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A strategy to reduce total cost of ownership of the U.S. Air Force's airfield pavements

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The U.S. Air Force (USAF) estimates it has a $33 billion (about 10 percent is airfield pavements) deferred maintenance backlog within its $263 billion infrastructure portfolio. Given the scope of this backlog and the importance of airfields, the USAF has a vested interest in finding strategies to help reverse this growing trend. Without an increase in funding, divestiture of excess infrastructure, or change in strategy, this backlog is estimated to climb to over $50 billion by 2030. Reversing the growing infrastructure backlog trend requires new methods and strategies to rethink how the USAF invests in its infrastructure. As such, the overall goal of this research is to develop a comprehensive and practical asset management approach to reduce the total cost of ownership of USAF airfield pavements. By reducing the cost of ownership, the goal is to reverse the growing maintenance backlog while maintaining a pavement portfolio capable of supporting USAF flying operations into the future. While this research is particularly relevant to the USAF, it seeks to fill research gaps within the current body of knowledge related to pavement management strategies for other agency types by presenting a practical, simulation-based methodology for work planning and budget allocation across a large pavement portfolio over a thirty-year period.

The dissertation presents the development of the BEAST and RAMPSS algorithms. The BEAST algorithm is a simulation tool capable of modeling behaviors and decisions of 109 organizations managing a global network of airfield pavements over thirty years. Additionally, the BEAST is used to forecast outcomes of USAF investment decisions utilizing its current management strategies and historical behaviors. The RAMPSS is a simulation algorithm designed to select the most economical maintenance strategy for each pavement section in the USAF's portfolio (i.e., individualized maintenance recommendation strategy for each pavement section). Analysis from the RAMPSS algorithm of the USAF's pavement portfolio suggests that airfields are generally more cost-effective to maintain if kept in better conditions with strategies other than localized preventative maintenance. The USAF's current maintenance strategy is unsustainable; however, switching to recommendations from RAMPSS (incorporated and modeled in the BEAST) provides a potentially significant course correction.

Keywords: Airfield, Infrastructure Investment, Infrastructure Maintenance, Lowest Life-Cycle Cost, Military, Pavement, Preventative Maintenance, Simulation

DISCLAIMER

The views expressed in this dissertation are those of the author and do not reflect the official policy or position of the United States Air Force (USAF), Department of Defense, or the United States Government. Permission to publish this dissertation was provided by the USAF.

DEDICATION

This dissertation is dedicated to my wife, Megan, and our two children, Emma and Hudson, for their unwavering love, support, and patience as I pursued this degree throughout multiple deployments and moves. To my parents, Tom and Ellen, and brother, John, thank you for the constant love and support throughout the years and instilling in me a passion for excellence and life-long learning.

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LIST OF SYMBOLS AND ACRONYMS

AASHTO	*American Association of State Highway and Transportation Officials*
ACC	*Air Combat Command*
ACN	*Aircraft Condition Number*
AETC	*Air Education and Training Command*
AFB	*Air Force Base*
AFCEC	*Air Force Civil Engineer Center*
AFCENT	*Air Force Central Command*
AFCESA	*Air Force Civil Engineer Support Agency*
AFGSC	*Air Force Global Strike Command*
AFI	*Air Force Instruction*
AFIMSC	*Air Force Installation and Mission Support Center*
AFSOC	*Air Force Special Operations Command*
AIP	*Airport Improvement Program*
AMC	*Air Mobility Command*
APE	*Airfield Pavement Evaluation*
ASCE	*American Society of Civil Engineers*
ASTM	*ASTM International*
BEAST	*Behavioral and Economic Airfield Simulation Tool*
BRAC	*Base Realignment and Closure*
CBR	*California Bearing Ratio*
CJCS	*Chairman of the Joint Chiefs of Staff*
COF	*Consequence of Failure*
CRA	*Continuing Resolution Authority*
CTO	*Construction Tasking Order*
DA/CA	*Design Agent / Construction Agent*
DCP	*Dynamic Cone Penetrometer*
DD 1391	*Department of Defense Form 1391*
DIME	*Diplomacy, Information, Military, and Economic*
DM/CM	*Design Manager / Construction Manager*
DoD	*Department of Defense*
DOT	*Department of Transportation*
ECP	*Electronic Cone Penetrometer*
ERDC	*Engineer Research and Development Center*
ESWL	*Equivalent Single-Wheel Load*
ETL	*Engineering Technical Letter*
EUAC	*Equivalent Uniform Annual Cost*
FAA	*Federal Aviation Administration*

FHWA	*Federal Highway Administration*
FYDP	*Future-Years Defense Plan*
FOD	*Foreign Object Debris*
FSM	*Facilities Sustainment Model*
FSRM	*Facilities Sustainment, Restoration, and Modernization*
HVAC	*Heating, Ventilation, and Air Conditioning*
HWD	*Heavy Weight Deflectometer*
I2S	*Infrastructure Investment Strategy*
ICAO	*International Civil Aviation Organization*
ICBM	*Intercontinental Ballistic Missile*
IPL	*Integrated Priority List*
JCS	*Joint Chiefs of Staff*
LTPP	*Long-Term Pavement Program*
M&R	*Maintenance and Repair*
MAJCOM	*Major Command*
MDI	*Mission Dependency Index*
ME	*Mechanistic-Empirical*
MEPDG	*Mechanistic-Empirical Pavement Design Guide*
MILCON	*Military Construction*
MOS	*Minimum Operating Strip*
MWHGL	*Multi-Wheel Heavy Gear Load*
NAVFAC	*Naval Facilities Command*
NDAA	*National Defense Authorization Act*
NDS	*National Defense Strategy*
NMS	*National Military Strategy*
NSS	*National Security Strategy*
O&M	*Operations and Maintenance*
OCO	*Overseas Contingency Operation*
OPT	*Operational Planning Team*
OSD	*Office of the Secretary of Defense*
OUSD(A&S)	*Office of the Under Secretary of Defense (Acquisition and Sustainment)*
OUSD(C)	*Office of the Under Secretary of Defense (Comptroller)*
P&D	*Planning and Design*
PACAF	*Pacific Air Forces*
PCI	*Pavement Condition Index*
PCI_{crit}	*Critical Pavement Condition Index Value*
PCN	*Pavement Condition Number*
PM	*Preventative Maintenance*
POF	*Probability of Failure*
R&M	*Restoration and Modernization*
RAMPSS	*Rapid Asset Modeling of Pavement Sustainment Strategies*
RED HORSE	*Rapid Engineer Deployable Heavy Operational Repair Squadron Engineers*
RPA	*Remotely Piloted Aircraft*
R_w	*Annual Deterioration Rate with Preventative Maintenance*
R_{w0}	*Annual Deterioration Rate without Preventative Maintenance*

SuPR	*Sustainment Pavement Repair*
UFC	*Unified Facilities Criteria*
USACE	*United States Army Corps of Engineers*
USAF	*United States Air Force*
USAFE	*United States Air Forces in Europe*
USCENTCOM	*United States Central Command*
VBA	*Visual Basic for Applications*
VTOL	*Vertical Takeoff and Landing*
WES	*Waterways Experiment Station*

CHAPTER I

INTRODUCTION

1.1 Introduction

More so than any other service in the Department of Defense (DoD), the U.S. Air Force's (USAF's) ability to project combat power is intrinsically linked to the condition and capabilities of its installations. General of the Air Force Henry "Hap" Arnold described air bases as the "determining factor in the success of air operations. The two-legged stool of men and planes would topple over without this equally important third leg" (Wilson and Goldfein 2019). Today's USAF has transformed since the days of "Hap" Arnold into a multi-domain force; however, the vast majority of its core missions still revolve around its ability to project combat airpower from its airbases (or installations). If an installation's airfield were unable to launch and recover aircraft, the USAF would lose the ability to fight in the air and project combat power from this operating location. As a result, the condition and capability of the USAF's airfield pavements are of utmost importance to its mission.

To support flying operations from its airfields, the USAF (and the Army Air Corps before it) has been actively working to improve how it designs, constructs, evaluates, and maintains its airfield pavements since 1941 when it began development of its first pavement design method (Ahlvin 1991). While the methods, guidance, and design philosophies have changed considerably over the last 79 years, it is fair to suggest that there is likely still room for improvement across all areas. In 2015, the U.S. Army Engineer Research Development Center (ERDC) conducted a full review of the DoD's airfield pavement program utilizing three panels of subject matter experts that looked at flexible design, rigid design, and pavement evaluation methods. Each panel assessed their respective assigned areas in its entirety to identify strengths, weaknesses, and make recommendations for improvement. The observations and recommendations from the panels generally focused on the theme that the DoD pavement design and evaluation methods are overly simplistic and conservative (Crosstek Solutions LLC 2015).

While there is some validity to this observation, it tends to overlook the fact that the DoD's methods are often both simplistic and conservative by military necessity to facilitate global operations. As of June 2017, the DoD had approximately 270,000 military personnel deployed to 180 countries, with 51,000 deployed to undisclosed locations (DMDC 2017). This large number of military personnel deployed in foreign countries around the world are often supported by air operations across a broad spectrum of operational conditions. As such, the DoD needs to maintain a high degree of flexibility to ensure that their pavement design and evaluation methods are adaptable to varying environmental conditions, materials, construction practices, operational constraints, and aircraft. This degree of flexibility is typically not required by other non-DoD pavement authorities, who would typically deal with far less variability and unknowns within their respective jurisdictions.

Furthermore, the USAF often relies upon engineers (and non-engineers) with limited pavement experience to make decisions regarding the suitability of a particular airfield to land a particular aircraft (Synovec et al. 2019). The DoD mitigates the risk in this scenario by intentionally keeping their design and evaluation methods simplistic and conservative. While additional technical rigor may improve pavement performance, it would come potentially at the cost of limiting operational effectiveness, given the realities of military operations and organization.

There are likely components of the DoD's design and evaluation methods that could be improved from a technical standpoint that could strike a balance between improving pavement performance and maintaining operational effectiveness. Along these lines, this research effort initially started as an effort to identify potential solutions to the most pressing needs from a practitioner's perspective. Through the early stages of this effort, it became evident that one of the most pressing needs for the USAF (and the DoD as a whole) is maintaining its growing and deteriorating infrastructure portfolio with an effectively stagnant budget.

The USAF is currently at a tipping point when it comes to infrastructure investment. With an estimated backlog in deferred maintenance and recapitalization of over $33 billion in 2019, the USAF estimates that its backlog will triple over the next thirty years if the status quo (i.e., funding levels, business processes, inventory, etc.) is maintained (Wilson and Goldfein 2019). Failure to take action now would likely lead to disastrous consequences with long-term implications that could force large divestitures of infrastructure. The USAF has enacted some reforms over the last two decades to address its infrastructure challenges. However, the execution of some of its strategies has produced unintended consequences that have exacerbated the problem. Among these reforms, the USAF implemented a centralized, risk-based asset management approach to maintaining its infrastructure. The risk-based approach was intended to ensure that the USAF prioritized resources to maintain the infrastructure that had high probabilities and consequences of failure to ensure that no mission stoppage occurred as a result of infrastructure degradation. Life-cycle cost approaches were not directly considered in the risk-based approach; therefore, the risk-based approach often prioritized projects that required funding towards an asset's highest lifecycle point. Over time in a resource-constrained environment, the risk-based approach effectively became a “worst first” approach that helped exacerbate the USAF’s backlog of deferred maintenance (Synovec et al. 2019).

Throughout its existence and multiple conflicts, the USAF has averaged, in constant year terrms, an annual budget of approximately $170 billion (OUSD(C) 2018a; Synovec et al. 2019). This total spending authority includes all budgetary requirements across all expense categories, including funding for personnel, weapon system acquisition, infrastructure, research and development, and aircraft fuel and maintenance. As a result, the cost of procuring new aircraft is typically offset by reducing expenditures in other expense categories. That said, with significant and sustained increases in funding, the USAF could potentially slow or even reverse the backlog growth. However, the size of the funding level increases required would require the USAF to forego or curtail other major investment actions, such as reducing its procurement goals for many of its aircraft recapitalization programs. With the USAF announcing in 2018 its intentions to increase to 386 operational squadrons, a 24 percent growth, relying solely on funding to solve the infrastructure backlog issue could prove unsustainable or unrealistic (SAF/PA 2018). As a result, the USAF needs to consider a change to its risk-based, asset management approach to one that prioritizes investment at the lowest lifecycle cost.

1.2 Problem Statement

As previously mentioned, the USAF estimates, as of 2019, its infrastructure maintenance and recapitalization backlog to be approximately $33 billion. This backlog estimate includes deferred costs across all infrastructure classes, to include airfield pavements, facilities, roads, utilities, warehouses, and housing. Furthermore, available funding is prioritized to corrective maintenance (i.e., maintenance necessary to repair a failed or deteriorated asset) rather than on preventative maintenance and other service life extension actions. As a result, assets in good condition often deteriorate at an increased rate. At the same time, the funding, which could be used to slow deterioration, is used to recapitalize and repair failed and deteriorated assets at or near the highest cost point. As discussed in detail in Chapter VI, this scenario (i.e., status quo) repeated annually at airfields across the USAF would result in the average pavement condition index (PCI) rating for the entire portfolio dropping from 82.5 to 62.7 over the next thirty years. Furthermore, the airfield pavement portion of the USAF's infrastructure maintenance backlog would grow from $2.3 billion to approximately $6.6 billion measured in constant year dollars.

The concept of developing an asset management strategy that prioritizes investment at the lowest lifecycle involves two key decisions points: (a) what work is required to maintain the pavement (i.e., work planning); and (b) how should all of the requirements be prioritized (i.e., budget allocation) (France-Mensah and O'Brien 2018). Furthermore, any new strategy needs to account for how the USAF funds and organizes its portfolio while continuing to ensure mission effectiveness such that the strategy is both actionable and realistic. In summary, the USAF needs a new asset management strategy that allows it to institute a lowest lifecycle cost approach for its entire inventory of airfield pavements in both its centralized and decentralized investment portfolios. This last distinction is important because the synergy between the centralized and decentralized portfolios has not typically existed in practice. Without synergy between the portfolios, the USAF effectively has 109 different organizations (accounting for both centralized and decentralized decision-makers) in the service making decisions that impact its pavement portfolio that may not align with or support the overall strategy.

Looking beyond the USAF, transportation authorities across the country are experiencing similar infrastructure challenges and are seeking more cost-effective pavement maintenance strategies to manage their large pavement portfolios (MAP-21 2012; ASCE 2017; Duncan and Schroeckenthaler 2017). As such, previous research has sought to address this need by developing a variety of optimization techniques and asset management strategies aimed at helping to maximize the limited budgets available for infrastructure maintenance. While this previous research has provided much insight into potential options, additional research is necessary to close several research gaps. Among these research gaps, research is minimal on airfield pavement management and budget allocation strategies for large-scale pavement portfolios with multiple decision-makers and budget portfolios.

1.3 Research Objectives

The primary objective of this dissertation is to develop a comprehensive and implementable asset management approach to reduce the total cost of ownership of airfield pavements for the USAF. The underlying premise of this research is to identify solutions for the USAF that influence the type and timing of maintenance utilized to maintain pavements to maximize the effectiveness of its funding thereby slowing, and potentially reversing, the growth of the maintenance backlog. While this research is particularly relevant to the USAF, it seeks to fill the research gaps discussed in the previous section and advance the state-of-knowledge for pavement management strategies by presenting a practical, simulation-based methodology for modeling the outcomes of implementing lowest lifecycle cost strategies across large pavement portfolios. To accomplish the primary objective, six secondary objectives were defined:

1. Define the scope of the DoD's pavement program and its uniqueness relative to non-DoD pavement authorities,
2. Discuss the process for how the DoD builds and maintains its airfield pavements,
3. Holistically evaluate and identify the current needs of the DoD's airfield pavement program,

4. Develop a simulation environment to model centralized and decentralized investment decisions inclusive of every airfield pavement in the USAF's portfolio,

5. Formulate a methodology and identify the lowest lifecycle cost maintenance strategy for every airfield pavement section, and

6. Compare the long-term impacts of the lowest lifecycle cost approach to the status quo methodology.

1.4 Scope

This research effort started with an extensive literature and preview review to understand the full scope of the DoD's pavement program across all facets: operations, design, evaluation, maintenance, funding, training, and construction. Additionally, the early stages of the research served to document the unique aspects of the DoD's pavement program and operations that make a comparison between a non-DoD transportation authority difficult. With the information from the literature gathered, a comprehensive needs assessment helped identify the most pressing airfield pavement needs for the DoD. While the needs assessment covered a wide variety of programmatic and technical aspects of the DoD's pavement program, this needs assessment ultimately helped identify one of the most pressing needs (perhaps the most pressing need) and, subsequently, the subject of this dissertation: reducing the total cost of ownership of airfield pavements. It is worth noting that the most pressing need in the context of this dissertation is related to the perceived long-term impact on the DoD's airfield pavements. Given the infrastructure challenges and backlog coupled with resource limitations, the most pressing need seemed to be reducing the cost of ownership to improve the sustainment of deteriorating pavements. Due to the availability of key financial and pavement condition data, the scope of this dissertation shifted at this point to a USAF-focused effort. As a general note, the analysis of the USAF's pavement network only includes paved airfield pavement sections recorded in the USAF's PAVER database.

1.5 Organization of Study

This dissertation is organized into nine chapters. From these nine chapters, three articles were drafted for submittal to peer-reviewed publications. At the time of this dissertation's publication, one article was published as a conference paper, and the other two articles were in various stages of the peer-review process with journals. Figure 1.1 depicts the relationships between these articles and the previously stated research objectives.

The first and last chapters are an introduction and conclusion, respectively. Chapters II through IV provide an extensive literature review on the USAF's and DoD's pavement programs, as well as a generalized needs assessment based on the observations from the holistic literature review. Much of the information from these chapters, particularly Chapter IV, was used to form the article submitted for publication as a conference paper. Chapter VI details the development of the Behavioral and Economic Airfield Simulation Tool (BEAST) used to analyze the USAF's current pavement management strategy. Chapter VII summarizes the development of the Rapid Asset Modeling of Pavement Sustainment Strategies (RAMPSS) algorithm. The RAMPSS algorithm was used to formulate individualized maintenance strategies for each pavement section in the USAF's pavement portfolio; these maintenance strategies were optimized to target maintenance approaches at the lowest lifecycle cost. Finally, Chapter VIII details the outcomes of the integration of the BEAST and RAMPSS. When combined, these algorithms provide insight on potential impacts of the USAF shifting to a lowest lifecycle cost maintenance approach. The remaining two peer-reviewed papers were formulated using components and portions of the discussion and analysis contained in Chapters VI through VIII. Because the chapters in this document are written as self-contained documents, some repetition will occur among the introductory and background sections for the different chapters.

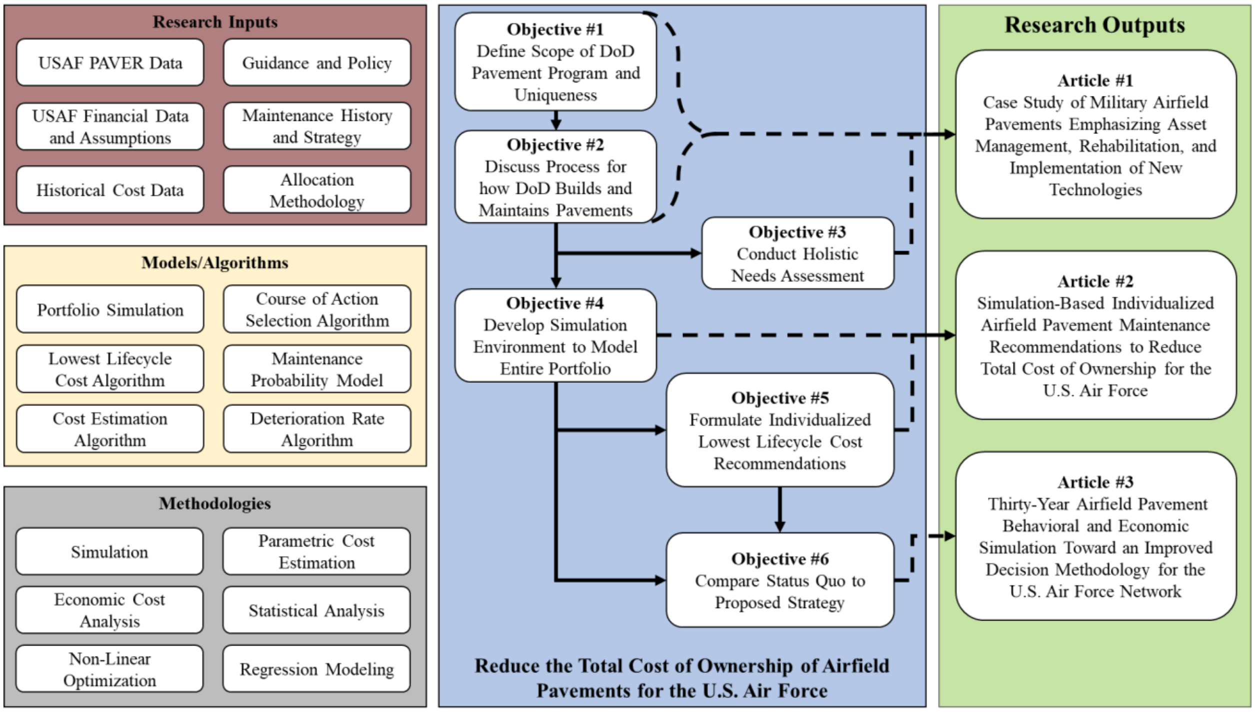


Figure 1.1 Summarized Research Approach

CHAPTER II

SCOPE OF THE DEPARTMENT OF DEFENSE'S AIRFIELD PAVEMENT PROGRAM

2.1 Overview of the Pavement Program

The purpose of this chapter is to describe the DoD's airfield pavement program while also capturing the capabilities and challenges inherent and unique to the DoD. These capabilities and limitations shape the current (and future) state of practice within the DoD. Discussions focus on seven main areas: (1) operating locations, (2) aircraft, (3) pavement materials, (4) pavement evaluation, (5) personnel, (6) airfield damage repair, and (7) finances. This chapter includes a brief discussion on airfield finances, with a more detailed discussion as it relates to timing and administrative processes provided in Chapter III.

2.2 Operating Locations

In June 2017, the U.S. military had approximately 270,000 personnel deployed to 180 countries, with 51,000 deployed to undisclosed locations. These deployments range from permanent operating locations and personnel levels of over 35,000 in Germany and Japan to small advisory missions consisting of one person in Namibia (DMDC 2017). While the number of personnel in a given country is relevant, it does not necessarily give a real insight into military missions and objectives. The U.S. military's mission in these 180 known countries is wide-ranging, but there is likely a requirement for pavement design and evaluation in the vast majority of these countries. The basis for this assertion is that the military relies on a robust logistical network to support its operations, which includes air mobility operations. It is very likely that if the U.S.

military is present in a country that supplies, equipment, or personnel will or have been moved to that country by aircraft.

Due to worldwide inconsistencies with pavement evaluation procedures and reporting pavement condition numbers (PCNs), the DoD typically elects to conduct its own pavement evaluation to reduce the risk of operating its aircraft from an unknown airfield. Furthermore, if military operations were to continue for an extended period of time, the DoD would likely elect to conduct a full structural and PCI survey to document the existing conditions in the event of a dispute over damage caused by the U.S. military. This is typical of actions that any tenant would want to take when entering into a lease agreement, whether it be an airfield or a house. In the event that apron space for parking aircraft was not readily available, the U.S. military would then consider building parking aprons and other supporting facilities.

2.3 Aircraft

As of September 2016, the USAF operated 5,369 total aircraft. This rather large aircraft fleet is comprised of 88 different types with an average age of approximately 27 years (AFA 2017). For comparison, Delta Airlines, which is one of the largest airlines in the world, operates 19 aircraft types totaling 847 aircraft (Delta Airlines 2017). With approximately 6.5 times more aircraft than Delta Airlines, the USAF only represents approximately 39 percent of the DoD's total aircraft inventory of 14,005 in the fiscal year 2017 (DoD 2016). A breakout of the 14,005 aircraft is shown below in Figure 2.1.

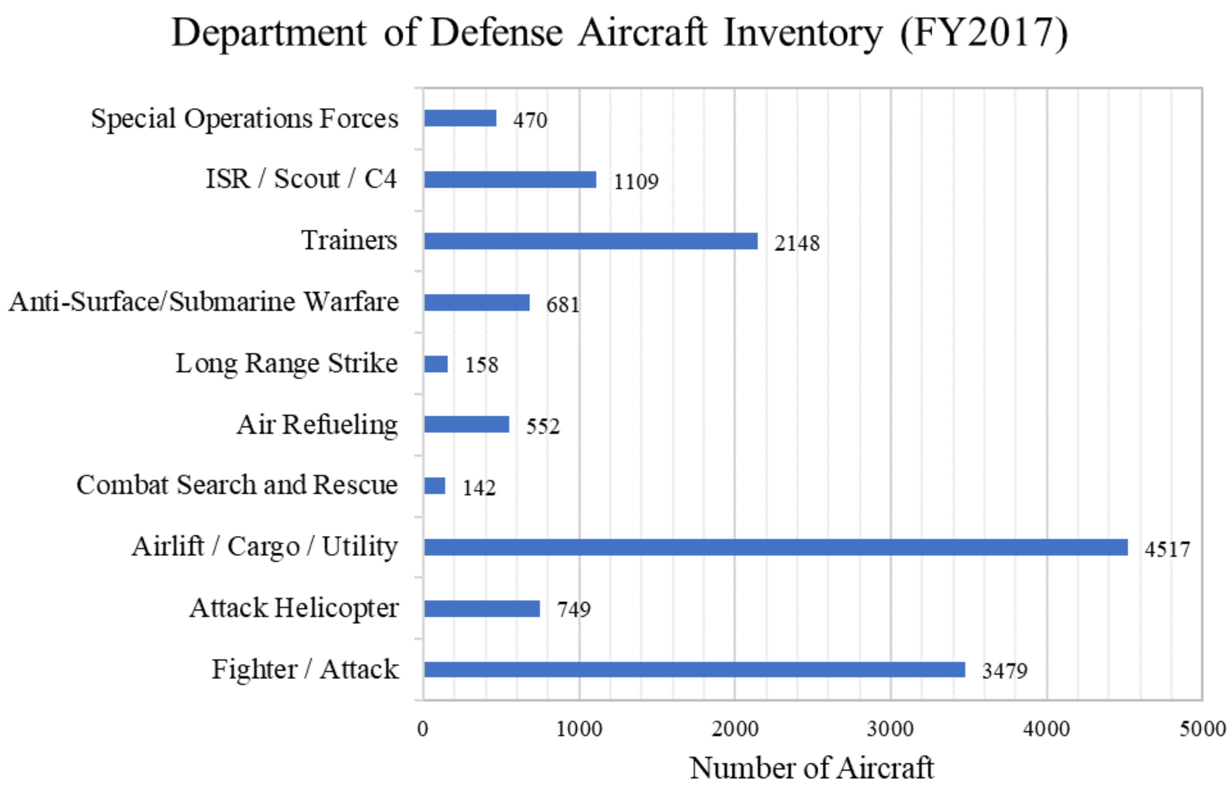


Figure 2.1 Quantity and Types of Aircraft within the Department of Defense (FY2017)

Additionally, due to the demands placed on the military's logistics network and mobility assets, it is common for the DoD to contract commercial carriers to move personnel and equipment worldwide by air. A military airfield has a wide range and variety of design considerations that highway pavements or other non-military airfields do not typically encounter. A small sampling of the aircraft that could land on a military airfield is shown in Table 2.1.

Table 2.1 Department of Defense Aircraft Group Types (created with data from USACE 2014)

Aircraft Group Index (Based on Gear Types and Aircraft Weights)													
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
C-12	A-10	CV-22	C-130	C-20	B-717	A-320	A-300	A-330	C-17	C-5	A-340	A-380	B-52
C-21	AT-38	CV-580	C-27J	C-37	C-9	A-321	A-310	A-350	IL-76		B-777	AN-124	
C-23	F-117	MH-53	C-295		DC-9	B-727	B-2A	B-1			DC-10-30	B-747	
C-38	F-15	MV-22	CN-235		T-43	B-737	B-707	B-767			DC-10-40	B-747-400	
C-41A	F-16					C-22	B-720	B-767			KC-10	B-747-8	
HH-60	F-22					C-40	B-757	B-787			MD-11	E-4	
RC-26	F-35					MD-81	C-32A	DC-10-10				VC-25	
RQ-4 Bk 10	RQ-4 Bk 20+					MD-82	DC-8	K-1011					
T-1	T-38					MD-83	E-3	KC-46					
T-37						MD-87	E-8C	MD-10					
T-6						MD-90	KC-135						
UH-1H (skid)						P-3	VC-137						

Looking at the two largest DoD aircraft categories, fighter and cargo aircraft represent the diverse and problematic loads on military airfields for a variety of reasons. Fighter aircraft can be characterized by relatively light loads (up to approximately 81 kips) with very high tire pressures (up to approximately 325 pounds per square inch). Furthermore, these aircraft typically have single-wheel gear assemblies. These aircraft typically require more attention to stresses and strains closest to the surface; whereas, heavier cargo aircraft with lower tire pressures require more considerations of stresses and strains deeper into the pavement. Besides load-related concerns, fighter aircraft can be heavily impacted by foreign object debris (FOD) due to the design and positioning of its engines and air intakes. Even small diameter FOD going through an engine could potentially cause an aircraft to crash. As such, it is no surprise that the F-16 is often jokingly referred to as a "FOD vacuum cleaner."

With regard to DoD's newest fighter aircraft, the Joint Strike Fighter (F-35), a new engineering issue has emerged primarily with the U.S. Marine Corps variant. The Marine Corps variant (i.e., F-35B) includes a vertical takeoff and landing (VTOL) capability that exposes the pavement to extreme thermal conditions. According to Autelitano et al. (2016), the F-35B during a VTOL operation exposes the surface of the pavement to temperatures exceeding 1706 °F at a rate of temperature rise of 185 °F per second. At these temperatures, bituminous materials would not be an option, and traditional concrete mixes would lose free moisture and begin to see a breakdown in the chemically-formed bonds that bound the aggregates together. Inevitably, traditional concrete pavements would deteriorate rather rapidly due to the extreme thermal conditions. Although not a fighter aircraft, the military's CV-22 Osprey causes a similar thermal load, albeit at a much less magnitude. The primary difference between the CV-22 and the F-35B with respect to pavement damage is that the CV-22 also exposes airfield pavements to chemical deterioration due to leaks of petroleum, oil, and lubricants (POL) from the engines when they are in the vertical position. The CV-22 and F-35 are among the DoD's newest aircraft, and both aircraft are anticipated to be in service for decades to come. As such, the DoD has studied both issues extensively over the past few years to publish guidance to address the problems (AFCEC 2014a; AFCEC 2014d).

With regard to cargo and mobility aircraft, DoD airfields can experience traffic ranging from small personal jets and propeller-driven aircraft (e.g., C-21, C-145, C-12, etc.) to the largest cargo aircraft in the world, the Antonov An-225. This broad spectrum of mobility aircraft includes a variety of gear configurations and operating weights. The DoD's two most common mobility aircraft are the C-17 and C-130, the latter of which includes over a dozen variants. These two aircraft are unique from other aircraft in the mobility inventory due to the rather wide spectrum of environments that they are required to operate. For example, C-17s and C-130s are capable of landing on paved, unpaved, and ice runways. Additionally, C-17s and C-130s are designed to be able to conduct tactical (or assault) takeoff and landing maneuvers on extremely short runways. Tactical landings can impart more stress on the runway pavement due to the speed and angle of approach required for the maneuver.

2.4 Pavement Materials

Within the continental U.S. and most first-world countries, paving materials broadly speaking, are fairly consistent and of high quality. Furthermore, the logistical network involved with sourcing raw materials, producing engineered intermediate products (e.g., modified asphalt binder), producing the finished product (e.g., hot-mix asphalt), and transporting materials is, by comparison, sophisticated and robust. Other areas of the world have varying degrees of paving material production capabilities.

The U.S. military has long operated in the Middle East but has, in more recent years, made a shift to Africa and the Indo-Pacific regions due to increased tensions in these regions. Of the over four thousand airfields in Africa, only 20 percent were paved as of the mid-2000s (UNECA 2007). Of the 20 percent of paved airfields, standard asphalt pavements were more often the exception as opposed to standard practice. Materials, experience, and equipment factors often lead to existing pavements being non-standard, such as macadam, bituminous surfaced treatment, or sand asphalt (Priddy and Rutland 2014). These non-standard approaches were not originally intended for airfields. Rather, they were initially introduced on the continent by European countries and the United Nations in an effort to build a road infrastructure across Africa quickly and in a cost-effective manner (Priddy and Rutland 2014). As a result, the local workers became experienced using these non-standard materials to construct pavements; therefore, it was merely a matter of time until these construction methods were utilized on airfield pavements.

