managing shore facilities relative to project selection, divestiture criteria, or facility condition. Thus, these focus areas have been driven largely by industry research and individual federal agency approaches. In 1990, the National Academies of Sciences and the National Resource

Council recommended that federal facilities be funded an annual minimum level of 2–4%, the "aggregate current replacement value of those facilities" specific for routine maintenance and repair activities to avoid future recapitalization costs (National Academies of Sciences, 1998).

Over the last 30 years, the field of facility asset management has rapidly emerged as a foundational engineering management challenge. Decades of facility investment without consideration of total cost of ownership, life cycle costing, and operation and support needs have necessitated collaborative government and industry engagement to resolve infrastructure challenges throughout the United States federal portfolio. In this vein, the National Academies of Sciences, the American Society of Civil Engineers, and the International Organization for Standardization (ISO) are three of the most prominent voices in the field of asset management. These groups provide research, guidance, and analysis to support the federal infrastructure portfolio. This research couples strategic need and future vision, to that of engineering analysis and consideration, to ensure that investment decisions are holistically assessed and can accommodate both current need and future growth.

2.3.1.1 Data Rich, Analytically Poor

According to the FRPC, the U.S. federal government must account for the vast real property inventory within its control. This documentation lends credence to taxpayer visibility on federal facilities but does not demonstrate the necessary data-driven investment decisions that must be made to maintain such facilities. Furthermore, from a holistic enterprise shore infrastructure portfolio approach, the federal government lacks the analytical tools and resources to process data while quantifying and incorporating

competing elements of risk, facility criticality, performance metrics, value benefit, among other integral asset management factors (Bunea, Mazzuchi, Sarkani, & Chang, 2006). Each agency has different means and methods for managing its shore infrastructure portfolio, and the prioritization techniques used to evaluate trade-off decisions is inconsistent both across the federal enterprise and within the federal agencies. Hence, federal departments and agencies have varying approaches to facility asset management, including asset prioritization and project selection.

2.3.2 Approaches to Facility Asset Management

2.3.2.1 Systems Approach

The International Standards Organization (ISO) 55001 define an asset as "an item, thing or entity that has potential or actual value to an organization," and asset management as "the coordinated activity of an organization to realize value from assets" (National Academies of Sciences, 2023). Key factors needed to realize such value necessitate a portfolio approach to facility asset management to incorporate metrics of mission alignment, performance, and readiness.

Failure to perform preventative maintenance increases the probability and frequency of failures, compounds the cost of repairs, deteriorates asset capability, and reduces service life (Arif, Bayraktar, & Chowdhury, 2016). Maintenance and repair restore an asset to its intended capabilities. When one or more system components do not receive routine or corrective maintenance, the system is jeopardized, resulting in a full replacement or major recapitalization (Gosavi, Murray, Tirumalasetty, & Shewade, 2015). Figure 2.2, obtained with permission from the author, illustrates the natural degradation of Facility Condition Index over Time, and the how management

interventions – if optimally planned – can prolong life by improving condition index and establishing a new degradation curve (Zhang & Gao, 2010).

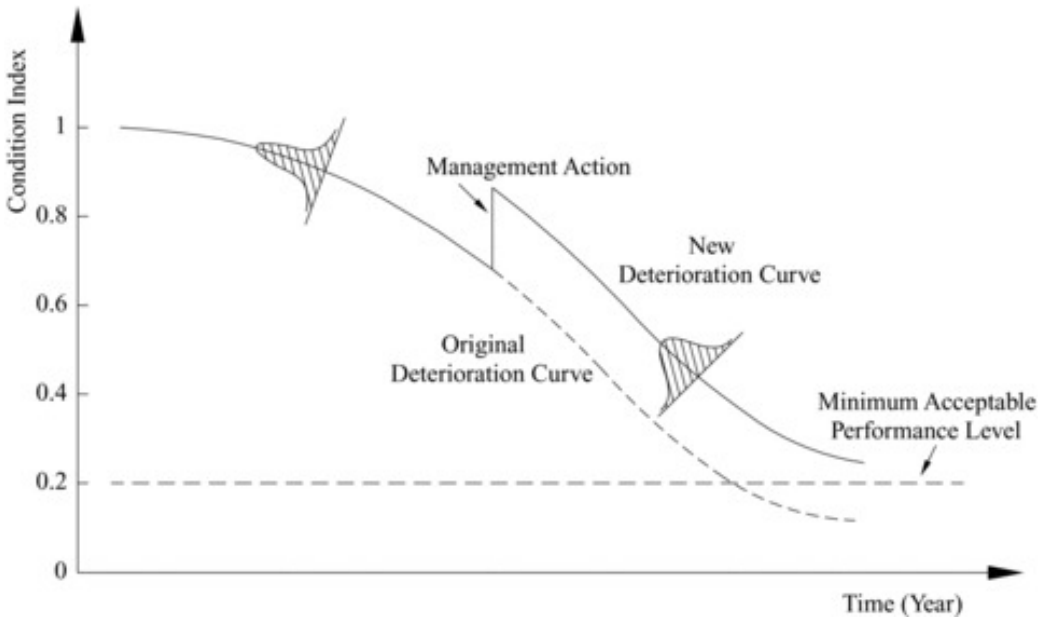

Figure 2.2 - S Curve of Time vs. Condition Index
(Zhang & Gao, 2010)

Furthermore, opportune investment in shore facilities improves both asset condition and organizational safety, efficiency, and objectives and reduces the total costs of ownership (Gosavi, Murray, Tirumalasetty, & Shewade, 2015). Figure 2.3, obtained with permission from the author, highlights some of the additional ancillary benefits associated with facility stewardship.

Mission-Related Outcomes	Compliance-Related Outcomes	Condition-Related Outcomes	Efficient Operations	Stakeholder-Driven Outcomes
Improved reliability	Fewer accidents and injuries	Improved condition	Less reactive, unplanned maintenance and repair	Customer satisfaction
Improved productivity	Fewer building-related illnesses	Reduced backlog of deferred maintenance and repairs	Lower operating costs	Improved public image
Functionality	Fewer insurance claims, lawsuits, and regulatory violations		Lower life-cycle costs	
Efficient space utilization			Cost avoidance	
			Reduced energy use	
			Reduced water use	
			Reduced greenhouse gas emissions	

Figure 2.3 - Benefits of Facility Stewardship

(National Academies of Sciences, 2012)

2.3.3 Capability Trap

The capability trap phenomena has far-reaching applications and was derived from the common term "firefighting." Within the field of facility management, capability trap exemplifies the investment and labor practices of focusing on short-term objectives instead of long-term, strategic needs (Faghihi, Kim, & Ford, 2022). This narrow focus causes long-term performance shortfalls, impacting future capability, and requires costly investments to overcorrect for historical inadequate investment practices. The repair costs associated with aging assets continue to escalate faster than the costs associated with performing basic maintenance actions to prevent such repairs. Research has shown that investment in preventative maintenance reduces corrective maintenance and recapitalization costs, maximizing the potential future capability for those shore facilities (Guevara, Garvin, & Ghaffarzadegan, 2017). Investment in routine, preventative

maintenance activities defines the most practical application of stewardship for shore infrastructure assets.

2.3.4 U.S. Coast Guard's Approach to Asset Management

2.3.4.1 Governance Structure

As shown in Figure 2.4, the Coast Guard Civil Engineering Program's governance stems from the Deputy Commandant of Mission Support and is structured into a policy office, CG-43, and execution components within the Shore Infrastructure Logistics Center (SILC).

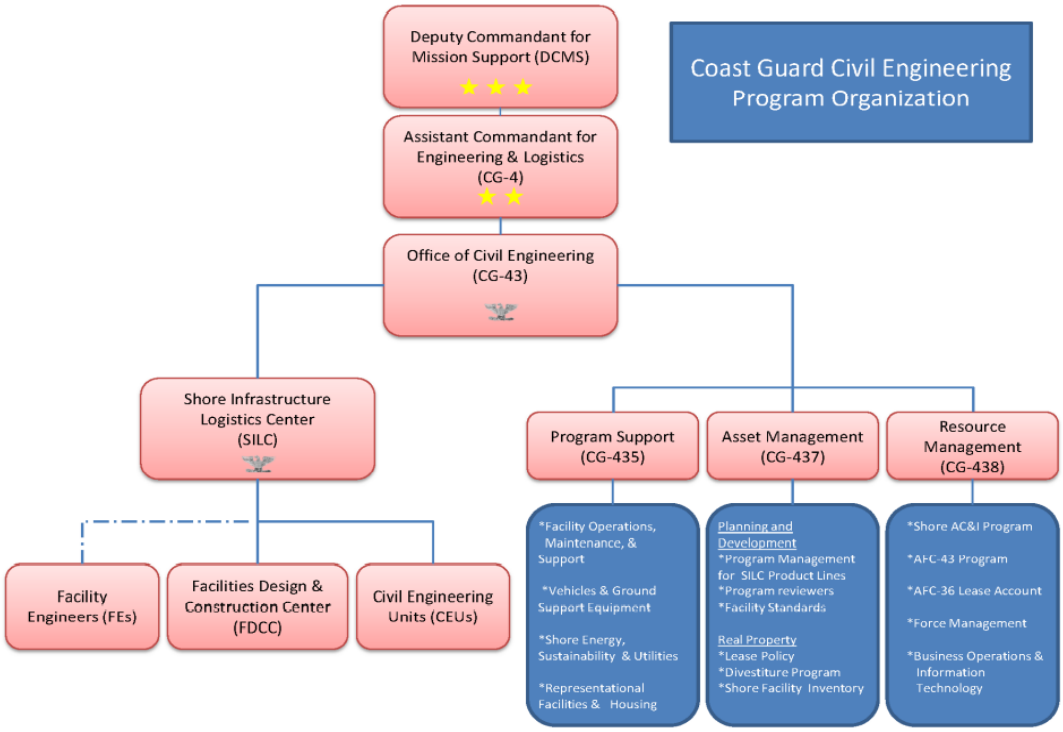

Figure 2.4 - U.S. Coast Guard Civil Engineering Governance Structure (COMDTINST M11000.11B, 2014)

The Coast Guard's Office of Civil Engineering (CG-43) is the technical authority for all shore infrastructure assets, establishing configuration standards, process control, and policy pertaining to asset management, resource management, and program support.

The SILC oversees regionally based civil engineering units (CEUs), Coast Guard-wide facility engineers, and the Facilities Design and Construction Center (FDCC) and provides technical guidance necessary to achieve strategic goals.

2.3.4.2 Execution Structure

The SILC is composed of five regionally based CEUs, 26 facility engineer-coded units, and two FDCC offices.

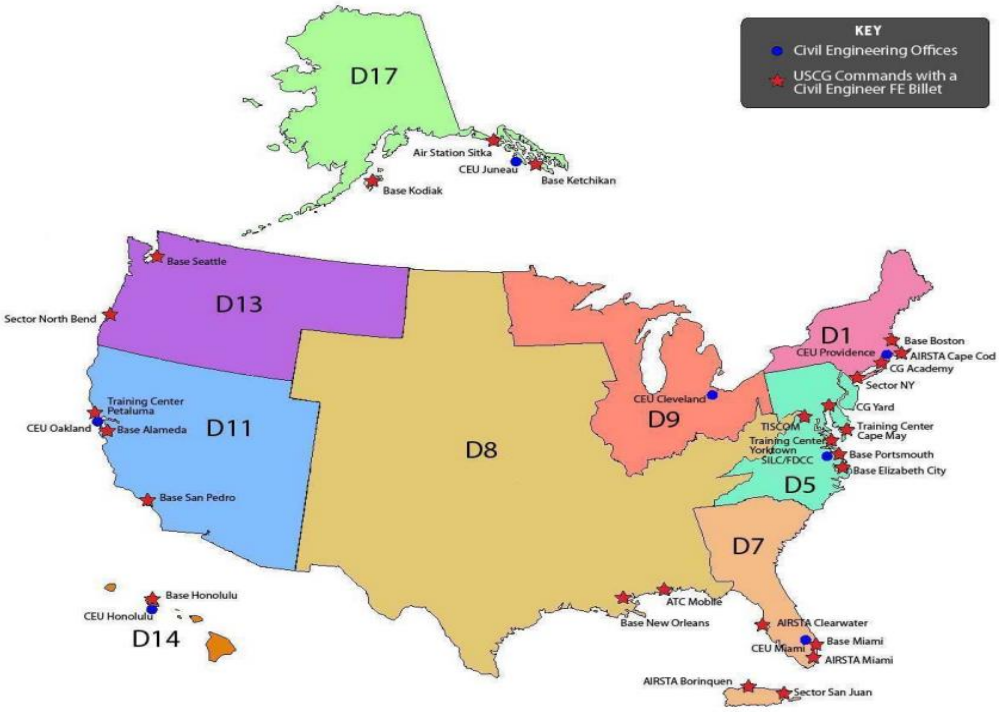

Figure 2.5 - U.S. Coast Guard Civil Engineering Management (COMDTINST M11000.11B, 2014)

Generally, CEUs are responsible for the regional prioritization and execution of all depot level maintenance and repair (DLM&R) within their areas of responsibility. The SILC provides holistic oversight over enterprise-wide asset types and is organized into five product lines based on asset function: Tactical Operations, Strategic Operations, Mission Readiness, Mission Support, and Waterways Operations. Annually, regional

CEUs and SILC product lines prioritize DLM&R projects. These projects are allocated specific percentages of the total annual DLM&R budget, and executed accordingly (United States Coast Guard Assistant Commandant for Engineering & Logistics, 2014). Additionally, the SILC ensures that local units perform necessary organizational level maintenance and repair (OLM&R).

2.3.5 Computerized Maintenance Management System

Computerized maintenance management systems (CMMS) are used to track assets and various data elements associated with those assets, and CMMS packages have varying levels of functionality. For instance, the U.S. Coast Guard utilizes an IBM Maximo Application Suite called the Shore Asset Management System (SAMS), which tracks preventative maintenance and corrective maintenance work orders associated with asset inventory. SAMS is used to generate the preventative maintenance schedule for all equipment associated with shore facility assets and to document corrective maintenance work orders to address equipment failures. Beyond this, SAMS is powerful data management software, but it has limited functionalities for all aspects of facility asset management. Primarily, SAMS is a tool used to schedule preventative maintenance, track completion, and store manually entered deferred maintenance project data resulting from condition assessments or other means. Hence, this system cannot currently predict facility conditional metrics or recommend future investments.

2.4 Business Rules

The U.S. Coast Guard is a branch of the armed services and is not subject to the policies and procedures pertinent to the Department of Defense. However, as an agency within the Department of Homeland Security, the Coast Guard has financial business

rules that are comparable yet distinctively separate from the other branches of the armed services.

2.4.1 Organizational Level Maintenance and Repair (OLM&R)

Organizational level maintenance and repair (OLM&R) constitutes the basic upkeep, maintenance, and minor repairs necessary to sustain a shore asset's life cycle. Timely, deliberate OLM&R investment helps avoid unscheduled maintenance, reduces the rate of equipment failure, and yields the lowest total ownership costs associated with an asset's life cycle. Additionally, OLM&R is performed by local personnel stationed at individual Coast Guard units, and OLM&R funding is prioritized locally. Overall, OLM&R performance varies by unit, based on factors including workforce type (uniformed military personnel -v- wage grade civilian employees -v- contracted services) and numerous unit characteristics, including asset age, condition, and local funding determinations. While the SILC measures performance across the enterprise, local unit commanders are responsible for prioritizing and executing OLM&R from their annual unit funding; their leadership and discretion influence facility performance and cause disparity amongst units.

2.4.2 Depot Level Maintenance and Repair (DLM&R)

Maintenance and repair beyond the organic capabilities of the specific Coast Guard unit, or that exceed budgetary threshold authorities, escalate to depot-level maintenance. In this vein, DLM&R includes all construction activity and asset modifications and rehabilitations that necessitate professional design and technical expertise. Generally, DLM&R project backlogs are managed by the Civil Engineering Units, prioritized locally and by product lines, and funded at the discretion of the CG-43

enterprise. Moreover, DLM&R has single-year funding, meaning funds are only available for the period of a single fiscal year (October 1–September 30).

2.4.3 Procurement, Construction, and Improvement (PC&I)

Procurement, Construction, and Improvement (PC&I) funding is congressionally appropriated to procure, construct, and improve new shore infrastructure assets or to rehabilitate or expand existing assets. Typically, PC&I involves five-year funding, meaning funds have a five-year window for obligation (COMDTINST M11000.11B, 2014). This funding is similar to DoD's Military Construction (MILCON) program.

2.4.4 Financial Resource Management Policy

The Coast Guard's Financial Resource Management Manual (FRMM) extensively details the resource management policy of the Coast Guard, establishes internal controls, and ensures adherence with Office of Management and Budget (OMB) and departmental policies and procedures. The FRMM stipulates policy thresholds for PC&I and DLM&R execution based on work type (MACID), asset type, investment relation to asset value, and reporting requirements (COMDINST M7100.3(s), 2019).

2.4.5 Project Drivers and Constraints

Project Drivers include maintenance, alteration, compliance, improvement, and demolition (MACID), and are used to express the scope of a DLM&R or PC&I project. Each driver has a definition rooted in the FRMM, stipulating thresholds based on the project driver and the type of funding utilized. A project is rarely 100% any single driver; most projects have elements of multiple drivers that constitute a project's MACID breakdown. Table 2.2 highlights a representative project's scope breakdown based on MACID to repair a pier.