In 2015, the USAF began constructing a new airbase in sub-Saharan Africa. This region is among the poorest and least developed areas in the world; needless to say, the logistical network in place to support such an endeavor was virtually non-existent (CIA 2020; Schmitt 2018). Based on the author's personal experience with this project, sourcing paving materials for the new airfield was an arduous task, since there were no existing suppliers in-country. Furthermore, few suppliers in the region were willing to bid on the materials contract, let alone mobilize equipment to the area. After months of going through the Government's procurement processes, all of the materials contracts were awarded to a regional contractor (i.e., the contractor was not from the country were construction was taking place, but was from a surrounding country). The selected contractor then needed to purchase and mobilize equipment, in addition to hiring new employees, to support the airfield construction effort. Based on the initial unit prices of materials ($238 per metric ton of asphalt and $350 per cubic meter of concrete), the USAF decided to forego common DoD airfield construction practices and construct the entire airfield with asphalt pavement. Most DoD airfields are a mix of selectively placed concrete and asphalt pavements. While these prices seem exorbitantly high compared to U.S. material prices, these costs are not uncommon when compared to the costs that the U.S. military has to pay in other remote and hostile locations in the Middle East.

From the award of the materials contract, it took over six months for the materials supplier to mobilize all of their equipment to the project site. The timeline for this process was exacerbated by ocean shipments required to move most of the equipment, country clearances and customs, and the lack of reliable road networks. For general awareness of the sourcing strategy, batch plants were sourced from eastern Europe, laboratory equipment came from China, and a rock crusher came from Turkey. Additionally, cement, asphalt binder, and supporting materials (e.g., dowels, reinforcing bars, etc.) were all shipped to the project site from various locations throughout Europe. Although raw aggregates were able to be sourced in-country, they were required to be trucked to the material supplier's location from the quarry approximately an hour away. For unbound materials, the contractor crushed the raw aggregates and then blended the aggregates piles to create the select fill, subbase, or base course material for the airfield. The blended material was then tested for quality control, loaded, and transported to the project site approximately 30 minutes away.

Given the logistics required to produce and deliver material to the project site, the project inherently had a high risk of delays to the construction schedule. Logistics coupled with lack of contractor experience at supplying materials on this scale all but guaranteed that delays would occur. Delays occurred commonly, and the project's schedule was noticeably impacted by the delays and the slower production rates for materials. The delays forced the USAF to make some tough decisions: secure a new materials supplier, accept a lengthened project schedule, or accept further deviations in your airfield criteria and specifications to save time?

The answer to that line of questions is relatively complicated. Bringing in a new materials supplier would take months. Also, the current contractor had been putting money into a starving local economy through the acquisition of materials, hiring of unskilled laborers, and through the general acquisitions associated with typical company overhead (i.e., the contractor formed good local relationships). Hiring a new contractor would likely have severed these ties, particularly if the replacement contractor was from outside the region.

On Government projects, cost overruns are incredibly challenging and should be avoided to the maximum extent possible. In the military, this often means asking Congress for additional funding, which requires an extensive and bureaucratic staffing process, which can take approximately four to six months. That said, if the cost is where risk is not tolerable, then according to basic project management principles (symbolized in the Project Management Triangle shown as Figure 2.2), risk must be taken in scope or schedule while hoping quality does not suffer. Typically, in contingency environments, the schedule is another area where taking risks is difficult. For most military operations, standing up new operations (i.e., deploying a brigade or a new flying mission) within an area of operations requires extensive planning that can take over a year, depending on the complexity and support requirements. That said, delaying a construction schedule by a noticeable amount of time causes significant second-and-third-order effects, as the planning, logistics, transportation, and procurement processes to support the operation that is dependent on construction being complete has already started. If cost overruns are a "third-rail" and delaying a project schedule is difficult, then the military engineer typically finds themself defending design decisions and arguing against reducing scope requirements. The engineer starts fielding questions such as, "what happens if we reduce subgrade compaction requirements?"; "what happens if we reduce pavement thickness and supporting layers considerably?"; or "can we build a reduced strength airfield and then upgrade it later?". Eventually, the engineer is very likely even to field directives to adjust construction plans to create a minimum operating strip (MOS) to get the flying operations started while construction continues. These are all relatively challenging situations and questions for an experienced pavements engineer. An inexperienced or junior engineer would likely be overwhelmed and potentially postured for failure.

The previous discussion about an actual airfield construction project where the author was involved is not uncommon when it comes to contingency construction supporting military operations. Throughout the last two decades, military engineers have experienced very similar challenges, particularly related to suppliers, contractors, and construction workers supporting their efforts. Although military operations in Afghanistan have declined, operations supporting the Global War on Terror have shifted to other parts of the Middle East, where these same issues continue to arise. While efforts in the Middle East grab several headlines, the U.S. military continues to operate on every continent in the world, supporting military, humanitarian, and scientific missions.

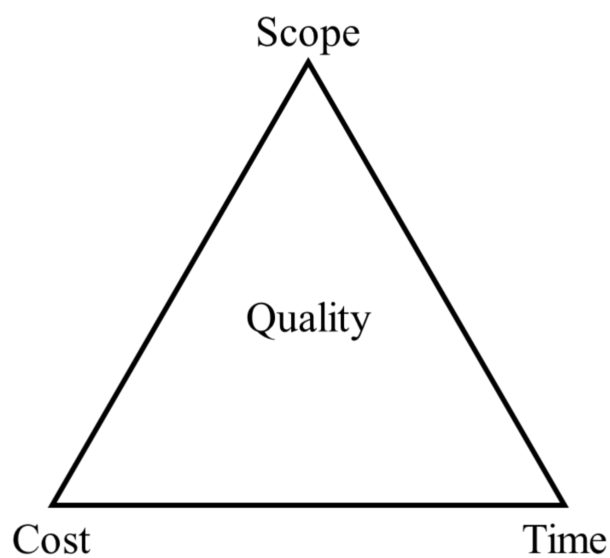


Figure 2.2 Project Management Triangle

These missions all vary in duration and predominantly take place outside of what most consider the “developed” world. As such, U.S. military aircraft operate from airfields comprised of substandard materials and built with substandard practices. This is far from the ideal scenario, but mission needs often force decision-makers to accept risk. As an example of this concept, the author has been asked on multiple occasions to certify airfields for flying operations that could only handle the design traffic for less than 10 passes.

The point of this section is not to disparage the practice of military pavements engineering, but rather to provide a framework on the decisions and circumstances that the military has made through the years to help address these issues. For example, the military relies heavily on the California Bearing Ratio (CBR) to characterize the load-carrying capacity of a given material. While this empirical material characteristic is often seen as overly simplistic, the CBR has a proven history of characterizing various materials from across the world enough to perform a sufficient structural design or evaluation. When CBR alone is not enough, the military relies on minimum thickness requirements, somewhat conservative specifications and compaction criteria, material equivalency factors, and simplifying heuristics for handling overlays or other uncommon pavement materials. These practices were implemented in an attempt to provide a conservative solution that had wide-ranging applications. Any attempt to modernize the DoD's pavement design and evaluation method needs to support using non-standard materials.

2.5 Pavement Evaluation

There are over a dozen organizations within the DoD that conduct airfield pavement evaluations. In a general sense, there are three primary types of pavement evaluations: (1) structural, (2) friction, and (3) PCI surveys (USAF 2017c). On a typical USAF airfield in the continental U.S., all three evaluation types would be completed on a recurring cycle by the USAF Airfield Pavement Evaluation Team (APE Team) or by a Government contractor. These all-encompassing evaluations are performed at enduring locations that are in need of a permanent evaluation that can certify the pavement for long-term operations (over 50,000 passes). For shorter-term operations, the USAF relies on less specialized teams to conduct the evaluations and often forgoes traditional friction assessments, since organizations in the USAF outside of the APE Team are typically not equipped and trained to conduct this type of testing. These shorter-term evaluations are typically referred to as contingency pavement evaluations, which include a structural evaluation and a PCI survey.

The APE Team conducts structural evaluations primarily using a trailer-mounted falling heavy weight deflectometer (HWD) over the course of approximately a week-long survey. During this time period, they are able to collect hundreds of sample points for every feature on an airfield. With this amount of data, the confidence level for reporting allowable gross load or allowable passes for a given feature is fairly high. Conversely, most structural evaluations conducted by other teams (i.e., not the APE Team) are conducted using manually-operated dynamic cone penetrometers (DCP). The DCP is much slower, as one DCP test takes the same amount of time as four or five HWD tests, and the data is not as robust. Additionally, a contingency structural evaluation is conducted in a matter of a few hours, primarily due to operational constraints (e.g., limited time on the airfield or security concerns). As a result, a contingency evaluation can only sample a handful of points for each pavement feature; in some cases, only one sample is taken per feature to meet the minimum requirement (AFCESA 2002). Needless to say, when compared to a permanent evaluation with hundreds of sample points, a contingency evaluation provides much lower statistical confidence. Table 2.2 provides a summary of the types of structural pavement evaluations used by the DoD and their corresponding generalized reliability.

Table 2.2 Summary of Contingency Pavement Evaluation Types (Created with data from AFCESA 2002; Smith and Muniz-Ruiz 2014)

Applicability of Evaluation Results			
Evaluation Tools	**Test Locations**	**Reliability of Results**	**Limitations Placed on Evaluation Results**
DCP Only	Expedient Criteria	Very Low	Limit operations to those prescribed by the allowable pass table in the evaluation report, but not to exceed 100 passes
Hilti Drill and DCP	Expedient Criteria	Low	Limit operations to those prescribed by the allowable pass table in the evaluation report, but not to exceed 100 passes
	Sustainment Criteria	Low	Limit operations to those prescribed by the allowable pass table in the evaluation report, but not to exceed 1,000 passes
Core Drill and DCP or ADCP	Sustainment Criteria	Medium	Limit operations to those prescribed by the allowable pass table in the evaluation report, but not to exceed 5,000 passes
	Permanent Criteria	Medium	No limitations placed upon operations beyond those prescribed by the allowable pass table in this evaluation
ECP	Sustainment Criteria	High	Limit operations to those prescribed by the allowable pass table in the evaluation report, but not to exceed 5,000 passes
	Permanent Criteria	High	No limitations placed upon operations beyond those prescribed by the allowable pass table in this evaluation
HWD and Core Drill or HWD and ECP or HWD and ADCP	Permanent Criteria	Very High	No limitations placed upon operations beyond those prescribed by the allowable pass table in this evaluation

ADCP: Automated Dynamic Cone Penetrometer
DCP: Dynamic Cone Penetrometer
ECP: Electronic Cone Penetrometer
HWD: Heavy Weight Deflectometer

2.5.1 Structural Evaluation Tools

The DoD uses two primary evaluation tools to conduct structural evaluations: the DCP and the HWD. The DCP is a slide-hammer type penetrometer that is manually operated and consists of four main components: the cone, rod, anvil, and hammer. The DoD uses a 17.6-pound hammer that falls a distance of 22.6 inches and measures to a depth of 48-inches for airfield evaluations (Smith and Muniz-Ruiz 2014). The important DCP consideration is that it directly measures a penetration index by counting the number of blows required to achieve a unit of penetration (typically one-inch); the penetration index, or DCP index, is then empirically correlated to a CBR or modulus of soil reaction (K-value) for asphalt and concrete pavements respectively.

The HWD is a trailer-mounted, non-destructive testing device that is used to measure pavement response to an applied, dynamic load. The dynamic load creates an impulse load by dropping weights from prescribed heights onto a plate that is placed on top of the pavement surface. The impulse response is then measured by sensors spaced at 12-inch intervals going out from the load plates (Priddy et al. 2014). The responses recorded by these sensors are then used in a back-calculation process (using multi-layered linear-elastic theory) to determine pavement layer modulus values. As a general note, DoD HWD back-calculation methods require the user know and input layer structure and thicknesses. For comparison, the DCP methods do not require this information.

2.5.2 Pavement Evaluation Process

An airfield pavement evaluation is initiated by a customer (e.g., U.S. Transportation Command, U.S. Special Operations Command, Air Forces Central Command, etc.) and then tasked to an available evaluation team typically located within or near the same area of operations. As a general note, proximity in this scenario does not necessarily imply familiarity with an airfield. As part of this tasking, the team is usually briefed on the requirement driving the evaluation (i.e., design traffic) and the amount of time available for the evaluation. After being tasked with an evaluation, the team begins its evaluation by reviewing all available data. This information would include previous pavement evaluation reports, aerial imagery, climactic data, current operational information, and available construction information. Using this data, the team would then develop its evaluation plan, identify a tentative list of airfield features and sections, determine potential test locations, and assess airfield geometrics. The pre-arrival work is summarized, as are the other pavement evaluation steps, in Figure 2.3.

Ideally, an airfield pavement evaluation team would have three members. Two members would conduct the DCP tests, while the other member focuses on conducting a visual distress inspection. Due to time constraints, the team does not typically process any of the data while on the ground (i.e., the team is primarily focused on recording data as opposed to processing data). That said, the team usually attempts to identify data outliers while in the field based upon quickly comparing DCP data from individual tests within the same sample section. If the DCP data within a sample section are not similar, the team should conduct additional DCP tests to gain further insight on the true character of the section or to identify a pavement section within the sample that needs to be treated as separate. Data collection continues in much the same fashion until the team completes its assessment, or the team has run out of time on the airfield; the latter is more typical for contingency airfield evaluations.

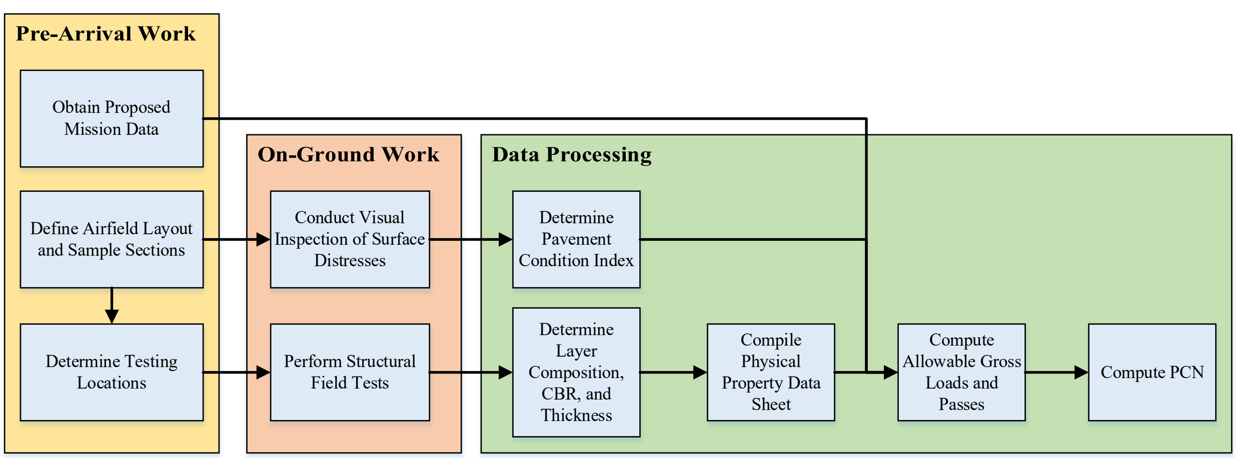


Figure 2.3 Summary of Contingency Airfield Pavement Evaluation Process

After the on-ground evaluation is complete, the team begins to process DCP and pavement condition survey data. The DCP data, captured in terms of the number of blows per unit of penetration, is converted to a DCP index, which is then correlated to a CBR value. The correlation to CBR from the DCP index results in a plot (see Figure 2.4) that depicts the instantaneous CBR value with relation to depth. Equation 2.1 relates DCP to CBR on typical projects (AFCESA 2002). Equation 2.1 results in a plot with a fair amount of large fluctuations.

$$CBR = \frac{292}{DCP^{1.12}} \tag{2.1}$$

With the plot completed, the evaluators then attempt to develop a layer structure for the pavement that best represents the CBR values with respect to depth. While computer programs, such as PCASE, can help with this process, it is ultimately up to the judgment of the evaluation team to determine the appropriate layer interfaces and pavement structure used for the evaluation. As will be discussed in detail in Chapter IV, based on the current equivalent layer theory used by the DoD, an incorrect layer structure can lead to a large disparity in results with differences in layer thicknesses of only an inch.

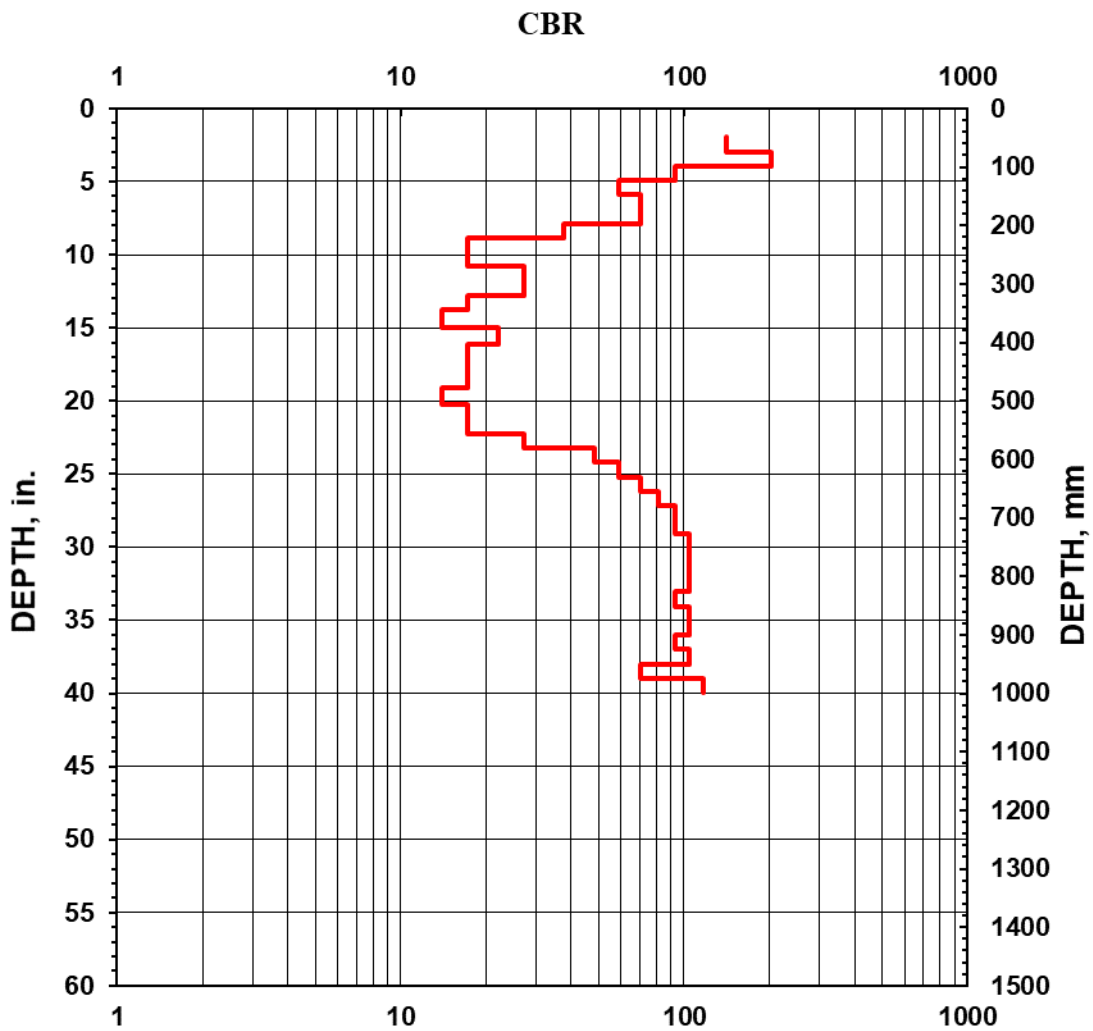


Figure 2.4 Example Dynamic Cone Penetrometer Result After Conversion to CBR Values

To calculate structural capacity using DCP data, pavement condition data from a PCI needs to be incorporated. The PCI rating, as used herein, was developed by the U.S. Army Corps of Engineers (USACE) in the 1970s and is a widely used standard universally for rating a pavement's condition (ASTM International 2018; Shahin 2005). As detailed in the list on the following page and summarized in ASTM D5340, a PCI value for a sample section is calculated using the recorded pavement distresses from the evaluation and several empirical models (AFCESA 2002; ASTM

International 2018; Shahin 2005). The PCI value for a given section is then categorized according to Table 2.3 to provide a generalized assessment of the pavement's condition for reporting purposes.

- Calculate the deduct values for each distress type and severity level using the measured quantities or calculated distress density.

- Determine the maximum number of deducts. If the total number of deducts is higher than the maximum number of deducts, then corrections will need to be made to the set of deduct values.

- Calculated the total corrected deduct value by adjusting in an iterative manner the values for the deduct values greater than five in a sequentially increasing order.

- Calculate the corrected deduct value for each iteration of the previous step.

- Subtract the maximum corrected deduct value from the previous step from 100 to determine the PCI value for the sample unit.

With values ranging from zero (i.e., failed pavement) to 100 (i.e., the pavement is in pristine condition), the PCI attempts to quantify the condition and structural integrity of a pavement by taking into account the type, severity, and extent of distresses present within a pavement sample area. While PCI does more heavily deduct for structural related distresses, it is important to note that it is not a true correlation to structural capacity (i.e., the PCI value will not always be indicative of the structural capacity of a pavement). That said, pavements with low PCI values typically have weakened pavement layers and substructures, due to the increased cracking and weakening of the surface course, causing increased infiltration of moisture into the substructure. The cumulative effect of these distresses over time causes a reduction in the structural capacity of the pavement.

Table 2.3 Pavement Condition Index Rating Descriptions

	Condition	Rating	Definition
	Excellent	86 – 100	Pavement has minor or no distresses and requires only routine maintenance
	Very Good	71 – 85	Pavement has scattered low severity distresses that should need only routine maintenance.
	Good	56 – 70	Pavement has a combination of generally low and medium severity distresses. Maintenance and repair needs should be routine to major in the near term.
	Fair	41 – 55	Pavement has low, medium, and high severity distresses that probably cause some operational problems. Maintenance and repair needs should range from routine to reconstruction in the near term.
	Poor	26 – 40	Pavement has predominantly medium and high severity distresses, causing considerable maintenance and operational problems. Near-term maintenance and repair needs will be intensive.
	Very Poor	11 – 25	Pavement has mainly high-severity distresses that cause operational restrictions. Repair needs are immediate.
	Failed	0 – 10	Pavement deterioration has progressed to the point that safe aircraft operations are no longer possible. Complete reconstruction is required.

Whether it is with rigid or flexible pavements, structural evaluations largely ignore the direct impacts of pavement distresses in determining the structural capacity for pavements with PCI values over 40 (considered in "poor" condition). As shown in Table 2.3, a pavement with a “fair” PCI value has low, medium, and high severity distresses that cause some operational issues. However, the structural capacity for pavements in this PCI range is still reported based on the results of the DCP or similar test (i.e., no adjustments for pavement distresses are incorporated). That said, a “poor” PCI would require a 25 percent reduction in allowable gross loads; when calculating allowable passes on pavements with “poor” and below PCI values, the DoD increases the aircraft weight used in determining allowable passes by 33 percent (AFCESA 2002). Within the DoD, a PCI value does not drive any changes to pavement material properties.

The Aircraft Classification Number/Pavement Classification Number (ACN/PCN) method was adopted in 1983 by the International Civil Aviation Organization (ICAO) as a step towards standardizing reporting on pavement strength (AFCESA 2002). Subsequently, the U.S. Government mandated the use of the ACN/PCN method in compliance with its international agreement with the ICAO under the purview of 49 U.S.C. § 40105. Worldwide, the ACN/PCN method is widely used; however, the implementation of the method varies due to the ICAO decision not to mandate a specific process or guidance by which an airport authority should determine the PCN. As a result, the established PCN for an airfield can vary depending on the evaluation method used (technical or using aircraft), aircraft traffic mix, and the number of passes (CROW 2004). Under the aircraft evaluation method, the subgrade support category (i.e., categorization of CBR or K-value) is not a direct input or even required to be known. To create standardization in PCN values, the USAF specifies that all PCNs, regardless of the airfield’s primary traffic mix, be reported on the basis of a C-17 aircraft at 585,000 pounds for 50,000 passes (AFCESA 2002). Conversely, the other DoD branches report PCNs based on the controlling aircraft at each airfield (USACE 2001; USACE 2014).

Figure 2.5 highlights the potential impact of a lack of standardization. Depending on the controlling aircraft and aircraft passes used in the technical evaluation, the PCN for this airfield pavement section could potentially vary between 19 on the low end and 73 at the high end. As a general note, the characteristics and structure of the pavement section were constant throughout; variables associated with the controlling aircraft were the only change. For comparison, the USAF would establish the PCN for this airfield pavement as 26 (expressed entirely as 26/F/A/W/T). With an ACN value of 30, the decision to use the airfield pavement could vary depending on the established PCN. For this reason, the potential exists for an airfield management team to publish a more favorable PCN due to the economics associated with potentially attracting larger or heavier aircraft (CROW 2004).

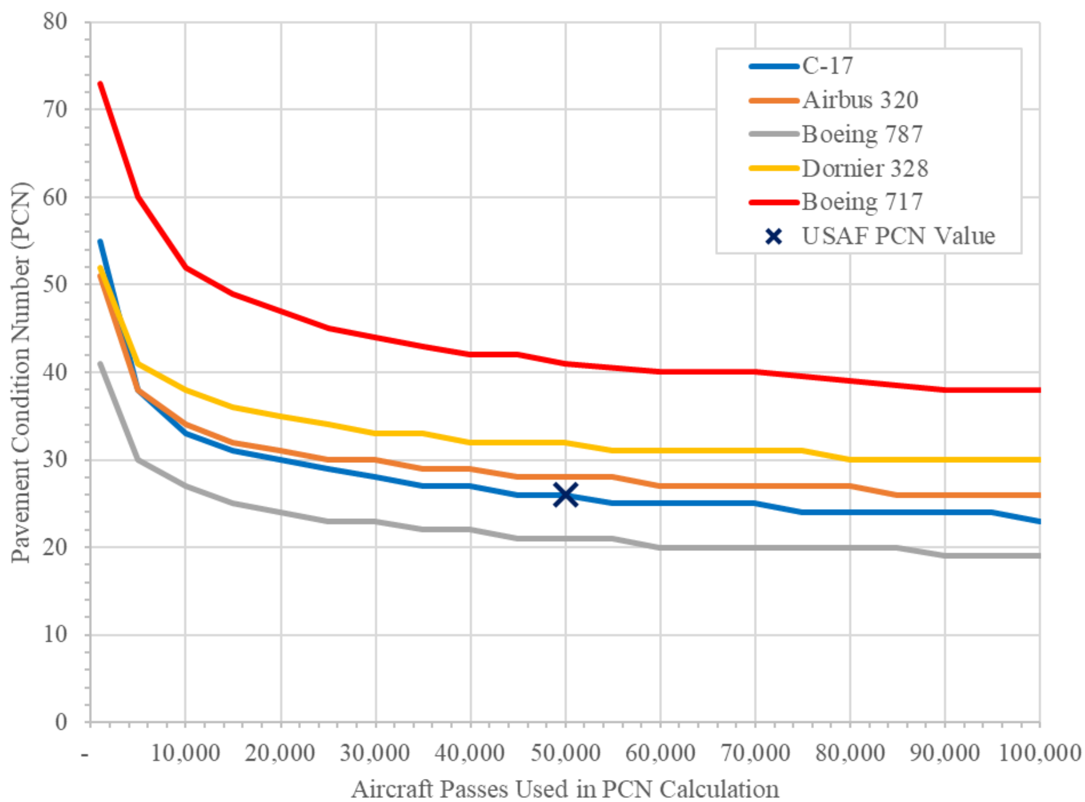


Figure 2.5 Pavement Condition Number as a Function of Controlling Aircraft and Passes

2.6 Personnel

Within the highway pavement industry, engineering decisions are typically made by a group of experienced pavement engineers. For state highway or U.S. interstate projects, these decisions would likely be made by Government engineers at varying levels of experience and expertise in a hierarchical fashion depending on the complexity and scope of the problem. In these scenarios, it is fairly easy for the engineer or group of engineers involved with the decision to visit the site to observe and evaluate the problem firsthand. On the contractor or material supplier side, a similar situation could be found, albeit with likely fewer resources for reachback support compared to the Federal Highway Administration (FHWA) or state department of transportation. That said, on a highway project in the U.S., it is unlikely that a decision-maker involved in a project would be inexperienced or unsupported. Furthermore, it is highly probable that all of the decision-makers, both on the Government and contractor's sides, have pre-existing working relationships and familiarity with each side's operations. Within the continental U.S., the DoD enjoys very similar benefits and relationships; however, in contingency environments in foreign countries, a majority of the previous statements regarding highway construction become less applicable.

In 2014, a young USAF Combat Controller led his three-person team to an airfield at an undisclosed location in the middle of the night. With approximately three hours on the ground and under cover of darkness, the three-person team conducted an expeditionary airfield pavement evaluation of the airfield to determine if cargo aircraft could land on a short-term basis. Using headlamps and one dynamic cone penetrometer to conduct their evaluation, the team left that night concluding that cargo aircraft could land at the airfield. The young Combat Controller was only two months out from attending his only formal training on pavement evaluation; he was the only individual on the team with any experience, yet they still came to the correct conclusion with respect to their objective.

The story summarized in the preceding paragraph is not uncommon, particularly in contingency environments. The USAF has its dedicated APE Team, which is a team comprised of highly skilled and experienced engineers and technicians that are equipped with and have access to the best pavement evaluation tools available in the DoD. That said, the USAF's APE Team typically only conducts evaluations on airfields located on enduring airbases. The majority of the enduring airbases are located in the continental U.S.; however, the USAF has several enduring airbases overseas in countries, such as Germany, the United Kingdom, Japan, and South Korea. The vast majority of airfields located outside these enduring locations are evaluated by numerous different USAF units, including Special Tactics Squadrons, Contingency Response Groups, RED HORSE Squadrons, and other Air Mobility Command assigned assets (AFCESA 2002). Although Contingency Response Groups often utilize an engineer to conduct airfield evaluations, there is no guarantee that their engineers have experience with pavements. As a result, RED HORSE Squadrons are typically the only entity conducting pavement evaluations for the USAF, apart from the APE Team, which has an internal pavement engineering capability and expertise.

When it comes to pavements engineering expertise within the DoD's military and civilian engineer ranks, the DoD focuses more on developing a breadth of experience and knowledge rather than depth. At the local and tactical levels, the DoD does not have enough personnel to maintain a sufficient level of engineering subject matter expertise at each operating location for all disciplines of engineering. As a result, the DoD makes a conscious push to develop its engineers at the local and tactical levels as more generalist engineers that have a sufficient understanding of several engineering disciplines but are not necessarily subject matter experts in any one area. The rationale for doing this is because the engineers at this level typically function as Project Managers or Contracting Officer's Representatives, where they typically function in the capacity as the Government's representative on infrastructure projects. Under this construct, engineering design and specification writing are typically completed using contracted design services.

On the military side, the push to develop more generalist engineers is also symptomatic of the DoD's personnel development model, which focuses on growing new officers into the service's corps of senior leaders. As part of this model, the military progresses its engineering officers through various tactical-level engineering roles before moving the officers on to progressively higher levels of management and leadership and away from direct engineering roles. Although the timing of this shift varies by military service, it is typical for the majority of a 20-year military career for an engineering officer to be served in primarily managerial and non-technical roles.

2.7 Airfield Damage Repair

The DoD's ability to project combat airpower worldwide is directly tied to the condition of its infrastructure. In the case of airpower, the success of an air campaign often rests heavily upon the condition of its airfield pavements. The military is often required to operate in hostile environments, which can lead to situations where airfield pavements can become damaged due to enemy attacks. After an attack, the military must repair its pavements as quickly as possible or risk losing air superiority within a theater of operations (LeMay Center for Doctrine 2017). To further complicate these issues, and as previously mentioned, military engineers in these environments typically have limited time, resources, and access to suitable materials (Mann et al. 2007).

Since the 1950s, the U.S. military has invested significant resources in developing techniques to rapidly repair damaged airfield pavements (Barna et al. 2010). These research efforts principally focused on the perceived threat from Cold War adversaries (i.e., large crater repair).

As such, U.S. military strategy over the past 50 years was to repair 12 large craters in less than four hours (Carlson 2013). These repairs principally focused on repairing damaged airfield pavements using expedient methods, primarily as a foreign object debris (FOD) cover (i.e., airfield matting) over a crushed stone or other approved base course material (Priddy et al. 2007). By definition, an expedient repair focuses on supporting 100 passes of an F-15E or C-17 aircraft.

In contrast, the Airfield Damage Repair Modernization Program led by the USACE over the last decade sought to change the entire strategy to match the challenges faced by military engineers during recent military operations in the Middle East. These challenges and lessons learned demonstrated that an airfield damage repair program needed to encompass more than just the post-attack recovery; the program needed to include contingencies for other forms of airfield damage that occur from load-induced distresses (Mellerski and Rutland 2009). The need to support typical airfield sustainment activities and the change in threats drove a change to the U.S. military strategy for the entire program. Instead of focusing on large craters, the Airfield Damage Repair Modernization Program seeks to repair up to 120 small craters and spalls in less than eight hours (Carlson 2013). Furthermore, the modernization program focuses on sustainment and semi-permanent repairs to support C-17 traffic, which typically amounts to more than one thousand passes depending on the thicknesses of the repaired layers (Carruth et al. 2015).

The primary product of the Airfield Damage Repair Modernization Program is the Sustainment Pavement Repair (SuPR) kit. The standard SuPR kit comes with all of the materials, tools, and equipment that a team of 37 personnel would need to complete repairs to 18 small craters or spalls (Carlson 2013). The kit consists of five 20-foot containers: two containers of rapid repair materials and three containers of tools and equipment. The tools and equipment include hand tools, generators, skid steer loader with attachments, asphalt drum mixer, concrete mixer, steel-drum roller, airfield saws, and air compressors. The commercial off-the-shelf rapid repair products included with the SuPR kits include enough capability to repair 80 cubic feet of concrete and 60 cubic feet of asphalt. Additionally, it includes 40 cubic feet of flowable fill, which is a low-strength cementitious material used in place of base course material due to the elimination of the requirement for compacted layers (AFCEC 2014c; Carruth et al. 2015).

For concrete repair, the proprietary rapid repair material is required to achieve compressive strengths of 3,000 and 5,000 psi after 2 and 24 hours, respectively (AFCESA 2008; Priddy 2011). The DoD designed the kits to be scalable and modular to adapt to the mission, requirements, and threats at a given airfield (Carlson 2013). The materials in the SuPR kits have limitations, but appear to offer much promise as the program continues to evolve. During full-scale load tests of repaired craters using the SuPR kit, repairs have demonstrated an ability to sustain over 1,500 passes of fully-loaded C-17 and F-15E aircraft (Carruth et al. 2015; Edwards et al. 2015; ERDC 2012; Priddy et al. 2007). SuPR kits have demonstrated the ability to repair pavement sections on a short-term basis, but long-term repair requires standard repair methods (i.e., full-depth repairs).

Crater repair is broken down into six primary steps: (1) FOD, upheaval, and deleterious material removal; (2) saw cutting of the damaged pavement; (3) excavation and removal of the pavement and damaged material from the crater; (4) flowable fill placement in the crater; (5) mixing, placement, and finishing the rapid set concrete cap (for a concrete repair); and (6) FOD removal and cleanup (Carruth et al. 2015; Edwards et al. 2015; ERDC 2012). All of these steps are accomplished using only the materials, tools, and equipment from the SuPR kit. The flowable fill is either placed dry and then covered with metered water in the excavated crater, or it is mixed prior to placement. It creates a stable base for placement of the concrete cap. It is a low-strength cementitious material; however, the strength of the material is superior to that of a compacted base course for the same thickness (Carruth et al. 2015). After the flowable fill sets, the concrete repair material is mixed in the portable concrete mixer and placed on the flowable fill. Within two hours, the concrete cap should have sufficient strength to allow aircraft passes over the repair (Edwards et al. 2015; ERDC 2012). As a general note, due to the higher level of repair (i.e., higher requirements for passes and aircraft type), the layer thicknesses should be determined or validated using a structural design software/method. Speed is a critical component of airfield damage repair; therefore, the structural design software/method used for layer thickness validation must be expedient.

While this research is not about airfield damage repair, the uniqueness of this issue as it relates to military operations makes it worth mentioning. Additionally, along with repairing pavements quickly, it would also not be uncommon for the military to establish an MOS while the repair is underway. The MOS allows for flying operations to resume quickly by establishing an expeditious runway (at a reduced size, but long and wide enough space for aircraft use) on a portion of the existing runway or another pavement feature (e.g., taxiway). For example, if the primary runway was damaged, a MOS could be established on the undamaged portion of the runway (with a displaced threshold and/or centerline), on a nearby taxiway, or an unpaved portion of the airfield.

Regardless of whether the military is rapidly repairing airfield damage or establishing a MOS, they need to be able to evaluate the pavement or design a repair quickly to ensure operations are not hindered. Any attempts to modernize the DoD's pavement design and evaluation method have to consider this fact. Because when it comes down to getting a plane low on fuel on the ground or getting a retaliatory flight of aircraft in the air, time is the most important consideration.

2.8 Finances

While project financing is discussed in more detail in Chapter III, this section serves as a brief introduction to infrastructure financing within the DoD. Funding for infrastructure projects in the military generally falls into two categories: (1) military construction (MILCON) appropriated; (2) operations and maintenance (O&M) appropriated. The primary difference between these categories is the appropriation that funds them and the associated programming rules.

2.8.1 Military Construction Projects

In general, MILCON projects must be line-item approved (i.e., specified) by Congress annually in the National Defense Authorization Act (NDAA). For the vast majority of MILCON projects, it is typically a five year or longer process for the project to be appropriated in an NDAA. The only projects that can typically be approved quicker than five years are projects that are urgent and vital to national security or national interest. These high priority projects will either be fast-tracked through the authorization and appropriations process or be approved by special authorities granted to the Secretary of Defense. The latter of which requires the Secretary to utilize unobligated funds (i.e., funds that are not already obligated to pay for an awarded construction contract) that were explicitly approved for other MILCON projects (10 U.S.C. § 2804; 10 U.S.C. § 2803). In general, MILCON projects are new construction or repair-by-replacement projects costing over $2 million, the latter of which typically does not apply to pavement projects (10 U.S.C. § 2811).

Once appropriated, MILCON funding is available for five years before it expires; expired MILCON funds are still useable to cover a limited set of circumstances for five years before the appropriation is considered canceled. This stipulation in the law is important as it allows for price changes associated with non-scope related project changes that result in price increases (e.g., unforeseen site conditions). This allowance has both a floor and a ceiling, as the price of a specified MILCON project can only be increased or decreased by less than 25 percent before it must be reapproved by Congress (10 U.S.C. § 2853). Any price increases within this threshold must be paid with unobligated MILCON appropriated funds (e.g., bid and costs savings from other MILCON projects that were returned unobligated to the overall appropriation) or by reducing the scope of the current project. The use of non-MILCON appropriations to pay for price changes is illegal.

Prior to the passage of the 2017 NDAA, scope changes on MILCON projects were limited to zero growth and a 25 percent reduction. The 2017 NDAA changed the law concerning scope increases to authorize a maximum 10 percent scope increase on MILCON projects (10 U.S.C. § 2853). The scope increase authorization is only applicable for "changed facility planning factors, technology and related design criteria, unforeseen site conditions, or finalized boundary surveys." Scope changes are still prohibited for increased or changed functional requirements (e.g., a significant increase in the number of people working in a facility) (USAF 2017a). As a general note, for MILCON projects, the scope is defined as the quantities of facilities (typically specified in terms of square meters) or individual components explicitly approved by Congress and stated on the project's programming documents. As an example, for a paving project, the programming documents would typically specify the maximum area of the paved surface.

2.8.2 Operations and Maintenance Projects

When it comes to pavement projects, if it is not a MILCON project, then it is generally an O&M appropriated project. These projects typically cover unspecified minor construction under two million dollars, sustainment projects, and repair projects. Sustainment projects include both life-cycle repair and maintenance designed to either extend the life of a facility or replace infrastructure that has reached its useful or design life. Conversely, repair projects are generally categorized as enhancement or modernization actions that take place before a facility or component has reached its useful or design life (USAF 2019b). The other unique aspect of O&M projects is that multiple types of work can be executed under the same project. For example, a project to widen and resurface an existing road would be categorized as both construction and sustainment work. This distinction is important as both categories of work would be considered separately for determining the approval processes and thresholds.

Funding for O&M projects is appropriated to the respective military branches annually in the appropriations bill by Congress as part of each services' general O&M accounts. Funding for O&M projects is authorized and available for one year only. After one year, any unspent O&M funding becomes expired and can be used under special circumstances for five years before the funds are canceled. O&M accounts provide each service with all of its general operating expenses, including jet fuel, office supplies, utility payments, civilian pay, travel expenses, and much more. Out of the O&M accounts, Congress carves out portions of the appropriation to specifically support critical Defense programs and activities, including the Facility Sustainment, Restoration, and Modernization (FSRM) program. These critical defense programs and activities typically include limitations on spending (both floors and ceilings) and rules on transferring funds out of these accounts. The FSRM program is considered a critical readiness program and includes strict limitations on the transfer of funds from this program without Congressional approval. As such, the services carefully monitor the expenditures and movement of funds appropriated to the FSRM program to ensure the Congressional limitation on these funds is met. For FSRM, the Congressional limitation is effectively a "floor" due to the strict transfer rules (i.e., expenditures are mandated to be greater than or equal to the appropriated amount). Since the limitation only establishes a floor, each service is free to transfer funding from other accounts in its O&M appropriation in the execution year following Congressional transfer rules to support additional FSRM requirements.

As a general note, the FSRM program is actually three individual budgetary programs: sustainment; restoration and modernization (R&M); and demolition. Sustainment is defined as the maintenance and repair of real property facilities and infrastructure to keep them in good working order (e.g., preventative maintenance). Additionally, sustainment also includes the replacement of real property assets and components when it has reached the end of its service life (e.g., replacing roofs at the end of their service life) (OUSD(C) 2019).

Restoration includes work to real property performed to repair facilities damaged by inadequate maintenance, damage, or excessive deterioration. Conversely, modernization provides a means to alter or modernize real property to implement new technologies, standards, functions, and mission sets. Additionally, R&M can include work to convert facilities to other uses, repair by replacement, and unspecified minor construction (OUSD(C) 2019). The primary distinguishing factor between sustainment and R&M is that sustainment is work executed following the standard lifecycle maintenance plan of a real property asset; whereas, R&M is work performed that would not typically be considered part of an asset's lifecycle maintenance plan. For example, it would be considered sustainment work to replace worn-out carpeting in an office; however, the same work would be classified as R&M if the sole purpose is to improve the aesthetics of the office space.

CHAPTER III

DEPARTMENT OF DEFENSE PROCESS FOR BUILDING AND MAINTAINING AIRFIELD PAVEMENTS

3.1 Generalized Airfield Lifecycle Process

The purpose of this Chapter is to outline the processes by the DoD plans, programs, funds, designs, constructs, and maintains airfield pavements over its lifespan. The contents of this chapter are presented sequentially. As such, the early stages of the process leading up to construction detail the steps and timelines for constructing a new airfield or pavement section as a result of a basing action. Subsequently, the later sections of this chapter detail the processes and timelines for funding and executing projects to maintain the new airfield or pavement sections.

3.2 Initial Planning

Imagine standing in the middle of a barren plot of land in sub-Saharan Africa conducting a site visit to support the design and construction of a new airfield for use by U.S. and host nation military forces. You and your team are going to spend several days on the ground, gathering as much data and information about the site and region as possible to inform your planning and design decisions. Given the unfamiliarity of this location, your team may travel around the region identifying local vendors to identify contractors, material sources, and estimated prices. A design site survey is critical to project delivery, but it occurs several years after the start of initial planning. Thousands of hours of planning and decision-making occurred to allow the site visit mentioned previously to occur. With this frame of reference in mind, initial planning starts in Washington, D.C., with the President of the United States.

In coordination with the National Security Council, the President of the United States publishes the National Security Strategy (NSS). The NSS identifies and establishes broad, over-arching objectives for the U.S. national security agencies utilizing the four major instruments of power: diplomatic, information, military, and economic (commonly referred to as DIME). The 2015 version of the NSS focuses on four major subject areas, each with multiple subtopics. With only 29 pages of content, the 2015 NSS dedicates a handful of paragraphs to any one subject (Obama 2015). That said, the Secretary of Defense utilizes the relevant objectives and guidance from the NSS to formulate a National Defense Strategy (NDS), which is effectively a document that establishes how the DoD will leverage its instruments of power to support the President's NSS. Subsequently, the Chairman of the Joint Chiefs of Staff (CJCS), in coordination with the Combatant Commanders and the respective Chiefs of Staff and Secretaries of the military branches, develops the National Military Strategy (NMS) utilizing the guidance and objectives outlined in the National Security Strategy (NSS) and National Defense Strategy (NDS) (JCS 2017).

All three of the strategy documents mentioned in the preceding paragraph are primarily in the public domain; therefore, typically, specific actions or guidance involving a particular objective is not disclosed in any of the three documents. That said, as the strategy and objectives move through the planning phases and down the chain of command, these specific decisions, actions, and guidance supporting a particular decision are becoming more refined behind the scenes. For example, the three primary strategy documents could issue an objective that says that the U.S. needs to be prepared to fight tomorrow's war against a major geopolitical, or a near-peer enemy. After years of planning behind the scenes, this objective could ultimately materialize as a major weapons system acquisition program, such as the F-35 Joint Strike Fighter. With regard to military strategic planning, the timelines considered often are between 4 and 25 years.

Going back to the previously mentioned scenario of building a new airfield in Africa, the concept of conducting military operations (e.g., counterterrorism, humanitarian, building partnership capacity, etc.) in Africa was derived from the NSS as an answer to how best to support an objective from that document. The decision, for example, to perform counterterrorism operations in Africa to mitigate the spread of extremist violence through the northern part of the continent (i.e., the objective from the NSS) would then have been followed up with discussions, analysis, and decisions on the best courses of action to achieve the objective. Assuming the decision was to use special operations forces to train host nation military personnel to combat regional violent extremist organizations. Military planners would then start looking at the requirements necessary to support these special operations forces and their training mission. Furthermore, military planners would also have to address issues pertaining to intelligence gathering on terrorist movements and locations. An answer to conducting intelligence gathering may inevitably lead to a decision to use remotely piloted aircraft, which require a robust system of supporting infrastructure, including an airfield to launch and recover aircraft. Military planners would then need to determine where to locate the remotely piloted aircraft such that they could reach all of the areas that the special operations forces would need. Through a strategic basing process, the military planners would then evaluate dozens of candidate locations using a lengthy list of criteria and requirements to narrow down the list of alternatives and ultimately decide on a location for the remotely piloted aircraft (JCS 2019).

With a basing decision in hand, the planning effort would then transition to an Operational Planning Team (OPT), comprised of cross-functional experts and planners. The objective of an OPT is to define the requirements, identify solutions, and execute all of the pre-operational planning efforts necessary to enable the operation. An OPT would look at issues such as basic life support, personnel numbers, infrastructure requirements, and force protection. Given the new airfield scenario, the infrastructure planners would look at developing the airfield from a community planning perspective, determining runway requirements and orientation, geometry, and aircraft support facilities and navigational aids (e.g., hangars, airfield lighting, etc.). With the airfield requirement defined, the OPT infrastructure planners would then begin to move into programming the facility requirements to begin the process of acquiring funding.

This section provides a brief summary of the initial planning efforts that would ultimately lead to an actual airfield construction project in a foreign country. Due to the security nature of this type of planning, the summary is purposely vague and nonspecific in certain facets. That said, it is important to recognize that this type of planning occurs behind the scenes for a year or more before it potentially advances to the latter stages of planning and execution. Furthermore, military planners working these types of requirements may work on several different operational planning efforts over a period of time, with only one effort potentially advancing from the initial planning stages.

3.3 Programming and Funding

With the basic requirements established, the OPT infrastructure planners usually work with the project programming experts in their office to develop a draft Department of Defense Form 1391 (DD 1391), capturing the basic requirements, scope, justification, and a corresponding parametric cost estimate. The cost estimate could be more refined if more information is known relating to local material and labor costs. However, often at this early stage, the cost estimate is based upon historical square footage costs adjusted for the locality. Furthermore, at this early stage in the process, the cost estimate and DD 1391 is typically unconstrained and conservative due to the large number of unknowns related to the project scope.

The draft DD 1391 is then sent to the OPT for review before being elevated up the chain of command. During this review of the DD 1391 by the chain of command, one of three actions are likely to occur: (1) there is enough confidence, priority, and politicking behind the project as drafted to move it forward; (2) the DD 1391 is returned for corrections to reduce the cost and/or scope to a more defendable and agreeable level; or (3) the DD 1391 is filed away, as the cost estimates prove too high to justify the operation. More often than not, the initial draft DD 1391 is returned to the planners to reduce the project scope and cost. The rationale for forcing constraints on projects is typically to preserve other projects within the MILCON appropriation, as the total MILCON appropriation remains relatively constant (when measured in constant dollars) year-to-year (OUSD(C) 2018a; Synovec et al. 2019).

While it is possible for Congress to increase the total appropriation of MILCON, it is typically done by transferring the funding from another program, component, or appropriation (see Figure 3.1); it is uncommon for the total DoD budget to be significantly increased. For this reason, new program starts (e.g., the F-35 Joint Strike Fighter program) requires cuts to other programs. The lone exception to these general guidelines tend to be supplemental appropriations, which support operations or recovery efforts that go above and beyond the DoD’s baseline operating budget (e.g., a major hurricane recovery effort).

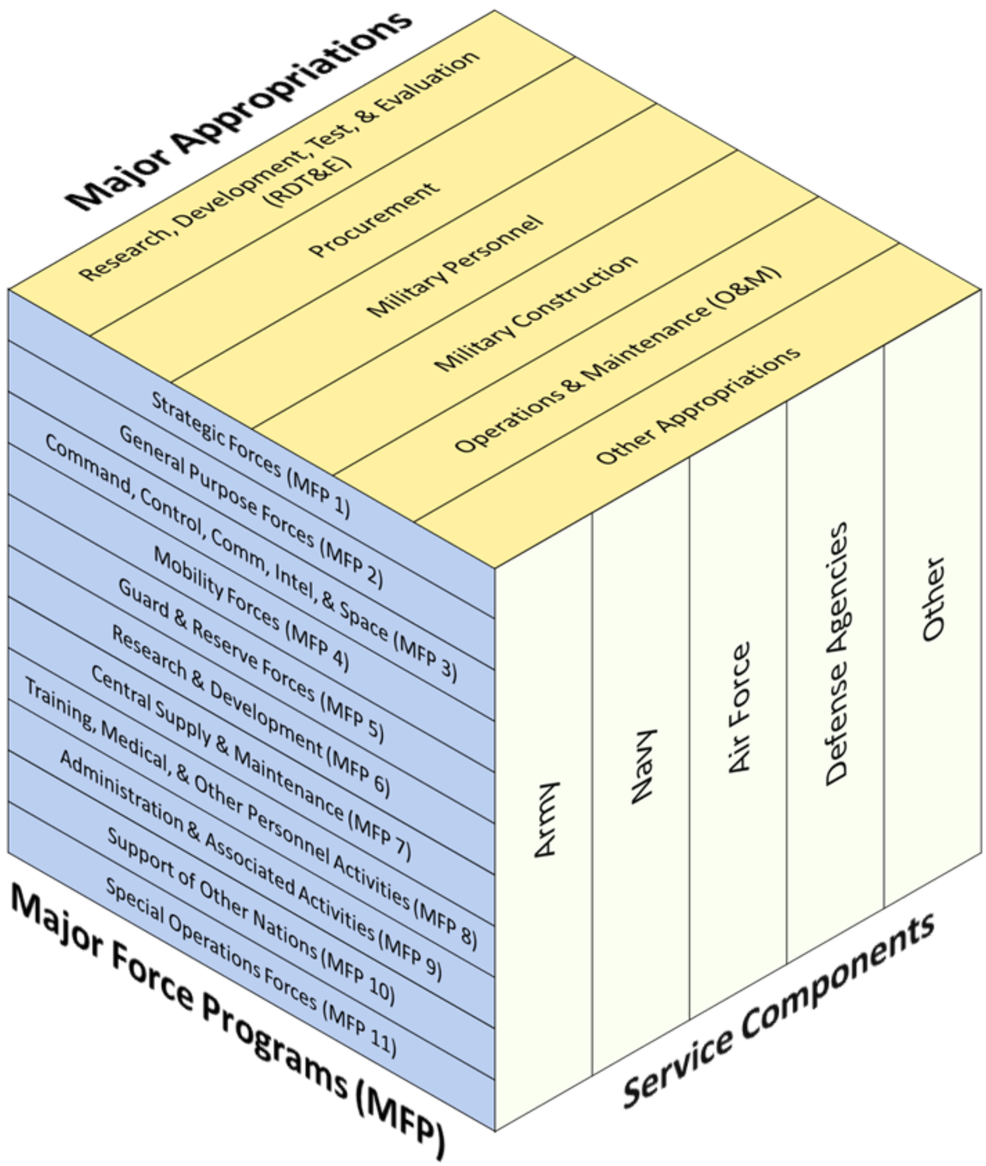


Figure 3.1 Future Years Defense Program Structure

With the DD 1391 returned for corrections, the planners work to effectively back-calculate the revised scope of the project based upon feedback from the chain of command. This feedback and revision loop continues until both the planners and the chain of command are satisfied with the product. Since the example for this chapter deals with building a new contingency airfield in

Africa, the project takes an unusual path towards eventual authorization and appropriation by Congress. Typical MILCON projects are programmed, budgeted, and advocated by the military service owning the installation or mission. With overseas contingency projects, the geographic Combatant Command is heavily involved in programming, advocating, and reviewing the MILCON project. Due to the funding construct within the DoD, the Combatant Command designates a lead service for a given project, location, or mission. The lead service is ultimately responsible for getting the project submitted to Congress in its budget submission through its internal business processes. The Combatant Command then prioritizes and advocates for its requirements with the Office of the Secretary of Defense (OSD), the Joint Chiefs of Staff, and Congress. Depending on the priority and criticality of the requirement, the project could be inserted in one of five years across the Future Years Defense Program (FYDP). If the project is not included in the FYDP, it must compete again in the next fiscal year.

As a general note, the FYDP is a five-year look (FY+2 to FY+6) at DoD spending that directly informs the President's Budget request; therefore, a project that is "inserted" in programming year of the FYDP (FY+2) would still be two years away from being funded. The reason for this delay is because the President's Budget is submitted to Congress in February of the fiscal year prior (FY+1) to the appropriation or execution year (FY+0). To align with the President's Budget Request submission, the DoD and its services must prepare its budget request during the fiscal year (FY+2) before submission of the President's Budget request (SAIC 2016).

The President's Budget (PB) request is submitted to Congress in February in the budgeting year (i.e., the fiscal year before the appropriation is supposed to start). Once received by Congress, it becomes part of a three-pronged process that culminates with the passage of the NDAA and the Defense Appropriations Act. As a general note, MILCON is typically included in a separate appropriations bill. However, both appropriations bills are typically combined with other appropriations bills to create an omnibus appropriation to fund large portions of the Federal government. As shown in Figure 3.2, the first major hurdle in DoD funding, and thereby project funding, is the House and Senate Budgetary Committees. The role of the Budgetary Committees is to establish revenue targets and set ceilings (i.e., spending caps) on budget authority and outlays for the Federal government's budget (SAIC 2016). The ceilings, once agreed upon in Conference and passed by floor vote, are provided to the Appropriations Committees for use as planning numbers when developing the Federal budget. As a general note, the Concurrent Budget Resolution is not a bill signed by the President into law; concurrent resolutions are internal Congressional documents.

The NDAA establishes the legislative authority to establish new or maintain a DoD program. Furthermore, the NDAA prescribes new DoD policies and makes changes to the public law on issues related to the DoD. The NDAA defines the scope of DoD programs and provides authorizations and restrictions on funding levels. The funding levels can either be open-ended (i.e., left to the Appropriations Bill) or specify certain amounts of funding authorization. That said, it does not create budgetary authority or specify total funding levels; this falls under the jurisdiction of the Appropriations Bill. Examples of recent NDAA authorities or law changes include: (1) prohibition on conducting additional base realignment and closure (BRAC) round; (2) facility conversion projects are now considered repair projects; and (3) authorization for funding of MILCON projects throughout the DoD (114th Congress 2016).

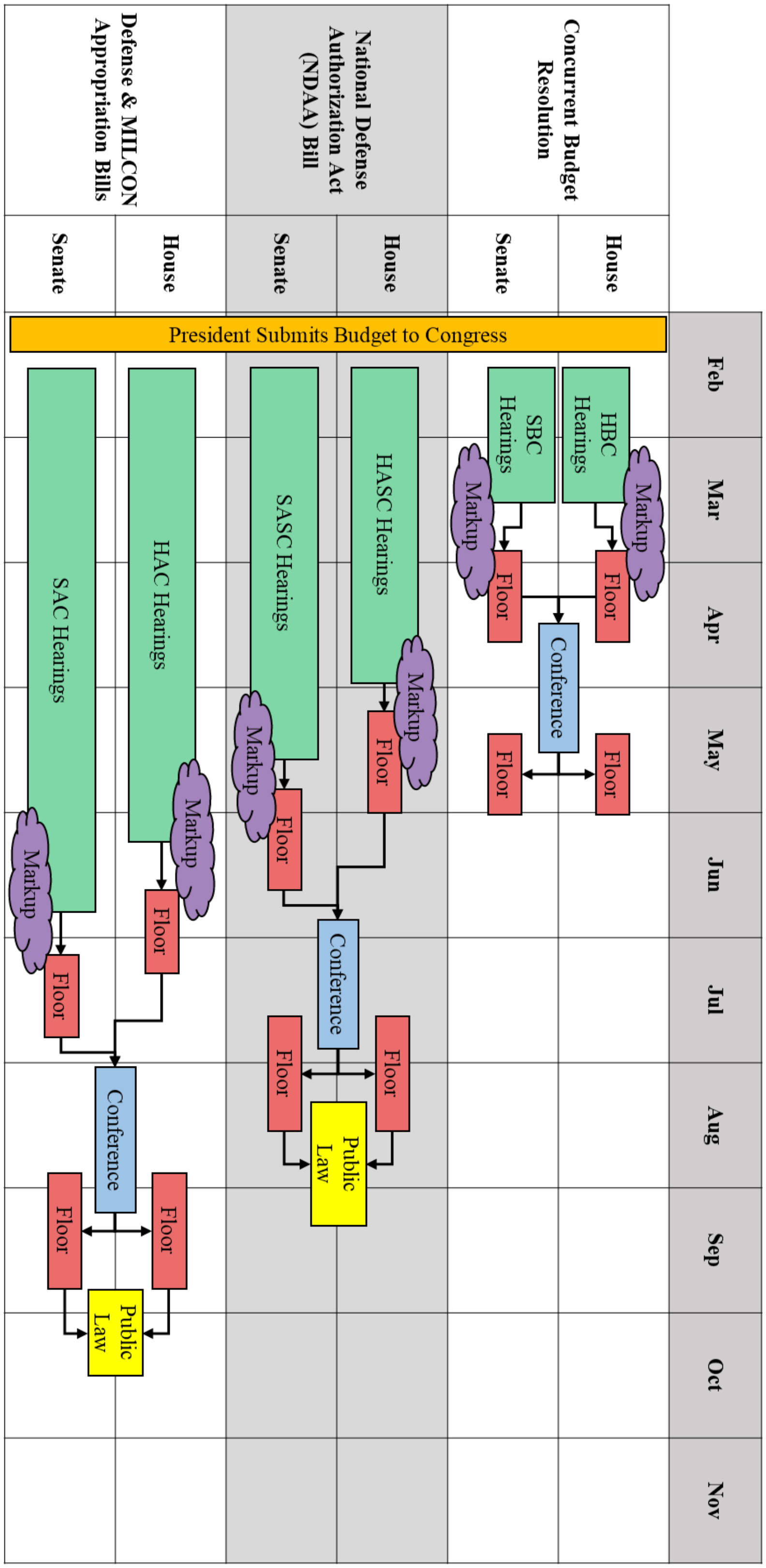


Figure 3.2 Notional Congressional Defense Budget Process

While the NDAA primarily addresses DoD policy changes and authorizes funding, the Defense Appropriations Bill provides the funding for authorized programs and projects outlined in the NDAA. As such, the Defense Appropriations Bill becomes is voted in Congress after the NDAA to ensure that all authorized programs are funded. Between 1985 and 2016, Congress used omnibus appropriations 22 times to fund discretionary programs across the Federal government. Between 2006 and 2016, omnibus appropriations were used every year (Saturno and Tollestrup 2016). The trend of using omnibus appropriations has continued to the current year. Due to the size of omnibus appropriations, the political negotiations required to pass such a large funding bill typically push the passage of the Appropriations Bill well into the new fiscal year. As a result, the DoD operates under continuing resolution authority (CRA) as authorized by Congress, which provides a stop-gap appropriation that funds the DoD at approximately 80 percent of the prior year's obligations (SAIC 2016).

Furthermore, under CRA, no new major appropriations or procurements are allowed to start. This stipulation directly impacts MILCON projects, as it leaves Project Managers and stakeholders on hold waiting for the passage of the appropriations bill. Once the appropriations bill is passed, it can take months for project funding to reach the Contracting Officer (SAIC 2016).

3.4 Design

With regard to MILCON projects, the DoD divides design and other pre-construction activities into two categories: (1) advanced planning; and (2) project design (USAF 2015). The latter of which, project design, is regulated by public law and is limited to costing no more than six percent of the estimated construction cost. Activities captured under this category include architecture and engineering services for "producing and delivering designs, plans, drawings, and specifications needed for any public works or utilities project" (10 U.S.C. § 9540). Planning related activities and studies not directly supporting a design activity product (e.g., a design charrette) are classified as advanced planning. The importance of this distinction is that project design activities are paid with the appropriation that is funding construction, limited to six percent of the construction cost; advanced planning is paid with O&M appropriations with no statutory limit on cost (10 U.S.C. § 9540; USAF 2017a). For MILCON projects, project design is funded using planning and design (P&D) funds from the MILCON appropriation.

Advanced planning activities start effectively as soon as the project scope has been conceptually defined and socialized among decision-makers with positive reactions. With positive feedback, the project team begins conducting a series of design charrettes with the project's stakeholders to define the project requirements fully. This requirement definition phase is typically aided by site visits and the development of installation or area development plans (i.e., macro-level base master plans). As advanced planning takes place before project design, these activities help inform the project programming documents to update cost estimates and scope as necessary to ensure that the Congressionally appropriated funding and scope achieve the project's full requirements.

Generally speaking, design on design-bid-build projects is completed in the fiscal year prior to the start of construction but can occur earlier. This timing implies that once a project is included in the President's Budget request, the DoD begins on project design. Design for MILCON projects is typically contracted out to architecture and engineering (A/E) firms in the private sector using one of the multiple pre-established A/E contracts within the DoD executed by the designated design and construction agent (DA/CA) (OUSD(A&S) 2018). The DA/CA is responsible under Federal statute for the execution of MILCON projects across the DoD and is the Government's primary interface between the Government and the contractor.

As a general note, the DA/CA on the overwhelming majority of MILCON projects is the Naval Facilities Engineering Command (NAVFAC) or the USACE, as stipulated by Federal statute (10 U.S.C. § 2851). There are a few instances where the Air Force Civil Engineer Center (AFCEC) may be the DA/CA on a project, but these instances are limited and require approval by the Office of the Secretary of Defense (OUSD(A&S) 2018). The Secretary of Defense is authorized under Federal statute to authorize other services and Government agencies to manage MILCON projects (i.e., fulfill DA/CA responsibilities) when it is in the best interest of the Government (10 U.S.C. § 2851). As a result, the AFCEC typically is allowed DA/CA responsibility for MILCON projects in the United Kingdom and on unique projects that require subject matter expertise inherent to the USAF with the approval of OUSD(A&S). This authority is typically limited to no more than five percent of the USAF's total MILCON portfolio (USACE 2015; OUSD(A&S) 2018).

On some projects, the DA/CA may elect to utilize in-house engineering to perform project design. There are a variety of reasons for opting for in-house design (e.g., flexibility, security, subject matter expertise, etc.), but it is typically a small percentage of the overall portfolio. It tends to be more common on contingency MILCON projects., but the most common use of in-house design capabilities for the DoD tends to be on contingency O&M projects.

With regard to project design, the DoD utilizes the Unified Facilities Criteria (UFC) as its governing design documents (OUSD(A&S) 2018). The many volumes of the UFCs reference several non-DoD standards to either adopt the standard outright or modify it for DoD purposes. Furthermore, because the UFC is a tri-service standard (i.e., the Army, USAF, and Navy collectively develop and adopt the standard), each service often incorporates additional service-specific criteria, when necessary, on top of the UFC standard. For example, the USAF utilizes

Engineering Technical Letters (ETL) and Air Force Instructions (AFI), among other documents and guides, to dictate additional design guidance. For airfields, the supplementary documentation provides specific guidance related to airfield markings and lighting, pavement materials, geometric criteria for contingency locations, and pavement specifications for unique aircraft such as the F-35 Joint Strike Fighter and remotely piloted aircraft.