Project Title: Repair Pier at Station Washington				
Project Estimate: $500K				
Project Driver: Maintenance (M)				
MACID Breakdown:				
M	A	C	I	D
60%	0%	10%	25%	5%
$300K	$0K	$50K	$125K	$25K

Table 2.2 - Sample MACID Breakdown

As shown in Table 2.2, the project to repair a pier at Coast Guard Station Washington includes multiple project drivers, with the primary driver being maintenance. While the primary project focus is maintenance (60% of costs), there are elements of code compliance, improvements, and demolition necessary to achieve the desired capability.

2.4.5.1 Maintenance

Maintenance restores an asset to its intended capability through reoccurring preventative efforts or corrective maintenance to address repairs. Maintenance excludes work to improve or alter an asset, including efforts necessary to modernize and make that asset meet design code requirements.

2.4.5.2 Alteration

Alterations adjust the physical characteristics of an asset to improve effectiveness or efficiency for adjusted or new operational needs for the asset. This process includes repurposing a space for a new, desired function (e.g., converting a storage space into a server room).

2.4.5.3 Code Compliance

Code compliance activities adhere to an asset's compliance with applicable codes, including but not limited to life safety, seismic, occupational health and safety, energy, and environmental regulations.

2.4.5.4 Improvement

Improvements expand or increase an asset's originally intended capability or capacity, including replacing asset components that create enhanced capability. Replacement-in-kind (RIK) refers to a one-for-one replacement. For instance, replacing a failing tar-shingle roof with a new tar-shingle roofing system is considered maintenance unless it provides an enhanced capability, such as a solar generative capability that acts as both a weatherproofing shingle and a power generation device.

2.4.5.5 Demolition

Demolition is performed for asset disposal and divestiture and may be necessary before future work elements necessary for an asset (e.g., demolishing existing timber piles to construct new [improvement] reinforced steel piles).

2.4.6 Plant Replacement Value (PRV)

The Plant Replacement Value (PRV) represents the investments necessary to reconstruct a shore infrastructure asset. For the USCG, this value is calculated in the CMMS and defined by the Unified Facilities Criteria (UFC) system governing all military installations (U.S. Department of Defense, 2022):

$$PRV_i = x_{FQ,i} * x_{ACF,i} * x_{LF,i} * x_{PDF,i} * x_{HF,i} * x_{CF,i} * x_{SIOH,i} * x_{INF,i}$$

Equation 2.1 - Plant Replacement Value

where

PRV_i = plant replacement value, expressed in dollars, for asset *i*;

$x_{FQ,i}$ = facility quantity (i.e. square feet) for asset *i;*

$x_{CCF,i}$ = area cost factor for asset *i;*

$x_{LF,i}$ = locality factor for asset *i;*

$x_{PDF,i}$ = planning and design factor (typically 1.09) for asset *i;*

$x_{HF,i}$ = historical factor (typically 1.05) for asset *i;*

$x_{CF,i}$ = contingency factor (typically 1.05) for asset *i;*

$x_{SIOH,i}$ = supervision, inspection, and overhead (typically 1.057) for asset *i; and*

$x_{INF,i}$ = inflation for asset *i.*

2.5 Asset Management Key Performance Indicators (KPI)

This section details each KPI, the correlation and value each indicator provides, and the precautions involved with utilizing indices to represent facility needs. As with all KPIs, accurate, timely data is integral to decision-based modeling.

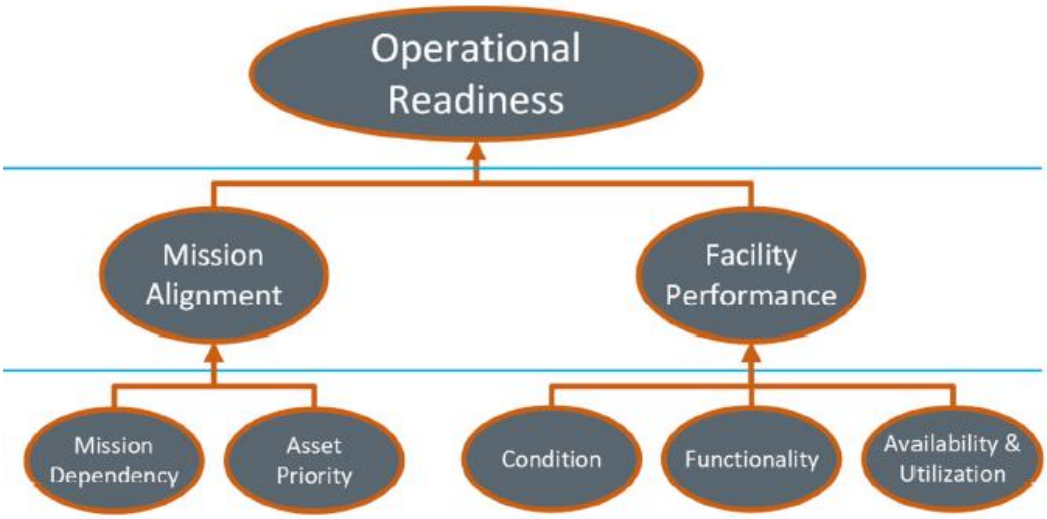

Figure 2.6 - KPP Overview and Relationships
(National Academies of Sciences, 1998)

Figure 2.6, obtained with permission of the author, best illustrates the relationship between seven (7) asset management key performance indicators (KPIs) that have been robustly studied by government and industry (National Academies of Sciences, 1998).

2.5.1 Facility Key Performance Indicators (KPI)

2.5.1.1 Condition Index (CI)

Condition index represents the ratio of deferred maintenance associated with an asset to that asset's plant replacement value (National Academies of Sciences, 2004). This ratio is described with the following equation:

$$CI_i = 100 * \left(1 - \frac{DM_i}{PRV_i}\right) \%$$

Equation 2.2 - Condition Index

where

CI_i = condition index for asset i;

DM_i = deferred maintenance, expressed in dollars, associated with asset *i; and*

PRV_i = plant replacement value, expressed in dollars, for asset *i.*

Deferred maintenance comprises all projects coded as *maintenance* listed on the project backlog. At times, projects coded as *demolition* also comprise the deferred maintenance backlog. Facility condition is an important yet narrowly focused metric that simply expresses an asset's total maintenance need. Government and industry collaboration between entities, including the U.S. Army Corps of Engineers and the American Society of Civil Engineers, have developed scales to qualitatively express an asset's condition and consistently relate assets to each another.

This scale, which can be tailored to specific organization (e.g., U.S. Coast Guard, Department of Defense) or asset type (e.g., pavement, structure) is typically expressed quantitatively from 0 to 100, with a score of 100 being "excellent, no noticeable defects" to 0 being "Failed; no longer functional" (McKay, Rens, Greimann, & Stecker, 1999). This quantitative scale is divided into zones (e.g., 0 to 30 is Zone 1), and recommended actions are associated with each zone to improve condition index for each asset. Additionally, the condition index may be considered through a systems thinking approach by evaluating the component and subcomponents within an asset system (Zhang X. , 2006), as follows:

$$CI_t^{bsc} = \sum_{e=1}^{m_{bsc}} W_{bsce} * CI_t^{bsce}$$

Equation 2.3 - Systems Approach Condition Index

where

CI_t^{bsc} = condition index of component c, in system s, in asset (building) *b;*

m_{bsc} = number of elements within the component *c*; and

W_{bsc} = assigned weight of each element *e* within component *c* where

$$1 = \sum_{e=1}^{m_{bsc}} W_{bsce}$$

2.5.1.2 Functional Index

The functional index (FI) is the ratio of non-maintenance (and/or demolition) activities, such as improvements, alterations, and code compliance upgrades, to that of the asset's plant replacement value. The FI describes the capability gap between the asset's intended function as designed and the desired current or future capability associated with that asset.

$$FI_i = 100 * \left(1 - \frac{DM_{CC,i} + DM_{IMP,i} + DM_{ALT,i}}{PRV_i}\right) \%$$

Equation 2.4 - Functional Index

where

FI_i = functional index for asset *i;*

$DM_{CC,i}$ = deferred code compliance, expressed in dollars, associated with asset *i;*

$DM_{IMP,i}$ = deferred improvements, expressed in dollars, associated with asset *i;*

$DM_{ALT,i}$ = deferred alterations, expressed in dollars, associated with asset *i;*

PRV_i = plant replacement value, expressed in dollars, for asset *i.*

2.5.1.3 Comprehensive Condition (Needs) Index

The condition index involves an asset's maintenance needs, but the comprehensive condition index , also referred to as the needs index (CCI/NI), holistically examines an asset's backlogged improvements, alterations, code compliance, environmental efforts, and miscellaneous facility needs associated (Cain & Kinnaman, 2004), as follows:

$$CCI_i = 100 * \left(1 - \frac{DM_{MR,i} + DM_{CC,i} + DM_{IMP,i} + DM_{ALT,i} + DM_{ENV,i} + DM_{MISC,i}}{PRV_i}\right) \%$$

Equation 2.5 - Comprehensive Condition Index

where

CCI_i = comprehensive condition index for asset *i;*

$DM_{MR,i}$ = deferred maintenance, expressed in dollars, associated with asset *i;*

$DM_{CC,i}$ = deferred code compliance, expressed in dollars, associated with asset *i;*

$DM_{IMP,i}$ = deferred improvements, expressed in dollars, associated with asset *i;*

$DM_{ALT,i}$ = deferred alterations, expressed in dollars, associated with asset *i;*

$DM_{ENV,i}$ = deferred environmental, expressed in dollars, associated with asset *i;*

$DM_{MISC,i}$ = deferred miscellaneous, expressed in dollars, associated with asset *i; and*

PRV_i = plant replacement value, expressed in dollars, for asset *i.*

The comprehensive condition index addresses an asset's overall facility needs and is often more closely aligned with strategic objectives, compared to condition index which focuses purely on the ratio of deferred maintenance to plant replacement value. Identifying the optimal balance between maintenance in the short run and strategic improvements in the long run is at the heart of tackling the capability trap that hinders facility performance.

2.5.1.4 Stewardship Index

The stewardship index relates the intersection point of an asset's condition index and functional index. This term describes the overall health of an asset based on its documented maintenance, improvement, alteration, code, and demolition projects, as shown here:

$$SI_i = 100 * \left(\frac{\sqrt{CI_i * FI_i}}{\sqrt{2}}\right)\%$$

Equation 2.6 - Stewardship Index

where

SI_i = stewardship condition index for asset *i*,

CI_i = condition index associated with asset *i, and*

FI_i = functional index associated with asset *i.*

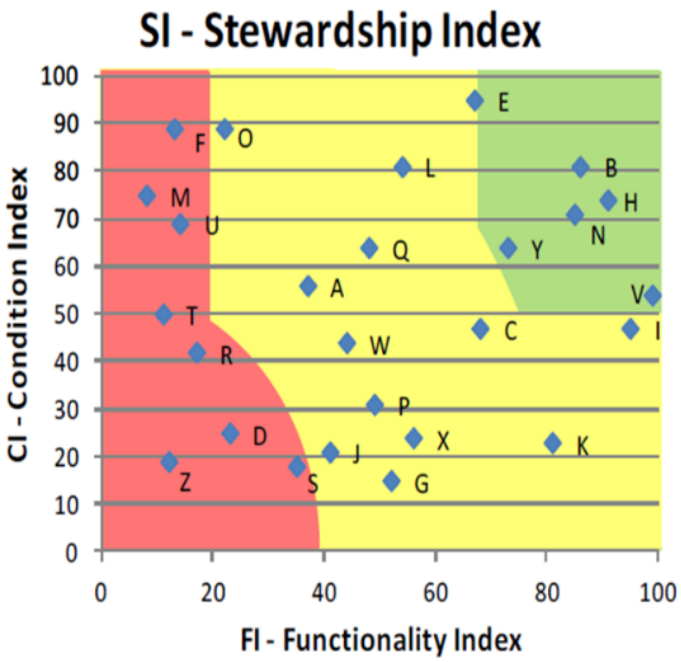

Figure 2.7 - Stewardship Index Scatterplot

(United States Coast Guard)

2.5.1.5 Space Utilization and Availability Indices

Space utilization and availability are integral aspects of an investment decision model. The space utilization index is a ratio of the actual space quantity to the required space quantity necessary to perform the functional requirements of the asset, expressed by the following equation:

$$SUI_i = 100 * \left(\frac{SA_i}{SR_i}\right)$$

Equation 2.7 - Space Utilization Index

where

SUI_i = space utilization index for asset *i,*

SA_i = space allocated for asset *i, and*

SR_i = space required for asset *i.*

An SUI > 100 indicates an excess of space that could be targeted for repurposing or divestiture. On the contrary, an SUI < 100 indicates a requirement shortfall. Additionally, SUI must be assessed through the lenses of performance and ability to achieve capability for decision-makers to evaluate whether the requirements are achievable in the allocated space.

2.5.2 Mission Alignment

2.5.2.1 Dependency Index (MDI)

The mission dependency index (MDI) is a tactical assessment jointly developed by the U.S. Coast Guard, the Navy, and NASA to relate an asset's criticality to the mission. In this vein, MDI addresses the question "What is the impact if this asset was lost?" and quantifies an asset's importance relative to mission, based on principles of probability and severity. This process constitutes Operational Risk Management (ORM), in terms of an asset's *interruptability* and *relocatability* based on the functional capabilities the asset provides (Dempsey, 2013), as shown here:

$$MDI_i = 26.54 * \left[MD_{w,i} + 0.125 * \frac{1}{n} \sum_{i=1}^{n} MD_{b,i} + 0.1 * \ln(n) \right]$$

Equation 2.8 - Mission Dependency Index

where

MDI_i = mission dependency index for asset *i,*

$MD_{w,i}$ = mission intra-dependency associated with asset *i,*

$MD_{b,i}$ = mission inter-dependency associated with asset *i, and*

n = number of mission interdependencies associated with asset *i.*

The MDI is conducted through a structured survey and may incorporate up to three levels of input: tactical, operational, and strategic. Overall, the MDI score is normalized among the three inputs, as follows:

$$MDI_{AVG.i} = \frac{\sqrt{MDI_{T,i}^2 + MDI_{O,i}^2 + MDI_{S,i}^2}}{\sqrt{3}}$$

Equation 2.9 - Final Mission Dependency Index

where

$MDI_{AVG,i}$ = final mission dependency index for asset *i,*

$MDI_{T,i}$ = tactical mission dependency index for asset *i,*

$MDI_{O,i}$ = operational mission dependency index for asset *i, and*

$MDI_{S,i}$ = strategic mission dependency index for asset *i.*

MDI Scores	Color	Nomenclature
100 - 85	red	Critical
84 - 70	orange	Significant
69 - 55	yellow	Relevant
54 - 40	green	Moderate
39 - 0	blue	Low

Figure 2.8 - MDI Scores and Correlations

(Dempsey, 2013)

Figures 2.8 and 2.9, both of which were obtained with the author's permission, provide practical examples of MDI application. Figure 2.8 correlates MDI with qualitative descriptors relative to the asset's criticality based on its relationship to the mission and the surveyed responses. Figure 2.9 categorizes a theoretical Coast Guard Base. Pier 1 is coded red with an MDI of 88, indicating that the functional capabilities of that asset (to provide moorage and utility services for a Coast Guard cutter) cannot be easily replicated or relocated.

Notably, a high MDI is purely a measure of its functional ability to be relocated or interrupted. Therefore, high MDI facilities indicate an asset's lack of resiliency and redundancy. Similarly, a low MDI does not necessarily mean that the asset is less critical; rather, such a value implies that the functional capabilities performed by the asset have redundancy and resiliency to be performed elsewhere.

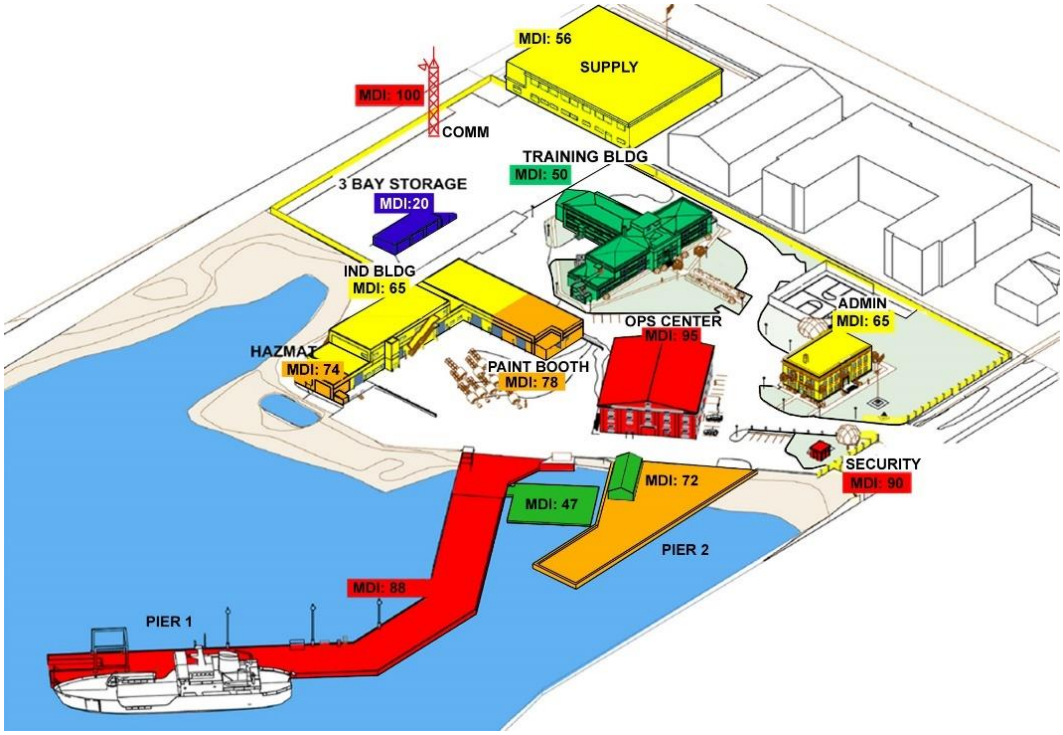

Figure 2.9 - MDI Example—USCG Base
(National Aeronautics and Space Administration, 2010)

2.5.2.2 MDI Critiques

Despite MDI's prevalent adaptation by many federal agencies and all military branches, some believe MDI fails to sufficiently link infrastructure assets to a strategic objective(s) and that its reliance on subjective, qualitative inputs from subject matter experts may inaccurately guide decisions (Eisenberg, Fish, & Alderson, 2022). Others have asserted that MDI is an over-simplified representation of facility importance and that MDI fails to adequately address organizational risk by ignoring factors such as climate vulnerability, unforeseen casualties, and other ancillary risks (Kujawski & Miller, 2009).