Unless otherwise specified, the two primary design documents governing airfields are UFC 3-260-01, *Airfield and Heliport Planning and Design*, and UFC 3-260-02, *Pavement Design for Airfields*; these UFCs cover airfield geometrics and pavement design respectively. While other UFCs might be necessary for completing the design (e.g., UFCs related to stormwater runoff, airfield lighting, and airfield marking), these two UFCs address the majority of the design-related situations encountered when designing DoD airfields.

The DoD designs airfields pavements with a 20-year service life (USACE 2001). While custom traffic mixes are used (most commonly in contingency settings), the DoD most commonly uses standard traffic mixes to design pavements. Within the USAF, there are six standard traffic mixes, with the "medium" traffic mix being the default without a Major Command (MAJCOM) directed change. The "medium" traffic mix consists of fully-loaded F-15Es, C-17s, and B-52s operating at 100,000, 400,000, and 400 passes, respectively (USACE 2001). Currently, there are no airfields in the USAF where all three of these aircraft operate with regularity (AFA 2017).

Furthermore, while a C-17 can operate at a variety of airfields, a B-52 is limited to airfields with runways that are at least 200 feet wide, further reducing the number of airfields that would even see B-52 traffic (AFCESA 2020a). That said, it is fair to say that with a "medium" traffic pattern being the default in the USAF that several airfields are likely overdesigned structurally, particularly airfields without any similar aircraft to those in the medium traffic mix. The concept of standard traffic mixes likely helps reduce the prevalence of rutting on DoD pavements, but sets its design method at odds with highway pavement design methods that rely on traffic studies and projecting future traffic volumes.

As previously mentioned, the DoD may utilize its internal engineering personnel to design some MILCON projects in contingency environments. This is primarily done in hostile-fire or remote locations, on sensitive projects, or on projects that have a large degree on uncertainty as it enables greater flexibility to accommodate unusual design constraints or user-driven changes. With the Africa design scenario described in this chapter, it would not be uncommon for the host-nation to impose certain restrictions that would impact siting, design, and construction. These restrictions could range from utilizing specific contractors and vendors to dictating stormwater runoff handling. Since the DoD is building infrastructure and relationships in foreign countries, it will, in most cases, be accommodating to most requests by the host nation.

3.5 Construction

While the DoD maintains a heavy construction capability, that capability is limited. As a result, the vast majority of MILCON projects constructed in the DoD are built using local or regional contractors. The decision to utilize local contracts in a developed country is likely to produce a quality product with an acceptable amount of risk; however, in developing and undeveloped countries, the risk and quality become much more of a concern. As an example known by the author, a contractor won a bid to construct a bundled set of MILCON projects in the Middle East. Before winning this bid, the contractor was an office furniture supplier in the local area. Sensing a potential for increased profits in the construction section, they decided to expand into construction and bid on the contract. After two years of poor performance and mismanagement, the contract was terminated for default. While two years is a relatively long time to allow a contractor to underperform, this is not an uncommon scenario for the DoD overseas.

With policies such as "Afghan First," the DoD often utilizes the local economy for contract support to the maximum extent possible to support the development of the host nation's private sector and the economic development of the country as a whole (NATO 2010). Mandates, such as "Afghan First," are a part of a broader strategy to utilize money as an instrument of power in combating insurgencies and illegal trafficking (JCS 2020). As a result, the DoD can stimulate the local economy but infuses a considerable risk to its infrastructure projects. When a contractor is underperforming, as suggested in the previous example, it is a sensitive topic to discuss terminating a contract for default. Firing a contractor in a location where attempts are being made to stimulate the economy and win support can be problematic. Furthermore, firing a contractor in a location without an abundance of other options may not help remedy the issues on the project. That said, with underperforming local contractors, the DoD may consider helping mentor the contractor to correct the deficiencies or make concessions.

The DM/CM is the specified individual or organization serving as the military service's or customer's representative. This individual is the primary point of contact for any customer or service-specific issues related to the project and is also the lead interface with the DA/CA. The AFCEC generally fulfills the DM/CM role on USAF MILCON projects.

To start the construction process, the DM/CM issues a Design Instruction (DI) to the DA/CA granting authority to advertise a particular project. This authority is typically granted when the project design is substantially completed, the current working estimate is revalidated as being under 110 percent of the programmed amount, and the project's priority within the entire MILCON program is lined up with the total available funding authority remaining (USAF 2017d). As a general note, each service will typically only advertise 80 percent of its MILCON program using the cumulative total of the current working estimates from each project relative to the total appropriation level. As a result, the top 1-to-n projects based on priority or project scoring are advertised at the beginning of the fiscal year until the 80 percent threshold is reached. The 80 percent threshold aligns with continuing resolution authority guidance and provides for flexibility in the event of high bids. The remaining 20 percent of the projects are funded as funds become available in sequential order until all funds are obligated.

Once the authority to advertise is provided to the DA/CA, they prepare and issue a request for proposals (RFP) to potential bidders. Once the proposals are submitted by the bidders, the DA/CA reviews the bids based on the selection criteria and technical acceptability; the DA/CA then issues a bid report to the DM/CM. The DM/CM reviews the bid report, seeks authority to award, and requests additional funding as necessary (AFCEE 2007). Depending on the ratio of the bid relative to the programmed amount, the process of seeking authority to award could take several weeks, if not months, in some select cases (USAF 2017d). With approval from the requesting service, the DM/CM issues authority to award and funding to the DA/CA, who awards the construction project contract to the winning bidder. This relationship continues throughout the project for each milestone during the construction and closeout phase.

3.6 Maintenance and Rehabilitation

Each of the military services handles maintenance and rehabilitation projects differently, particularly on their permanent installations (i.e., non-contingency locations). In contingency locations, it is not uncommon for projects irrespective of military service to be programmed, funded, and awarded in the year of execution due to the use of overseas contingency funds and decentralized asset management approaches. This management approach allows for enhanced flexibility but principally relies on an abundance of resources and funding to accomplish the work.

While O&M funded projects are expedited in contingency environments, airfield work typically requires an increased level of coordination due to the significance of closing a section of the airfield. For example, at the height of Operation ENDURING FREEDOM, Bagram Airfield in Afghanistan was the most heavily used military air based in the world (Stewart and Mattos 2013). The primary runway was of such strategic importance that shutting it down for any length of time to make necessary repairs would hinder military and logistical operations throughout the country. As such, preventative maintenance, and even corrective maintenance, were typically deferred unless it jeopardized aircraft safety or success of the mission. When corrective maintenance became unavoidable, the military decided to completely rebuild a failed Soviet-built runway that ran parallel to the primary runway so that air traffic could be moved off the primary runway and on to the newly rebuilt secondary runway while the primary runway could be repaired (Stewart and Mattos 2013).

Outside of contingency environments, the processes among the services are more methodical for programming and approving O&M projects. For the sake of brevity, only the USAF's process is detailed in this section. The USAF has two categories of O&M projects: centralized and decentralized (see Figure 3.3). The decentralized projects are typically small-scale projects best described as work orders and small projects that provide preventative maintenance or minor repair. As such, the execution and funding of these projects are decentralized and managed exclusively at the installation-level. Installations are provided sustainment funding annually in a proportional amount relative to the installation's size, as determined using its estimated annual sustainment requirement calculated using the DoD's Facilities Sustainment Model (FSM).

The FSM-derived annual sustainment requirement is an equation that relates facility type, quantity, and a square footage sustainment cost (unique to the facility type or category code). Additionally, it factors in future-year inflation factors to estimate the annual sustainment costs for infrastructure assets across the FYDP (see Equation 3.1) (USACE 2020). Each service budgets for FSRM using the cumulative total of its FSM-derived annual sustainment requirement. This sustainment requirement is provided to Congress in its annual budget submission for appropriation. While the FSM is primarily a budgetary tool for Congressional budget submissions, the USAF elects to use it to determine its decentralized FSRM allocations to its installations.

$$SR = Q \; x \; SUC \; x \; SACF \; x \; I \tag{3.1}$$

where,

SR	=	FSM calculated sustainment requirement, in dollars
Q	=	facility quantity (e.g., 15,000 square feet)
SUC	=	sustainment unit cost as a function of facility category code (e.g., \$3.41 per square foot)
SACF	=	sustainment area cost factor, unitless (e.g., 1.15)
I	=	future-year escalation for operations and maintenance accounts, typically two percent escalation per year (e.g., 1.02)

The funding issued to each installation in this manner is generally considered discretionary and up to the judgment of the installation's leadership to prioritize and execute projects. Additionally, decentralized FSRM is also used to purchase work order supplies used by the installations to maintain its facilities using its in-house labor force. Therefore, preventative maintenance for airfield pavements is a local issue that must compete against other preventative maintenance and facilities work orders.

Additionally, as of late-2018, the USAF decided to no longer include projects below a certain dollar threshold in its centralized portfolio; this decision took effect in the fiscal year 2020. Before this decision, projects, regardless of dollar value, were eligible to compete in the centralized portfolio, with all R&M, demolition, and minor construction projects required to compete. Installations would submit projects annually to compete in the centralized portfolio. If the project scored above the funding cutoff line, the installation would receive funding from the centralized portfolio for the project. The funds for centralized projects are in addition to the funds received from the decentralized allocation. With the decision to add a funding threshold in 2018 for the centralized portfolio, the USAF now requires installations to fund sustainment projects below $2 million and R&M projects (includes R&M repair and minor construction) below $1 million (see Figure 3.3) (USAF 2019b). While there are a few exceptions to these thresholds, they are, by design, narrow in scope to prevent minor projects from competing in the centralized portfolio. The decision certainly helps reduce the administrative burden on planning small projects due to not submitting them with the required documentation to the centralized portfolio for review and scoring. However, it adds additional requirements to a limited, decentralized portfolio budget.

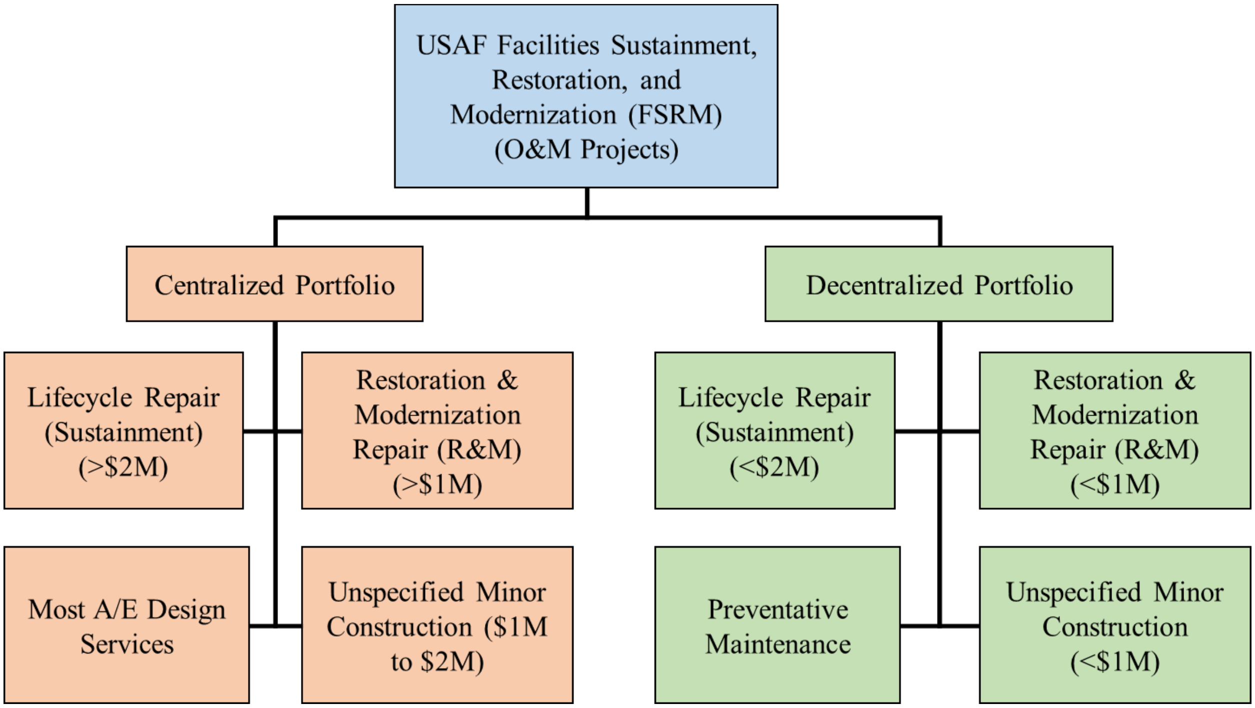


Figure 3.3 Types of USAF Operations and Maintenance Projects

As indicated in Figure 3.3, the centralized portfolio includes larger cost projects, typically requiring considerable engineering design and oversight. Within the USAF, centralized projects are executed locally (i.e., contracted and managed at the installation where the work is accomplished), but the projects are prioritized, funded, and approved and funded centrally at the AFCEC. The centralized program is a multi-year program that scores different types of projects (e.g., repair, minor construction, and sustainment) and facilities using an objective scoring model that relates the probability of failure (POF), the consequence of failure (COF), and Commander's priority to develop a 1-to-n list of USAF projects. A funding line is then applied to the 1-to-n list, which identifies the projects that will be funded in the following fiscal year. The AFCEC then manually adjusts the list as necessary to ensure that all projects approved for funding in the following fiscal year are ready for execution (e.g., design and planning are accomplished). If a project above the line needs to be designed prior to execution, the AFCEC provides design funds as necessary. Additionally, the AFCEC considers project timing when making manual adjustments, which would consider mission-related situations or reinvestment timing (i.e., targeting the "sweet spot" for facility investment based on facility condition).

Projects not funded in a given fiscal year are resubmitted the following year against other repeat submissions and new requirements. The COF is a static, numerical assessment of the USAF's mission dependency on a real property asset; this numerical assessment is referred to as the Mission Dependency Index (MDI), with a range of values from one to 100. The POF is a conditions-based assessment of a real property asset's observed facility condition index; for pavements, the POF is a function of PCI. Facilities with low condition index have high POF scores. While the consequence of failure for a given project is unlikely to change year-to-year, the POF and Commander's priority could change enough to push the project above the funding line.

3.7 Summary

This chapter summarizes the evolution of an airfield project within the DoD from the initial concept to construction to maintaining and repairing the completed airfield. While not meant to be all-encompassing, the purpose was to provide background for readers unfamiliar with DoD practices and processes. Further detail on the various aspects of this chapter is included in the subsequent chapters.

CHAPTER IV

REVIEW OF THE DEPARTMENT OF DEFENSE'S AIRFIELD PAVEMENT DESIGN AND EVALUATION METHODS

Some of the content of this chapter was used and consolidated into an article published in the proceedings of the 2019 Geo-Congress: 8th International Conference on Case Histories in Geotechnical Engineering. The as-published article (Synovec et al. 2019) can be accessed using the following internet address: https://ascelibrary.org/doi/10.1061/9780784482124.038. While there are similarities between the article and portions of this chapter, the content has been substantially reorganized, reformatted, and edited to meet Mississippi State University's dissertation formatting guidelines and the flow of the overall dissertation.

4.1 Overview

This chapter provides a holistic review of the DoD's current pavement design and evaluation methods, including views of recognized subject matter experts in the respective fields. Furthermore, this review provides an introduction to the history and major components of each element of the DoD's airfield pavements program. The cumulative observations from the overall review are then compared to the USAF's PAVER data to identify trends and potential shortcomings. The rationale behind this approach is to ground potential shortcomings or areas for improvements in the design and evaluation methods against, what is ultimately, the end product or goal: pavement performance. With these comparisons in mind, the chapter finishes with a summary of the major observations and findings, to include what appears to be the most pressing issue facing the DoD's airfield pavement program.

Due to the author's high-level access to USAF pavement condition databases and financial records, this chapter heavily focuses on USAF airfield pavements. Several of the findings and observations of this chapter are likely to extend to the entire DoD, as each of the military services utilizes the UFC for designing and evaluating its pavements. Furthermore, the entire DoD is experiencing similar challenges with growing infrastructure maintenance backlogs (OUSD(C) 2019; OUSD(C) 2018b; Serbu 2018; Serbu 2019).

4.2 Design and Evaluation Methods

In 2015, the U.S. Army's ERDC conducted a full review of its airfield pavement program utilizing three panels of subject matter experts that looked at flexible design, rigid design, and pavement evaluation methods (Crosstek Solutions LLC 2015). The subject matter experts that took part in each panel were considered leaders in their respective field that corresponded to the panel that they were assigned. Each panel assessed their respective assigned areas in its entirety to identify strengths, weaknesses, and make recommendations for improvement. This section provides a brief synopsis of the observations and recommendations of the expert panels. Additionally, this section includes feedback, critiques, and recommendations from other reports and literature where available.

4.2.1 Flexible Pavement Design

The DoD's flexible pavement design method is based on the California Bearing Ratio (CBR). This material property has been used as the design basis since the inception of the DoD's flexible design methods. For background, the CBR of a material is recorded as a percentage, which represents the soil's strength relative to the strength of crushed limestone from California in the 1920s to 1930s time frame (CBR 100 material). Mostly clay or silt soils typically have very low CBR values; whereas, soils of mostly sand or gravel tend to have noticeably higher CBR values. A material can have a CBR value of 100 or more; however, these values are typically recorded as 100 percent for design and evaluation. Although the CBR was used for several years prior by highway authorities, it was not the until 1940s when the CBR was first adopted as a critical characteristic for airfield pavement design.

The relative ease at which the CBR of a soil can be determined has enabled the material property to remain in widespread use today, particularly for pavement evaluations. A soil's CBR can be tested in the field or laboratory. That said, it is important to note that the CBR test is not a direct test of a material's strength. The CBR test evaluates a material's resistance to penetration relative to the penetration resistance of crushed limestone. This makes the CBR test an index test and not a viable choice as an input to a mechanistic design method (FHWA 2015).

4.2.1.1 History

The USACE began developing the first CBR method in 1941 after watching one of the Army Air Corps' new bombers, the XB-19, break through concrete and immediately rut asphalt pavements in preparation for its maiden flight (Gonzalez et al. 2012). With war on the horizon, the USACE needed a pavement design method to accommodate the new heavy bombers of the era. According to Ahlvin (1991), the USACE recognized developing a new rational method for designing airfield pavements would take too long and require developing a new material characterization technique. As a result, the USACE decided, as a matter of expediency, to adopt the CBR method used by the California Department of Transportation (Caltrans) for designing highways.

USACE developed the first design curves in the early 1940s. These curves were extrapolations of the highway design curves used by Caltrans to accommodate for the larger applied loads expected from heavy bombers. The extrapolations were developed mainly based on the opinions of subject matter experts (T. A. Middlebrooks, G. E. Bertram, O. J. Porter, and Arthur Casagrande), without the benefit of full-scale accelerated pavement tests. These tests were subsequently completed in the late-1940s, validating the extrapolations for single-wheel loads up to 200 kips.

In developing the original design curves, the USACE engineers used several methods of extrapolation and engineering judgment to manually plot the curves for various single-wheel loads (i.e., the team did not utilize a mathematical formula to calculate the values). As a result, the design curves could only be copied by tracing or replotting the curves for most of the 1940s (Ahlvin 1991). It was not until 1949 that the USACE developed an equation to calculate the values for its design curves. Based on the assumption that for a constant contact pressure, the ratio of pavement thickness to loaded area radius is constant, the relationship for the design curves was expressed as Equation 4.1 (Gonzalez et al. 2012). This early CBR design method relied upon a chart in the design guidance that provided values for the constant K for a given CBR and contact pressure.

$$z = ar = a\sqrt{\frac{P}{\pi p}} = \frac{a}{\sqrt{\pi p}}\sqrt{P} = K\sqrt{P} \tag{4.1}$$

where,

z = thickness of required pavement (all layers above subgrade)

a = arbitrary constant

r = radius of the loaded area

P = total wheel load

p = contact pressure

K = constant when a and p are constant

Upon further testing and aircraft development in the 1940s and 1950s, it became apparent that the original CBR model needed updates to accommodate varying contact pressures and multiple wheel gear assemblies. Equation 4.2 represents the evolution of the original CBR model. The use of the number "8.1" in the denominator of Equation 4.2 represents the repurposing and extrapolating of the variable "K" from the original CBR equation; the "K" curves were extrapolated for contact pressure of 100 to 200 psi. The number 8.1 represents the average value of the constant "D" and the CBR of the soil; the researchers found that a value of 8.1 in the denominator was "substantially constant for CBR values under 10 to 12" (Gonzalez et al. 2012). This latest version of the CBR design equation incorporated several new design parameters. However, it was still highly empirical, offered limited ability to predict performance based on first principles, handle climatic inputs, and accommodate various levels of traffic (i.e., coverages or passes).

$$t = \sqrt{P\left(\frac{1}{8.1 * CBR} - \frac{1}{p\pi}\right)} = \sqrt{P\left(\frac{1}{8.1 * CBR} - \frac{A}{\pi}\right)} \tag{4.2}$$

where,

t = required total thickness of the layers above the layer of interest

P = single-wheel load or equivalent single-wheel load (ESWL)

CBR = California Bearing Ratio (of the layer of interest)

p = contact pressure

A = contact area

The original CBR equation provided a design thickness based upon a static number of coverages (5,000 coverages). This coverage level represented the design service life at the time (i.e., the standard number of coverages to consider during design for a 20-year design life) (Ahlvin 1991; Gonzalez et al. 2012). With notice that the USAF was adopting the use of traffic zones on its airfields that would allow for reduced pavement thicknesses on less critical pavements (e.g., runway interiors or shoulders), the USACE needed a method to vary the number of coverages used for design. Utilizing test data from 39 full-scale, accelerated test sections, the USACE developed a regression equation for 27 to 133 percent of the full design coverage level. This regression equation (Equation 4.3) is entirely empirical and utilizes only design coverages as an input variable to Equation 4.4. It is important to note that this regression equation was applied for all aircraft loading configurations.

$$Traffic\ Adjustment\ Factor = 2.3\log(C) + 0.15 \tag{4.3}$$

$$t = (2.3\log(C) + 0.15)\sqrt{\frac{P}{8.1CBR} - \frac{A}{\pi}} \tag{4.4}$$

where,

C = Coverages

The idea of 5,000 coverage design life for a 20-year design life did not last long past the introduction of the B-47 aircraft in 1952. This new bomber introduced the bicycle gear configuration and a phenomenon known as porpoising. This phenomenon caused the aircraft to experience a resonant response when the aircraft's two main gear encountered successive bumps or grade changes at the aircraft's critical spacing (Ahlvin 1991). Furthermore, the bicycle gear configuration imposed two passes on a pavement for each aircraft operation, thereby imposing pavement damage over twice that anticipated in 5,000 coverages. As a result, pavements that were designed with a 20-year design life were experiencing pavement failures after only four years of operation (Ahlvin 1991). To mitigate these issues, the DoD revised its airfield construction specifications for compaction and grade tolerances.

Besides introducing the phenomenon of porpoising, the B-47 slashed the regeneration rate over the bomber that it replaced. The B-36 took several days to regenerate the aircraft after missions; whereas, the B -47 could be regenerated and flown again in a matter of hours. The B-47 was able to fly at a much higher rate per aircraft per year than its predecessor, further increasing the number of aircraft passes on a given pavement section. To compensate for the increased aircraft passes, the DoD increased its standard pavement design life to 30,000 coverages (this was later reduced to 25,000) (Ahlvin 1991). Although the standard was increased from 5,000 to 30,000 coverages, Equation 4.3 was not changed; the regression model comprising the equation was simply extended to account for the higher coverage levels.

With the introduction of the Boeing 747 and the Lockheed C-5 in the 1970s, aircraft gross weights were more than 750,000 pounds. With the heavier weights, aircraft designers utilized complex gear configurations that featured between 18 and 28 wheels to offer larger aircraft that provided ground flotation criterion similar to predecessor aircraft (Ahlvin et al. 1970). This criterion included considerations for individual wheel loads, contact pressures, and wheel spacing. Even with similar ground flotation criteria, pavement engineers were concerned that these new aircraft would have a detrimental impact on pavements due to the increase in gross weight and the introduction of complex gear configurations.

To evaluate these concerns, USACE engineers from the Waterways Experiment Station (WES) conducted a series of full-scale accelerated pavement tests to traffic pavement sections with C-5 and 747 main gear assemblies. The two-year pavement study resulted in considerable changes to the CBR design method, principally with the incorporation of the variable alpha (α). The inclusion of the α variable combined the influences of dynamic coverage levels and multiple gear configurations. As a result of the full-scale testing, the USACE concluded that the original regression equation for coverage levels (Equation 4.3) was only applicable for single-wheel loads (Hayhoe 2006).

With heavy multiple-gear loads, research indicated that the previous CBR design equation (Equation 4.4) led to pavement sections that were significantly thicker than required. Therefore, the new α variable served effectively as a thickness reduction variable for multiple-gear loads. It accomplished the thickness reduction outcome by providing a more apt translation of multiple-gear loads into equivalent single-wheel loads (ESWL).

The new α factors were derived using test data from the multiple-wheel heavy gear load (MWHGL) tests for various coverage levels and the number of wheels on the controlling main gear. Due to the limited amount of data points available to derive the original α factors, researchers extrapolated the data available to produce the α curves for other multiple-gear assemblies. Unfortunately, this action produced curves that were extrapolated beyond the limits of the data available, leading to a significant amount of criticism of the α factors throughout its usage for flexible pavement design and evaluation (FAA 1993; Gonzalez et al. 2012; Hayhoe 2006). The criticism ultimately prompted the Information and Technology Center for Transport and Knowledge (CROW) to state in its independent review of the PCN that "it is now widely recognized that the Corps CBR method cannot adequately compute [or predict] pavement damage caused by new large aircraft" (CROW 2004).

Using the new variable α to analyze the MWHGL tests, researchers from the USACE realized that merely inserting the α variable into the classical form of the CBR equation was insufficient. When the ratio of CBR to contact pressure exceeded 0.25, the predicted data from the classical CBR equation formulation began to diverge significantly from the actual data (Ahlvin et al. 1970; Hayhoe 2006). As a result of this realization, the classical form of the CBR equation was replaced with a third-order equation (Equation 4.5). This latest version of the CBR design equation (known as CBR-Alpha) remained in effect until the late-2000s. It was used by the International Civil Aviation Organization (ICAO) for PCN determination.

$$t = \alpha\sqrt{A}\begin{bmatrix} -0.0481 - 1.1562\left(\log\frac{CBR}{P_e}\right) - 0.6414\left(\log\frac{CBR}{P_e}\right)^2 \\ -0.4730\left(\log\frac{CBR}{P_e}\right)^3 \end{bmatrix} \tag{4.5}$$

where,

α	=	load-repetition factor (a function of the number of wheels on the main gear and coverages)
A	=	contact area measured in square inches
P_e	=	Equivalent single-wheel load or single-wheel load contact pressure measured in pounds per square inch

CBR = California Bearing Ratio of the supporting layer

t = required thickness above the supported layer measured in inches

Propelled by the criticism in the CROW report about the ability of the CBR method to accurately characterize the damage from new large aircraft, Gonzalez et al. (2012), began developing a replacement for the CBR-Alpha method in the late 2000s. This replacement became known as the CBR-Beta method due to its inclusion of a beta variable as a replacement for and improvement upon the alpha variable. The primary objective of the move from the CBR-Alpha to CBR-Beta was to develop a procedure that was more mechanistic to allow for the incorporation of validated performance criteria.

Rooted at the core of the CBR-Beta method is the redevelopment of the primary thickness equation from the CBR-Alpha method using the Boussinesq-Frohlich stress distribution model. The alpha variable in the CBR-Alpha method (see Equation 4.5) is a thickness adjustment factor and is a function of traffic volume (i.e., coverages) and the number of wheels (Gonzalez 2015). For single-wheel loads, alpha is a function of traffic volume only. To effectively replace the α variable, the newly created beta variable needed to account for variable levels of traffic volume. As such, Gonzalez et al. (2012) developed the newly created beta variable (β) to be a function of traffic volume, subgrade CBR, and allowable vertical stress (see Equation 4.6 and Equation 4.7).

$$\sigma_{allowable} = \frac{CBR * \beta}{\pi} \tag{4.6}$$

$$log(\beta) = \frac{1.5441 + 0.0730 * log(coverages)}{1 + 0.2354 * log(coverages)} \tag{4.7}$$

where,

$\sigma_{allowable}$	=	allowable vertical stress on the top of the subgrade
CBR	=	subgrade California Bearing Ratio (CBR)
coverages	=	coverages of a given aircraft on the pavement

For single-wheel loads, the flexible pavement design method is straightforward and noniterative, using Equation 4.8 (Gonzalez et al. 2012). This new CBR equation incorporates the Boussinesq-Frohlich stress distribution model and the allowable stress criteria (see Equation 4.6), allowing it to calculate the thickness required using a few given inputs. It is important to note that this equation only considers the vertical stress at the layer of interest (i.e., the layer being protected by the calculated thickness above it). As a general note, the CBR equations are used to calculate the thickness of all unbound materials in the pavement. The bound materials (i.e., asphalt layers) are typically determined using minimum thickness criteria, which is based upon the type of aircraft, traffic area, and CBR of the base course material.

$$t = \frac{r}{\sqrt{\left(\frac{1}{1-\frac{\beta * CBR}{\pi * p}}\right)^{\frac{2}{n}} - 1}} \tag{4.8}$$

$$n = 2\left(\frac{CBR}{6}\right)^{0.1912} \tag{4.9}$$

where,

t	=	thickness, inches
r	=	loaded radius, inches
p	=	contact pressure, psi
n	=	Frohlich's concentration factor

The other major change associated with the CBR-Beta design method was the shift from ESWL to the use of superposition principles to account for the cumulative effect of each wheel in a multi-wheel gear assembly. To perform a multi-wheel analysis, the designer starts by calculating β using Equation 4.7, with the singular input of design coverages. This β value is then used in Equation 4.6 to determine the allowable vertical stress. As previously mentioned, due to the interaction of the various wheels and overlapping of applied stresses, multi-wheel assemblies need to be investigated at points directly below the wheel and between the wheels. The applied stresses are calculated and added together to determine the cumulative applied stress at each point of interest. The maximum cumulative vertical stress determined from this analysis is then compared to the previously calculated allowable stress to determine if the pavement has enough thickness above the layer of interest. If the allowable stress is less than the calculated cumulative applied stress, then additional thickness is required. An initial thickness is initially assumed and is subsequently adjusted, in an iterative fashion, until the allowable stress is equal to the cumulative applied stress.

One of the major appeals of the CBR-Beta method (and CBR methods in general) is that the method can be used to design new and evaluate existing pavements using similar inputs and tools from the same program with little extra required training. Furthermore, the CBR-Beta method can handle unsurfaced airfields with minor modifications. All of these factors provide a high level of flexibility to the DoD, particularly as it requires a wide range of people and backgrounds to be able to use its design and evaluation methods anywhere in the world to support a variety of different scenarios.

4.2.1.2 Views of Others

The flexible pavement design panel primarily focused on the CBR-Beta design method for their review and recommendations. While the panel members praised the simplicity and expediency of the current CBR-Beta methods, they cautioned that the method is too simplistic. As summarized by Crosstek Solutions, LLC (2015), the panel of subject matter experts felt the CBR-Beta method has six key weaknesses:

1. It does not adequately consider the deterioration modes associated with thermal cracking and rutting. While the CBR-Beta utilizes rutting criteria (1-inch rut in the subgrade) as its failure criteria, the panel members argued that ignoring a direct consideration of the rutting resistance of the layers above the subgrade creates non-quantifiable uncertainty, as these layers are considered by specification only.

2. It does not adequately address climate and environmental effects. Asphalt thickness is assigned primarily based upon minimum thickness criteria (same criteria used in all climatic zones). It does not account for the range of asphalt properties impacted by climate and environmental effects. With regard to unbound materials, the CBR-Beta considers the impact of frost and thawing conditions (using empirical adjustment factors in place of CBR values); however, it does not adequately address moisture and temperature variations in arid and semi-arid climatic zones. The CBR-Beta method also does not account for variable groundwater levels and impact on subgrade CBR.

3. It does not adequately account for thick asphalt or stabilized layers. According to the panel members, the CBR-Beta method was not calibrated for these layer types and relied heavily on highly empirical equivalency factors. The current equivalency factors were calibrated using the CBR-Alpha method and are considered insufficient.

4. The asphalt fatigue algorithm is insufficient, as it focuses on excessive rutting and does not consider fatigue cracking.

5. Material characterization is insufficient and relies upon the CBR value to characterize the unbound material stiffness. A laboratory soaked CBR test is typical, which the panel members felt led to overly conservative CBR inputs.