2.5.2.3 Mission Essentiality Index

The mission essentiality index (MEI) is a strategic assessment that relates an asset's function to its overall mission. Addressing the question of "what assets most directly affect the outcome of strategic objectives," MEI provides a holistic, hierarchal, functional breakdown of assets based on their mission essentiality (Department of Defense, 1997). The U.S. Coast Guard, among other federal and military agencies, utilizes an MEI with variable analysis. Generally, MEI is a relative indicator of asset function to other assets on a scale 0 to 100, where the most essential functions receive the highest scores, and the least essential functions receive the lowest.

2.5.3 Operational Readiness Index

The operational readiness index (ORI) is a recent development in the field of facility management, representing an attempt to influence investment decisions by

holistically accounting for an asset's mission essential and alignment indices (United States Army National Guard, 2014). In this vein, ISO 55000 defines the Principle of Operational Readiness as "the relationship between an organization's operational readiness and the levels of facility operational readiness delivered by federal facility renewal strategies must be balanced across a range of relevant investment horizons and resourcing strategies" (National Academies of Sciences, 2023).

$$ORI_i = \frac{\sqrt{MDI_i^2 + SI_i^2}}{\sqrt{2}}$$

Equation 2.10 - Operational Readiness Index

where

ORI_i = operational readiness index for asset *i,*

MDI_i = mission dependency index for asset *i, and*

SI_i = stewardship condition index for asset *i.*

2.5.4 Managing Assets versus Asset Management

The challenges within asset management are intuitive to comprehend, yet highly complex to solve due to the volume of constraints and variables within which to operate. Decades of asset investment without cradle-to-grave analysis have incurred an irrecoverable deferred maintenance backlog that, absent an unlikely absorbent capital influx, will remain a challenge for decades to come. Theory surrounding the field of facility asset management has emerged as the application of methodologies sheds light on previous blind spots, such as incorporating operational risk and strategic foresight.

Recent literature has explored the subtle nuance yet important distinction between two concepts: managing assets versus asset management (National Academies of Sciences, 2023). That is, managing assets is the application of metrics and models to describe the state of a facility, and asset management is the strategic governing, typically non-engineering aspect that dictates the investment decisions involving assets. This process necessitates the integration of tactical, operational, and strategic inputs with an engineering analysis to dictate investment decisions that are transparent and accountable to taxpayers.

2.6 Prioritization Methodologies

Asset management requires prioritizing assets and projects associated with those assets to maximize effectiveness (as defined by the desired metrics of the decision-maker) within the operating environment (typically, resource-constrained). Many economic models frame investment decisions, yet attaining optimal outcomes is hindered by complexity between competing objectives, budget uncertainty, and site or project constraints (Hsieh & Liu, 1997). Hence, model complexity and computational effort to optimize such problems require forethought, although advances in computational technology over the last 20 years have improved and enabled significant computational capability (Hsieh & Liu, 1997).

2.6.1 Behavioral Economics

Investment trade-offs are inherent in a portfolio approach to asset management, and decision outcomes are strongly tied to subjective elements of human behavior, including personal experience and intuition. Despite data-driven, objective decision support tools that can optimize a parameter, modeled outcomes may yield a counter-

intuitive solution that is ultimately rejected by management. Thus, trust is essential for any data-driven prioritization methodology, driving the development of models and algorithms to portray data in a relatable way that is compatible with human understanding and optimizes the intended objective. Studies have shown that relating maintenance decisions based on *avoidance of failure* versus *gain of capability* can improve stakeholder concurrence of selected investments necessary to achieve ideal end states (Saad & Hegazy, 2015).

2.6.2 Cost–Benefit Analysis

Pavement maintenance has extensive literature concerning investment strategy, and cost–benefit analysis (CBA) is a common method used to prioritize asset investments. A CBA is performed at project and network levels to develop a ratio of repair impacts to added service life and a comparison of aforementioned ratios to other projects with respect to condition scores (indices). Repairs yielding the lowest ratio are identified as the optimal candidates for investment (France-Mensah & O'Brien, 2018), as shown here:

$$AL_m = \frac{p_{pm}}{\left[-\ln\left(\frac{CS_{net}}{\min\left(CS_b + \Delta CS_{pm}, 100\right)}\right)\right]^{\frac{1}{\beta_{pm}}}}$$

Equation 2.11 - Pavement Cost–Benefit Analysis

where

AL_m = added life

p_{pm} = curve parameters for traffic level

CS_{net} = threshold condition score

CS_b = condition score prior to repair

β_{pm} = added life for treatment option CS_{pm} = estimated condition score post repair

and

$$CAL_m = \frac{C_m}{AL_m}$$

where

CAL_m = ratio of repair cost to added life C_m = repair costs

AL_m = added life

2.6.3 Multi-Objective Optimization Models

Multi-objective optimization (MOO) is quite suitable for prioritizing assets and projects and can effectively yield optimized outcomes that account for tactical, operational, and strategic priorities, within the bounds of policy, resource, and business rule constraints. This complexity necessitates clearly defined metrics and the weighting of such metrics, ensuring that the optimized outcome satisfies the presented conditions. Typically, reducing life cycle costs and maximizing service life are objective outcomes of asset investment strategies, realized through metrics like condition index and the other indices described in Section 2.5. Variables such as condition, life cycle, safety, and performance are essential to ensure optimized solutions holistically maximize asset equities (Frangopol & Liu, 2005).

2.6.3.1 Heuristic-Based Model

Multi-objective optimization is a practical decision tool used to assist decision-makers by defining the objectives, decision variables, and constraints necessary to obtain

the desired objective. Traditional multi-objective optimization models rely on heuristics, which may deliver suboptimal outcomes. However, some heuristic-based models, such as the nondominated sorting genetic algorithm II (NSGA II), have delivered consistently better, more efficient (Pareto) solutions than other MOO models (Chen, Henning, Raith, & Shamseldin, 2015). Sensitivity analysis of heuristics produced elements of a mathematical model provide value-added insight to the model's construction, producing more optimal results.

2.6.3.1.1 Multi-Stage Heuristics

Investment decisions can be approached as nonlinear, binary (0-1), multi-objective functions. In this way, a two-stage approach utilizing the concept of gray relation can prioritize assets against each other, using heuristics to facilitate tradeoffs among these priorities and to remove nonlinear elements of (Hsieh & Liu, 1997). This approach involves the attributes of an asset and computing the gray relation between alternatives that best achieve an asset's optimal state.

2.6.3.2 Integer Linear Programming

For most pavement rehabilitation projects, the objective function is to maximize (improve) the asset's condition, as indicated below (France-Mensah & O'Brien, 2018):

$$\max Z_1 = \sum_{i=1}^{I} \sum_{m=1}^{M} \sum_{t=1}^{T} (N_i L_i e_{im}) x_{imt}$$

Equation 2.12 - Pavement Optimization Example

(France-Mensah & O'Brien, 2018)

where

Z_1 = condition score improvement for pavement section *i*,

N_1 = # of lanes in pavement section *i*,

L_1 = length of pavement (miles) in pavement section *i*,

e_{im} = treatment *m*'s condition improvement on pavement section *i, and*

x_{imt} = binary decision (0 or 1) for treatment *m* selection for pavement section *i.*

In a Texas Department of Transportation (T-DOT) case study, investment prioritizations that adapted integer linear programming outperformed the CBA, yielding an annual 0.3% decrease in condition score versus a 1.17% decrease. Thus, in this study, despite value-added processes to optimize investment decisions, budget allocation failed to meet the demand of a failing infrastructure network.

2.6.3.3 Markov Optimization

Markov decision processes (MDP) and semi-Markov decision processes (SMDP) are probabilistic models with broad applications, such as infrastructure maintenance and investment decisions. Particularly, Markov chains are useful for infrastructure investment decisions because they can integrate both hard and soft data obtained from facility condition assessments (FCAs) and model performance changes in the condition index based on budget allocations. Generally, MDP and SMDP must operate under the

assumption that FCA data is accurate to estimate future facility degradation with or without investment.

Hence, these approaches require deliberate, planned, scheduled investigations to properly quantify the current state conditions (Yang & Xie, 2021). An MDP must account for decision milestones; current and predicted future states (in this case, condition index); probability of future outcomes; and performance of future outcomes. Thus, a mathematical objective function could be formulated based on the determined decision variables and within the identified constraints (Zhang X. , 2006).

2.6.4 Worst-first

Worst-first (W-F) is a common investment strategy for shore infrastructure investment, yet it lacks the data-driven and life-cycle approach found in a business case analysis. As its name implies, W-F utilizes asset condition data as the primary metric to allocate resources for maintenance and repair activities. Implications of a W-F approach speak towards the capability trap concept described in Section 2.3.3, where short-term benefits are realized in lieu of long-term strategic operational needs.

An analysis of the W-F approach for 3,178 miles of roadway in Bryan County, Texas, indicated that a W-F approach incurred 43% more poor condition pavements than a business case analysis approach, which prioritized investment in preventative maintenance and repair activities (Menendez, Siabil, Narciso, & Gharaibeh, 2013). Additionally, this study indicated that disadvantages associated with a W-F approach could be mitigated through a balance of W-F and BCA techniques, delineated with distinct M&R fund prioritization techniques, to execute highest-need projects first after being validated through a BCA.

2.6.6 Benchmarking

Using objectively generated benchmarks is a viable decision-making process for investment decisions in shore infrastructure based on current and desired levels of asset performance. Data accuracy, stored in a CMMS (Section 2.3.5), is crucial in both accurate data mining and trend analysis. However, employing objectively vetted benchmarks is not universal for infrastructure investment decisions. That is, certain classifications of assets such as healthcare facilities have achieved benchmark standards pertaining to facility maintenance but cannot be used for other types of infrastructure due to wide variations in elements like asset type, function, and code restrictions (Weeks & Leite, 2021).

Benchmarking requires accurate historical performance data, including but not limited to the relationship between the ratio of actual preventative and corrective maintenance performed on an asset, and the likelihood of future corrective maintenance activities based upon those historical investments. Figure 2.10, obtained with permission from the author, illustrates a performance feedback loop for benchmarking facility maintenance data, both preventative and corrective, in order to reduce the costs (including labor) associated with future maintenance and repair activities (Weeks & Leite, 2021).

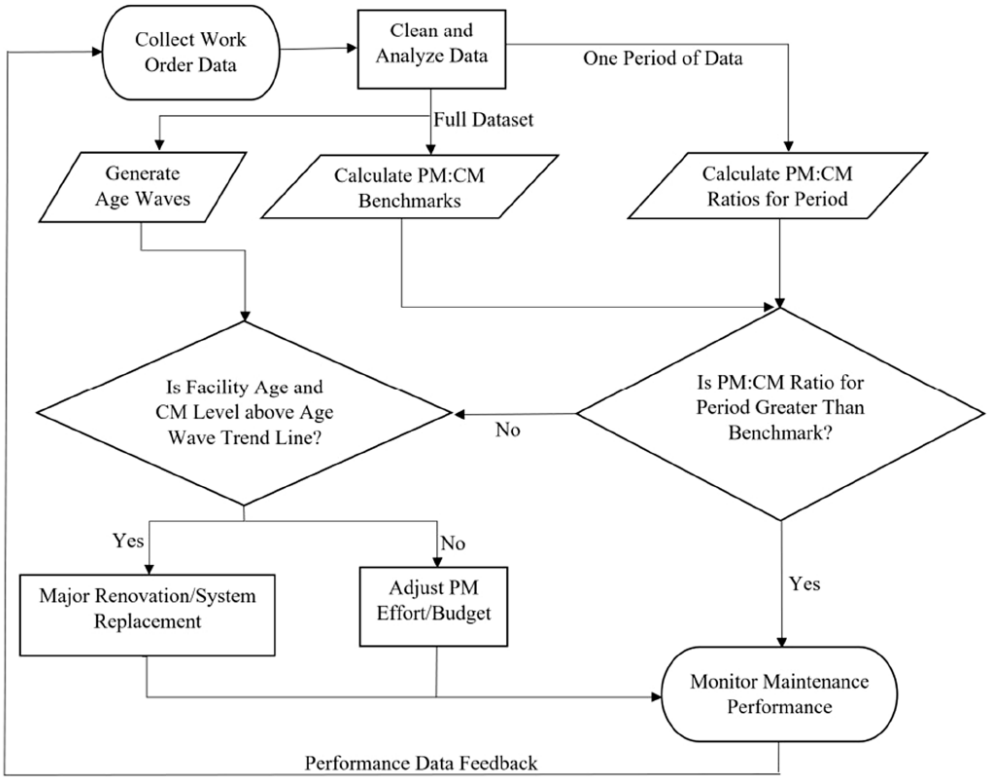

Figure 2.10 - Benchmark Loops

(Weeks & Leite, 2021)

2.6.5 Simulation

Simulation is an effective decision-making and risk management tool in the field of facility asset management. By optimizing investment decisions to maintain higher levels of condition prior to failure, these techniques can lower the total cost of ownership over a facility's life cycle. The RAMPSS (*Rapid Asset Modeling of Pavement Sustainment Strategies)* simulation algorithm optimizes investment strategies for the U.S. Air Force's pavement portfolio consisting of "over 1.6 billion square feet" of apron and runway to select specific maintenance and repair needs (Synovec & Howard, 2021). The key decision variable for RAMPSS is the critical condition index, CI_{crit}, which marks a condition that, without immediate investment, initiates rapid degradation. Additionally,

RAMPSS maximizes *CI* by selecting specific asset components and assigns each component a treatment type of either localized or global preventative maintenance or corrective maintenance. Ultimately, the RAMPSS algorithm produced a simulated annualized savings of $126M (Synovec & Howard, 2021) based on repair cost avoidance.

2.6.6 Multi-Criteria Decision Analysis

Multi-criteria decision analysis (MCDA) rank orders and compares projects, tasks, and assets based on attributes selected by the decision-maker to select ranked alternatives (Floyd, Barker, Claudio, & Whitman, 2017). Typically, attributes are weighted, evaluated, and scored. The fuzzy analytical hierarchy process (AHP) is a common MCDA approach, a beneficial technique because it incorporates linguistic qualitative variables (e.g. Low Risk, High Risk) (Azadeh & Zadeh, 2015). However, like many models, MDCA is susceptible to subjectivity based on arbitrary comparative analysis used to weigh, compare, and rank attributes. Overall, MCDA is an effective methodology, yet it requires prudent attribute selection and weighting with key stakeholders to select alternatives and make tradeoffs as dictated by resource availability and operational need.

2.6.7 Social Network Theory

Social network theory examines patterns and interrelationships between assets and between an asset's components and functions. Research on the U.S. highway data system generated a Highway Infrastructure Data Integration (HIDI), integrating data across agencies to broaden data quantity and accessibility (Woldesenbet, Jeong, & Park, 2015). Thus, HIDI enhances a decision-maker's power to capture, consolidate, and analyze data by providing previously inaccessible insights, improving outcomes.

2.6.8 Asset Prioritization Decision-Making Methodologies

To drive investment decisions for infrastructure assets, one must prioritize assets and make investments utilizing metric data, as discussed in Sections 2.6.1–2.6.9. Various methods can be used to generate an asset priority list (API), which can be summarized in the following two approaches.

2.6.8.1 Unweighted Approach

A routine but suboptimal method of prioritizing assets is purely utilizing unweighted metrics to drive investment decisions. These unconventional methods include making decisions based on MDI, CI, or other indices affiliated with an asset and then making investment decisions based on that precedence. Table 2.3 offers an example of utilizing one metric, the mission dependency index, as the sole decision variable.

Asset Rank	Asset Number	Asset Name	MDI	Project Title	Project Driver	Project Cost
1	10013	Communications Tower	93	Structural Repairs	Maintenance	$ 350,000
2	20756	Runway R1-22R	87	Expand Runway 300 Linear Feet	Improvement	$ 15,000,000
3	92571	Barrack Living Space	63	Replace EPDM Roof System	Maintenance	$ 2,500,000
3	92571	Barrack Living Space	63	Renovate Bathrooms	Maintenance	$ 500,000
4	18638	Administrative Building	37	Repurpose Procurement Shop	Alteration	$ 75,000
5	43298	Sidewalk	5	Demolish Sidewalk	Demolition	$ 15,000

Table 2.3 - Unweighted Approach Using MDI as Key Decision Variable

Unweighted single-variable approaches for asset selection could be effective, but they do not consider the various other facility metrics available to the decision-maker.

2.6.8.2 Weighted Approach

On the other hand, weighted approaches account for multiple variables and enable the decision-maker to make informed decisions utilizing multiple metrics. In this vein,

multi-attribute value theory (MAVT) is a method used to weigh attributes of a system and generate a function representing the entire system based on what is defined as follows:

$$v(x) = \sum_{i=1}^{n} w_i * v_i(x_i)$$

where

$v(x)$ = MAVT function,

n = number of attributes,

$v_i(x_i)$ = normalized single attribute value function of x_i, and

w_i = attribute (x_i) weight,

with w_i subject to

$$\sum_{i=1}^{n} w_i = 1$$

Additionally, MAVT has been adapted by the Department of the Interior, among other agencies, to prioritize assets based on specific asset attributes (Yassan, 2020).

$$v_i = 0.8v_{MDI,i} + 0.05v_{HC,i} + 0.10v_{CC,i} + 0.05v_{MU,i}$$

Equation 2.13 - DOIs Asset Prioritization Index (API)

where

v_i = normalized value for asset *i*,

$v_{MDI,i}$ = normalized mission dependency index for asset *i*,

$v_{HC,i}$ = normalized hazard condition for asset *i*,

$v_{CC,i}$ = normalized core capabilities for asset *i*, and

$v_{MU,i}$ = normalized mission uniqueness for asset *i*.

The U.S. Coast Guard utilizes comparable but different metrics pertaining to hazard conditions, core capabilities, and mission uniqueness, as defined and utilized by the Department of Interior. The proposed asset prioritization for the Coast Guard is as follows:

$$v_i = 0.8v_{MDI,i} + 0.20v_{MEI,i}$$

Equation 2.14 - USCG Proposed Asset Prioritization Index (API)

where

v_i = normalized value for asset *i*,

$v_{MDI,i}$ = normalized mission dependency index for asset *i*, and

$v_{HC,i}$ = normalized mission essentiality index for asset *i*.

2.7 Conclusion

Facility asset management is a prominent engineering management challenge. The challenges faced in the field of facility management, especially optimizing limited investment resources toward the greatest needs, are simple problems but difficult to solve. Thus, federal agencies must continue to collaborate with industry to optimize taxpayer funding for the vast portfolio of highways, military bases, bridges, and utility

systems. This process can maximize economic productivity, helping agencies remain relevant on the global stage and ensuring the safety of U.S. citizens.

Chapter 3: Methodology

3.1 Introduction

A Government Accountability Office (GAO) 2019 report revealed it would take 395 years for the Coast Guard to break even with deferred maintenance and recapitalization backlogs based on historical funding (United States Government Accountability Office (GAO), 2019). Although funding levels since 2018 have shown more positive trends compared to the previous decades, the current investment levels cannot sustain the Coast Guard's $27B shore plant portfolio.

Chapter 3 evaluates the methodology used to gather, process, and analyze data for a mathematical multi-objective optimization model. Section 3.2 summarizes the U.S. Coast Guard's shore infrastructure portfolio and categorizes it by location and project features. Section 3.3 examines the performance of shore facilities and overlays historical funding with the U.S. Coast Guard's requirements-based budget. Section 3.4 presents a data analysis, and Section 3.5 highlights asset attributes and characteristics. Section 3.6 describes this study's baseline analysis to benchmark data and measure the performance of both the actual execution approach and the optimized model approach.

Next, Section 3.7 describes the mathematical optimization model formulation to include the objective function, decision variables, constraints, and various asset and location characteristics. Constructing the optimization within the R Studio platform is described in Section 3.8. Lastly, Section 3.9 discusses the criteria used to perform model validation and sensitivity analysis.

3.2 Data Summary

The U.S. Coast Guard is the only military service outside of the Department of Defense, and falls under the Department of Homeland Security. The Coast Guard operates 43,550 shore infrastructure assets across 3,320 sites, valued at $27.4 billion. Shore infrastructure assets are categorized as either buildings, structures, or land and are either leased or owned.

% Total Count	# Assets	Description	Value	% Total Value
100.0%	43,550	Total assets	$27.4B	100.0%
79.1%	34,461	Structures	$9.6B	35.1%
15.5%	6,740	Buildings	$17.8B	64.9%
5.4%	2,349	Land	$0.00B	0.0%
Owned				
93.0%	40,519	Total	$24.3B	88.8%
77.2%	33606	Structures	$8.8B	32.2%
14.0%	6078	Buildings	$15.5B	56.6%
1.9%	835	Land	$0.00B	0.0%
Leased				
7.0%	3,031	Total	$3.1B	11.2%
2.0%	855	Structures	$785.7M	2.9%
1.5%	662	Buildings	$2.3B	8.3%
3.5%	1514	Land	$0.00B	0.0%

Table 3.1 - Asset Breakdown

3.2.1 Land

Overall, 5.4% of the Coast Guard's shore infrastructure assets constitute land. The Coast Guard does not appraise its land value until required to do so for disposition, and it

does not correlate land with any maintenance or repair activities. Typically, projects associated with land assets include environmental remediation or restoration efforts and are not considered maintenance or repair activities.

3.2.2 Buildings

In the Coast Guard, 15.5% of the shore infrastructure assets constitute buildings, accounting for 64.9% of the Coast Guard's total plant replacement value. Buildings include all facilities that are fully enclosed, affixed to the ground, accessible, and often inhabited by personnel. Examples of buildings that the Coast Guard operates include Search and Rescue Stations, Command Centers, administrative facilities, barracks or military housing, and aircraft hangers.

3.2.3. Structures

Approximately 79.1% of the Coast Guard's shore infrastructure assets constitute structures, accounting for 35.1% of the Coast Guard's total plant replacement value. Structures are assets that do not meet the definition of a building but are permanent and perform a function. Examples of structures include aircraft runways, communications towers, piers and bulkheads, utility systems, and fixed Aids to Navigation (AtoN). The latter includes all permanently fixed waterway navigation structures, including ranges, channel markers, and lighted towers to aid mariners.

3.3 State of USCG Infrastructure and Facilities

3.3.1 Actual versus Required Investment

As established by the National Research Council in 1990, the annual investment benchmark for federal shore infrastructure assets is 2–4% of their aggregate plant

replacement value (PRV). This percentage represents the basic maintenance and repair (M&R) costs necessary to sustain an asset and does not account for non-M&R activities, such as alterations, improvements, or full rehabilitation or recapitalizations.

The total PRV for the U.S. Coast Guard is $27.4B, accounting for both owned and leased assets, and is $24.3B after discounting leased assets. Leased assets are discounted from benchmarking performance metrics due to business rules that forbid companies from investing DLM&R funds and require them to invest PC&I appropriations for all leased assets. In 2016, the U.S. Coast Guard adapted a requirements-based budget (RBB) to manage its shore infrastructure portfolio (United States Government Accountability Office (GAO), 2019). This amount was based on the National Research Council's 2–4% annual investment benchmark described in Section 2.3.1. However, the Coast Guard has never achieved the objective 4% mark, as shown in Figure 3.1, with the exception of Fiscal Year 2022 following Public Law 117-58's Infrastructure Investment and Jobs Act (IIJA).

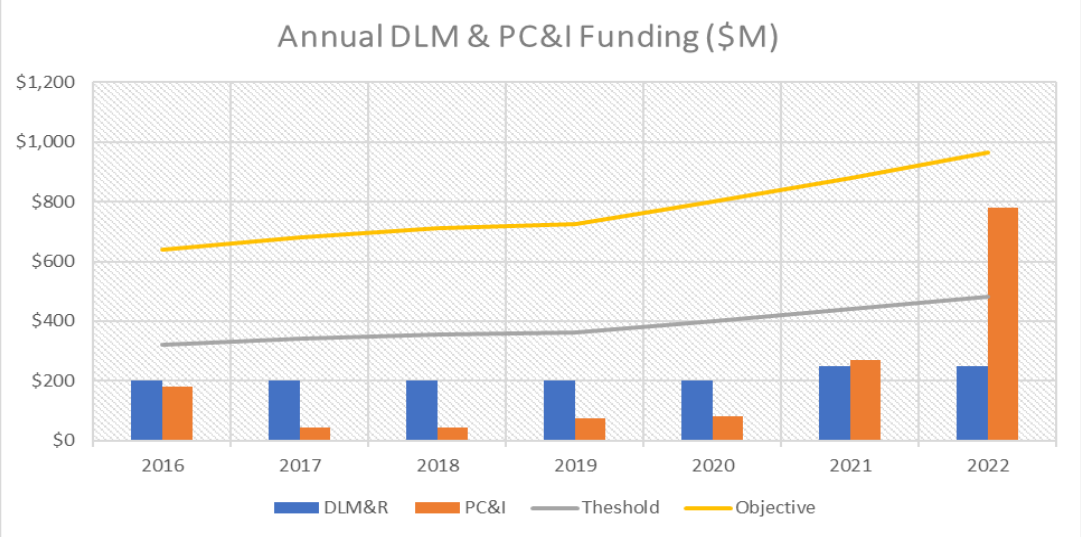

Figure 3.1 - Annual DLM & PC&I Funding

Notably, funding indicated in Figure 3.1, including IIJA funding, does not correlate to actual M&R investment for prioritized critical infrastructure assets. This funding represents total infrastructure funding for all MACID-driven projects across the shore portfolio. For example, the Bipartisan Infrastructure Law allotted $120M for the construction of new daycare centers (117-58, 2022). The 2–4% investment objective is specific to routine investments needed to sustain a facility for its designed lifespan.

In 2023, the National Research Council (NRC) published recommendations to rectify federal accounting barriers that impede facility asset management, especially language in the Office of Management and Budget's (OMB) Circular A-11 section 83, which asserts that this policy, pertaining to object classification, involves the "purchasing action and not the asset" (Office of Management and Budget, 2016). The NRC wrote the following*:*

"This means federal real property asset managers are unable to evaluate basic resource- and investment decision-making objectives…absent a correction to OMB's object classification convention, federal agencies will continue to be unable to produce requirements-based budgets …" (National Academies of Sciences, 2023)

3.4 Data Analysis

3.4.1 Sourcing and Manipulation

In this study, all data was sourced from the Coast Guard's Computerized Maintenance Management System (CMMS), an IBM platform designated as the Coast Guard's Shore Asset Management System (SAMS). Three separate queries were pulled: depot-level maintenance and repair (DLM&R) backlog; procurement, construction, and improvement (PC&I) Backlog; and site data.

All asset attributes detailed in Section 3.4 were masked and randomized with a number generator and subject to Microsoft Excel's VLookup function to protect critical facility data while maintaining the ability to correlate backlog data with site data. Additionally, backlog project data was masked and randomized, except estimated project costs, to protect project data while maintaining data accuracy for analysis.

3.4.2 CMMS Limitations

However, SAMS cannot archive documents, posing challenges pertaining to facility condition assessment (FCA) documentation associated with particular assets. Generally, SAMS is used by the Coast Guard as a tool to track, schedule, and manage OLM&R and document site and project information. This method requires significant user input and validation to ensure the data is correct. A separate database, the Coast Guard Technical Information Management System (CG-TIMS), is utilized for site records, drawings, and assessments.

Moreover, SAMS adjusts an asset's plant replacement value based on updates to the Unified Facilities Code (UFC) in accordance with Equation 2.1. However, projects on the backlog in SAMS do not annually adjust for inflation and require manual validation of project scope and cost data. In this vein, U.S. Coast Guard policy requires that facility condition assessments (FCAs) occur triennially. During the FCA process, project backlogs associated with the facility are validated, and projects are added based on FCA findings. However, manpower constraints necessitate that the Coast Guard prioritize where to conduct FCAs across its 40,586 structures and buildings that constitute the facility portfolio. While the plant replacement value is automatically annually adjusted in SAMS—typically increasing—many backlog projects are not validated to account for

cost estimate increases, thereby indicating a false improvement in condition index based on the formula described in Section 2.5.1.1 (DM / PRV).

Beyond this, OLM&R performance is tracked in the CMMS and reviewed by the Civil Engineering Directorate's Shore Infrastructure Logistics Center (SILC), but it cannot precisely track costing data associated with OLM&R. Additionally, OLM&R usage varies by worker type (contracted services, federal civilian employees, or active-duty military personnel), obscuring the data by not considering the actual labor and material costs associated with OLM&R expenses.

3.4.3 Project Backlog Cost Estimates

Backlogged projects receive rough order of magnitude (ROM) costs that are entered into SAMS, along with a basic scope highlighting the problem and recommended solution. These ROM costs are not budget-ready estimates, but they allow the regional Civil Engineering Units to prioritize and build annual budgets based on the ROM project costs. Since backlogged projects are not thoroughly scoped upon entering, actual costs typically exceed ROM costs.

3.4.4 Asset and Project Data Scrubbing

In this study, site and project data in CMMS were imperfect and thus required scrubbing to ensure that analysis could be performed. First, site data was examined to ensure that data pertaining to plant replacement value, mission dependency index, mission essentiality index, and asset type were documented. Of the 43,550 assets, 2,349 constituted land which was not valued, and an additional 615 assets lacked PRV data. Removing these assets nets 40,586 assets for examination.

% Total Count	# Assets	Description	Value	% Total Value	Average Age (years)
100.0%	40,586	Total assets	$27.4B	100.0%	33.5
83.4%	33,846	Structures	$9.6B	35.1%	30.9
16.6%	6,740	Buildings	$17.8B	64.9%	47.9
Owned					
97.8%	39,682	Total	$24.3B	88.8%	33.5
82.8%	33604	Structures	$8.8B	32.2%	30.9
15.0%	6078	Buildings	$15.5B	56.6%	48.0
Leased					
2.2%	904	Total	$3.1B	11.2%	11.4
0.6%	242	Structures	$785.7M	2.9%	21.8
1.6%	662	Buildings	$2.3B	8.3%	5.1

Table 3.2 - Scrubbed Asset Breakdown

After scrubbing the asset data, the backlog was scrubbed to ensure required asset characteristics were documented in the CMMS, including ROM cost, project driver, site data associated with the project, fund source, and project number. These asset characteristics are described in Section 3.5. Projects that did not include cost data were removed from consideration.

3.4.5 Cost Adjustments

As stated in Section 3.4.2, the plant replacement values were from the current year (2022), yet backlogged projects remained stagnant from when they were entered until they were manually modified. Project cost data was manipulated by utilizing the SAMS *Modified Date* field and then applying the 10-year average Consumer Price Index inflation percentage of 2.49% to better reflect backlogged project costs in relation to facility values and thus more accurately analyze facility condition for assets and projects

in 2022 dollars (U.S. Bureau of Labor Statistics). Inflationary cost increases were prescribed utilizing Equation 3.1:

$$C_{c,p} = C_{o,p}(1 + r)^n$$

Equation 3.1: Inflationary Impact Considerations

where

$C_{c,p}$ = current cost of project *p*,

$C_{o,p}$ = original cost of project *p*,

r = rate of inflation (Consumer Price Index 10-year average of 2.49%), and

n = compounding period (years).

These cost adjustments were performed on the dataset prior to performing the baseline analysis and the optimization.

3.4.6 Organizational Level Maintenance and Repair (OLM&R) Backlogs

In this study, organizational-level maintenance and repair (OLM&R) backlogs were not considered. As described in Section 2.4.1, while depot-level maintenance and repair (DLM&R) is consolidated, regionally executed and prioritized OML&R is executed at the discretion of the local unit commanders. Additionally, the OLM&R funding source supports a unit's operational needs that do not include maintenance of shore infrastructure, such as vessel maintenance, personal protective equipment (PPE), administration support services, command initiatives, certain utility costs, and other expenses.

3.4.7 Depot-Level Maintenance and Repair (DLM&R) Backlog

The maintenance and repair deficiency backlog comprised 9,936 projects valued at $2.204B. These projects were categorized by their project drivers: maintenance (M), improvement (I), alteration (A), code compliance (C), and demolition (D). Of the 40,586 owned infrastructure assets in the portfolio, 3,698 had associated projects.