6. The CBR-Beta method only calculates vertical stress and ignores other stresses, deflections, and strains.

The panel members recommended that the DoD should adopt methods and algorithms in-use or under development for highway pavements. The overarching recommendations were to adopt the Association of American State Highway and Transportation Officials' (AASHTO) Mechanistic-Empirical (ME) design software (supports AASHTO's MEPDG) and incorporate additional elements from performance and nonlinear stress modeling from research conducted by or overseen by the panel members. This observation is not to discredit their recommendations, but rather to identify the potential bias that might exist, as dozens of other models and algorithms exist that claim to provide comparable benefits as those recommended by the panel members. Separating the specific, named solutions from the other recommendations, the panel members recommended the following areas for improvement and further research (Crosstek Solutions LLC 2015):

1. The DoD needs to revisit the method in which it inputs and accounts for the lateral distribution of aircraft across the pavement surface. This relook should consider the entire anticipated traffic mix over the life of the pavement, and it should be distress-specific (fatigue and rutting) using a probabilistic approach.

2. The DoD should incorporate secondary and tertiary deformations of the asphalt and unbound layers as it relates to overall permanent deformation.

3. A revision to the DoD's flexible design methods should incorporate performance modeling for bottom-up, top-down, thermal, and reflective cracking. As such, the DoD should establish failure criteria for these distresses that are specific to the type of airfield pavement (i.e., runway, taxiway, apron, etc.).

4. The DoD needs to revisit how it accounts for climatic effects in its design methods, particularly as it relates to moisture and freeze-thaw modeling.

5. A revised DoD design method should incorporate three-dimensional (3D) nonlinear, mechanistic modeling that can represent the dynamic effects of moving gears.

6. The current trend for highway pavements, particularly on heavily trafficked roads, is to design perpetual pavements that can be rehabilitated in a manner that reduces traffic delays and high user costs. For airfields, minimized airfield closures is a potential benefit.

7. The DoD should establish an airfield pavement-specific long-term pavement performance (LTPP) program similar to the FHWA program.

4.2.1.3 Summary

There are two major observations from the previous two sections. First, based on the historical development of the CBR methods, the DoD tends to rely on a catalyst to spur a major evolution of its design methods. One could interpret this tendency to be overly reactionary, which certainly has some merits. However, the alternative interpretation is that there is little advantage in changing something that appears to be working. Both suppositions rely on the overall premise that the outcomes of the design method (i.e., pavement performance) are the most important objective. As such, the outcomes should drive decisions to explore changes based on the perceived value of the output gained by the input of additional effort and resources.

This value proposition is known in economics as the “Law of Diminishing Returns” (see Figure 4.1). The theory states that at a given point in a system, the input of additional resources begins to produce diminishing returns. This inflection point is known as the point of diminishing returns. Over time, the continual addition of resources produces negative returns (Ricardo 1815). While the Law of Diminishing Returns is easily explained in the context industry or production-driven contexts, it is less intuitive in other settings. In statistics, the Law of Diminishing Returns is best exemplified in regression modeling. Generally speaking, the addition of variables to a regression model increases the fit of the model to a given data sample. However, the increase of additional variables can cause the model to “overfit” the data and provide the researcher with a model that is, in fact, less representative of the actual sample population (Freedman 1983). The cause of this phenomenon is that the additional variables are merely responding to the “noise” that exists in the sample data, giving the impression a given regression model has a higher degree of fit. While the variables may help address noise in the sample data, the variables may have little characterizing value to the overall causal relationship between the input (independent) variables and the dependent variable.

Extending this theory to pavements, the Law of Diminishing Returns would suggest that there are only so many variables and material properties that have a significant impact on predicting pavement performance. As such, if a change pavement design methodology drove a large input to time and cost to produce a similar result (or potentially one with only slight improvements), the change to that methodology was likely, not worth the additional effort as measured by the diminished return on investment. While likely not necessarily publicly discussed, this concept has played out in the transportation and paving industry over the past several decades. For example, AASHTO has a Mechanistic-Empirical Pavement Design Guide (MEPDG), and it is still not universally used by state transportation authorities. The most common reasons for not adopting the MEPDG have included: (1) district offices were resistant to change due to the higher comfort level with the inputs and outputs of empirical methods; (2) the MEPDG is too complex for most practicing engineers; and (3) a lack of resources to locally calibrate and train staff (Pierce and McGovern 2014). As further evidence, the South Carolina Department of Transportation (SCDOT) states in their current pavement design guide that it still uses the 1972 edition of the *AASHTO Guidelines for Pavement Design* for new asphalt pavements because the newer design guides have not been able to "reliably provide superior results when compared to current methods" (SCDOT 2008).

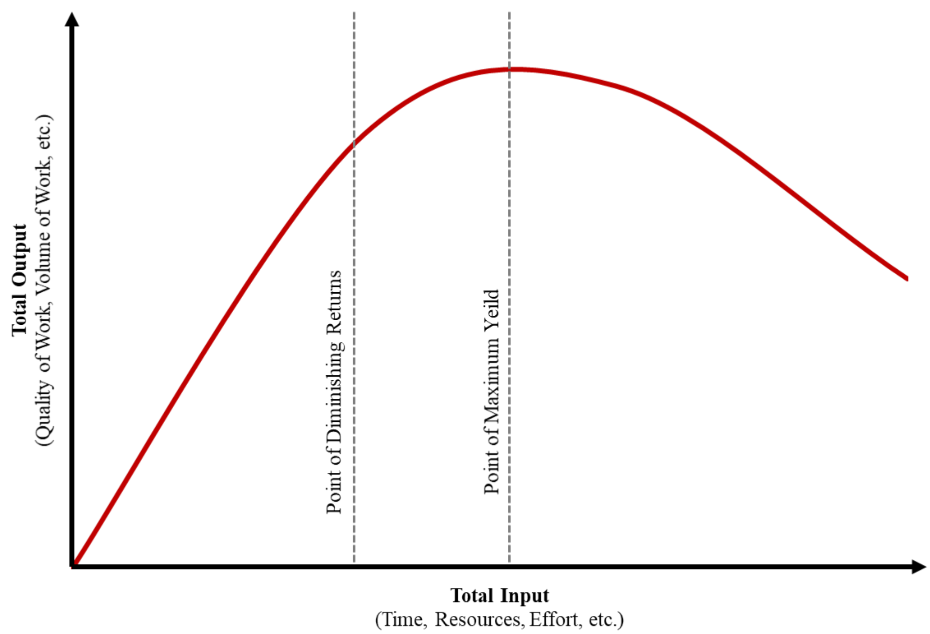


Figure 4.1 Visual Representative of the Law of Diminishing Returns

As with the preceding CBR methods, the CBR-Beta method is focused on preventing failure in the subgrade, primarily the formation of rutting behavior exceeding one inch. As a result of this singular focus, the CBR design methods are calibrated from test data against this one-inch rut failure criterion, effectively ignoring potential failure modes in other pavement layers. To deal with these other failure modes, the DoD has issued specifications, minimum CBR values for pavement materials, and minimum thickness requirements; however, none of these products have satisfactorily addressed all concerns. According to a group of subject matter experts from across the U.S. (non-USACE affiliated), the DoD's CBR method does not include sufficient provisions for protection from thermal or block cracking. Currently, the DoD relies on policy to assign asphalt thicknesses rather than using material properties, loading conditions, or climatic considerations. Furthermore, the team of subject matter experts went on to say that the CBR method ignores the effects of asphalt properties relative to temperature and loading frequency, seasonal changes in material properties (Crosstek Solutions LLC 2015).

Review of the CBR-Beta (and CBR methods in general) input variables reveals there is only one variable that is used to characterize a material: CBR. This rather simplistic approach to material characterization is purposeful for reasons that are discussed in detail in the gap analysis section of this literature and practice review. The CBR of an unbound material at an instant in time is affected by environmental conditions (i.e., moisture and frost) and by the properties of the material itself. Excess moisture in the pavement is typically handled with drainage layers and by utilizing the soaked CBR value for the subgrade, which is less than the CBR value for the subgrade at the optimum moisture content. Frost is typically handled by using frost area soil support index (FASSI) values as opposed to measured subgrade CBR values (USACE 2001). With regard to material properties, the DoD relies heavily on material and construction specifications to control these aspects; however, there is ultimately no guarantee that the use of these specifications adequately removes uncertainty or risk.

The mechanistic-empirical (mostly empirical) CBR-Beta method utilizes Boussinesq solutions to comprise its mechanistic component. Boussinesq solutions are based upon the assumption that the soil can be modeled as a homogenous half-space; however, pavements are not homogenous. As a result, the CBR-Beta method ignores the effects of the materials above the subgrade and bonding conditions between layers. To help the method differentiate between 20 inches of base course and subbase course material, the DoD uses material equivalencies to equate the two materials. It is important to note that the DoD only uses these material equivalencies when the material in question is more than the minimum thickness value.

As an example, a pavement has 5 inches of asphalt, 10 inches of base course material (CBR 80), and 10 inches of subbase course material (CBR 50), which is 25 inches of actual material above the subgrade. For CBR 80 base course materials, the minimum thickness is typically six inches; therefore, four inches of the base course would be converted to subbase material using an equivalency factor of two. For computations, this pavement would then be evaluated as having 33 inches of material above the subgrade. As a general note, the CBR value of the subbase has no impact on the equivalent thickness unless it is CBR 80 or CBR 100. Stabilized base course materials are typically evaluated using the minimum thickness criteria for 100 CBR materials and then multiplied by an additional factor to convert it to subbase material. This layer equivalency method creates situations in which the CBR-Beta method can experience asymptotic behavior with slight variations in layer thicknesses. In general, equivalency factors are highly empirical and overly simplistic.

As previously mentioned, the CBR-Beta method was calibrated to prevent subgrade failure, which is typically composed of materials with CBR values under 20. The calibration was accomplished using full-scale test sections comprised of typical asphalt, base, and subbase course materials of various thicknesses that were designed before the start of the trafficking test to fail in the subgrade prior to any other layer. Without a large amount of failure data from the base course, for example, it would be difficult to calibrate the design method for higher-strength materials without making conservative assumptions or extrapolations. As a result, the CBR-Beta method is not likely well-suited to accurately evaluate the required pavement thickness needed to protect higher strength subgrades.

4.2.2 Rigid Pavement Design

The DoD officially uses two rigid pavement design methods for its airfields: (1) linear elastic analysis and (2) a Westergaard-based approach (USACE 2001). Of these two methods, the Westergaard-based approach is more widely used based on the author's experience. The method is very familiar to experienced engineers and relatively easy to learn for newer engineers. The Westergaard method is available in equation-format, graphically, and digitally in PCASE. As described in the next section, a large part of its ease of use is that it has not changed a lot throughout the years; however, the method still produces reasonable results for a wide variety of environments, materials, and traffic mixes (Crosstek Solutions LLC 2015).

4.2.2.1 History

Similar to the historical start of the early CBR design methods for flexible airfield pavements, the DoD developed its first rigid pavement design method in 1941 after a major pavement failure involving the new XB-19 aircraft as it rolled out of the hangar on its maiden flight (Ahlvin 1991; Bly 2013). Shortly thereafter, the USACE conducted a thorough study of established design procedures, which were overwhelming all for highways. Among the methods evaluated, the Westergaard method showed the most promise. This method was developed for the Bureau of Public Roads in 1926 and was later extended to airport pavements after the Arlington Road Tests in 1939 (Ahlvin 1991). The method, at the time, was designed around a center-point loaded concrete slab on top of a liquid subgrade loaded by a loaded circular area. After trafficking tests in 1942 and 1943, the USACE realized the concept of a center-point loaded slab is not conservative enough. However, in lieu of viable alternatives, the USACE published its first rigid pavement design guide using the Westergaard method for interior slab loading and contained several provisions to address edge loading. Among these provisions, the USACE required all load transfer or thickened edges at all joints, and it included a safety factor to the Westergaard method to account for the edge loading condition (Ahlvin 1991). It was not until years later and the completion of additional trafficking tests, that edge loading models were developed, validated, and included in the rigid pavement design guide (Westergaard 1948). As a general note, the Westergaard solutions also include a third loading condition: corner loading. However, the airfield pavement design primarily relies on the edge loading condition (Gonzalez et al. 2013; USACE 2001).

As described by Hutchinson (1966), the USACE continued to research rigid airfield pavement design to revise the design and construction criteria until about 1955. Around this time, the USACE felt that its rigid design method was adequate for current aircraft and would be adequate for the foreseeable future. As such, the USACE shifted its research focus to developing better joint materials, rigid pavement repair, and concrete overlays. As described by Ahlvin (1991), the MWHGL tests in the early 1970s, which significantly changed the CBR method used for flexible pavements, largely confirmed that the USACE's rigid pavement criteria (based on the Westergaard solutions) was still valid and could be extended to the newer, heavier aircraft. As such, the Westergaard solutions are still used today as the basis for the DoD's rigid airfield pavement design (Crosstek Solutions LLC 2015; USACE 2001).

4.2.2.2 Views of Others

The rigid design panel reviewed related training materials, UFC, and technical reports for their review and recommendations. Similar to the flexible pavement panel, the rigid panel members praised the simplicity and expediency of the current rigid design method. Furthermore, they believe that the DoD's current design method produces reasonable results within a range of inputs and is well aligned with the DoD's current pavement evaluation tools and procedures. However, the panel members expressed concern that the rigid design method requires significant revision. As summarized by Crosstek Solutions, LLC (2015), panel members believed that the rigid design method has seven key weaknesses:

1. The rigid design method does not utilize finite element analysis methods.

2. The DoD method does not consider joint faulting and loss of load transfer efficiency.

3. The fatigue algorithm relating the (layered-elastic analysis) calculated stresses is based on historical full-scale testing results that are over 50 years old, and it undervalues the importance of load transfer.

4. The current design inputs have minimal ability to consider anything other than strength and modulus, particularly when the method does not consider a characteristic such as the coefficient of thermal expansion.

5. The current failure criteria ignore several failure modes (e.g., temperature or moisture curling) known to impact concrete pavements. The panel members recommended that the DoD should develop and calibrate performance models to account for these distresses. Furthermore, the panel members stated that research suggests that the cumulative damage factor (CDF) equaling one does not define pavement failure reliably or consistently.

6. The current rigid design method does not make attempts to optimize the design of the pavement by minimizing the life-cycle cost.

7. The current DoD method does not directly consider the effect of climatic changes.

Similarly, to the flexible design panel, the rigid design panel recommended the DoD adopt the AASHTO ME pavement design procedure. Furthermore, the panel recommended that the DoD shift from using layered-elastic analysis and the Westergaard methods to a finite element methodology. Lastly, the panel members recommended that the DoD should consider incorporating emerging admixtures, load transfer devices, and construction methods to its rigid pavement program (Crosstek Solutions LLC 2015).

4.2.2.3 Summary

The overwhelming majority of recent pavement research focuses on highway pavements. Therefore, it is unsurprising that a panel of rigid pavements experts would identify perceived weaknesses and provide recommended improvements that ultimately point towards making airfield pavements more in line with highway pavements. It should be noted, however, that highway and airfield pavements are distinctly different in the types and frequency of loading. Furthermore, airfield pavements are far more likely to experience environmental-related distresses than structural-related distresses (Rushing et al. 2014; Synovec et al. 2019). Additionally, the scope and problem set of the DoD is vastly different than a typical transportation agency. This is not to suggest that the recommendations of the panel members should be dismissed—far from it. It is merely a recognition that what may seem like an apparent weakness to one person may, in actuality, be a purposeful component or choice. Deciphering between the theoretical and practical application is ultimately an art and a science. It takes a comprehensive understanding of the internal decision-making, operating environments, and constraints of a given organization. That said, there are certainly some weaknesses and recommendations from the panel that would be beneficial for the DoD to explore both for pavement design and evaluation (e.g., load transfer or failure criteria).

4.2.3 Pavement Evaluation

Pavement evaluation is discussed in detail in Chapter II, and its history, as a part of the DoD's pavement program, is less documented. The evaluation procedures are effectively a back-calculation of the design procedures of the flexible and rigid design methods to determine the number of allowable passes. The typical processes involve using a measurement device (e.g., DCP or HWD) to characterize the individual layer properties. In the case of the DCP, the device can also be used, in conjunction with engineering judgment (instead of direct measurement via core drilling), to estimate layer thicknesses. With the estimated layer properties and thicknesses, flexible and rigid design methods are then used to back-calculate the number of allowable passes.

Based on the inherent linkage between pavement evaluation and design, it is likely that the concept of evaluating allowable passes for a given pavement started shortly after the USACE developed the design process. As evidence of this assumption, the first known technical report on airfield pavement evaluation was published in 1951 by the USACE (WES 1951). It focused on evaluating overseas airfield pavements, which is still a topic of great interest and application to the DoD. Since this first publication, subsequent research looked at a variety of topics focusing on material characterization, including non-standard materials, back-calculation techniques, and unsurfaced airfields (Anderson 1990; Griffin and Tingle 2009; Priddy et al. 2014; Priddy and Rutland 2014; Weiss 1980).

4.2.3.1 Views of Others

While contingency evaluations are a large part of the DoD's pavement evaluation program, the pavement evaluation panel primarily focused on the sustainment-type evaluations for their review and recommendations. The panel members praised the DoD's pavement evaluation method for a variety of reasons, including the widespread implementation throughout civilian and military organizations and the use of ACN, PCN, and PCI condition ratings. As summarized by Crosstek Solutions, LLC (2015), however, panel members believed that the pavement evaluation program has three key weaknesses:

1. The pavement evaluation methodology does not consider the nonlinear behavior of unbound materials or direction-dependent moduli.

2. The back-calculation methods used by the DoD are too simplistic and do not fully account for material characterization considerations. Furthermore, the models do not account for the variety of failure modes known to impact airfield pavements.

3. The pavement evaluation program only has a limited focus on "project-level" decision-making tools; the panel members feel that the DoD focuses too heavily on network-level identification tools. Furthermore, from the panel's perspective, the DoD does not adequately address or identify the root cause of the pavement deterioration to know what needs replacement or strengthening.

To address these weaknesses, the panel members recommended that the DoD should adopt a variety of alternative evaluation software and technologies. The evaluation software recommended by the panel primarily focused on shifting to finite element analysis methods. The technologies recommended also focused on a variety of emerging nondestructive evaluation tools, such as ground-penetrating radar and rolling dynamic deflectometers (Crosstek Solutions LLC 2015). Some of these software elements and technologies may benefit the sustainment-type evaluations, but none of the recommendations provided by the panel members appeared directed towards contingency evaluations.

4.2.3.2 Summary

Pavement evaluation methods and techniques are discussed in detail in Chapter II. This section summarizes this previously discussed material and includes the views of subjects matter experts not affiliated with the DoD. While their observations have merit, the observations overly focus on sustainment-type evaluations at non-contingency locations. In sustainment-type settings, the PCI survey is the most important outcome for an evaluation, as it helps monitor pavement deterioration and help drive investment decisions. In non-contingency environments, structural capacity is effectively a secondary concern because the DoD does not have a significant number of structural-related distresses on its airfields (Rushing et al. 2014; Synovec et al. 2019). When structural deficiencies emerge, decreases in structural capacity are typically preceded by large decreases in PCI ratings. This correlated relationship is in large part due to the conservative approach the DoD takes towards pavement design. Therefore, the number of allowable passes on a typical non-contingency USAF airfield pavement section can routinely eclipse one hundred thousand allowable passes (Stribling et al. 2017).

The same typically cannot be stated for contingency airfields. In the author's experience, it is not uncommon to see airfield pavements where the PCI rating and structural capacity are uncorrelated. Additionally, sustainment evaluations are typically completed over several weeks, while contingency evaluations are completed in as little as a few hours. With limited time to conduct a thorough evaluation and the prevalent usage of non-standard materials and construction, contingency evaluations are both inherently necessary and risky (Priddy and Rutland 2014). Reducing risk in this area must continue to be a focus for the DoD. As such, the panel of subject matter experts may have overlooked or under emphasized a critical component of the uniqueness of DoD pavement evaluation by focusing heavily on sustainment evaluation processes and techniques.

4.3 Current State of U.S. Air Force Pavements

Based on internal PAVER records from October 2017, the USAF is responsible for 1.3 billion square feet of paved surface in various locations throughout the world. The USAF has approximately 546 million square feet of asphalt pavements (approximately 42 percent of their total portfolio) and 760 million square feet of concrete pavements. As a general note, approximately 138 million square feet of the previous total of asphalt pavements are asphalt overlays, either asphalt over asphalt or asphalt over concrete (USAF 2017b).

Figure 4.2 summarizes USAF PCI values. Approximately 60 percent of the USAF's asphalt pavements currently have a PCI rating of "good," which is defined by a numerical PCI value between 86 and 100. A total of 17 percent and 15 percent of asphalt pavements are rated as either "satisfactory" or "fair," respectively. The remaining 7 percent of asphalt pavements are rated as "poor" or worse.

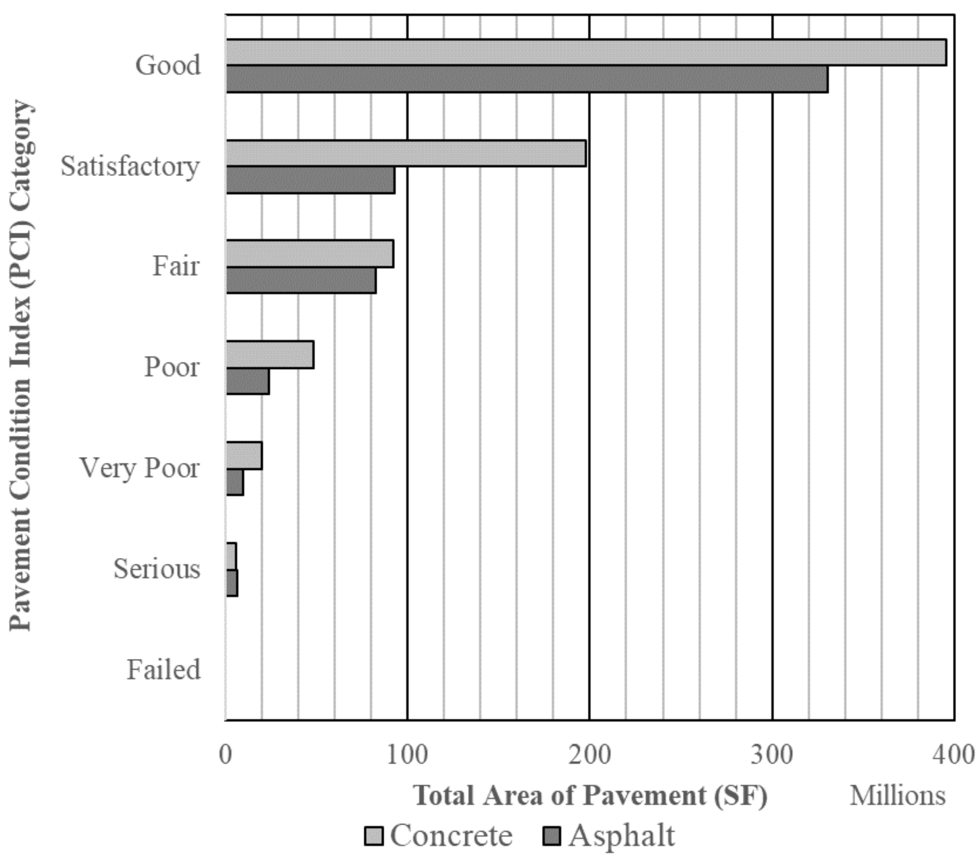


Figure 4.2 Overall Quantity of USAF Pavements by Pavement Condition Index and Type

As shown in Figure 4.3, apron and overrun pavements show a statistical difference in PCI when compared to the other primary types of branches on an airfield. Since this analysis is still taking a cursory look at the data and using PCI as a comparison, the PCI values for the analysis were weighted using the total area of the section considered to avoid issues with overly significant data skewing the data. The branches in the analysis are comprised of different areas (i.e., when unweighted, a small section with a low PCI value could disproportionately impact the results as it could carry the same weight as a large section with a high PCI value). As shown in Figure 4.4, the typical asphalt branch in the USAF is under 10 thousand square feet with a PCI rating of Good; however, several data points fall outside of this generalized description. Furthermore, approximately 25 percent of the asphalt branches have surface areas over 10 thousand square feet.

As shown in Figure 4.3, runways are statistically in better condition than most other branch types; shoulders are the lone branch rated higher than runways. Runway pavements being statistically better than most other pavement branches is largely unsurprising given the dependency of the USAF's mission on runways. As such, the USAF's current pavement maintenance strategy prioritizes runway pavements, thereby increasing the probability of funding for runway pavements in a given year. By contrast, overruns and aprons would be seen as less of a priority and would likely see higher levels of deferred maintenance, resulting in pavements generally in worse condition. While this is an initial explanation looking at the data, further analysis of the data is necessary to determine the validity of this assumption.

As an aside, Figure 4.3 depicts a one-way plot created using JMP. The plot contains several shapes that summarize the quantiles calculated from the data, as well as the means analysis of variance. The red horizontal lines above and below the red rectangle depict the 10 and 90 percent quantiles. The rectangle drawn around a range of points for each grouping depicts the 25, 50 (i.e., the median), and 75 percent quantiles. Additionally, the green diamond depicts the 95 percent confidence interval of the mean for each grouping. Lastly, the grey horizontal line that stretches across the entire length of the x-axis represents the overall mean of the data with all groupings considered.

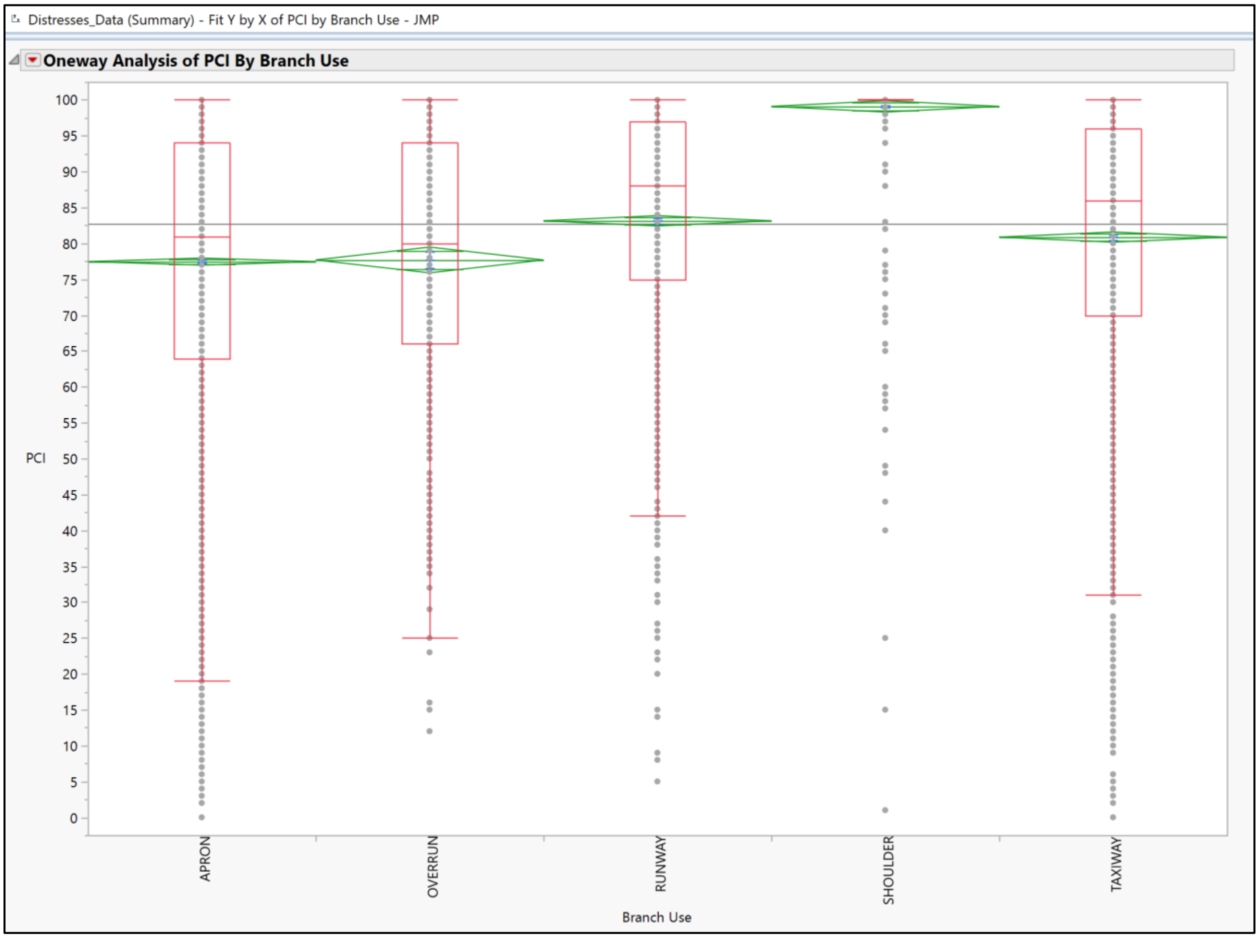
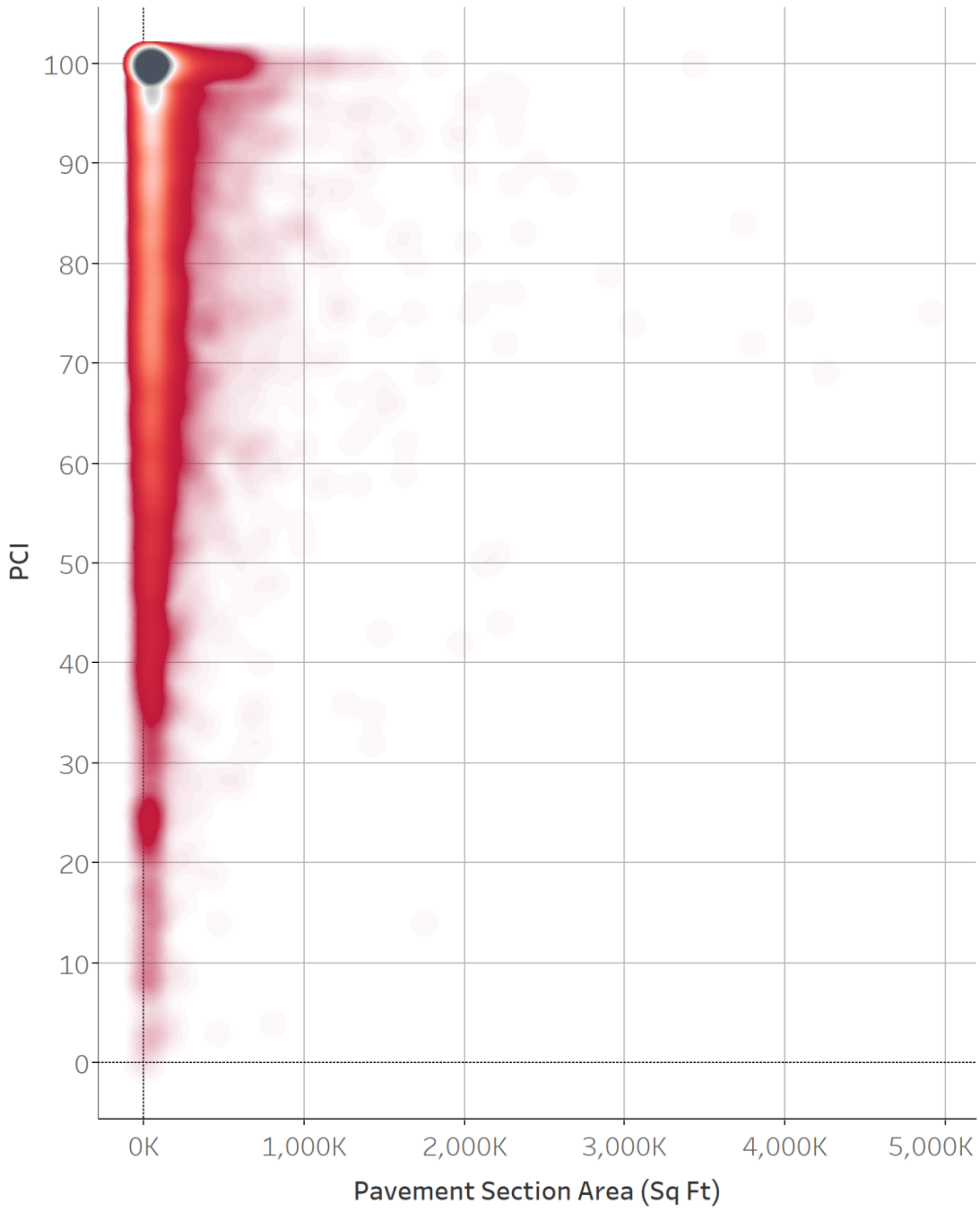


Figure 4.3 Quantity of USAF Pavements by Weighted Pavement Condition Index and Branch Use

As depicted in Figure 4.3, airfield shoulders are rated demonstrably higher by weighted PCI than any other pavement branch. Furthermore, shoulders are not designed or intended for regular aircraft loadings; their primary purpose is for foreign object debris (FOD) covering adjacent to airfield pavements that receive regular trafficking. As a result, it seems more likely that shoulders would see higher rates of deferred maintenance due to their perceived less importance to mission criticality. Additionally, while aircraft shoulders do not experience trafficking, shoulders are exposed to environmental and climatic effects (similar to other airfield pavements) that cause pavement distresses. As such, it seems peculiar that the weighted PCI values for shoulders would be significantly higher than other airfield pavements. The primary reason for this disparity in the data is that the USAF does not typically evaluate the PCI or structural capability of tertiary pavements, which includes paved shoulders (AFCEC 2017c). As a result, the validity of the data for tertiary pavements is questionable. When shoulders are removed from some of the previous analysis, the numbers change dramatically, particularly for asphalt pavements.