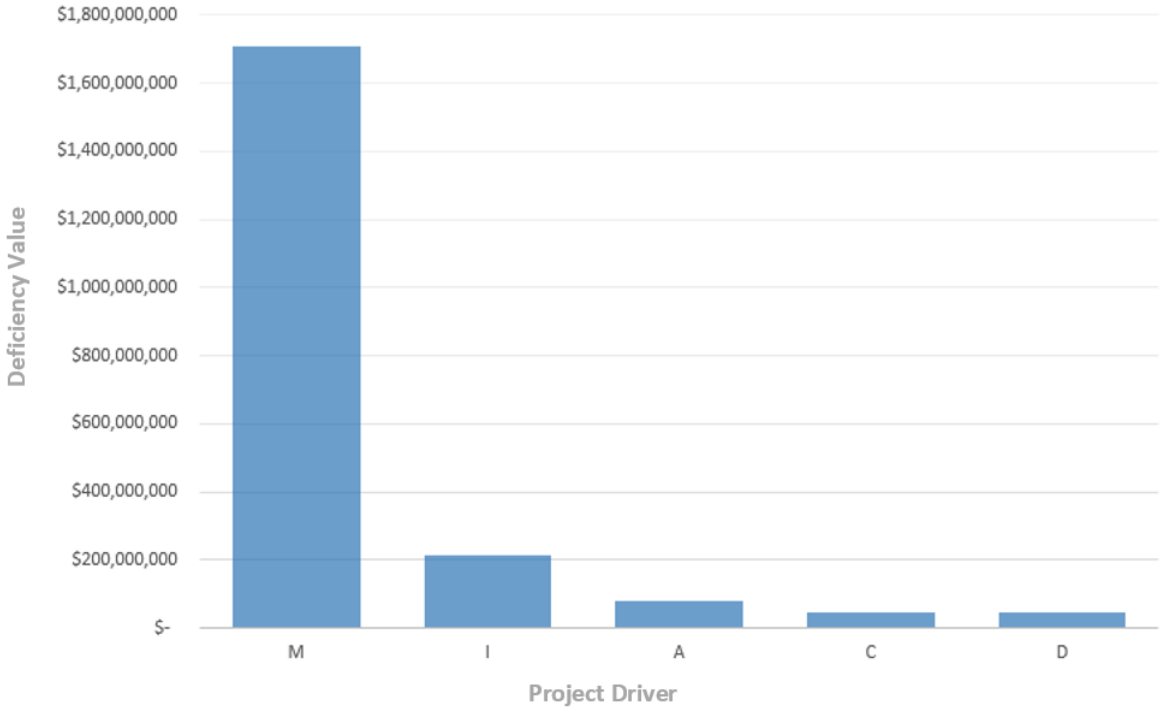

Figure 3.2 - DLM&R Deficiency Backlog

As indicated in Figure 3.2, maintenance-driven projects yielded most of the DLM&R backlog, creating a natural Pareto distribution of 81.7% maintenance and 18.3% cumulative improvement, alteration, code, and demolition.

3.4.8 Procurement, Construction, and Improvement Backlog

The procurement, construction, and improvement (PC&I) project backlog consists of 390 projects, valued at $1.545B. These projects are categorized by their project drivers. As shown in Figure 3.3, improvement-driven projects yielded the slight majority of the

PC&I backlog at 54.3%, followed by maintenance-driven projects at 44.4% and the remaining drivers at 1.3%. These figures are significantly low, failing to represent the significant, undocumented project costs necessary over the next 20 years to outfit shore infrastructure in support of future operational assets (e.g. planes, ships) that are larger and more technologically complex and necessitate shore infrastructure investment.

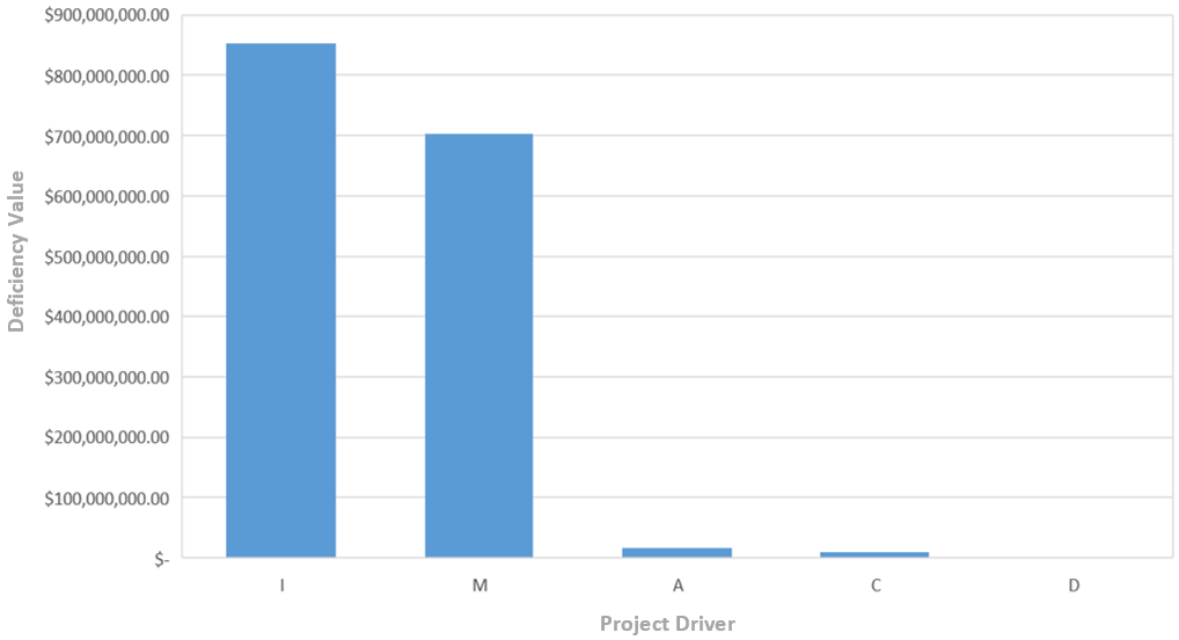

Figure 3.3 - PC&I Deficiency Backlog

3.5 Asset Characteristics

The Coast Guard utilizes multiple descriptors to categorize its shore facilities. In this study, the primary metrics utilized to distinguish shore facilities were site and asset number, site type, plant replacement value, age, operational jurisdiction, and category code.

3.5.1 Site and Asset Designations

A site may be composed of multiple separate, unique real property assets (buildings, structures, or land). This holistic descriptor encompasses all shore infrastructure assets located onboard the installation. Example: Site Number 1234 is "Coast Guard Base Washington." This site, Base Washington, includes assets 7481 ("Floating Dock"), asset 3463 ("Station Building"), and asset 2589 ("Roadway"). Both metrics, site number and asset number, were utilized as decision variables. The specific site numbers and asset numbers were altered through a random number generator to mask the data.

3.5.2 Asset Function

Additionally, shore infrastructure assets are categorized based on their function. For example, in this study, each asset pertaining to waterfront infrastructure had a unique descriptor. There were five overarching categories of assets, referred to as product lines, and 13 subsets of those product lines, referred to as asset lines. The specific product lines and asset lines had been masked. Asset functions were categorized by the corresponding Category Code according to the Department of Defense's Unified Facilities Criteria (UFC). The UFC code distinguished shore infrastructure assets by their type and purpose, and 235 UFC codes characterized the 43,550 assets in the Coast Guard's shore infrastructure portfolio.

3.5.3 Asset Categorization

Next, UFC codes were grouped by asset and product lines, and the Coast Guard utilized these groupings as a key metric for developing an asset's mission essentiality, producing a mission essentiality index (MEI), as described in Section 2.5.2.3. As

indicated by open-sourced Coast Guard data from the Government Accountability Office (GAO) shown in Table 3.3, the Aviation Asset Line included assets such as runways, landing areas, and hangars. Each of these assets had a corresponding UFC code, which was used to develop that asset's MEI.

Asset Line	Examples of assets	Number of assets	Replacement Value ($)
Aviation	Runways, landing areas, hangars	333	2,595,816,173
Waterfront	Piers, wharfs, boathouses, small boat lifts	1,590	2,507,680,516
Shore operations	Stations, maintenance buildings, cutter support operations	1,027	1,913,350,877
Sector/ District	Regional operations centers, command buildings, warehouses	483	2,066,839,441
Technology	Communication towers, vessel traffic service, Rescue 21[a]	1,937	877,523,263
Civil works	Utility distribution, water lines, pipelines, fuel storage	6,633	1,858,048,879
Base services	Vehicle garages, parking, hazardous materials storage	4,219	1,068,509,668
Industrial	Maintenance shops, corrosion control facilities, ship lifts	52	466,672,941
Community services	Medical, dining, physical fitness and recreation	1,148	1,400,869,367
Training	Flight simulators, rescue training facilities	177	418,653,799
Housing	Housing	2,961	2,934,936,066
Total:	—	**20,560**	**18,108,900,990**

Legend: "—" = not available or applicable.

Table 3.3 - Asset Breakdown by Asset Line
(United States Government Accountability Office (GAO), 2019)

3.5.4 Ownership

Shore infrastructure sites and assets are either owned or leased. Of the 43,550 real property assets that constitute the U.S. Coast Guard's shore infrastructure portfolio, the majority was owned, and only 7% was leased. All land, both owned and leased, was omitted from the analysis since land is not valued until the time of divestiture. Furthermore, backlogged maintenance and repair projects are tied to buildings and structures, not land.

3.5.5 Age

Overall, 1,680 sites did not have any data regarding age or commissioning. Additionally, 619 of these assets were removed due to lacking PRV data, netting 1,061 assets without age data. Of these 1,061 assets, 867 were leased and 194 were owned. The average age of each type of shore infrastructure is indicated in Table 3.2.

3.5.6 Operational Jurisdictions

Shore infrastructure assets are categorized based on their location, which is specific to their geographical region. In this study, U.S. Coast Guard operational jurisdictions were categorized by "regions" and "subsets," with subsets falling with regions. There were nine regions and 37 subsets among the regions, and every shore infrastructure asset fell within a region and the subset of that region. The specific regions and subsets were masked.

3.5.7 Plant Replacement Value (PRV)

As described in Section 2.4.6, PRV is the cost necessary to replace an asset to achieve the designed functionality (e.g. no improvement or enhanced capability). The 2022 enterprise PRV value for all shore infrastructure assets totaled $27.4B. In this vein, 2,964 assets had no PRV data and were eliminated from the dataset because it was likely one could perform a condition index analysis without PRV data. Beyond this, 2,349 (79.3%) of these assets constituted land that was both owned and leased. The remaining 615 assets (20.7%) without PRV data were leased structures, which were also removed from the dataset. After discounting leased assets, the PRV for all Coast Guard shore infrastructure was determined to be $24.3B.

3.6 Baseline Analysis

3.6.1 Five-Year Horizon

To generate a baseline, five years of depot-level maintenance and repair (DLM&R) execution data were used. A query was performed using the Coast Guard's CMMS database, the Shore Asset Management System (SAMS), to identify projects that had been awarded between October 1, 2017, and September 30, 2022. This period covered five federal fiscal years of DLM&R execution data for Fiscal Years (FY) 2018, 2019, 2020, 2021, and 2022. Projects during this period were scrubbed to ensure that sufficient data existed associated with the project data to perform the optimization analysis. Projects that had an award date but no award amount indicated were removed from the analysis. Additionally, projects that indicated an award date and amount but were not correlated with a specific infrastructure asset were removed from the data. Overall, 2,716 projects totaling $509.3M comprised the baseline execution amount for DLM&R expenditures during the five-year period. Although all data was randomized, projects that were executed were given a unique descriptor to indicate that they had been performed. This process allowed the researcher to contrast baseline, actual, and optimized performance.

3.6.2 Baseline Condition Index

A baseline condition index was first calculated for the period beginning on October 1, 2017 (the start of FY 2018) to measure performance against the actual five-year execution data (the 2,716 projects executed) and the optimized approach via the mathematical optimization model. As detailed in Section 2.5.1.1, condition index was a

function of the maintenance project backlog, which adjusted over time based on project status (e.g., cancelled, completed, slated).

To calculate a baseline CI for 2017, the researcher made certain assumptions about what the project backlog was in 2017 since the CMMS backlog is a snapshot in time and does not have the ability to trend historical backlog data. The 2018 baseline condition was expressed through the following simplistic equation:

$$PB_{FY18} = PB_{FY22} + CP_{2018\text{-}2022}$$

Equation 3.2 :Historical Backlog Adjustment

where

PB_{FY18} = project backlog starting in fiscal year 2018 (October 1, 2017),

PB_{FY22} = project backlog at conclusion of fiscal year 2022 (September 20, 2022),

PB_{2017} = completed projects between start of FY 2018 and end of FY 2022.

Utilizing actual execution data, the researcher developed the project backlog for October 1, 2017 and calculated the condition index using Equation 2.2 for each asset. The baseline condition index (CI_B) was calculated to be 66.67%, reflecting the average condition index for U.S. Coast Guard shore infrastructure prior to FY 2018 (e.g., prior to October 1, 2017).

3.6.3 Condition Index Delta (Actual Investments)

To identify the actual impacts on the asset condition index from FY 2018 to 2022, the 2,716 projects executed during that period were related to the plant replacement value (PRV) of the projects' associated assets. The condition index by the end of FY 2022

(CI_{FY22}) was determined to be 75.85%, indicating that the average condition index for U.S. Coast Guard infrastructure following actual investments made between FY 2018 and 2022 (October 1, 2017–September 30, 2022) improved by 9.18%. Therefore, the methods used to dictate investment decisions by the U.S. Coast Guard improved the condition index over time but did not incorporate a strategic prioritized asset hierarchy, such as the proposed asset priority index (API) described in Equation 2.14.

3.7 Mathematical Optimization Formulation

The optimization model required the selection of projects that would maximize the condition index associated with critical infrastructure assets based on the API. Utilizing the API—a weighted function of the mission dependency index (MDI) and mission essentiality index (MEI)—locations were ranked to tailor investment approaches accordingly.

3.7.1 Objective Function

The objective function optimized the condition index for critical shore facilities. This process necessitated selecting the most impactful projects for the most critical assets. An integral aspect of this objective was to create a tangible listing of projects that, if executed, would improve the condition index of critical assets.

3.7.2 Decision Variables

The decision (or manipulated) variables used to optimize the objective were the project numbers associated with each project. Overall, 10,876 projects constituted the project backlog, of which 9,936 were associated with the DLM&R backlog. The selection or non-selection of a project indicated compliance within the prescribed constraints to optimize the objective function of maximizing the condition index for critical facilities.

3.7.3 Constraints

3.7.3.1 Budget

Budgets for DLM&R projects are allocated annually. In lieu of formulating an annualized listing of projects, a five-year budget up to $509.3M was utilized to generate a single listing. This figure represented the actual expenditure of funds for shore infrastructure over the five-year period of analysis.

3.7.3.2 Fund Source

All projects are associated with one of six funding sources, as indicated in Table 3.3. Depot-level maintenance and repair (DLM&R) funding was applied as a constraint among the six possible sources. Funding sources are dictated by business rules regarding the scope of work and estimated cost of projects.

Description	Code
Depot Level Maintenance & Repair	DLM&R
Organizational Level Maintenance & Repair	OLM&R
Procurement, Construction, & Improvement	PC&I
Major Acquisition Systems Infrastructure	MASI PC&I
Environmental Compliance & Restoration	EC&R
Supplemental Funding	PC&I Supp

Table 3.4 - Fund Source Types

3.7.3.3 Project Drivers

As detailed in Section 2.4.5, projects are designated by their MACID driver: maintenance (M), alteration (A), compliance (C), improvement (I), or demolition (D). Maintenance “M” driven projects were prioritized for condition index. Projects of other drivers (A, C, I, D) were also prioritized according to the asset’s API, although these projects were not considered for the condition index.

3.7.3.4 Depot Level Maintenance and Repair Project Costs (Improvements)

Generally, DLM&R projects with Improvement "I" drivers are subject to congressional thresholds to ensure operations and support (O&S) funding (DLM&R) are not being used for recapitalization (PC&I) efforts. Through the *Minor Construction Authority*, Congress grants the U.S. Coast Guard authority to use improvement-driven DLM&R funds for minor construction efforts up to $2,000,000 in total improvement costs for each location, indicated by the location number (COMDTINST M11000.11B, 2014).

The Coast Guard's civil engineering program, CG-43, has further restricted this authority to $1,800,000 as a preventative measure to account for possible project growth due to unforeseen risks and site conditions without exceeding the congressionally mandated minor construction authority. This policy governs improvements associated with an individual project, and the cumulative improvement costs across multiple projects for a specific site within a 12-month period. The total improvement costs per site could not exceed $1,800,00 within a 12-month period.

3.7.3.5 Asset Plant Replacement Value Thresholds

The sum of all project costs within a 12-month period could not exceed 75% of the asset's PRV. This sum was not specific to a project driver and applied to the sum of costs across M-, A-, C-, I-, and D-driven projects. As described in Section 2.4.5, a project driver represents the highest percentage MACID element, and projects typically have multiple MACID elements. In this study, a threshold check was developed in RStudio to relate the project's total cost to that of the asset's PRV.

3.7.3.6 Ownership

Generally, DLM&R funding is not authorized for use on leased facilities, following the Coast Guard Financial Resource Management Manual. All infrastructure investments for leased facilities were required to be given with OLM&R funding up to the MC threshold, and all work at leased facilities, regardless of intent, was considered improvement ("I") work. Work that exceeded the minor construction authority threshold necessitated PC&I funding. Leased facilities were not included in the prioritization process.

3.7.3.7 Plant Replacement Value

In this study, asset PRV as a limiting factor for investment opportunities based on the minor construction thresholds indicated in Section 3.7.3.5., and PRV was a key variable for condition index calculations.

3.7.4 Parameters

3.7.4.1 Asset Number

In this work, there were 43,550 unique assets, of which 40,586 constituted structures and buildings. Every project was tied to a single unique asset, denoted by its asset number.

3.7.4.2 Location Number

Coast Guard assets were spread across 4,841 separate locations. Locations were prioritized according to the Asset Priority Index (API) in Section 2.6.10.2. The study used Coast Guard MDI data, and MEI was calculated from the Coast Guard's tiered approach to essentiality.