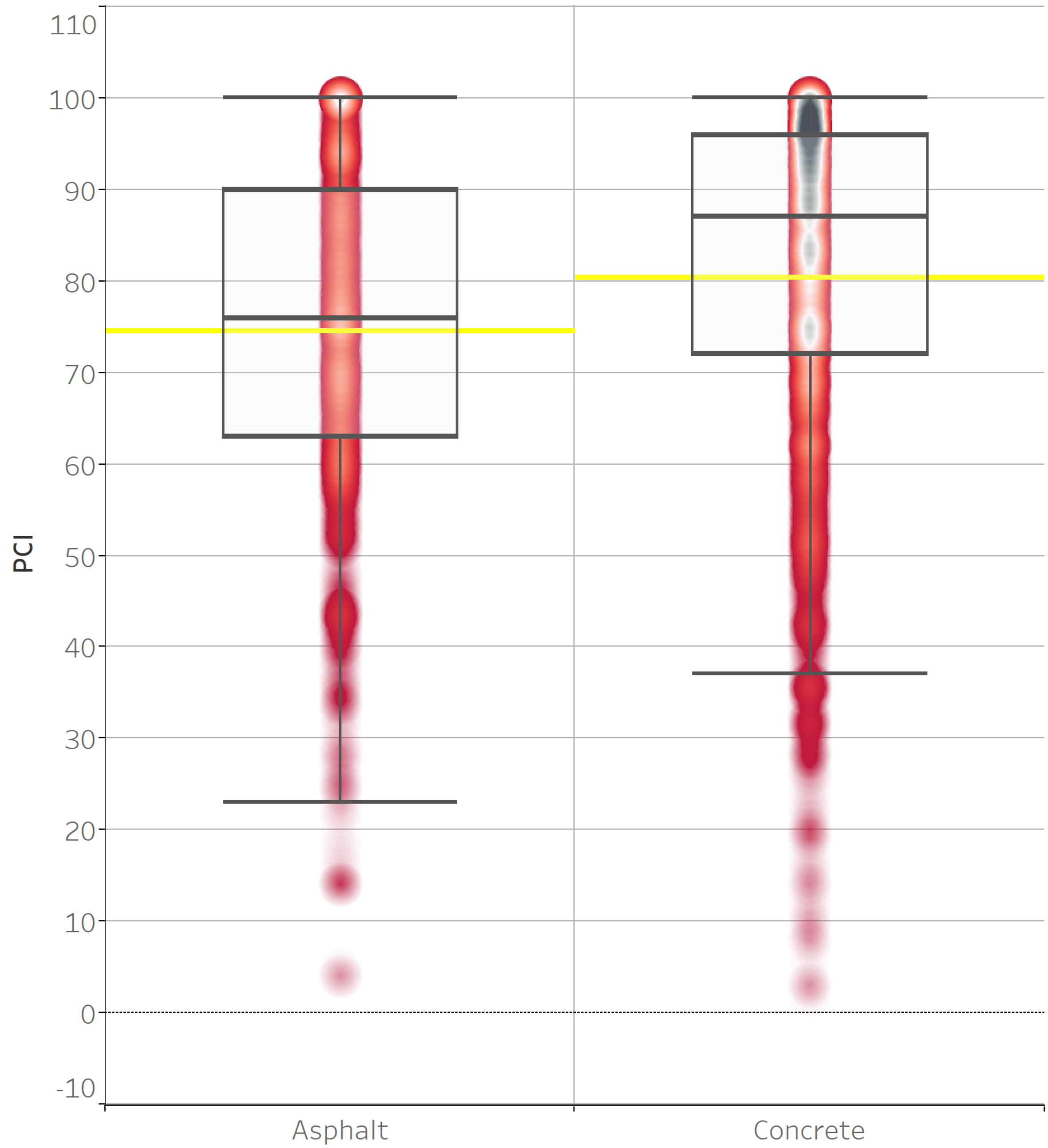
When the analysis included the shoulder data, the statistical analysis indicated that asphalt pavements were currently in better condition than concrete pavements. While this is a true statement based solely on the USAF's raw data, it only tells a portion of the story. Based on policy, the USAF does not evaluate paved shoulders during its structural or PCI assessments; therefore, it is likely that the data concerning shoulders is either outdated or inaccurate. As such, paved shoulders were removed from the analysis (see Figure 4.5).

When the paved shoulders were removed, the median and mean weighted PCI values for asphalt pavements dropped from approximately 94 and 85 to 77 and 76, respectively. For comparison, the weighted median and mean PCI values are 87 and 81, respectively, for concrete pavements (see Figure 4.5). More analysis is needed to determine why such a disparity between the two pavement types exists.



Notes: The Density Plot Above Depicts the Currently Assessed PCI Value of all Pavement Sections Relative to it Size. Scale Above is from Red to White to Black Corresponding to Low, Medium, and High Frequencies of Occurrences Respectively.

Figure 4.4 Comparison of Pavement Area to Pavement Condition Index for the USAF's Asphalt Pavements



Notes: The Density Plot Above Depicts the Currently Assessed PCI Value of all Pavement Sections Relative to its Surface Type. Scale Above is from Red to White to Black Corresponding to Low, Medium, and High Frequencies of Occurrences Respectively. Statistical Analysis Presented Above Depicts a Standard Box Plot and a Weighted Average (Yellow Line).

Figure 4.5 Comparison of Weighted Pavement Condition Index Values by Pavement Type

4.3.1 Climactic Impacts

All of the pavements were grouped based on their location into the four climatic regions using for FHWA's LTPP program (FHWA 2018). For airfields located outside of the regions considered in the LTPP program (i.e., outside of the U.S.), the airfields were broadly categorized using the category "International." The international category includes airfields throughout Europe, the Middle East, and eastern Asia. Based on the locations involved, it is likely more representative of the USAF as a whole; however, it is a complicated category to consider due variations with airfield ownership and agreements between the host nation and the U.S.

The one-way plot in Figure 4.6 shows a statistically significant difference in weighted PCI values between pavements from regions that experience a freeze cycle and regions without a freeze cycle. Furthermore, the data shows that pavements in the two no freeze regions are statistically similar, with dry environments having slightly less "poor" pavements based upon weighted PCI than wet environments. While it is easy to identify the freeze cycle as the cause of this disparity between pavements in freeze and non-freeze regions, further analysis of the actual distresses observed at the airfields in these regions is needed. The rationale for this caution is the fact that this discrepancy could be caused or exacerbated by an unintended policy, funding, or maintenance decision.

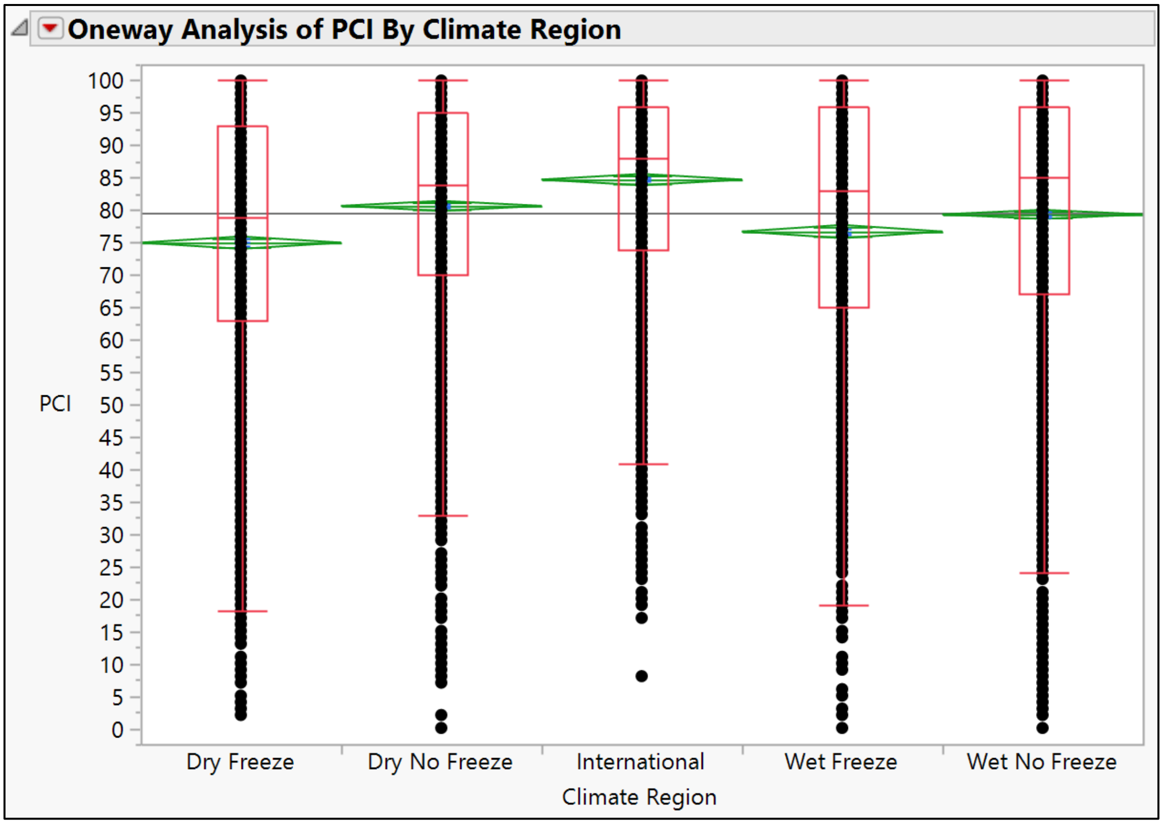


Figure 4.6 Comparison of Weighted Pavement Condition Index and Climate Region

As shown in Figure 4.7, pavements in the "wet freeze" region have experienced more recent local or major work (i.e., construction or repair beyond simple maintenance) than any other group. As previously mentioned, the "wet freeze" region is statistically among the worst of the climatic regions. The "dry freeze" region was statistically the worst region by PCI; however, the pavements in this region do not see a similar increase in new projects when compared to the "wet freeze" region. It is worth noting that both freeze regions have been experiencing new projects at an increased rate when compared to pavements from the non-freeze regions, albeit to varying degrees. Based on this observation, it appears that the USAF's infrastructure investment policy is likely indirectly favoring these projects. This commentary is not to suggest that the investment policy (more specifically, the scoring models) is directly prioritizing projects in freeze regions. However, the scoring model is likely rewarding the deteriorated state of pavements in freeze regions (as shown in Figure 4.6). As a reminder, the current scoring model prioritizes pavements with a higher POF. For pavements, high POF scores are commensurate with pavement sections with low PCI values. While data suggesting more recent local or major work on an airfield is indicative of increases in project funding, it is not necessarily a failsafe variable at predicting PCI.

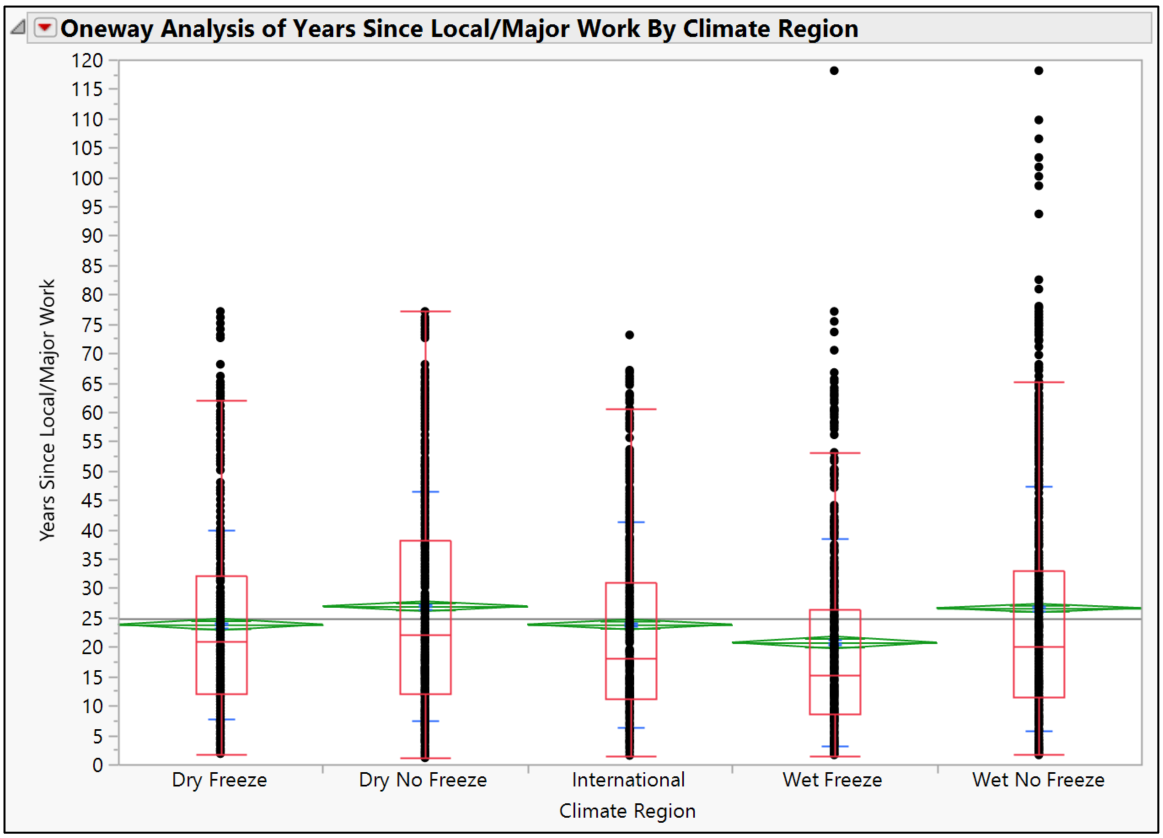


Figure 4.7 Comparison of Years Since Last Major Work and Climate Region

As the graph in Figure 4.8 demonstrates, it is important to remember that the correlation between PCI and the time since the last local or major work is not what one might expect, in so much, as there is not a correlation when applied to actual data. A typical observer might expect that anytime a pavement section is repaired that the PCI should reset itself to near 100 percent, in the sense that the correlation between these two variables follows a decay function. The reality that is often not communicated well by engineers is that repairs are often difficult for a variety of reasons. For example, to fully repair the root cause of a problematic pavement section on an airfield might require a full-depth repair; however, due to issues with funding, misidentifying the root cause, or shutting down the section for the repair, a decision is made to overlay the section instead. While an overlay in this situation is likely to appease decision-makers and slow the deterioration, it ultimately will not address the root cause. The simplified repair increases the PCI in the short-term, but the pavement likely reverts to the previous condition over time.

Getting back to the previous discussion about the disparity between pavements in freeze and non-freeze regions, Table 4.1 summarizes the results of the comparison between probable distress cause (see Table 4.2) and climatic region using mean values of the PCI deduct values for the recorded distresses. From Table 4.1, climate and durability related distresses have a more significant influence on the overall PCI values when compared to the other distresses causes. Within the climate and durability distresses, the deduct values are highest in the dry freeze region. The wet freeze and wet no-freeze regions were statistically close; the wet-freeze region has seen the most recent major construction or repair efforts on average of all climatic regions. As such, the wet-freeze region was likely worse than the no-freeze region within the last few years. Similarly, the dry freeze region has seen more recent local and major work, which stands to reason that the pavement distresses should begin to improve over time.

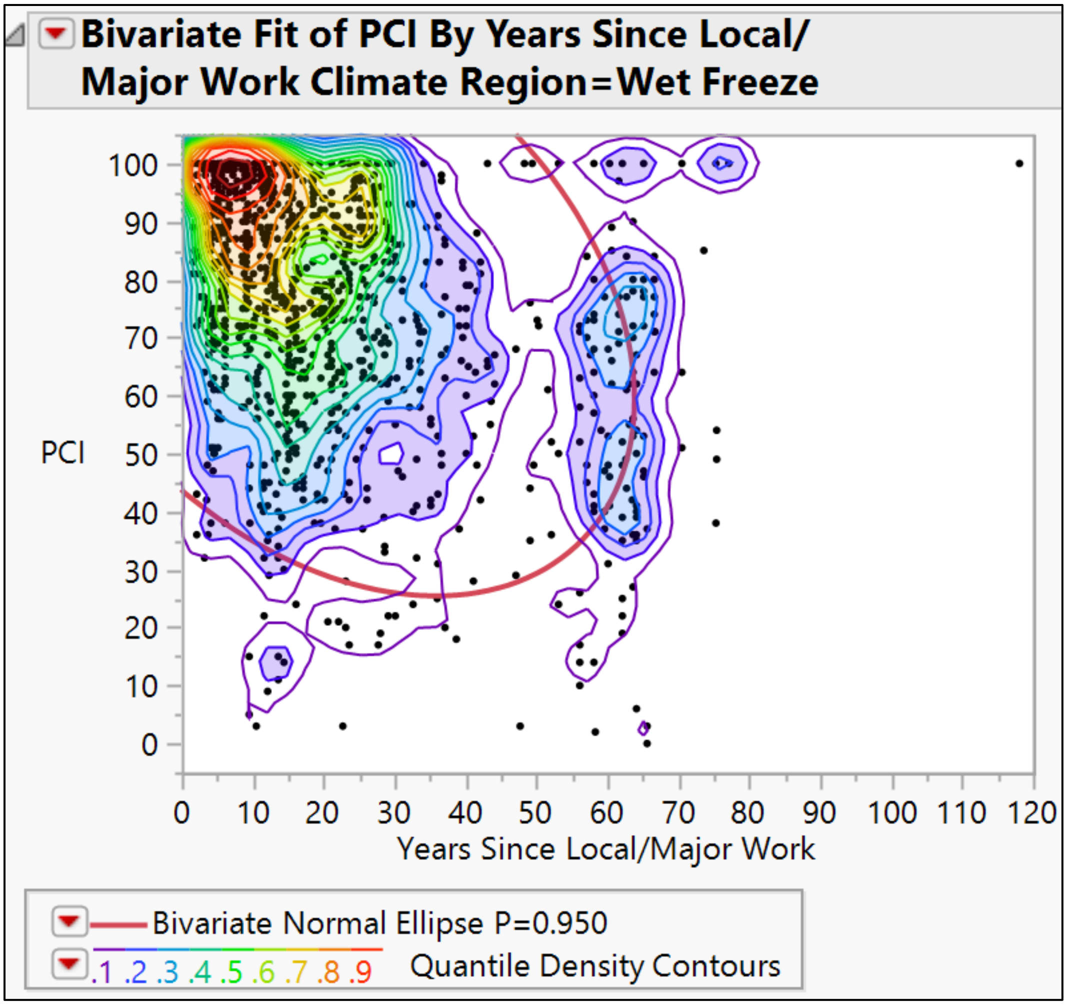


Figure 4.8 Comparison of Pavement Condition Index and the Number of Years Since the Last Local or Major Work for the "Wet Freeze" Climate Region

Table 4.1 Comparison of Weighted Mean Pavement Condition Index Values by Climatic Region and Probable Distress Cause

Probable Distress Cause	**Climatic Region**				**Distress Mean**
	Dry Freeze	**Wet Freeze**	**Dry No Freeze**	**Wet No Freeze**	
Climate/Durability	9.62	8.50	7.85	8.84	8.34
Load	7.53	5.34	6.30	6.21	6.33
Other	2.35	2.67	2.31	1.92	2.18
Regional Mean	5.39	4.76	4.17	4.35	4.48

Table 4.3 summarizes the probable distress causes (as defined by the DoD) and climatic regions as a percentage of the total pavement inventory. Since climate and durability distresses are present on approximately 45 percent of the USAF's pavements, it is clear that these distresses are a widespread issue. The widespread nature of the distresses could potentially be the reason for the elevated deduct values (shown in Table 4.1); however, this explanation fails to identify the root cause of the problem.

Of the over 730 million square feet of airfield pavements with climate and durability related distresses, the four most prevalent distresses are joint seal damage, weathering, block cracking, and raveling (see Figure 4.9). With regard to raveling, weathering, and block cracking, the USAF recommends that no maintenance treatment be used to correct these two distresses until the distresses become high severity. Additionally, the USAF recommends ignoring joint seal damage until the distress reaches medium severity (AFCEC 2014b). These same comments can apply to most climate and durability distresses since 69 percent of these distresses require no action according to the USAF's current maintenance recommendations. As a result, it is likely that most climate and durability related issues are continuing to deteriorate until it reaches a higher severity condition (at which point, the USAF maintenance strategy recommends action), furthering increasing its deduct value while not necessarily increasing the density of the distress. Economic considerations likely drive this policy decision to defer preventative maintenance in this scenario; however, further analysis is needed to confirm. Furthermore, it is important to consider whether any cost-effective options exist to extend the preventative maintenance timelines.

Table 4.2 Probable Distress Causes by Distress Type (Created with information from Shahin and Welborn 2014)

Probable Distress Types as Defined by the DoD				
Distress Code	Distress Type	Climate/Durability	Load	Other
41	ALLIGATOR CRACKING		X	
42	BLEEDING			X
43	BLOCK CRACKING	X		
44	CORRUGATION			X
45	DEPRESSION			X
46	JET BLAST			X
47	JOINT REFLECTION CRACKING	X		
48	LONGITUDINAL/TRANSVERSE CRACKING	X		
49	OIL SPILLAGE			X
50	PATCHING	X		
51	POLISHED AGGREGATE			X
52	RAVELING	X		
53	RUTTING		X	
54	SHOVING			X
55	SLIPPAGE CRACKING			X
56	SWELLING			X
57	WEATHERING	X		
61	BLOW-UP	X		
62	CORNER BREAK		X	
63	LINEAR CRACKING		X	
64	DURABILITY CRACKING	X		
65	JOINT SEAL DAMAGE	X		
66	SMALL PATCH			X
67	LARGE PATCH/UTILITY			X
68	POPOUTS			X
69	PUMPING			X
70	SCALING			X
71	FAULTING			X
72	SHATTERED SLAB		X	
73	SHRINKAGE CRACKING			X
74	JOINT SPALLING			X
75	CORNER SPALLING			X
76	ASR			X

Table 4.3 Total Distressed Pavement as a Percentage of the USAF's Total Pavement Inventory

Probable Distress Cause	**Climatic Region**				**Total**
	Dry Freeze	**Wet Freeze**	**Dry No Freeze**	**Wet No Freeze**	
Climate/Durability	10%	7%	12%	16%	45%
Load	1%	1%	1%	2%	5%
Other	3%	3%	5%	5%	16%
Total	14%	11%	19%	23%	66%

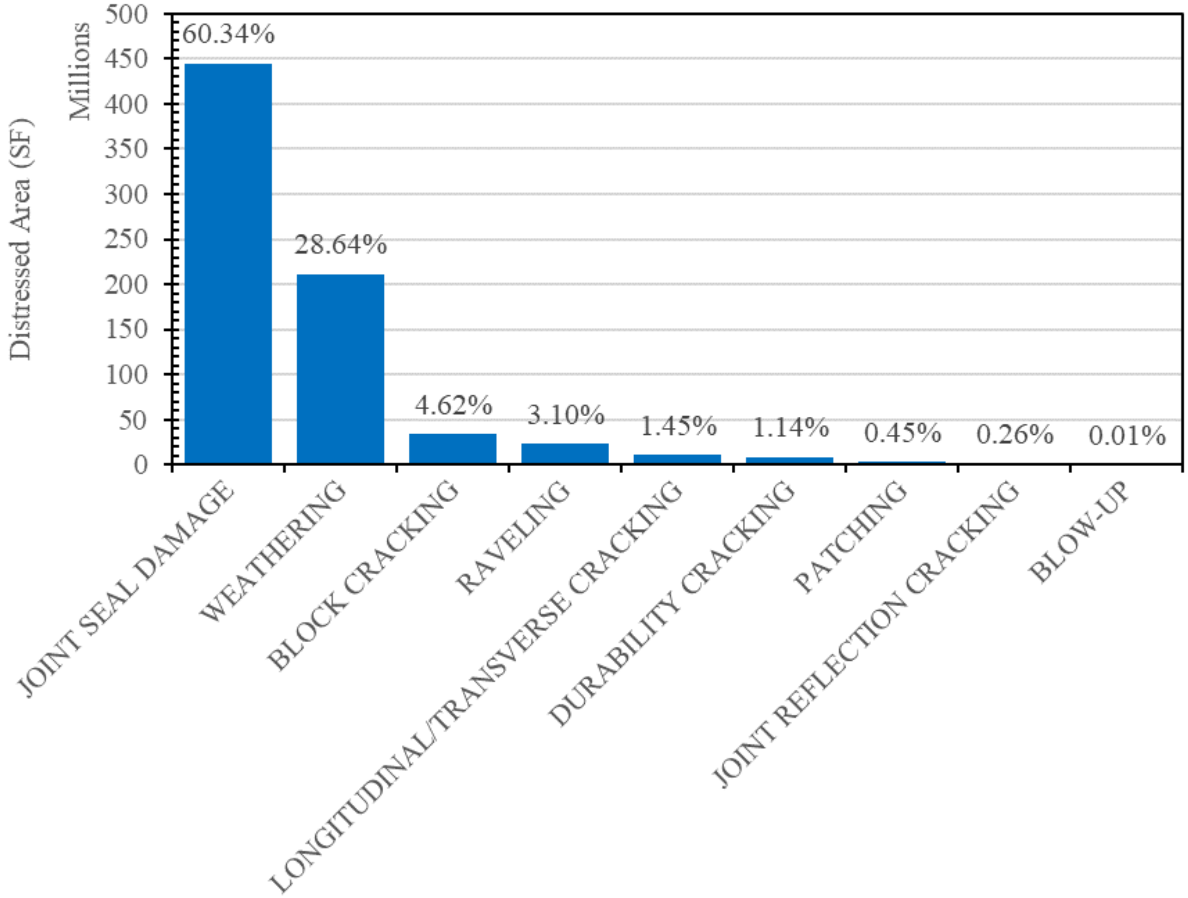


Figure 4.9 Total Surface Area of Climate and Durability Related Distresses

4.3.2 Mission Impact

Switching gears slightly from the climatic discussions, Figure 4.10 compares the weighted PCI values for each USAF MAJCOM. The MAJCOMs group USAF mission sets based upon their common contribution to a USAF core capability. For example, Air Mobility Command (AMC) is responsible for the logistics component of the USAF mission. As such, the majority of aerial refuelers, mobility aircraft, and personnel transport aircraft are assigned to AMC airfields. Exceptions to generalization would be those aircraft assigned to geographic commands (i.e., U.S.

Air Forces in Europe or Pacific Air Forces), the reserve components (i.e., the Air National Guard or the Air Force Reserve Command) or special missions (e.g., Air Force One).

Looking at weighted PCI values based on MAJCOMs sheds light on several variables that affect pavement performance. For example, Air Education and Training Command (AETC) primarily flies lighter aircraft that are used to train new pilots and aircrew. That said, while AETC flies small aircraft, the volume of traffic is much higher than at other MAJCOMs due to the number of flight hours required to train student pilots. Furthermore, all of the AETC airfields are in non-freeze climate regions. Lastly, up until the fiscal year 2016, all MAJCOMs budgeted for and established their policies for maintaining, recapitalizing, and constructing their pavements (to include all budgetary and investment decisions). At the start of the fiscal year 2016, all responsibilities for these decisions and actions were centralized at the Air Force Installation and Mission Support Center (AFIMSC).

From analyzing the one-way plot shown in Figure 4.10, the USAF's airfields that are in the best condition are located in AETC, Air Forces Central (AFCENT), U.S. Air Forces in Europe (USAFE), and Air Force Special Operations Command (AFSOC). Conversely, the worst airfields are in Air Force Global Strike Command (AFGSC) and the Air National Guard (ANG). As a general note, while AFCENT is technically under Air Combat Command (ACC), due to the overseas contingency operations (OCO) funding and its direct relationship with U.S. Central Command (USCENTCOM), it is often thought of and viewed by many in the USAF as an unofficial MAJCOM. For general awareness, both AFCENT airfields (only two were in the database) are in the Middle East in areas that are best described as dry with no freeze cycles.

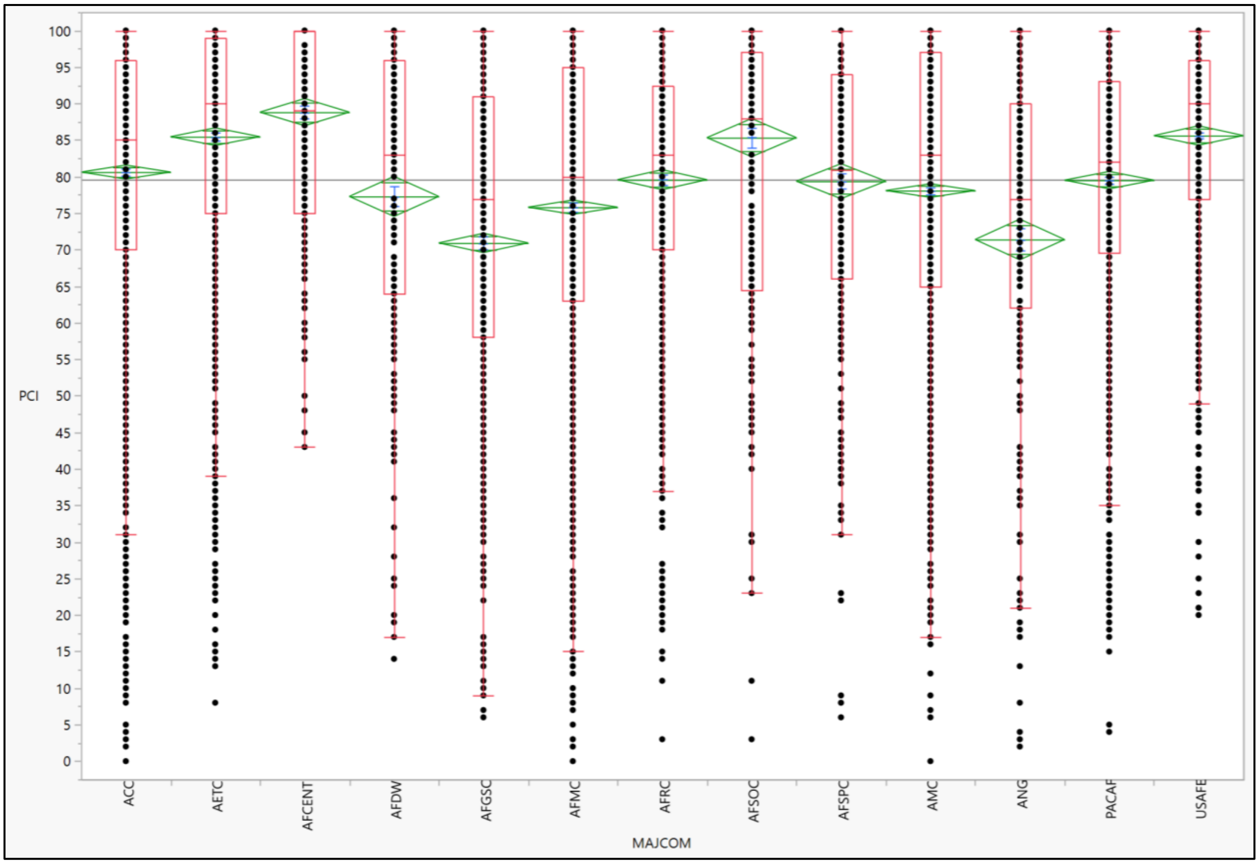


Figure 4.10 Comparison of Weighted Pavement Condition Index by USAF Major Command

AFGSC is responsible for the global strike mission set, which includes intercontinental ballistic missiles (ICBMs) and strategic bombers. While the strategic bombers are easy to understand the correlation to the airfield, the ICBM portion of the mission is not quite as intuitive. This portion of the AFGSC mission primarily relies upon helicopters and occasional mobility aircraft to support the movement of personnel and equipment. That said, the strategic bombing mission would be considered the critical traffic at AFGSC installations; however, this traffic is only present at five airfields across the MAJCOM. Additionally, AFGSC has six of its eight airfields located in climate regions that experience freezing temperatures annually.