Tier	MEI Conversion
I	1.000
II	0.750
III	0.500
IV	0.250

Table 3.5 - MEI Construction

3.8 Optimization Model Software

Developing the mathematical optimization model utilized the R programming language, with R Studio as the development environment. Two data files were uploaded to R Studio: Location Data and Project Data. Location data was acquired by the CMMS and included MDI and MEI metrics used to calculate the API. A representative sample of location data is shown in Table 3.6.

Location_Number	Location_PRV	Own_Lease	MDI	MEI	Type
431655	$ 542,107.00	O	1.000	1.000	S
299205	$ 16,973,746.00	O	1.000	1.000	B
250275	$ 77,479.00	O	1.000	1.000	S
250270	$ 2,074,614.00	L	1.000	1.000	B
250390	$ 1,028,779.00	O	0.867	1.000	S
330085	$ 156,018.00	O	0.867	1.000	S
252250	$ 1,648,365.00	O	0.733	1.000	S
252230	$ 55,734.00	L	0.733	0.750	S
252255	$ 1,050,380.00	O	0.733	0.750	S
319725	$ 44,229,678.00	O	0.533	0.100	S
369715	$ 13,137,874.00	O	0.200	0.250	B

Table 3.6 - Sample Location Data Input

Project data was also acquired by the CMMS and included projects per location and a component breakdown between total project costs and improvement costs. Minor data manipulation was performed in Microsoft Excel to convert the CMMS MACID

project breakdown, indicated by percentage, into dollar amounts based on the total ROM cost. A representative sample of project data is shown in Table 3.7.

Location	Location PRV	Project_Number	Driver	Project_Cost	I_Cost
250000	$22,635.00	102511	I	$6,920.15	$4,844.10
250570	$4,326,242.00	102071	M	$1,438,221.48	$ -
256675	$1,878,316.00	100970	I	$66,855.55	$66,855.55
284800	$7,168.00	108327	I	$77,089.10	$61,671.28
290580	$1,751,042.00	104852	M	$80,532.75	$ -
290580	$1,751,042.00	100290	I	$55,819.31	$55,819.31
297160	$595,660.00	105826	M	$79,685.84	$ -
297160	$595,660.00	100779	C	$21,249.56	$ -
298360	$12,085,398.00	102145	I	$58,097.26	$55,192.39
298360	$12,085,398.00	102146	M	$23,238.90	$ -

Table 3.7 - Sample Project Data Input

Utilizing RStudio, the researcher input the raw data to develop an optimization model maximizing condition index based on a generated API. The model's construction is shown in Figure 3.4 (RStudio, 2020). Data wrangling techniques were the primary functions utilized in R to perform data manipulation necessary to group, summarize, and combine location and project datasets based on constraints. The data wrangling packages used are indicated in Figure 3.4, include *tidyverse, tidyr*, and *dplyr*. Other packages used include *readxl, writexl, stringr,* and *openxlsx***.** Chapter 4 provides an analysis of the optimization model's results.

FinalProject.R*

Source on Save

```r
# MAXIMIZE CONDITION INDEX FOR PRIORITY LOCATIONS###############################

# This optimization model optimizes the condition index based on 7 constraints and results in both the
# optimal index and the prioritized projects to achieve that index.

# 1) Load Applicable Packages
library(readxl)
library(MASS)
library(dplyr)
library(tidyverse)
library(pacman)
library(openxlsx)
library(party)
library(stringr)
library(tidyr)
library(writexl)

# 2) Set the Working Directory
setwd("C:/Users/cpf35/OneDrive/Desktop/RoptimizerCI")

# 3) Load & Input Data

# a) Budget Data
Investment_Allocation <- 509300000

# b) API Weighted Data
MDI_weight <- 0.8
MEI_weight <- 0.2

# c) Location Data
Location_Data <- read_excel("ProjectLocationData_Final.xlsx", sheet = "Master_Locations",
col_types = c("numeric", "numeric", "text", "numeric", "numeric", "text"))

# d) Project Data
Project_Data <- read_excel("ProjectLocationData_Final.xlsx", sheet = "M&R_Backlog",
col_types = c("numeric", "numeric", "numeric", "text", "numeric", "numeric"))

# PERFORM BASELINE CI CALCULATION BY LOCATION ##################################################

# 1) Calculate SUM(Project Costs where Driver = M). CI is based on only "M" Projects.
M_Project_Data <- Project_Data %>%
  group_by(Location) %>%
  filter(Driver == "M") %>%
  summarise(cost_sum = sum(Project_Cost))
colnames(M_Project_Data)[colnames(M_Project_Data) == "cost_sum"] <- "Total M Costs"

# 2) Merge with Location data and,
# 3) Compute API & Rank Order Location by API (high to low)
Location_Data1 <- merge(M_Project_Data, Location_Data, by.x = "Location", by.y="Location") %>%
  mutate("API" = Location_Data1$MDI*MDI_weight + Location_Data1$MEI*MEI_weight) %>%
  arrange(desc(Location_Data1$API))

# 4) Generate CI Function.
Location_Data1$CI <- round(1 - (Location_Data1$`Total M Costs`/Location_Data1$Location_PRV), 4)
Location_Data1 <- Location_Data1 %>%
  rename(Original_CI = CI) %>%
  mutate(Original_CI = ifelse(Original_CI < 0,0,Original_CI))

# 5) Generate Threshold Conditions
Project_Data1 <- Project_Data %>%
  mutate("Project_ThresholdCheck" = Project_Data$Project_Cost/Project_Data$Location_PRV) %>%
  mutate("Improvement_ThresholdCheck" = Project_Data$I_Cost/Project_Data$Location_PRV)

# APPLY PROJECT CONSTRAINTS ####################################################################

# 1) OWN -V- LEASE
Location_Data2 <- Location_Data1 %>% filter(Location_Data1$Own_Lease == "O")

# 2) INDIVIDUAL PROJECT SUM OF (M A C I D) COSTS <75% LOCATION VALUE.
# a) Compute "Threshold Check" (Cost/Value).
# b) Discard if Threshold is greater than or equal to 0.75.
Project_Data1 %>%
  filter(Project_Data1$Project_ThresholdCheck < 0.75)
Project_Data2 <- Project_Data1 %>% filter(Project_Data1$Project_ThresholdCheck < 0.75)

# 3) INDIVIDUAL "I" PROJECTS < $750K.
# a) Separate Driver I" Projects to apply additional constraints.
Project_Data3 <- Project_Data2 %>% filter(Project_Data2$Driver!='I')
I_Projects <- Project_Data2 %>% filter(Project_Data2$Driver=='I')
I_Projects_750 <- I_Projects %>% filter(I_Projects$Project_Cost<750000)
```

```r

# COMBINE PROJECTS BY LOCATION
Project_Data4 <- full_join(Project_Data3, I_Projects_750)

# 4) MULTIPLE PROJECT SUM OF (M A C I D) COSTS <75% LOCATION VALUE BASED ON THRESHOLD VALUE.

# Rank 'Threshold Checks' by Location & Sort within location, largest to smallest projects
Project_Data5 <- Project_Data4 %>%
  with(Project_Data4,order(Location,desc(Project_ThresholdCheck)))

# Sum individual project 'Threshold Checks' by Location.
Project_Data5 <- Project_Data5 %>%
  group_by(Location) %>%
  mutate(Threshold_CumSum_ByLocation = cumsum(Project_ThresholdCheck))

# Project Selection (All Projects w/ Cumulative Sum <0.75)
Project_Data6 <- Project_Data5 %>%
  filter(Threshold_CumSum_ByLocation < 0.75)

# 5) MULTIPLE PROJECT "I" COST COMPONENTS < $1,800,000
Project_Data7 <- Project_Data6 %>%
  group_by(Location) %>%
  mutate(I_CumSum = cumsum(I_Cost)) %>%
  filter(I_CumSum < 1800000)

# 6) PROJECT DRIVER "M"
Project_Data8 <- Project_Data7 %>%
  filter(Driver == "M")

# CONSTRAINT 7) BUDGET (see above)

# APPLIED CONSTRAINTS GENERATE THE "ELIGABLE PROJECT LIST"

# CREATE THE OBJECTIVE FUNCTION TO SELECT THE PROJECT LISTING NEEDED TO MAXIMIZE CI #

# 1) Clean up the Project Listing (removed unnecessary variables)

Eligable_Projects <- Project_Data8[ , names(Project_Data8) %in% c("Location","Project", "Driver","Project_Cost")]
Eligable_Locations <- Location_Data2[ , names(Location_Data2) %in% c("Location","Location_PRV", "Original_CI","API")]

# 2) Combine Project & Location Datasets

MergedData <- merge(Eligable_Projects,Eligable_Locations,by="Location",all.x=T, all.y = T,sort=F) %>%
  arrange(Original_CI) %>%
  arrange(desc(API)) %>%
  drop_na()

MergedData1 <- MergedData %>%
  mutate(CumSum = cumsum(Project_Cost))

  # This tells me what projects to do.
Final <- MergedData1 %>%
  mutate(Invest = if_else(CumSum <= Investment_Allocation,0,1)) %>%
  mutate(Balance = Invest * Project_Cost)

FinalCI <- Final %>%
 group_by(Location,Location_PRV,Original_CI,Invest,API) %>%
  summarise(Total_Project_Cost = sum(Project_Cost))%>%
  mutate(Balance = Invest * Total_Project_Cost) %>%
  mutate(New_CI = 1 - Balance/Location_PRV) %>%
  mutate(Percent_Change = (New_CI - Original_CI) / New_CI) %>%
  arrange(desc(API)) %>%
  arrange(New_CI)

library(writexl)
write.xlsx(Final,"Final.xlsx")

library(writexl)
write.xlsx(Final,"FinalCI.xlsx")

mean(Eligable_Locations$Original_CI)
mean(FinalCI$New_CI)


```

Figure 3.4 - R Programming Language Model Builder

Applying the constraints described in Section 3.7.3 resulted in a decrease from 40,586 to 3,656 viable locations and a decrease from 9,936 to 6,823 viable projects.

These quantities represented the locations associated with projects that would improve the condition index if selected within the allocated budget conditions in the precedence of the governing asset priority listing.

3.9 Model Validation

Model validation concerns the accuracy of model outputs compared with the anticipated or perceived results (Gass, 1982). Multiple validation methods exist; for linear programming mathematical optimization models, two common forms include validation *by results* and validation *by construct* (McCarl & Apland, 1986). Validation *by results* compares model outputs with hypothesized results, and validation *by construct* mean a model's ability to measure, evaluate, or optimize the intended parameter based on the physical construct of the model.

Additionally, sensitivity analysis is considered a form of model validation, performed by adjusting a model's input variable(s) to measure impact on the resulting outputs (Trucano, Swiler, Igusba, Oberkampf, & Pilch, 2006). In this study, a sensitivity analysis was performed on the Asset Priority Index (API) used to generate the asset hierarchy upon which to based infrastructure investments. The results of model validation both *by results* and *by construct*, as well as the sensitivity analysis, are highlighted in Sections 4.4 and 4.5, respectively.

Chapter 4: Results

4.1 Introduction

This section summarized the results and analysis of the mathematical optimization model constructed in R Studio. Section 4.2 highlighted the results of the model and compared the results derived from the model with results from the initial Fiscal Year 2018 (CI_{FY18}) and actual Fiscal Year 2022 (CI_{FY22}) conditions. Section 4.3 described the results of the five research questions and hypotheses. A sensitivity analysis in Section 4.4 explored several manipulated scenarios by modifying the Asset Priority Index (API) to obtain further optimized results. Lastly, Section 4.5 detailed the criteria and analysis used to validate the model.

4.2 Optimization Model Results

The objective function was achieved, resulting in an 85.49% optimized condition index, representing the optimized index by the end of Fiscal Year 2022 (CI_{opt}). This process caused an 18.82% increase from the baseline condition index, starting in Fiscal Year 2018 (CI_{FY18}), and a 9.64% increase from the actual condition index achieved by the end of Fiscal Year 2022 (CI_{FY22}).

CI_{FY18} (Baseline)	CI_{FY22} (Actual)	CI_{opt} (Optimized)
66.67%	75.85%	85.49%

Table 4.1 - Condition Index Results and Comparison

The optimization output from R Studio is depicted in Table 4.1, documenting the project priority listing necessary to achieve the objective function to maximize the condition index. A binary function was generated to select an investment and the resulting deferred maintenance balance following that investment. These binary functions

facilitated the generation of new CI values, which were measured against the original CI values for each unique location. A key feature of the output was quantitatively framing the impact of the action (improved CI based on project selection) for critical facilities based on API to drive practical and transparent investment decisions.

Location	Project	Driver	Project_Cost	Location_PRV	API	Original_CI	CumSum	Invest	Balance	New_CI	Percent_Change
250270	102251	M	$ 191,929.78	$ 542,107.00	1.0000	0.5771	$ 191,929.78	0	0	1.0000	0.4229
250270	102250	M	$ 37,319.68	$ 542,107.00	1.0000	0.5771	$ 229,249.45	0	0	1.0000	0.4229
250390	100863	M	$ 33,200.44	$ 5,201,226.00	1.0000	0.9936	$ 262,449.90	0	0	1.0000	0.0064
252230	100430	M	$ 96,385.91	$ 207,436.00	1.0000	0.5353	$ 358,835.81	0	0	1.0000	0.4647
252250	100247	M	$ 45,663.67	$ 68,455.00	1.0000	0.3329	$ 404,499.48	0	0	1.0000	0.6671
252255	100434	M	$ 38,628.84	$ 798,178.00	1.0000	0.9516	$ 443,128.31	0	0	1.0000	0.0484
252830	500034	M	$ 300,000.00	$ 1,671,748.00	1.0000	0.6366	$ 743,128.31	0	0	1.0000	0.3634
252830	105871	M	$ 307,464.82	$ 1,671,748.00	1.0000	0.6366	$ 1,050,593.13	0	0	1.0000	0.3634
254165	101281	M	$ 81,379.99	$ 14,372,047.00	1.0000	0.9542	$ 1,131,973.12	0	0	1.0000	0.0458
254165	108224	M	$ 8,226.16	$ 14,372,047.00	1.0000	0.9542	$ 1,140,199.28	0	0	1.0000	0.0458
254165	104530	M	$ 257,726.13	$ 14,372,047.00	1.0000	0.9542	$ 1,397,925.41	0	0	1.0000	0.0458
254165	105060	M	$ 247,566.51	$ 14,372,047.00	1.0000	0.9542	$ 1,645,491.92	0	0	1.0000	0.0458
254165	100455	M	$ 30,927.14	$ 14,372,047.00	1.0000	0.9542	$ 1,676,419.05	0	0	1.0000	0.0458
254165	103833	M	$ 33,023.54	$ 14,372,047.00	1.0000	0.9542	$ 1,709,442.60	0	0	1.0000	0.0458
254185	103766	M	$ 264,165.92	$ 3,970,445.00	1.0000	0.9335	$ 1,973,608.52	0	0	1.0000	0.0665
254530	102346	M	$ 390,990.09	$ 2,038,563.00	1.0000	0.7522	$ 2,364,598.61	0	0	1.0000	0.2478
254530	107314	M	$ 114,097.31	$ 2,038,563.00	1.0000	0.7522	$ 2,478,695.93	0	0	1.0000	0.2478
254665	103769	M	$ 410,821.52	$ 3,849,878.00	1.0000	0.3674	$ 2,889,517.45	0	0	1.0000	0.6326
254665	500147	M	$ 2,024,707.83	$ 3,849,878.00	1.0000	0.3674	$ 4,914,225.28	0	0	1.0000	0.6326
254670	107780	M	$ 82,577.94	$ 16,973,746.00	1.0000	0.9022	$ 4,996,803.23	0	0	1.0000	0.0978
254670	105654	M	$ 319,818.35	$ 16,973,746.00	1.0000	0.9022	$ 5,316,621.57	0	0	1.0000	0.0978
254670	500149	M	$ 87,948.56	$ 16,973,746.00	1.0000	0.9022	$ 5,404,570.13	0	0	1.0000	0.0978
254670	107078	M	$ 311,906.54	$ 16,973,746.00	1.0000	0.9022	$ 5,716,476.67	0	0	1.0000	0.0978
254670	107389	M	$ 125,387.90	$ 16,973,746.00	1.0000	0.9022	$ 5,841,864.57	0	0	1.0000	0.0978
254670	500154	M	$ 7,410.04	$ 16,973,746.00	1.0000	0.9022	$ 5,849,274.61	0	0	1.0000	0.0978
254670	106942	M	$ 41,657.61	$ 16,973,746.00	1.0000	0.9022	$ 5,890,932.22	0	0	1.0000	0.0978
254670	107781	M	$ 66,711.65	$ 16,973,746.00	1.0000	0.9022	$ 5,957,643.87	0	0	1.0000	0.0978
254670	105228	M	$ 161,315.14	$ 16,973,746.00	1.0000	0.9022	$ 6,118,959.01	0	0	1.0000	0.0978
254670	108407	M	$ 308,086.57	$ 16,973,746.00	1.0000	0.9022	$ 6,427,045.58	0	0	1.0000	0.0978

Table 4.2 - Optimized Results (R) Output

4.3 Hypotheses Analysis

4.3.1 Hypothesis 1 (Thesis) and Results

Question: By what percentage will an optimization model improve the condition index against Fiscal Year (FY) 2018 baseline conditions?

Hypothesis: The optimization model will improve the condition index by at least 10% compared with FY 2018 baseline conditions.

Result: The results of the optimization model indicated an 18.82% improvement in the condition index against the FY 2018 baseline conditions. The model selected the highest impact projects for improvements to condition index across the Coast Guard's shore infrastructure portfolio.

4.3.2 Hypothesis 2 and Results

Question: By what percentage will an optimization model improve condition index against actual FY 2022 conditions?

Hypothesis: The optimization model will improve the condition index by 5% when compared with actual FY 2022 conditions.

Result: The model results indicated a 9.64% improvement to the condition index against actual FY 2022 conditions. This change was a 9.64% increase in condition index when compared with the actual U.S. Coast Guard project selection strategy between October 1, 2017, and September 30, 2022.

4.3.3 Hypothesis 3 and Results

Question: What is the percent variance in project count between the optimized project selection and the actual project selection between the start of FY 2018 and the conclusion of FY 2022?

Hypothesis: The percent variance between an optimized and actual selection of projects between the start of FY 2018 and the conclusion of FY 2022 was 10%.

Result: Table 4.3 provides a summarizes the project listing variance. The optimized listing selected 2,488 projects, compared with the 2,136 actual projects selected between FY 2018 and FY 2022, an increase of 352 projects, or 16.48%. This key statistic

indicated programmatic impacts on the ability to execute the optimized project selection based on contracting, design, and project management capacity limitations.

5-Year Project Listing	
Optimized	2,488
Actual	2,136
Increase of:	16.48%
	352

Table 4.3 - Project Listing Variance

However, as indicated in Figure 4.1, many locations are associated with multiple projects. Since the optimization model's programming satisfies the constraints necessary for project consideration, projects associated with identical locations can be consolidated into single or combined contract actions to generate efficient designs and reduce the quantity of contracting actions. Additionally, this process significantly improved a critical asset's deferred maintenance project backlog - criticality defined by its API.

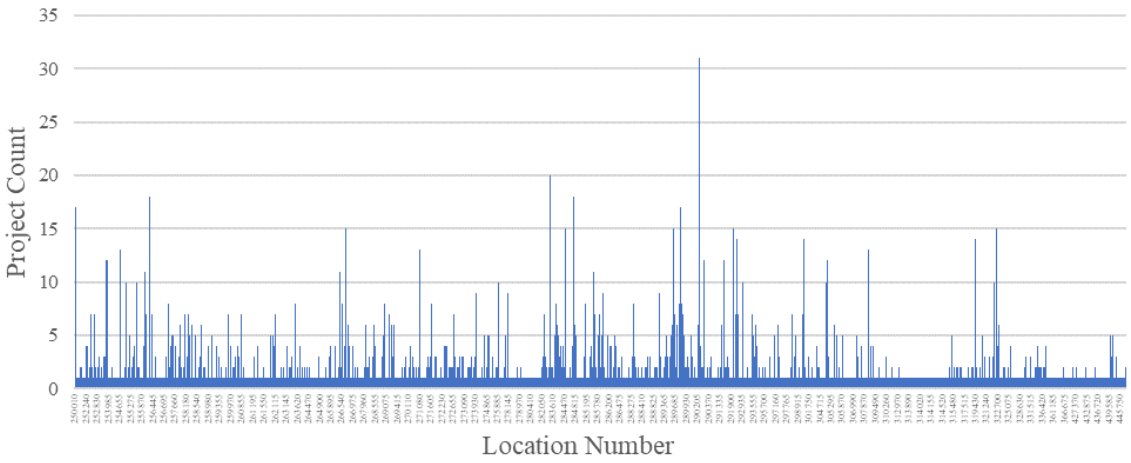

Figure 4.1 - Project Count by Location

4.3.4 Hypothesis 4 and Results

Question: What is the regional variance between an optimized selection of projects and the actual selection of projects for the between the beginning of FY 2018 and the conclusion of FY 2022?

Hypothesis: The regional variance between an optimized selection of projects and the actual selection of projects was within 25% by area and 15% by region for the period between the beginning of FY 2018 and the conclusion of FY 2022.

Result: The regional variance between an optimized selection of projects and the actual selection of projects was 63.07% by area and 39.28% by region for the period between the start of FY 2018 and the conclusion of FY 2022. Figures 4.2 and 4.3 best visualize the project count's impact on regions and areas. As described in Section 2.3.4.2, regions and their sub-regions, referred to as “areas,” define the operational jurisdiction of U.S. Coast Guard shore infrastructure assets.

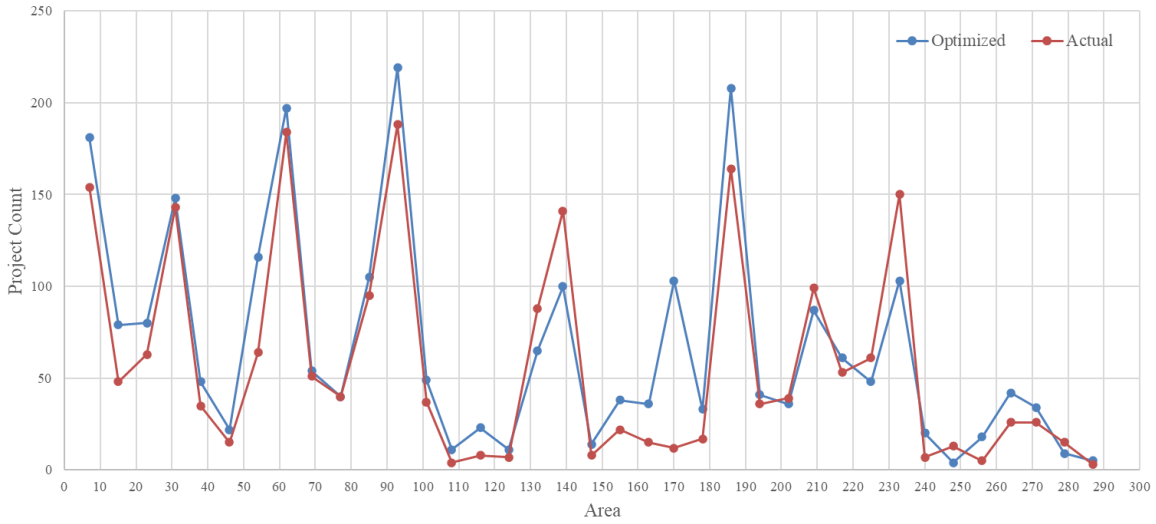

Figure 4.2 - Project Count Comparison by Area

Hypothesis 4 elaborates the finding generated under Hypothesis 3 by focusing on the tactical execution impacts based on the increased project quantity due to the

optimization model. While many areas exhibited significant variance between actual and optimized project selection, variance at the regional level was less impacted and thus had a lesser impact on the U.S. Coast Guard's regional execution strategy.

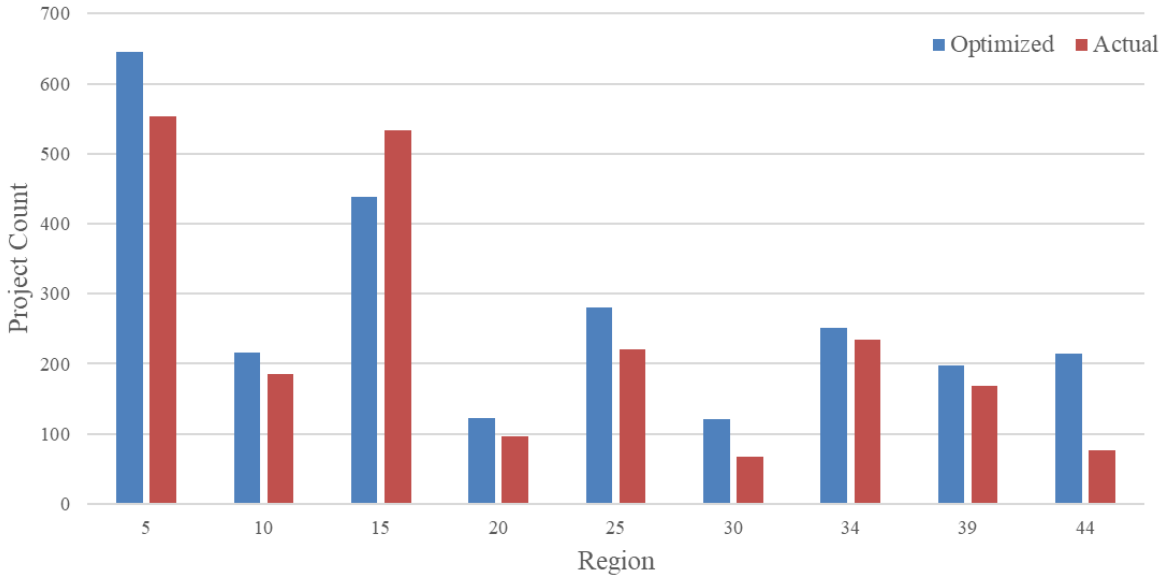

Figure 4.3 - Project Count Comparison by Region

Project selection varies by region, and different operational commanders have different objectives to achieve with DLM funding. Figures 4.2 and 4.3 provide transparency in making informed decisions for the operational commanders by highlighting the greatest maintenance needs across the U.S. Coast Guard.

4.3.5 Hypothesis 5 and Results

Question: What is the regional execution impact between an optimized selection of projects and the actual selection of projects between the beginning of FY 2018 and the conclusion of FY 2022?

Hypothesis: The regional execution impact between an optimized selection of projects and the actual selection of projects between the beginning of FY 2018 and the conclusion of FY 2022 was within 20% for each civil engineering unit.

Result: The regional execution impact between an optimized selection of projects and the actual selection of projects between the beginning of FY 2018 and the conclusion of FY 2022 averaged a 31.8% increase across the Civil Engineering Units. Figure 4.4 depicts the execution impacts of project count variance associated with each regional civil engineering unit (CEU) over the five-year period.

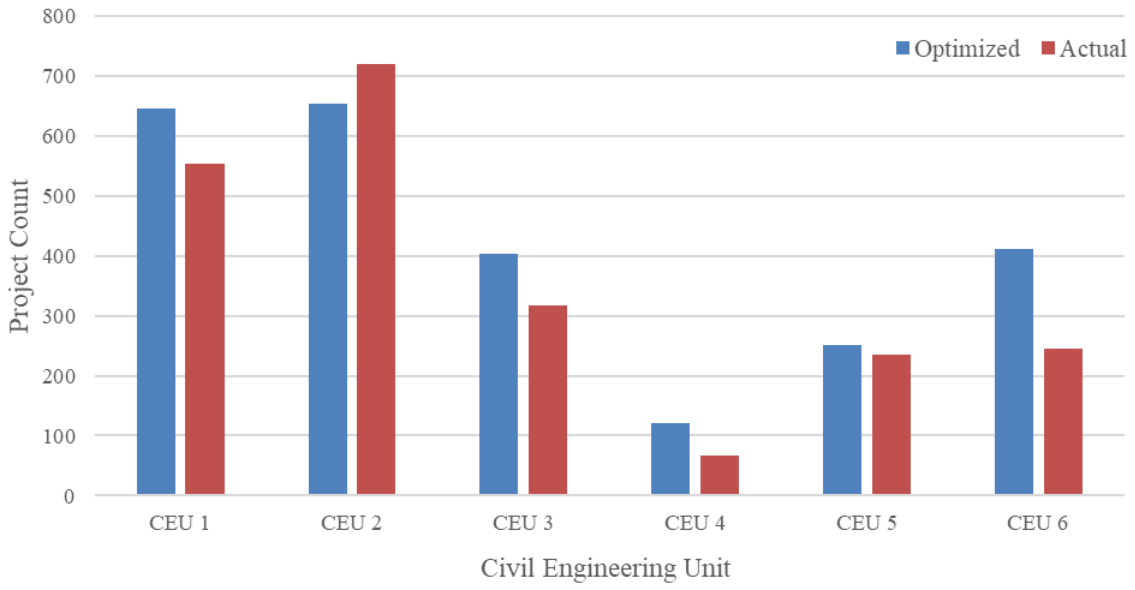

Figure 4.4 - Project Count Comparison by Civil Engineering Unit

CEU	Optimized # Projects	Actual # Projects	% Increase
CEU 1	646	553	16.82%
CEU 2	654	719	-9.04%
CEU 3	404	317	27.44%
CEU 4	121	67	80.60%
CEU 5	251	235	6.81%
CEU 6	412	245	68.16%

Table 4.4 - CEU Delta between actual and optimized project lists.

Each CEU provided DLM&R support for specific regions, and some regions were geographically split and serviced by separate CEUs, each covering specific areas within those regions. Thus, understanding resourcing and staffing impacts on the CEU's executability is integral to ensuring design, contracting, and execution resources are available based on the demand signal. Identifying where projects are most needed also drives a leadership discussion on how to optimize the use of regionally based resources (CEUs), which could involve resource sharing by having external CEU support outside their normal regional areas of responsibility (AOR) to supplement another CEU's AOR.

4.4 Model Validation

Validation *by construct* and *by results* are two prominent validation techniques for linear programming models. According to Section 3.9, model validation was achieved both *by construct* and *by results* in this study. A review of the hypotheses and actual outcomes was performed to examine validity by construct—specifically, Hypotheses 1 and 2, both of which increased the condition index when compared to actual and baseline results. Research Question 1 hypothesized a 10% improvement to the condition index from the FY 2018 Baseline Conditions, and the optimized improvement was 18.82%.

Research Question 2 hypothesized a 5% increase in the condition index from the actual FY 2022 conditions, and the optimized improvement was 9.64%.

Both hypotheses were validated by the model at higher levels than predicted, indicating that the model was validated by construction. However, Hypotheses 3–5 were not analyzed because they involved validation by construct, making these hypotheses ancillary to the objective function, so they were measured to analyze the residual impacts of achieving the objective function.

Considering validity by results, the objective function of the model – to maximize condition index – was achieved and apparent by observation of the model's outputs, as displayed in Table 4.2. Thus, the model's construct, as designed, satisfied the intent of the objective function to maximize the condition index.

4.5 Sensitivity Analysis

The optimization model generated an asset priority index (API) to prioritize facilities, which is based on a weighted approach to the mission dependency index (MDI) and mission essentiality index (MEI), as described below in Equation 2.14:

$$v_i = 0.8v_{MDI,i} + 0.20v_{MEI,i}$$

where

v_i = normalized value for asset *i*,

$v_{MDI,i}$ = normalized mission dependency index for asset *i*, and

$v_{HC,i}$ = normalized mission essentiality index for asset *i*.

A sensitivity analysis was performed on the weighted approach indicated in Equation 2.14 by adjusting the weights for MDI and MEI and comparing variations

against the baseline API. This sensitivity analysis indicated that the proposed API did not produce the highest CI value for critical facilities, as summarized in Table 4.5:

Asset Priority Index		Condition Index
API_{Base}	0.8MDI + 0.2MEI	85.49%
API_{alt1}	0.6MDI + 0.4MEI	87.34%
API_{alt2}	0.5MDI + 0.5MEI	87.64%
API_{alt3}	0.4MDI + 0.6MEI	88.20%
API_{alt4}	0.2MDI + 0.8MEI	86.20%
API_{alt5}	1.0MDI + 0.0MEI	88.41%
API_{alt6}	0.0MDI + 1.0MEI	88.59%

Table 4.5 - Sensitivity Analysis Results

However, the definition of *criticality* and how this term is understood in the context of strategic mission essentiality (MEI) and mission dependency (MDI) require leadership determination to tailor the engineered solution. Investments should be tailored for facilities that are functionally essential and have limited ability to replicate or duplicate their functions.

The proposed API model indicated in Equation 2.14 references the Department of the Interior's approach described in Section 2.6.10.2, encompassing additional metrics currently unavailable to the U.S. Coast Guard. The constructed model prioritizes locations first by API and second by CI_{FY18} to target the most critical, worst-condition locations first. Across the 40,586 locations, 3,698 had associated projects (9,936), and many had identical MDI and MEI data, resulting in identical APIs. Because the model ranked locations based on API, there were variations in grouping, resulting in minor variations in CI_{opt} calculations. This issue became evident during the sensitivity analysis because the model was run multiple times. However, despite these minor variations, each

weighted variation of MDI and MEI improved an index from both CI_{FY18} and CI_{FY22} metrics.

Chapter 5: Conclusions

5.1 Conclusions

The mathematical optimization model discussed in Chapters 3 and 4 accomplished the objective of maximizing the condition index. An essential aspect of this Praxis research was to produce transparent outputs demonstrating the connection between project selection, site selection, mission essentiality, mission dependency, and impacts such as improvement in condition index. These investment decisions operate within defined constraints that govern such investments and were transparently indicated in the optimization model's construction.

According to the British statistician George Box, "All models are wrong, but some are useful." In this vein, the optimization model's trustworthiness and transparency are crucial because investment decisions are frequently influenced by non-engineering managers. The latter can include operational military commanders or congressional appropriators, who have the financial resources and decision power over shore investment determinations. This model utilizes data taken directly from the Coast Guard's Shore Asset Management System (SAMS), exhibits the business rules adhered to by the Coast Guard, and provides an optimized list of executable projects that will improve condition index for critical shore assets.

Effective asset management goes beyond optimizing investment approaches solely to maximize the condition index. Holistic asset management considers all life cycle costs; optimized approaches for depot-level maintenance and repair (DLM&R); organizational-level maintenance and repair (OLM&R); and procurement, construction, and improvement (PC&I) projects within the federal government. A well-vetted asset

priority index (API), which assigns asset priorities based on mission essentiality and dependency, helps ensure that limited funding is allocated to critical facilities.