Continuing with the AFGSC discussion, after a series of significant events within the last decade, the DoD launched a concerted effort to revitalize and prioritize its nuclear enterprise (AFGSC oversees the USAF's nuclear enterprise). As document by Alston (2008), the end of the Cold War and the shift to the Global War on Terrorism resulted in the nuclear enterprise falling victim to significant manpower and resource cuts as priorities shifted elsewhere. The result of this shift in priority resulted in fragmented decision making within the nuclear enterprise and severely limited investment in facilities. Prompted by a series of events and mishaps, the DoD began prioritizing the nuclear enterprise and focusing resources towards bolstering and improving nuclear-related infrastructure. Most of the funding has occurred within the last decade, and improvements are slowly beginning to occur, as evidenced by a recent project at Minot Air Force Base (AFB). The Minot AFB runway was considered the worst runway on an active-duty installation in 2009, and in 2014, the base completed a three-year, full-depth repair of the entire runway at the cost of $56.7 million (Bradfield and Hernandez 2014). While the recent investment in AFGSC infrastructure is greatly needed, the lack of investment and prioritization in the two decades prior is likely a major cause for the pavement conditions shown in Figure 4.10.

4.3.3 Distress Types

The two most prevalent airfield pavement distresses in the USAF current are weathering (see Figure 4.11) and joint seal damage (see Figure 4.12). Both of these distresses are classified as climate and durability related distresses (Shahin and Welborn 2014). The prevalence of both distresses reinforces the observations made in the previous section about the potential issue the USAF (and potentially the DoD) has with climate-related distresses. While it is easy to describe something with significant prevalence as an issue or a problem, it is perhaps a bit of a rush to judgment unless the effect is fully quantified or understood. The rationale for this caution is that for a climate and durability related distress, it is unlikely that the distress could be entirely avoided with better design or materials at competitive economic conditions. However, better materials or design methodologies could perhaps prolong the time between preventative maintenance actions. That said, better materials or more involved design methods likely cost more money and consume more initial resources, so the problem becomes more of an economic-based decision. The economics behind the decision need to determine if it is more economical to keep the status quo or adopt a potentially more expensive upfront solution to save money over the lifecycle.

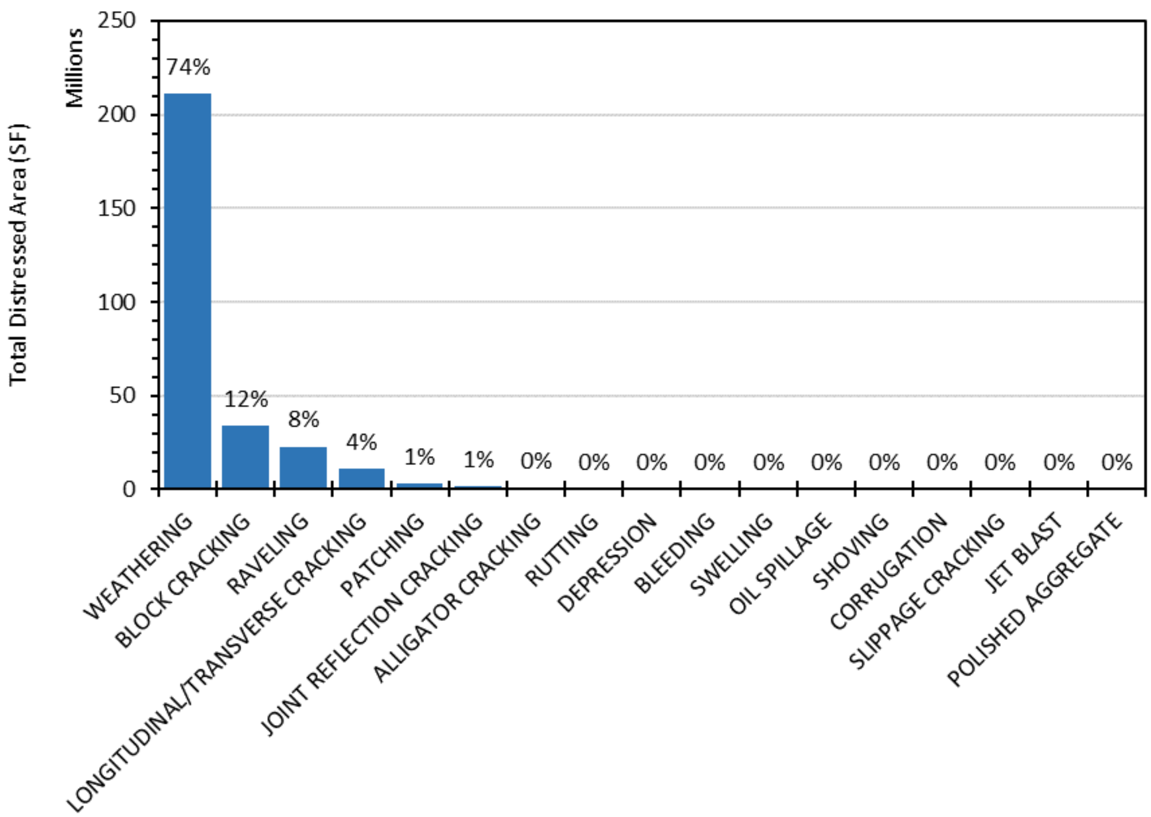


Figure 4.11 Total Distressed Area by Distress Type of Asphalt Pavements in the USAF Inventory

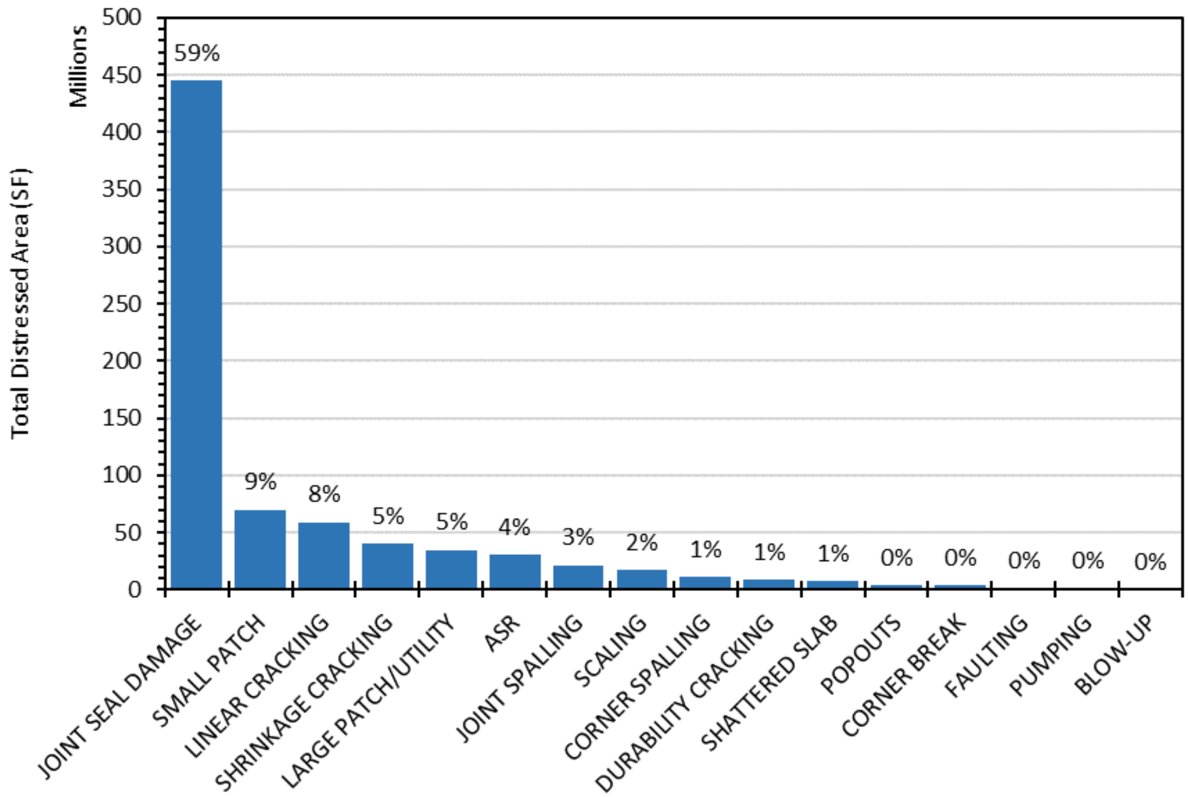


Figure 4.12 Total Distressed Area by Distress Type of Concrete Pavements in the USAF Inventory

As previously mentioned, it is unlikely that climate and durability related distresses can be entirely avoided with better materials or modeling. As such, any potential change would have to consider impacts on preventative maintenance intervals. For example, if a new performance model were instituted that required additional resources or materials upfront, the analysis would need to know the impact this change would have on preventative maintenance intervals. It is assumed that this change would lengthen the interval relative to the status quo; if it did not, it would not make economic sense to change. However, if the change was able to extend the interval by one year over the design life, the change could be economically viable. The DoD uses a 20-year design life, so a shift from a five-year to a six-year interval would potentially eliminate a preventative maintenance action in year 20. The elimination of this maintenance action in year 20, when converted to present value, could potentially justify increasing expenditures upfront. This economic analysis specifically assumes that preventative maintenance occurs at the prescribed intervals (e.g., replacing joint seals at the manufacturer-recommended intervals); however, the reality is that preventative maintenance rarely occurs at the prescribed intervals, particularly in the USAF. As such, a holistic analysis would also need to address the outcomes associated with deferring preventative maintenance (i.e., the maintenance, in theory, is every five years; however, the actual interval is closer to seven years).

Continuing with this stream of thought, damaged joint seals are replaced to prevent further damage to the pavement due to the propagation of spalls, cracking, corner breaks, faulting, pumping, and blow-ups. While it is relatively easy to understand the potential cause-effect links from a theoretical standpoint, it is less understood how probable a damaged joint seal is likely to eventually cause a joint spall. While a joint spall is caused by incompressible material infiltrating a pavement joint, the joint should not experience spalling if the joint seal is in good condition and preventing incompressible material from entering the joint. As such, a joint would not be anticipated to spall if joint seal damage is not present in a pavement section; however, the presence of joint seal damage would not definitively lead to joint spalling. That said, a damaged joint seal in the presence of high foreign object debris (FOD) settings, is likely to lead to a joint spalling at a relatively significant probability. This causal-effect relationship can be applied to several other distresses, each with its own probability associated with the relationship that is mitigated or exacerbated by contributing factors. For example, a damaged joint seal in a low FOD setting (e.g., low dust and regularly swept settings), is less likely to lead to joint spalling, as the incompressible material ingredient in this relationship would potentially be missing.

The probabilities associated with all of the potential outcomes could then be combined into a Bayesian formulation to understand the opportunity cost of holistically doing nothing. This formulation would need to be time and condition-dependent, as these two variables would cause the outcome probabilities to vary. For example, a joint seal that is lightly damaged early in its lifecycle will most likely experience continued seal deterioration and little else. However, over time, this damaged joint seal would become a higher severity distress that likely leads to other distresses as a result of joint infiltration.

This line of thought is important to consider in the discussion of airfield pavement distress types, as it is easy to see the symptom (i.e., the observable and measurable surface distress) and ignore the root cause. This concept is even more critical concerning USAF pavements since the predominant distresses are non-load related. As such, it is important to consider, the USAF's airfield pavements could likely be significantly improved simply by placing more emphasis on sealing pavements (e.g., joint seal or crack seal) to prevent or mitigate the onset of more severe distresses.

4.3.4 Maintenance, Inspection, and Repair Policies

As shown in Figure 4.13, the vast majority of USAF pavement sections plot on a one-to-one line comparing pavement age and time since last major or local repair work. According to the PAVER data obtained for this research effort, approximately 85 percent of USAF pavement sections have not received any major or local repair work since it was constructed. It is possible that some of these sections have received some work that was not documented in PAVER; however, the use of the same contracted support for the PCI studies and PAVER updates makes this possibility less likely. That said, approximately 58 percent of the USAF pavement sections have exceeded its 20-year design life. While design life in the DoD focuses on aircraft passes (i.e., structural-related concerns), the expectation, in reality, is that DoD pavements should last well beyond their 20-year design life. As evident by the limited number of structural related distresses currently present in the PAVER data, USAF pavements are likely overdesigned. A 20-year design traffic mix is still sufficient to support pavements beyond the design life (i.e., after 20 years, the USAF does not experience an increase in structural related distresses and failures).

As previously mentioned in Chapter III, sustainment funding for DoD facilities is estimated and programmed using the DoD's FSM. The FSM is based upon historical costs for facilities of a given category code (i.e., similar facilities that support a similar function) regardless of facility condition. Additionally, the FSM also accounts for civilian personnel costs; military personnel costs are funded through a different appropriation and method. Across the DoD, the services are not funded at their estimated FSM total; instead, each service is funded at 80 percent or less (OUSD(C) 2018b). With a deficit in sustainment funding, each service must prioritize its funding to meet its most pressing infrastructure needs. In the USAF, facility sustainment funding is divided between centralized and decentralized portfolios. While major pavement repair projects compete in the centralized portfolio for funding, preventative maintenance projects and actions are part of the decentralized program. As a result, each installation's leadership team dictates how much funding and resources go towards executing an airfield pavement preventative maintenance program.

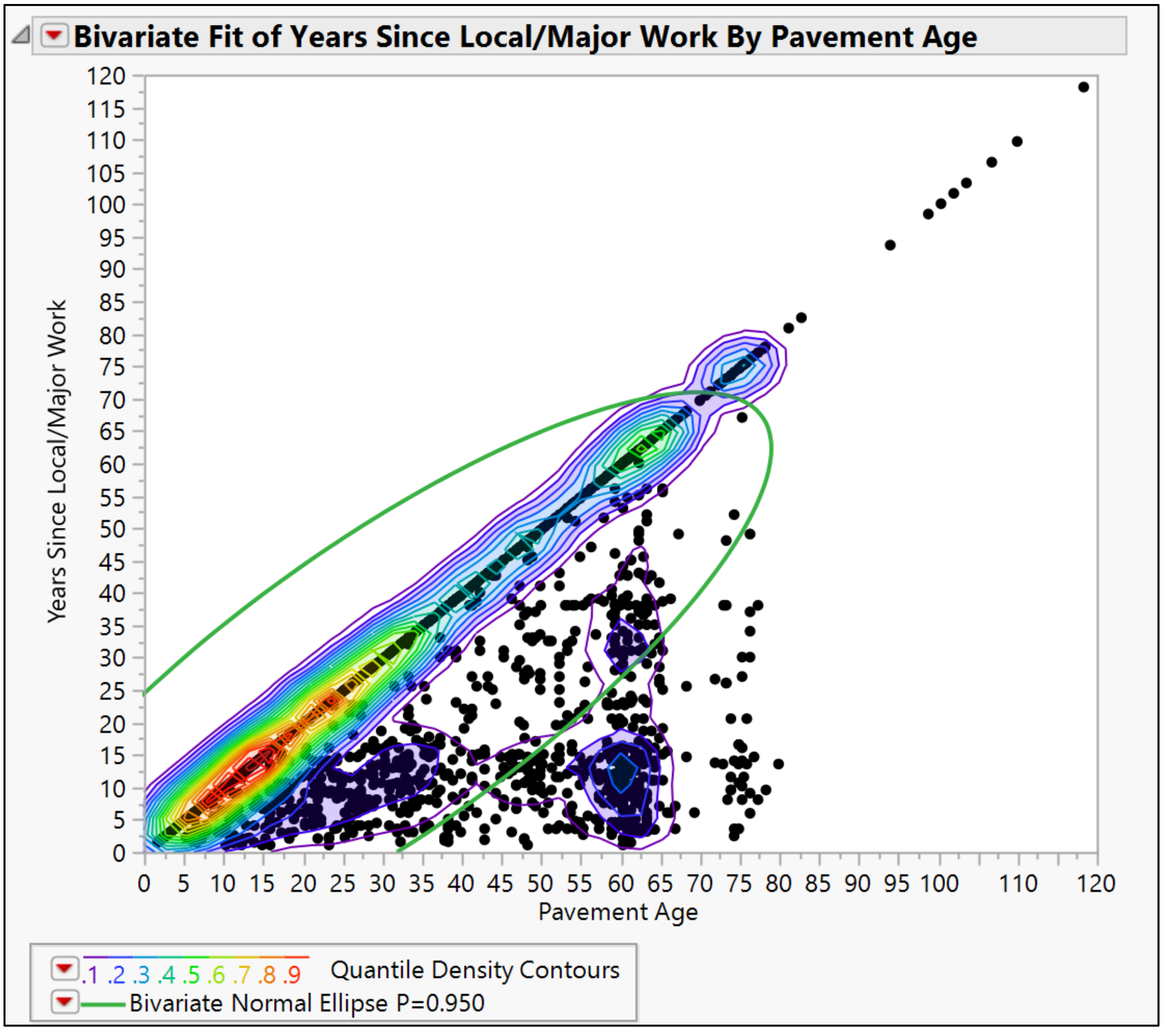


Figure 4.13 Comparison of Pavement Age and Time Since Last Local or Major Repair

While this may seem relatively straightforward, the airfield pavement preventative maintenance funding is competing for the same resources being used to maintain the installation's entire portfolio of infrastructure and facilities. With only a portion of the funding that is required, tradeoffs have to be made at the local level to determine which requirements will receive funding. In most cases, decentralized funding goes toward requirements that have a high degree of short-term impact. The rationale for this comment is that the DoD will typically only leave a Commander in place for two years, which means that he or she only has limited time to demonstrate their abilities and impacts to their higher-level Commander. Based on the duration of their command tour, a Commander is judged heavily by short-term impacts, not as much on long-term outcomes. As such, the impacts of deferring maintenance are unlikely to come to fruition during that particular commander's tenure.

Unfortunately, this construct typically relegates many preventative maintenance actions (pavements included) to a lower priority. Installations with newer facilities or with higher overall facility conditions are likely able to afford to do more preventative maintenance on the airfield (and the installation as a whole) as less of the installation's funding is tied to executing corrective maintenance actions. Conversely, installations with older infrastructure or worse facility conditions would likely be unable to afford airfield pavement preventative maintenance (or in most other facilities), as a larger percentage of its funding is likely committed to corrective maintenance.

As recently as 2009, Minot AFB was considered the worst active-duty airfield in the USAF. A complete reconstruction of its failing runway in 2014 at the cost of $56.7 million helped eliminate this unenviable distinction (Bradfield and Hernandez 2014). That said, based on the USAF's PAVER data, Minot AFB is still among the worst airfields in the inventory based upon weighted PCI. PAVER is the pavement management system used by the DoD that combines historical and current pavement condition survey data to provide sustainment recommendations and predictive modeling for pavement degradation. PCI is a numerical metric used to quantify the distresses present in a given pavement section using a standardized approach as defined in ASTM D5340 for surveying the distresses and calculating an overall numerical condition index from 0 to 100 where 100 is most desirable.

Based on estimates derived from PAVER, the USAF needs to invest approximately $115 million over a ten-year period to elevate Minot AFB's airfield weighted PCI from among the worst to slightly above average. Included in this $115 million estimate is approximately $1.1 million in annual local maintenance that would be up to the leadership of Minot AFB to fund out of its decentralized portfolio. Based upon the author's personal knowledge, while Minot AFB would receive enough decentralized funding annually to cover the $1.1 million estimate, it is highly unlikely that this full amount would be spent on airfield maintenance. The installation's decentralized funding would also be needed to fund preventative and corrective maintenance on all roads, utilities, and facilities on the installation in addition to any work required on the airfield. As such, preventative maintenance of airfield pavements is likely to take a lower priority relative to funding a new heating, ventilation, and air conditioning (HVAC) unit on a squadron operations facility or repairing aging utility infrastructure. Funding these latter examples are primary examples that installation leadership teams make to keep the quality of life and operations going in an environment of constrained resources and aging infrastructure. In this operating environment, it is difficult to justify spending funds on requirements that do not have a direct and immediate impact without a strong business case or service-wide policy.

While increasing funding would certainly help, it is difficult to quantify the amount of funding each installation would need to address all of the already deferred maintenance items that would be prioritized locally ahead of pavement maintenance. Estimates from the AFIMSC (2018) indicate that the total deferred maintenance backlog (inclusive of all real property facilities and infrastructure) in the USAF is currently more than $33 billion. Barring any significant changes to funding levels or policies, by 2030, this maintenance backlog is forecasted to be over $70 billion.

Offutt AFB is another airfield that is among the worst in the USAF. The installation is about to start a full-depth repair of its runway in the next years as a result of deferred maintenance and insufficient repairs. The repair project contract was recently awarded at a value of $143.9

million, and the project is anticipated to last two years (AFIMSC 2020). During this time, all of the aircraft will be temporarily relocated to another airfield in Lincoln, NE to keep the operational and training missions going. While reconstructing the runway ensures the mission at Offutt AFB for several decades, the project itself consumes upwards of ten percent of the total funding in the USAF's centralized portfolio (AFIMSC 2019). The sizeable portion of the portfolio's resources that this project consumes would result in potentially dozens of projects not getting funded, further adding to the USAF's $33-billion maintenance backlog.

Sections of the Offutt AFB runway were reconstructed in 2006; however, it was a "band-aid" on a larger problem, as only select failing sections of the runway were reconstructed. The result is a runway that is comprised of 24 distinct asphalt and concrete sections ranging in age from 14 to 69 years that, when taken as a whole, is in desperate need of a full-depth repair (see Figure 4.14) (Wade et al. 2015). The reason for selecting the "band-aid" fix in 2006 was due to funding and limiting the closure of the runway to maintain operations (Liewer 2017). Since Offutt AFB only has one runway, a runway closure is also an airfield closure. Closing the airfield requires temporarily relocating all assigned aircraft, support equipment, and operations and maintenance personnel to another airfield at considerable costs.

Given the number of resources estimated to repair the failing Offutt AFB runway, the textbook asset management solution in this scenario would be to invest the $143.9 million cost into other maintenance and rehabilitation projects that keep "good" pavements "good." However, the USAF (and the DoD in general) is operationally and structurally aligned as a service not to support this type of asset management approach. This observation, coupled with statutory roadblocks and self-inflicted process decisions, lends itself to the USAF continuing to fund the Offutt AFB runway repair and countless similar projects.

Figure 4.14 Photos of Offutt AFB’s Taxiway and Runway Intersection (left) and Runway Repairs (right)

While the USAF’s permanent bases in the U.S. present their own unique set of challenges and priorities, in contingency locations, local leadership’s primary focus is mission execution. As a result, the need to keep the mission going often forces leadership to make tough choices and develop creative solutions to challenges, to include infrastructure-related issues. As an example, at an overseas location, there is an airfield that is inadequate to support the mission aircraft. Pavements across the airfield are deteriorating at an alarming rate, and the primary reason appears to stem from a change in the primary mission aircraft to a much heavier aircraft. Over the course of approximately three years, significant structural failures on taxiways and the primary runway have appeared. Rutting of more than three inches has been observed in certain sections. Even with these failures well documented, this airfield (and its failed pavements) is still heavily used to support flying operations. This need to support operations has driven local leadership to make unique decisions to keep the airfield operational. Rather than shutting down a failed taxiway section due to excessive rutting, local leadership elected to offset a taxiway centerline to continue to use the taxiway while keeping aircraft away from the existing rutting (see Figure 4.15). Inevitably, the new traffic pattern on this taxiway is likely to cause the same rutting as the original centerline. That said, local leadership will continue to execute expedient repairs and make decisions based on the immediate need to keep the mission going.

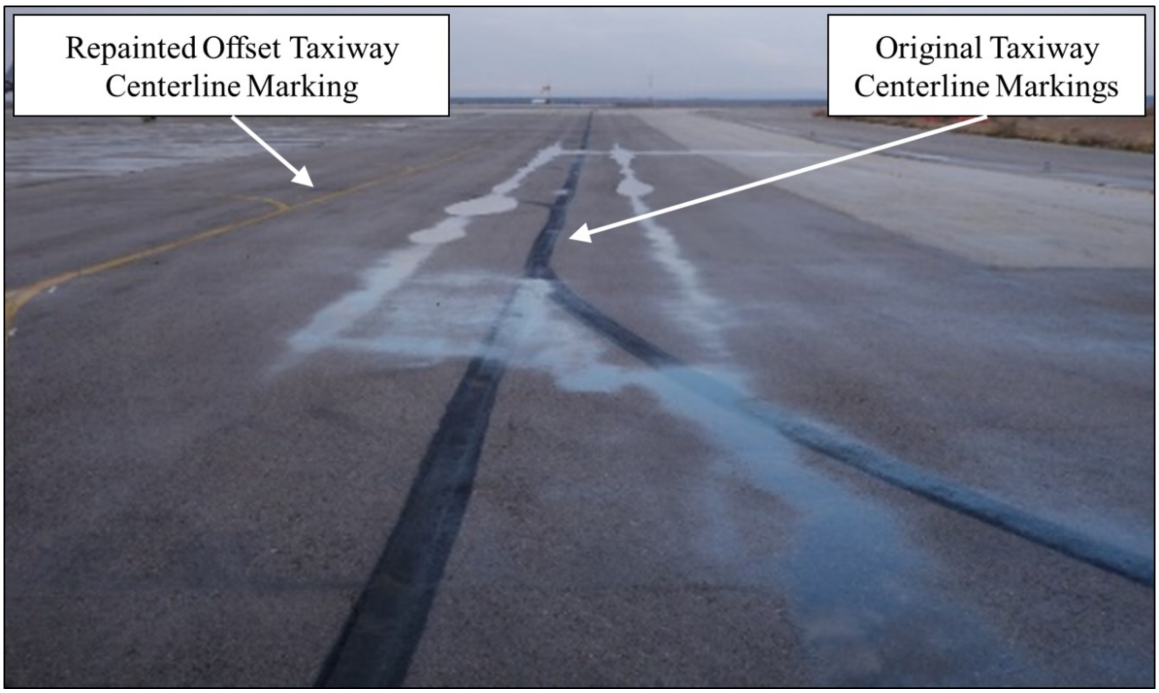


Figure 4.15 Offset Taxiway Centerline at an Overseas Location

This scenario is not necessarily unique, as it speaks to some underlying differences between the DoD and other transportation or highway authorities. First, it is important to recognize that the USAF views its airfields as part of an overarching "base system" that functions as a power or force projection platform for its weapons systems (JCS 2016; LeMay Center for Doctrine 2017). The base system includes all of the people, infrastructure, equipment, and information necessary to support the weapon systems with the realization that flying operations cannot happen without the full integration and capabilities of all components of the base system. As such, in a contingency environment, closing a runway for repair can be effectively synonymous with taking a major weapons system out of the fight, which is why the USAF goes to great lengths to avoid closures or relocate aircraft during closures.

Secondly, much like an aircraft carrier, aircraft are assigned to a given DoD airfield. While it may seem a relatively straightforward process to relocate aircraft on a permanent basis to a more suitable and capable airfield, this is not the case. In actuality, relocating military aircraft to another DoD airfield requires an extensive amount of Congressional, environmental, financial, and legal processes that typically proves, for all intents and purposes, an insurmountable barrier to accomplish quickly (or at all). This fact coupled with the standard configuration of a typical USAF airfield (i.e., one primary runway, parallel taxiway, and one or two primary parking aprons) helps solidify the observation that the USAF is hindered in fully implementing an asset management approach, including pavement maintenance programs that would closely resemble what might be observed in a Department of Transportation (DOT), due to a lack of tolerable or reasonable alternatives.

Analysis of the USAF's PAVER data demonstrates a statistically significant difference in the mean weighted PCI values of airfields with more than one runway (i.e., reasonable alternatives) when compared to single runway airfields; the weighted mean PCI value for airfields with more than runway is approximately four points higher than single-runway airfields. As such, the data tends to support that airfields with multiple runways (and subsequently multiple primary taxiways) are in better condition, which could be a result of a higher willingness by local leadership to close pavement sections for maintenance as the result of a closure having a lower impact on flying operations.

4.4 Challenges Implementing New Technologies and Methodologies

As previously mentioned, the U.S. military has over a quarter-million personnel deployed around the world. Supporting these personnel requires all facets of airpower and a global network of airfields. In a perfect world, all of these airfields would be in pristine condition and built to typical U.S. standards using conventional construction materials and methods. However, in the practical world in which these operations take place, the airfields used by the U.S. military plot along the full spectrum of materials, methods, conditions, environments, and geometries. These scenarios add to the challenges the DoD has to balance when considering changes to its processes and methods and should be considered when reading the remainder of this section.

Within the highway pavement industry, engineering decisions are typically made by a group of experienced pavement engineers. For state highway or U.S. interstate projects, these decisions would likely be made by Government engineers at varying levels of experience and expertise in a hierarchical fashion depending on the complexity and scope of the problem. Primary decisions would typically be made by engineers with over 5 years of experience. Conversely, when it comes to pavements related matters within DoD, this robust network is not necessarily present.

When it comes to pavements engineering expertise within the DoD's military and civilian engineer ranks, the DoD generally focuses more on developing a breadth of experience and knowledge rather than depth. At the local and tactical levels, the DoD does not have enough personnel to maintain a sufficient level of engineering subject matter expertise at each operating location for all disciplines of engineering. As a result, the DoD makes a conscious push to develop its engineers at the local and tactical levels as more generalist engineers that have a sufficient understanding of several engineering disciplines but are not necessarily subject matter experts in any one area. The rationale for doing this is because the engineers at this level typically function as Project Managers or Contracting Officer's Representatives, where they typically function in the capacity as the Government's representative on contracted infrastructure projects. As a general note, at the higher levels of leadership and management, the DoD maintains a few subject matter experts across almost every infrastructure and force protection-related engineering disciplines. Also, note that DoD engineers are very skilled (statements mentioned above should in no way be interpreted otherwise), they are just required to perform many types of work. Subject matter experts are typically available for reachback support by phone or email but do not usually travel to observe and evaluate most problems that they encounter.

On the military side, the push to develop more generalist engineers is also systematic of the DoD's personnel development model, which focuses on growing new officers into the service's corps of senior leaders. As part of this model, the military progresses its engineering officers through various tactical-level engineering roles before moving the officers on to progressively higher levels of management and leadership and away from direct engineering roles. Although the timing of this shift varies by military service, it is typical for the majority of a 20-year military career for an engineering officer to be served in primarily managerial and non-technical roles. Furthermore, due to the nature of the engineering missions of the U.S. Army and the U.S. Marine Corps, their engineers are considered combat engineers who focus on core capabilities such as route clearance and denial. As a result of this focus, the engineering officers of these two services are not required to be degreed engineers. The reason for highlighting the general development of engineering officers is that they are typically the only decision-maker for engineering related issues in most contingency environments. Figure 4.16 shows two examples of recent decisions made in contingency environments by DoD engineers, neither of which are allowed by the DoD's specifications. Furthermore, military engineers are not the only people making engineering determinations within the DoD.

Figure 4.16 (Left) Site-made/improvised "Speed Dowels," which are not authorized in the DoD; and (Right) rope material used as a joint seal on a new parking apron

As previously discussed, a young USAF Combat Controller led a three-person team in the middle of the night to conduct an airfield evaluation. With approximately three hours on the ground and under cover of darkness, the three-person team conducted an expeditionary airfield pavement evaluation of the airfield to determine if cargo aircraft could land at the airfield on a short-term basis. Using headlamps and one dynamic cone penetrometer to conduct their evaluation, the team left that night, concluding that cargo aircraft could land at the airfield. The young Combat

Controller was only two months out from attending his only formal training on pavement evaluation, and he was the only individual on the team with any experience. Yet, they still came to the correct conclusion concerning their objective. This story is not uncommon, particularly in contingency environments.

A common theme amongst consultants who have looked at the DoD's pavement methods is that the methods are too simplistic (Crosstek Solutions LLC 2015). The characterization is likely very accurate; however, the simplicity is most likely the reason it works well for the DoD. That is not to say that there are no areas for improvement. However, the methods need to work in a wide variety of circumstances and incorporate personnel with a lack of specialized pavements expertise. For example, the Combat Controller mentioned previously is a highly trained warfighter and air controller; however, he is not an engineer or pavements expert. That said, in a two-week course, the DoD was able to teach him how to collect airfield data, interpret it, and quickly make engineering recommendations as to the capability of an airfield anywhere in the world under a variety of circumstances. The ability to rapidly teach a technical method to someone without a background in the subject is a powerful force multiplier in a sense, and it speaks to something that the DoD has (knowingly or unknowingly) done: it removed much risk from the local level.

This risk mitigation was accomplished through standardization at the DoD-level of design guidance and specifications that take conservative approaches to widen the applicability and lower the amount of risk associated with local-level decisions. This approach effectively limits local-level decisions to key inputs that can only be made at a local-level versus at the DoD-level (e.g., subgrade CBR). In contingency environments with a limited (and often inexperienced) contractor base, high expectations coupled with short timelines, and nonstandard materials, the need for simplicity is crucial. With the DoD's conscious development of its local-level engineers as generalists, adding more inputs and reducing assumptions, as would likely be required of more mechanistic and predictive methods, is problematic at a local-level and likely would increase the reliance on contractor support.