The outputs of an optimization model always yield better results than traditional approaches if the data is accurate, validated, and well-managed. As mentioned in Chapter 4, certain portions of the U.S. Coast Guard's project and location data were not considered in this study due to incomplete data. To facilitate investment decisions based on criticality, data and the subsequent decisions relying on that data must be properly managed and transparent.

5.2 Contributions to Body of Knowledge

The model constructed in this report is the first of its kind that optimizes the condition index for the U.S. Coast Guard's shore infrastructure locations and assets. The current approach to managing shore infrastructure investments, as described in Section 2.6.8.1, involves an unweighted asset priority with limited data-driven inputs toward project selection. By applying this model to U.S. Coast Guard facilities, one can achieve immediate improvements to the condition index, surpassing the performance from the past five years using the Coast Guard's current unweighted, non-hierarchical approach.

Moreover, the Asset Priority Index (API) presented in this praxis research, along with the sensitivity analysis performed on the study's weighted components, is also the first of its kind to be considered for shore DLM&R investment decisions. No other existing model utilizes this model's API with the constraints identified in the U.S. Coast Guard Financial Resource Management and Civil Engineering Manuals.

5.3 Opportunities for Future Research

Multiple pursuits could further the research explored in this praxis, both in the United States and abroad. The U.S. Coast Guard and other federal agencies could pursue the following steps.

1. Incorporate Sustainment Management System Data

The USCG is currently adapting the U.S. Army Corps of Engineers (USACE) Builder Sustainment Management System (SMS) to better analyze facility data and proactively allocate resources across the portfolio of shore infrastructure assets (BUILDER™ Sustainment Management System, 2012). Outputs from the Builder platform could be combined with data from SAMS to provide a more robust model than the status quo for shore infrastructure investment decisions.

2. Incorporate Automated Cost Estimating System Data

Currently, the USCG is adopting the USACE's Tri-Service Automated Cost Engineering System (TRACES) cost-estimating system. With triennial facility condition assessments, TRACES will improve the accuracy of project estimates documented in CMMS.

3. Validate Mission Dependency Index Data

The USCG is validating its Mission Dependency Index (MDI) data, promising new MDI data available by 2024, which should be used to drive investment decisions. The combination of Builder, TRACES, and improved MDI data directly feeds into this optimization model and will provide more accurate results than current MDI data.

4. Validate Mission Essentiality Index Data

To enhance the effectiveness of the optimization model, the USCG should further refine the mission essentiality index (MEI). This refinement will increase granularity among asset types, producing more optimal outputs. By differentiating asset types more effectively, a MEI will enable more precise, informed decision-making when comparing essential assets.

5. Tailor to Other Objective Functions

The condition index is only one metric used to measure facility performance. This model should be adapted to optimize other indices, such as the comprehensive condition index (CCI or needs index), tailoring the constraints and business rules as needed. Additionally, asset management should focus on more than just the condition index of shore facilities, and a portfolio approach to asset management should seek to optimize more than only CI.

6. Tailor to Other Project Backlogs

This model involved only depot-level maintenance and the repair backlog, so other models could be developed to focus on procurement, construction, and improvement (PC&I) projects. Furthermore, approaches like the mathematical optimization model explored in this report could be applied to other agencies outside the U.S. Coast Guard to make data-driven, informed decisions.

7. Expand Asset Priority Index

Other metrics should be considered within the asset priority index (API) once they are available. For instance, a future opportunity for the U.S. The Coast Guard's API could include data from the Coast Guard's ongoing Shore Infrastructure Vulnerability Assessment (SIVA). In this vein, SIVA analyzes Coast Guard facilities and overlays the

risks and severity of potential hazards based on the geographical and physical locations of Coast Guard facilities. Once completed in 2025, SIVA data will be instrumental in helping the API prioritize projects and account for these risks.

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Appendix A - Raw Project Data Backlog (masked snapshot)

Location	Location_PRV	Project	Driver	Project_Cost	I_Cost
250000	$ 22,635.00	102511	I	$ 6,920.15	$ 4,844.10
250010	$ 3,735,733.00	100293	M	$ 405,165.65	$ -
250010	$ 3,735,733.00	500001	M	$ 127,640.00	$ -
250010	$ 3,735,733.00	102519	M	$ 52,639.61	$ 2,631.98
250010	$ 3,735,733.00	500002	M	$ 47,167.00	$ -
250010	$ 3,735,733.00	100292	C	$ 41,111.42	$ 8,222.28
250010	$ 3,735,733.00	102248	M	$ 29,908.56	$ -
250010	$ 3,735,733.00	102259	M	$ 25,821.25	$ -
250010	$ 3,735,733.00	103208	M	$ 25,821.25	$ -
250010	$ 3,735,733.00	103206	M	$ 22,628.03	$ -
250010	$ 3,735,733.00	103205	M	$ 20,570.94	$ -
250010	$ 3,735,733.00	102258	M	$ 16,773.22	$ -
250010	$ 3,735,733.00	103204	M	$ 15,428.20	$ -
250010	$ 3,735,733.00	103207	C	$ 10,285.47	$ -
250010	$ 3,735,733.00	103390	M	$ 10,277.85	$ -
250010	$ 3,735,733.00	103392	M	$ 10,277.85	$ -
250010	$ 3,735,733.00	500003	M	$ 8,796.00	$ -
250010	$ 3,735,733.00	500000	M	$ 7,767.00	$ -
250010	$ 3,735,733.00	103389	M	$ 7,194.50	$ -
250010	$ 3,735,733.00	103391	M	$ 5,138.93	$ -
250010	$ 3,735,733.00	106770	A	$ 1,915.40	$ -
250030	$ 35,372.00	500004	M	$ 17,197.64	$ -
250055	$ 75,000.00	500005	M	$ 6,100.00	$ -
250065	$ 4,353,342.00	500007	A	$ 256,804.00	$ 15,408.24
250065	$ 4,353,342.00	500006	M	$ 23,076.00	$ -
250120	$ 2,968,983.00	103844	M	$ 22,072.10	$ -
250230	$ 8,004.00	500008	M	$ 8,900.00	$ -
250270	$ 542,107.00	102251	M	$ 191,929.78	$ 9,596.49
250270	$ 542,107.00	102250	M	$ 37,319.68	$ -
250305	$ 158,431.00	503657	M	$ 7,750.00	$ -

Appendix B - Raw Project Data Completed (masked snapshot)

Location	Location_PRV	Project	Driver	Project_Cost	I_Cost
250010	$ 3,735,733.00	500001	M	$ 127,640.00	$ -
250010	$ 3,735,733.00	500002	M	$ 47,167.00	$ -
250010	$ 3,735,733.00	500003	M	$ 8,796.00	$ -
250010	$ 3,735,733.00	500000	M	$ 7,767.00	$ -
250030	$ 35,372.00	500004	M	$ 17,197.64	$ -
250055	$ 75,000.00	500005	M	$ 6,100.00	$ -
250065	$ 4,353,342.00	500007	A	$ 256,804.00	$ 15,408.24
250065	$ 4,353,342.00	500006	M	$ 23,076.00	$ -
250230	$ 8,004.00	500008	M	$ 8,900.00	$ -
250305	$ 158,431.00	503657	M	$ 7,750.00	$ -
250310	$ 215,129.00	503658	M	$ 7,750.00	$ -
250335	$ 2,418,229.00	500009	M	$ 12,039.90	$ -
250355	$ 3,331,699.00	500010	M	$ 13,250.00	$ -
250455	$ 895,518.00	500011	M	$ 45,248.60	$ -
250470	$ 1,112,796.00	500012	M	$ 50,185.89	$ -
250490	$ 1,769,429.00	500013	M	$ 48,174.25	$ -
250565	$ 4,301,517.00	500015	M	$ 777,219.58	$ -
250565	$ 4,301,517.00	500014	M	$ 151,830.70	$ -
250570	$ 4,326,242.00	500016	M	$ 1,247,403.00	$ -
250575	$ 4,301,517.00	500018	M	$ 897,632.00	$ -
250575	$ 4,301,517.00	500017	M	$ 23,902.00	$ -
250580	$ 8,726,147.00	500019	M	$ 808,515.72	$ -
250620	$ 364,459.00	500020	M	$ 26,550.67	$ -
250620	$ 364,459.00	503660	M	$ 7,977.81	$ -
252240	$ 2,676,407.00	500021	M	$ 212,000.00	$ -
252285	$ 28,229.00	500022	M	$ 35,450.00	$ -
252360	$ 2,672,300.00	500023	M	$ 1,399,387.00	$ -
252575	$ 2,425,537.00	500029	M	$ 246,815.00	$ -
252575	$ 2,425,537.00	500025	M	$ 28,233.56	$ -

Appendix C - Raw Location Data (masked snapshot)

Location	Location_PRV	Own_Lease	MDI	MEI	Type
250000	$ 22,635.00	O	0.867	1.000	S
250005	$ 121,065.00	O	0.200	0.500	B
250010	$ 3,735,733.00	O	0.867	0.750	B
250015	$ 26,688.00	O	0.012	0.250	S
250020	$ 52,282.00	O	0.012	0.250	S
250025	$ 80,569.00	O	0.012	0.250	S
250030	$ 35,372.00	O	0.533	0.750	S
250035	$ 103,082.00	O	0.867	0.750	S
250040	$ 4,340.00	O	0.733	0.750	S
250045	$ 104,915.00	O	0.133	0.250	S
250050	$ 35,677.00	O	0.600	0.750	S
250055	$ 75.00	O	0.667	0.750	S
250060	$ 22,444.00	O	0.012	0.250	B
250065	$ 4,353,342.00	O	0.533	0.250	B
250070	$ 21,195.00	O	0.533	0.250	S
250075	$ 27,280.00	O	0.533	0.750	S
250080	$ 12,863,870.00	O	0.533	0.750	S
250085	$ 7,662.00	O	0.533	0.750	S
250090	$ 6,035.00	O	0.533	0.750	S
250095	$ 184,781.00	O	0.867	0.750	S
250100	$ 125,713.00	O	0.733	0.750	S
250105	$ 642,983.00	O	0.333	0.750	S
250110	$ 58,364.00	O	0.667	0.750	S
250115	$ 21,871.00	O	0.533	0.500	B
250120	$ 2,968,983.00	O	0.667	0.500	B
250125	$ 263,453.00	O	0.467	0.500	B
250130	$ 154,093.00	O	0.667	0.750	S
250135	$ 7,779.00	O	0.667	0.750	S
250140	$ 11,434.00	O	0.667	0.750	S
250145	$ 23,516.00	O	0.333	0.750	S

Appendix D - R Input

```
# MAXIMIZE CONDITION INDEX FOR PRIORITY LOCATIONS################################

# This optimization model optimizes the condition index based on 7 constraints and results in
both the
# optimal index and the prioritized projects to achieve that index.

# 1) Load Applicable Packages
library(readxl)
library(MASS)
library(dplyr)
library(tidyverse)
library(pacman)
library(openxlsx)
library(party)
library(stringr)
library(tidyr)
library(writexl)

# 2) Set the Working Directory
setwd("C:/Users/cpf35/OneDrive/Desktop/RoptimizerCI")

# 3) Load & Input Data
# a) Budget Data
Investment_Allocation <- 509300000

# b) API Weighted Data
MDI_weight <- 0.8
MEI_weight <- 0.2

# c) Location Data
Location_Data <- read_excel("ProjectLocationData_Final.xlsx", sheet = "Master_Locations",
col_types = c("numeric", "numeric", "text", "numeric", "numeric", "text"))

# d) Project Data
Project_Data <- read_excel("ProjectLocationData_Final.xlsx", sheet = "M&R_Backlog",
col_types = c("numeric", "numeric", "numeric", "text", "numeric", "numeric"))

# PERFORM BASELINE CI CALCULATION BY LOCATION
#####################################################

# 1) Calculate SUM(Project Costs where Driver = M). CI is based on only "M" Projects.
M_Project_Data <- Project_Data %>%
  group_by(Location) %>%
  filter(Driver == "M") %>%
  summarise(cost_sum = sum(Project_Cost))
colnames(M_Project_Data)[colnames(M_Project_Data) == "cost_sum"] <- "Total M Costs"
```

```
# 2) Merge with Location data and,
# 3) Compute API & Rank Order Location by API (high to low)
Location_Data1 <- merge(M_Project_Data, Location_Data, by.x = "Location", by.y="Location")
%>%
  mutate("API" = Location_Data1$MDI*MDI_weight + Location_Data1$MEI*MEI_weight) %>%
  arrange(desc(Location_Data1$API))

# 4) Generate CI Function.
Location_Data1$CI <- round(1 - (Location_Data1$`Total M
Costs`/Location_Data1$Location_PRV), 4)
Location_Data1 <- Location_Data1 %>%
  rename(Original_CI = CI) %>%
  mutate(Original_CI = ifelse(Original_CI < 0,0,Original_CI))

# 5) Generate Threshold Conditions
Project_Data1 <- Project_Data %>%
  mutate("Project_ThresholdCheck" = Project_Data$Project_Cost/Project_Data$Location_PRV)
%>%
  mutate("Improvement_ThresholdCheck" = Project_Data$I_Cost/Project_Data$Location_PRV)

# APPLY PROJECT CONSTRAINTS
#########################################################################

# 1) OWN -V- LEASE
Location_Data2 <- Location_Data1 %>% filter(Location_Data1$Own_Lease == "O")

# 2) INDIVIDUAL PROJECT SUM OF (M A C I D) COSTS <75% LOCATION VALUE.
# a) Compute "Threshold Check" (Cost/Value).
# b) Discard if Threshold is greater than or equal to 0.75.
Project_Data1 %>%
  filter(Project_Data1$Project_ThresholdCheck < 0.75)
Project_Data2 <- Project_Data1 %>% filter(Project_Data1$Project_ThresholdCheck < 0.75)

# 3) INDIVIDUAL "I" PROJECTS < $750K.
# a) Separate Driver I" Projects to apply additional constraints.
Project_Data3 <- Project_Data2 %>% filter(Project_Data2$Driver!='I')
I_Projects <- Project_Data2 %>% filter(Project_Data2$Driver=='I')
I_Projects_750 <- I_Projects %>% filter(I_Projects$Project_Cost<750000)

# COMBINE PROJECTS BY LOCATION
Project_Data4 <- full_join(Project_Data3, I_Projects_750)

# 4) MULTIPLE PROJECT SUM OF (M A C I D) COSTS <75% LOCATION VALUE BASED ON
THRESHOLD VALUE.

# Rank 'Threshold Checks' by Location & Sort within location, largest to smallest projects
Project_Data5 <- Project_Data4 %>%
```

```
  with(Project_Data4,order(Location,desc(Project_ThresholdCheck)))

# Sum individual project 'Threshold Checks' by Location.
Project_Data5 <- Project_Data5 %>%
  group_by(Location) %>%
  mutate(Threshold_CumSum_ByLocation = cumsum(Project_ThresholdCheck))

# Project Selection (All Projects w/ Cumulative Sum <0.75)
Project_Data6 <- Project_Data5 %>%
  filter(Threshold_CumSum_ByLocation < 0.75)

# 5) MULTIPLE PROJECT "I" COST COMPONENTS < $1,800,000
Project_Data7 <- Project_Data6 %>%
  group_by(Location) %>%
  mutate(I_CumSum = cumsum(I_Cost)) %>%
  filter(I_CumSum < 1800000)

# 6) PROJECT DRIVER "M"
Project_Data8 <- Project_Data7 %>%
  filter(Driver == "M")

# CONSTRAINT 7) BUDGET (see above)

# APPLIED CONSTRAINTS GENERATE THE "ELIGABLE PROJECT LIST"

# CREATE THE OBJECTIVE FUNCTION TO SELECT THE PROJECT LISTING NEEDED TO MAXIMIZE CI
#

# 1) Clean up the Project Listing (removed unnecessary variables)

Eligable_Projects <- Project_Data8[ , names(Project_Data8) %in% c("Location","Project",
"Driver","Project_Cost")]
Eligable_Locations <- Location_Data2[ , names(Location_Data2) %in%
c("Location","Location_PRV", "Original_CI","API")]

# 2) Combine Project & Location Datasets

MergedData <- merge(Eligable_Projects,Eligable_Locations,by="Location",all.x=T, all.y =
T,sort=F) %>%
  arrange(Original_CI) %>%
  arrange(desc(API)) %>%
  drop_na()

MergedData1 <- MergedData %>%
  mutate(CumSum = cumsum(Project_Cost))

Final <- MergedData1 %>%
  mutate(Invest = if_else(CumSum <= Investment_Allocation,0,1)) %>%
```

```
  mutate(Balance = Invest * Project_Cost)

FinalCI <- Final %>%
 group_by(Location,Location_PRV,Original_CI,Invest,API) %>%
  summarise(Total_Project_Cost = sum(Project_Cost))%>%
  mutate(Balance = Invest * Total_Project_Cost) %>%
  mutate(New_CI = 1 - Balance/Location_PRV) %>%
  mutate(Percent_Change = (New_CI - Original_CI) / New_CI) %>%
  arrange(desc(API)) %>%
  arrange(New_CI)

library(writexl)
write.xlsx(Final,"Final.xlsx")

library(writexl)
write.xlsx(Final,"FinalCI.xlsx")

mean(Eligable_Locations$Original_CI)
mean(FinalCI$New_CI)
```