With full consideration of these operating conditions and constraints, the DoD has to balance maximizing performance outcomes with the operational needs of the military. As such, the DoD will typically be understandably slow at adopting new technologies and methods until it fully understands the full impacts of a change. Furthermore, it is likely to accept a more conservative solution if it means reducing risk. As an example of this comment, according to the USAF's PAVER data, approximately 58 percent of USAF pavements have exceeded its 20-year design life, and 85 percent of pavements have not received any significant repairs or rehabilitation during its lifetime. That said, only about five percent of USAF pavements by total surface area has load-related distress, with the vast majority of these distresses being low-severity in nature and occurring in conjunction with other non-load related distresses.

The key takeaway from this section is that while there is no shortage of new research that could potentially improve a particular facet of pavements engineering a good percentage of these concepts and methods may not reach implementation because of a variety of factors that are inherent to the operational scheme of a particular transportation entity. These factors are often well known to a practitioner; however, these same factors may be overlooked or unknown by research entities. <u>As such, the topics discussed in this dissertation seek to holistically review, from a practitioner's perspective, the DoD's pavement program and its ability to implement new pavement design concepts and technologies.</u>

4.5 Needs Assessment Summary

In general, the DoD designs against structural failures (although typically not all of the structural failure modes) and relies upon design guidance and specifications to control other failure modes. Based on a review of the PAVER data, it certainly appears that the current manner in which the DoD designs pavements is accomplishing its goal of preventing structural failures, as very few load-related distresses were observed. The vast majority of the load-related distresses were on concrete pavements, of which linear cracking was the overwhelming distress. That said, the DoD currently uses a 20-year design life for its pavements; however, 58 percent of the USAF pavements have exceeded its 20-year design life with few experiencing load-related distresses. Since the 20-year design life is based on an estimated number of aircraft passes, it likely that the estimated aircraft traffic is contributing to this disparity (i.e., the traffic mix is likely overestimated). Furthermore, the aircraft design group is assessed typically in terms of equivalent passes of the controlling aircraft, which by default, assumes that the trafficking of the various aircraft in the design group occurs over the same points; this is not a valid assumption in reality in most cases. This issue is further compounded by the use of standard design groups to perform structural design (as directed by UFC 3-260-02) even if none of the aircraft in the design group would ever use the airfield at the prescribed pass levels or at all.

Additionally, on the topic of limited occurrences of load-related distresses, construction practices and material specifications are likely adding to the over design. For example, with asphalt pavements, the DoD has typically relied on the soaked CBR test to determine the CBR of the subgrade for design purposes (USACE 2001). The CBR value produced using this test represents the worst-case CBR value of the subgrade material typically and is highly conservative. Furthermore, due to the compaction requirements used by the DoD, the general contractor would recompact the subgrade or use select materials to meet the density requirements up to several feet below the surface. This compaction effort results in higher CBR values in the subgrade and select materials than determined using the laboratory soaked CBR test and subsequently used in the structural design. Above the subgrade, the contractor is likely to round up the design thicknesses to more constructible thicknesses or to provide a factor of safety to ensure that the minimum thickness requirement per the design is satisfied.

While this may seem counterintuitive, overdesigning pavements is not necessarily a bad practice. On the surface, an overdesigned pavement would appear to be an inefficient use of resources in a financially constrained environment. Conversely, an overdesigned pavement is likely to last longer (with proper maintenance throughout its lifespan), which can be viewed as a positive given the USAF's inventory of pavements that currently exceed its design life. Furthermore, overdesigned pavements can increase flexibility for the end-user. This flexibility could make the difference in whether the DoD can relocate aircraft from one installation to another for a variety of reasons. Lastly, overdesigned pavements build inherent factors of safety into the pavement design and construction process. This idea is very similar to practices utilized by other engineering fields (e.g., structural engineering). That said, the primary issue with referring to the conservative pavement design approach as an inherent factor of safety is that it would be exceedingly difficult to quantify. Furthermore, the DoD does not recognize these approaches as a factor of safety.

On the topic of non-load related distresses, the USAF's airfield pavements are experiencing a high prevalence of climate and durability related distresses. Research by Rushing et al. (2014) confirms that issue is not confined to the USAF but is also an issue for U.S. Army airfields. As such, this issue likely extends to the other DoD services as well. While the panel members from the previously discussed study believe that the answer to this problem is to incorporate sophisticated performance models that consider the environmental conditions and impacts, the benefits to the DoD are inherently theoretical at this point, as highway transportation authorities are still assessing the long-term implications of the MEPDG. Furthermore, the DoD would need to assess whether any potential benefits from components of the MEPDG could more simply be incorporated by updating their specifications and design guide.

In general, the DoD pavement design methods appear to be effective at achieving the desired results (i.e., preventing structural failure in the mode of interest). That said, the panel members from the previously mentioned study are also correct in asserting that the DoD methods can be improved. While the panel members had an ample number of solutions and recommendations, the DoD needs to be vigilant in their evaluation of the panel's recommendations to avoid not adopting overly complicated and complex procedures, thereby reducing the flexibility of its methods. Based on a review of the panel members' recommendations; the USAF PAVER data; and current policies and practices, the following questions are recommended for further investigation:

- If the USAF were to adopt a wholesale maintenance approach, what would it look like, and where would the "broken glass" be? Furthermore, could a change in strategy help slow or reverse the airfield pavement maintenance backlog?

- Given that non-load related distresses are the most prevalent distress affecting the DoD's airfield pavements, are there any concepts from the MEPDG that could potentially benefit this issue? If so, is there a more direct manner in which to potentially accomplish the same end state?

- Is it possible to quantify the range of what could be considered a factor of safety for the overdesign of USAF airfield pavements?

- What is the evolution of an initial-level pavement distress (e.g., joint seal damage) to more advanced-level distresses (e.g., joint spalls)? Can this evolutionary chain be mapped using a Bayesian-type formulation to provide an enhanced estimation of pavement deterioration over time?

- What could the DoD do to modify their design procedures or construction and material specifications to account for its most prevalent distresses, and at what cost?

- Is there a more reliable method to evaluate or design nonstandard pavement layer thicknesses or structures?

- Can the CBR-β method be modified to evaluate failure modes in layers above the subgrade reliably?

- Is there a more reliable method for the DoD to account for equivalent material thicknesses?

- How can the USAF utilize new technologies to improve the quality, reliability, and speed of airfield evaluations?

While this list is not intended to be all-encompassing, it does provide a sampling of potential areas of future focus for pavement research. Furthermore, each of these potential research questions would be impactful for the DoD; however, the development of a new pavement maintenance strategy seems to be by far the most impactful. As such, it was selected as the focus of this dissertation research after performing a comprehensive assessment that has been document thus far in the document.

The USAF, more so than other DoD services, relies on its installations as a warfighting platform. These warfighting platforms are used to project air power anywhere in the world. As a critical node to these warfighting platforms and the operational concept of airpower, airfield pavements are among the most vital infrastructure assets in the USAF's inventory. While airfield pavements have a direct tie to mission effectiveness, it would be fair to suggest that many USAF senior leaders do not overly concern themselves about condition and status. These perspectives are often based upon their experiences that pavements do not typically catastrophically fail, thereby creating the perception at a macro-level that the condition of airfield pavements is at least sufficient to support operations for the foreseeable future. This perception can be dangerous in the context of budgetary decisions, as senior leaders prioritize funding in a resource-constrained environment to requirements and problems that have (often short or near-term) meaningful impacts such as needs for aircraft (Synovec et al. 2019). As a result, senior leaders often take a risk in sustaining airfield pavements, and infrastructure in general, to mitigate perceived short-term risk in other areas. These higher priority short-term risks can include other infrastructure classes (e.g., facilities, utilities, structures, etc.), but often, these priorities involve investments outside of infrastructure (e.g., new aircraft acquisitions).

As a mitigation effort to address its infrastructure funding gap, the USAF over the last two decades has taken meaningful steps to implement a centralized, risk-based asset management approach to maintaining its infrastructure. This risk-based approach was intended to ensure that the USAF prioritized resources to maintain the infrastructure that has high probabilities and consequences of failure to ensure that no mission stoppage occurs as a result of infrastructure degradation. Life-cycle cost approaches have not been directly considered in the risk-based approach; therefore, the risk-based approach often prioritizes projects that require funding towards an asset's highest life-cycle point. Over time in a resource-constrained environment, the risk-based approach effectively became a "worst first" approach that helped exacerbate the USAF's backlog of deferred maintenance (Synovec et al. 2019). With an estimated backlog in deferred maintenance and recapitalization of over $33 billion in 2019, the USAF estimates that its backlog will triple over the next thirty years if the status quo (i.e., funding levels, business processes, inventory, etc.) is maintained (Wilson and Goldfein 2019).

With this background in mind, this dissertation research focuses on developing methodologies, strategies, and algorithms to provide the USAF an alternative option to the status quo. This option is one that prioritizes the lowest lifecycle cost investment, which, if developed in an implementable fashion, could help the USAF reverse course. If the status quo is allowed to continue, it is likely that the USAF would face severe operational challenges, as it balances operational missions with failing infrastructure. While there are a lot of theoretical challenges facing the DoD's pavement program, maintaining its global network of airfield pavements in a fiscally constrained environment is most certainly its largest and most impactful problem.

CHAPTER V

LITERATURE REVIEW OF THE STATE OF PRACTICE OF PAVEMENT MANAGEMENT SYSTEMS AND STRATEGIES

This chapter contains portions of two technical papers submitted to two peer-reviewed journals. The first paper (Synovec and Howard Forthcoming) and the second paper (Synovec et al. Forthcoming) are both in the peer-review process as of this dissertation's completion. While there are similarities between the two articles and this chapter, the content has been substantially reorganized, reformatted, and edited to meet Mississippi State University's dissertation formatting guidelines and the flow of the overall dissertation.

5.1 Overview

The concept of developing an asset management strategy involves two key decision points: (a) what work is required to maintain the pavement (i.e., work planning); and (b) how should all of the requirements be prioritized (i.e., budget allocation) (France-Mensah and O'Brien 2018). This chapter presents the available and relevant literature review related to these two decision points, focusing primarily on pavement management strategies. Information is provided on the USAF's status quo, strategies of comparable Federal agencies, and current peer-reviewed research on the subject.

In the construct of asset management, the deterioration of a facility is typically visualized graphically using a curve that depicts an exponential decrease in facility condition over its lifetime. The curve reinforces two points: (1) if a facility is built and not maintained, it will ultimately fail or reach a condition of being inoperable; and (2) with proper investment and preventative maintenance, the lifespan of a facility can be extended. That said, pavement deterioration often resembles the curve shown in Figure 5.1 (AFCEC 2014b).

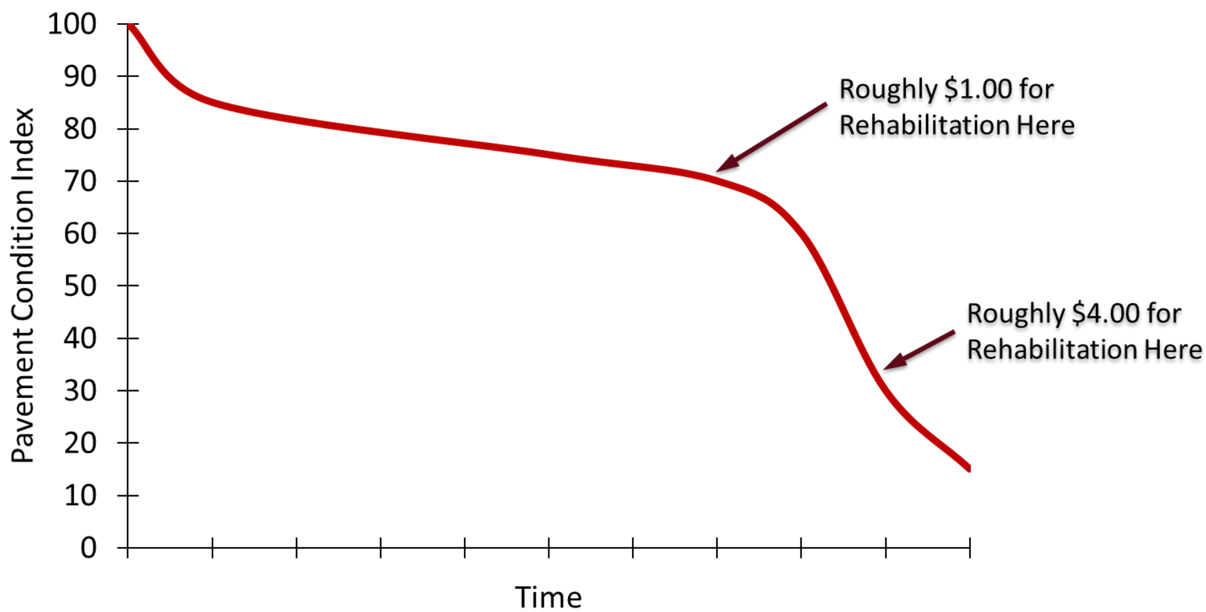


Figure 5.1 Typical Pavement Condition Deterioration Curve Concept

An important point to make about the PCI deterioration curve is that the curve focuses on modeling the PCI over time at the family-level. A family is a collection of like sections located at the same installation. For example, a family would include all primary, concrete taxiways, which might include several sections meeting this criterion. The deterioration curve attempts to predict the representative (family) pavement's PCI over time by fitting a curve to known section PCI values over time. Therefore, the PCI curve does not directly model the deterioration of individual distresses. The curve models the PCI value, which is a combination of deduct values calculated from individual pavement distresses.

Building a simulation to model the USAF's airfield pavements portfolio is a difficult task. The simulation needs to incorporate deterioration rates; restoration and preventative maintenance decisions; deferred maintenance; and resourcing. The simulation would need to run at the network level (due to the funding and allocation models) while using deterioration models built at the family level to forecast outcomes at the section level that collectively provide network-level outcomes. The complexity of modeling this level of detail makes it difficult to develop a business case for advocating for additional resources or building a decision-support tool. In a resource-constrained environment, the inability to articulate a business case can make it difficult to defend the current infrastructure budget, much less advocate for additional funds. This is particularly true in the DoD, where senior leaders (typically not engineers) commonly have to decide between funding aircraft procurement or increasing manning levels in the service. Being able to receive additional funding for infrastructure requires a robust, well-developed business case that becomes too difficult to ignore.

5.2 USAF's Pavement Management Approach

The USAF, more so than other DoD services, relies on its installations as a warfighting platform. These warfighting platforms are used to project air power anywhere in the world. As a critical node to these warfighting platforms and the operational concept of airpower, airfield pavements are among the most vital infrastructure assets in the USAF's inventory. While airfield pavements have a direct tie to mission effectiveness, it would be fair to suggest that many USAF senior leaders do not overly concern themselves about condition and status. These perspectives are often based upon their experiences that pavements do not typically catastrophically fail, thereby creating the perception at a macro-level that the condition of airfield pavements is at least sufficient to support operations for the foreseeable future. This perception can be dangerous in the context of budgetary decisions, as senior leaders prioritize funding in a resource-constrained environment to requirements and problems that have (often short or near-term) meaningful impacts such as needs for aircraft (Synovec et al. 2019). As a result, senior leaders often take a risk in sustaining airfield pavements, and infrastructure in general, to mitigate perceived short-term risk in other areas. These higher priority short-term risks can include other infrastructure classes (e.g., facilities, utilities, structures, etc.), but often, these priorities involve investments outside of infrastructure (e.g., new aircraft acquisitions) (Synovec and Howard Forthcoming).

While today's USAF is a multi-domain force, the majority of its core missions still revolve around its ability to project combat airpower. If an airfield is unable to launch and recover aircraft, the USAF effectively loses the ability to fight in the air; therefore, the condition of its airfields and pavements are of the utmost importance. While pavements are undoubtedly important to sustaining flying operations, the budget to maintain pavements (and other infrastructure classes) is not unlimited and has traditionally been underfunded.

As a mitigation effort to reduce the funding gap, the USAF over the last two decades has taken meaningful steps to implement a centralized, risk-based asset management approach to maintaining its infrastructure. This risk-based approach was intended to ensure that the USAF prioritized resources to maintain the infrastructure that has high probabilities and consequences of failure to ensure that no mission stoppage occurs as a result of infrastructure degradation. Life-cycle cost approaches have not been directly considered in the risk-based approach; therefore, the risk-based approach often prioritizes projects that require funding towards an asset's highest life-cycle point. Over time in a resource-constrained environment, the risk-based approach effectively became a “worst first” approach that helped exacerbate the USAF’s backlog of deferred maintenance (Synovec et al. 2019). With an estimated backlog in deferred maintenance and recapitalization of over $33 billion in 2019, the USAF estimates that its backlog will triple over the next thirty years if the status quo (i.e., funding levels, business processes, inventory, etc.) is maintained (Wilson and Goldfein 2019).

With formidable and sustained funding increases, the USAF could potentially slow or even reverse the backlog growth. However, the size of the funding level increases needed would require the USAF to forego or curtail other major investment actions, such as reducing its procurement goals for many of its aircraft recapitalization programs. With the USAF announcing in 2018 its intentions to increase to 386 operational squadrons, a 24 percent growth, relying solely on increased funding to solve the infrastructure backlog, could prove unsustainable or unrealistic (SAF/PA 2018). As a result, the USAF needs to consider a change to its risk-based, asset management approach to one that prioritizes investment at the lowest life-cycle cost.

5.2.1 Background

As previously mentioned, at the USAF headquarters level, the overall infrastructure sustainment portfolio is extremely underfunded due to the USAF taking a risk in its infrastructure portfolio to fund other high priority missions and portfolios (e.g., aircraft acquisition, weapon system sustainment, etc.) (Synovec et al. 2019; Wilson and Goldfein 2019). The DoD utilizes its FSM to estimate annual infrastructure sustainment costs. As of 2018, each DoD service was only funding its total infrastructure portfolio at 80 percent or less of estimated sustainment requirements (OUSD(C) 2018b). As such, internal estimates from the USAF, as of 2019, estimate this backlog to be in excess $33 billion and rising (Wilson and Goldfein 2019). Under the USAF’s new Infrastructure Investment Strategy (I2S), the USAF hoped to significantly increase infrastructure investments closer to a goal of two percent of the plant replacement value; however, the plan is already at risk and funds are being redirected to higher priority efforts. In the last two fiscal years, the USAF diverted significant amounts of funds from its infrastructure sustainment account to support hurricane and natural disaster recovery at multiple USAF installations (Cohen 2019). Additionally, in its fiscal year 2021 budget submission to Congress, the USAF reduced its infrastructure spending by $854 million, approximately 21 percent less than the previous fiscal year (SAF/FM 2020).

Below the headquarters level, the USAF's infrastructure sustainment portfolio is divided into two relatively equally funded portfolios: centralized and decentralized funding. The decentralized portfolio is distributed primarily based on installation size for local prioritization and execution. The centralized portfolio is budgeted, prioritized, and managed by the AFIMSC. This portfolio division effectively creates two funding sources with different rules, prioritization, and processes, similar to the multiple funding sources encountered by a state transportation agency (France-Mensah et al. 2019). Unlike typical state transportation agencies, requirements from all infrastructure categories (e.g., pavements, facilities, utilities, etc.) compete for the same funding in the USAF's sustainment portfolio (centralized or decentralized).

With 108 airfields in the simulation, there are effectively 109 decision-makers involved in the USAF's centralized and decentralized portfolios. Each Civil Engineer Squadron (similar to Public Works Departments in other military services) has one decision-maker who develops requirements, maintains infrastructure, plans and manages projects, and executes their allocated decentralized sustainment funding (i.e., Execution Plan). The remaining decision-maker is the AFIMSC, which controls the centralized portfolio and the budget allocation of the decentralized portfolio. Additionally, AFIMSC is responsible for developing future budgets for infrastructure spending. These relationships and sphere of controls are shown in Figure 5.2. This figure is relevant in the context of this research because, ultimately, any proposed solutions for improving airfield pavement maintenance must exist within this process map, as these processes and relationships are used to maintain all categories of infrastructure.

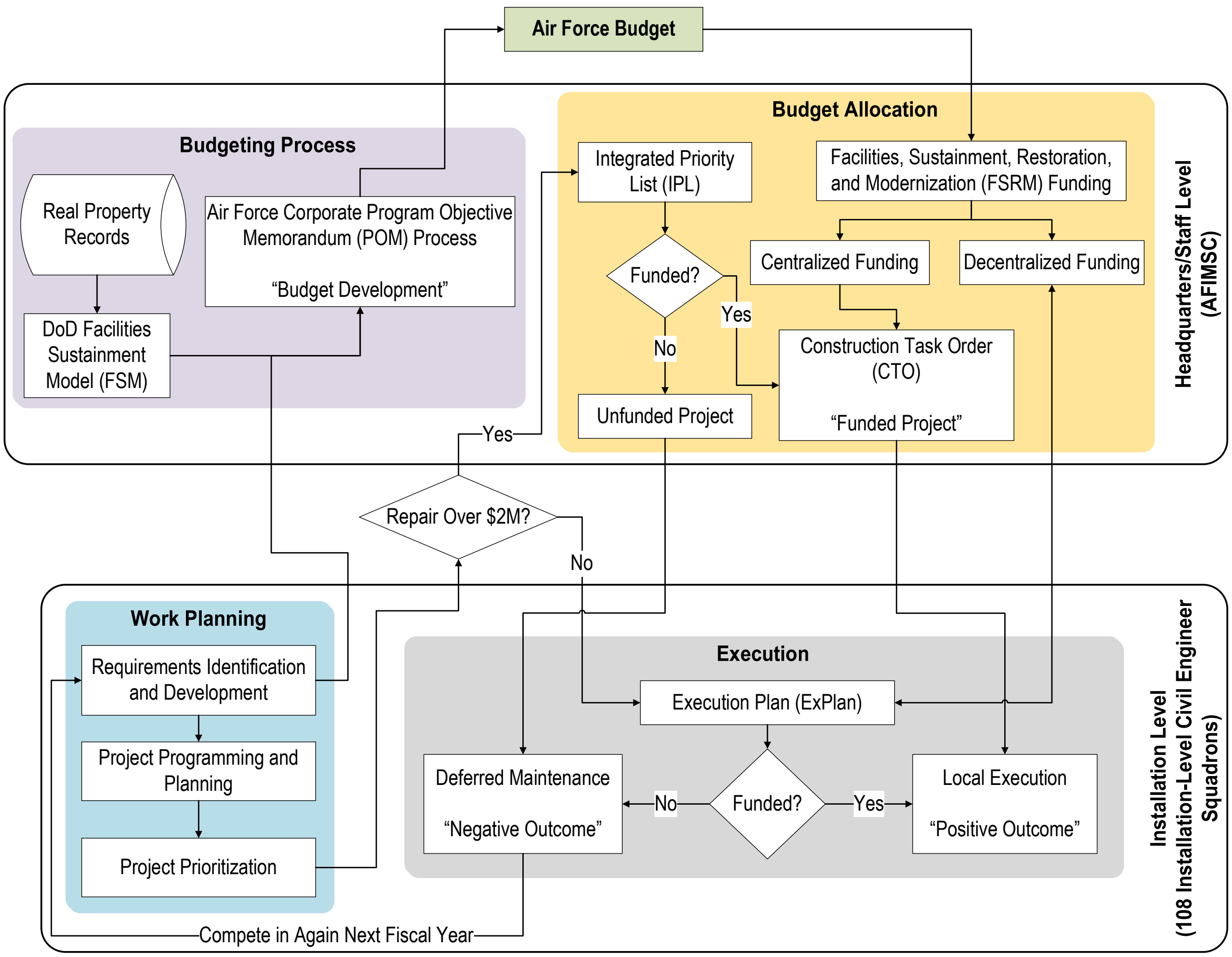


Figure 5.2 Overview of the USAF's Infrastructure Funding Process

The USAF's decentralized portfolio typically funds all preventative and small corrective maintenance (less than $2 million) requirements (see Figure 3.3 and Figure 5.2). These funds are directly issued to each installation annually to accomplish local sustainment requirements based upon their local prioritization and investment strategy (represented in Figure 5.2 as the ExPlan). While these funds would support sustainment of pavements, as previously mentioned, these funds also include sustainment and repairs of buildings, structures, and utility systems. This caveat is important as funds that could support preventative maintenance actions for airfield pavements are routinely directed to other infrastructure requirements with a perceived higher impact or to repairs that produce a more immediate and visible result. For example, repairing the roof leak on a headquarters facility or renovating an installation's quality of life facility is typically prioritized over airfield sustainment, particularly if the impacts of deferring action are perceived to be long-term. Since each USAF installation establishes its decentralized priorities, some USAF installations have been successful at accomplishing and maintaining a recurring preventative maintenance program. On the contrary, several installations have been unsuccessful at doing the same. Using the data included in PAVER, the pavement management software utilized by the DoD and other agencies, it is possible to estimate some basic probabilities for each installation about its likelihood of conducting preventative maintenance based on its historical records.

The USAF's centralized project portfolio funds individual projects based on its scoring relative to other projects competing for financial resources across the service. Scoring within the centralized portfolio is generally based on the product of scores from two categories: (a) COF and (b) POF. Projects are subsequently funded starting at the highest score and then working in descending order of score until the centralized funds are exhausted. Similar to the decentralized portfolio, the centralized portfolio is used to fund projects across all of the various infrastructure portfolios (e.g., facilities, pavements, utilities). Furthermore, it does not fence sections of the portfolio to fund specific infrastructure (i.e., funds are not set aside specifically to fund pavements projects).

5.2.2 Work Planning

The USAF outlines its guidance for work planning for airfield pavements in a series of documents with the primary guidance document being ETL 14-3, *Preventative Maintenance Plan for Airfield Pavements* (AFCEC 2014b). While the ETL provides multiple suggestions and tools for developing a work plan for various maintenance actions corresponding to the distresses present in a given pavement section, the document acknowledges that work planning is ultimately a function of engineering judgment (AFCEC 2014b). Furthermore, the ETL directs that work planning be accomplished at the local or installation level. ETLs, in general, are considered guidance documents in the USAF and not a policy or instruction (i.e., enforceable) document. ETLs can be made enforceable through the inclusion of compulsory use statements referencing the ETL in AFIs. That said, the ETL provides key takeaways about how the USAF currently approaches work planning for its airfield pavements.

Work planning is ultimately an exercise of engineering judgment conducted at the local installation level for a given pavement section or branch on an airfield. With the conscious decision to develop more generalist engineers in the USAF, work planning at the local level is not always accomplished by an experienced pavements engineer (Synovec et al. 2019). Furthermore, it is unrealistic to assume that all maintenance requirements receive the same level of scrutiny about the analysis of cost-effectiveness and timing. It is also unlikely that most installation pavements engineers fully utilize tools available such as the DoD's sustainment management system (PAVER). This last comment is based on a review of the USAF's PAVER database, in which it was observed that many installations had not updated their data in several years. While PAVER can inform work planning, it requires recurring database updates to maintain data and recommendations currency. Furthermore, while PAVER has the ability to recommend projects, it is not typically used to program or select projects for execution.

The USAF does not downward direct the execution of a given project within a specific fiscal year. Instead, the USAF relies on local engineers at each installation to leverage the data and analysis in PAVER, coupled with local assessments of the pavement degradation and condition, mission impacts, and phasing to develop a long-term plan for pavement investment and program projects for a given fiscal year. All of the programmed local projects then compete within the centralized program for funding. Since there is not enough funding for all of the projects programmed for a given fiscal year, any project not funded is rolled over to compete in the following year's program until it is eventually funded (see Figure 5.2).

There are four categories for pavement maintenance and repair actions: (1) localized preventative maintenance; (2) global preventative maintenance; (3) stopgap maintenance; and (4) major maintenance and repair (M&R). The first three maintenance options are the responsibility of the decentralized portfolio and local installations, while major M&R actions are the responsibility of the centralized portfolio with decentralized execution (see Table 5.1). Funds within each respective portfolio are not typically transferred between portfolios as a matter of policy, and each portfolio is governed by a different set of business rules and prioritization models. Regardless of which portfolio is responsible for a given maintenance requirement, pavement maintenance requirements must compete for funding and prioritization against other maintenance requirements across infrastructure categories. As a result, it becomes exceedingly challenging to synch the two portfolios in a constrained budgetary environment to ensure maintenance actions are completed as planned (e.g., funding may not be available to complete previously scheduled preventative maintenance).

Table 5.1 Summary of USAF Airfield Pavement Maintenance Options

Portfolio	Maintenance Options
Decentralized Portfolio Maintenance Options	Localized Preventative Maintenance (Local PM): Performed on individual pavement distresses to slow rate of deterioration. *Examples Include: Crack Sealing, Patching, Joint Seal Replacement, Slab Replacement, etc.* Global Preventative Maintenance (Global PM): Performed on a large-scale, usually covering at least one entire section on a recurring time interval. *Examples Include: Fog Seals, Rejuvenators, Slurry Seal, Microsurfacing, etc.* Stopgap Maintenance (Stopgap): Performed to maintain the safety of flight with actions that mitigate individual distresses on pavements that are already below the critical PCI. *Examples Include: Patching, Slab Replacement, Undersealing, Grinding, etc.*
Centralized Portfolio Maintenance Options	Major Maintenance and Repair (Major M&R): Performed to repair, rehabilitate, or reconstruct deteriorated pavements at or below the critical PCI. *Examples Include: Full Depth Repair, Partial Depth Repair, Mill and Overlay, Slab Replacement, etc.*

The USAF defines the line between preventative maintenance actions (both localized and global) and corrective maintenance (major M&R and stopgap) as the critical PCI value (PCI_{crit}). Due to limitations in the PAVER framework, the USAF determines the inflection point for the cost-effectiveness of preventative maintenance based on universally-applied (i.e., not locally or individually calibrated) critical PCI values. For primary pavements (e.g., runway, parallel taxiway, and main parking apron), the critical PCI value is 70, and the critical PCI value is 55 for secondary (e.g., ladder taxiway) and tertiary (e.g., overrun) pavements. When a pavement's PCI value deteriorates below the critical PCI, the USAF recommends that preventative maintenance no longer be performed, and efforts shift to major maintenance and repair actions (AFCEC 2014b). Since the critical PCI values are universally determined, the critical PCIs may be either too high or too low for some pavement sections in the context of achieving the lowest cost of ownership.

For pavements above the critical PCI values, the USAF recommends various preventative maintenance and localized repair actions depending on the distress type and severity. These recommendations vary—from doing nothing to patching—and attempt to help influence local decision making towards cost-effective options (AFCEC 2014b). Furthermore, these recommendations are examples of what the USAF refers to as localized preventative maintenance (i.e., maintenance that is applied only to the distressed area of a pavement section). The USAF also utilizes global preventative maintenance practices, which are maintenance actions applied to an entire pavement section on a recurring schedule regardless of observed pavement distresses. For example, a global preventative maintenance action would replace all of the joint seals on a concrete parking apron every five years. Conversely, localized maintenance would only replace distressed joint seals on an as-needed basis. While joint seals would likely be a good option for global preventative maintenance actions, the USAF, by policy, limits global preventative maintenance currently to asphalt pavements (AFCEC 2014b; USAF 2017c).

Lastly, the USAF summarizes an economic analysis methodology in ETL 14-3 to help develop a business case for conducting preventative maintenance versus foregoing preventative maintenance. This economic analysis utilizes an equivalent uniform annual cost (EUAC) based methodology to calculate the opportunity cost of foregoing preventative maintenance. This analysis provides a framework for developing a preventative maintenance business case, and it makes three key generalizations to ease calculations: (a) pavement deterioration is characterized using linear regression models; (b) unit costs are held constant regardless of condition; and (c) interest and inflation rates are omitted (AFCEC 2014b). Furthermore, the business case analysis presented in ETL 14-3 utilizes a methodology that compares two opposing maintenance strategies (e.g., annual preventative maintenance and operated until failure) utilizing separate time periods for the evaluation of each strategy (i.e., strategy X is evaluated over a period of 27 years, and strategy Y is evaluated over a period of 35 years). This varying period of evaluation, coupled with the three generalizations, produces a scenario in which a misleading business case could be produced using the EUAC method. A standard period of evaluation or study is recommended when using the EUAC methodology (Eschenbach 2011; GHD Inc 2012).

5.2.3 Budget Allocation

As described in this section, the USAF's centralized infrastructure investment program is structurally set up to promote "worst first" asset management. The centralized program racks and stacks every construction and major repair project from across the USAF based upon a combination of two components (see Figure 5.3) to determine the overall score for a typical project that is competing against all other centralized projects (e.g., facility renovations, utility upgrades, etc.) for funding. The USAF funds projects in priority order and descending order based on combined score until funding is exhausted. The first component, COF, is comprised of two components: MDI and Major Command (MAJCOM) priority. MDI, the larger of the two components by percentage, assigns a value (0 to 99) to all facilities and pavement based on its criticality to supporting the installation's mission.

Until the fiscal year 2020, the USAF integrated criticality to mission by assigning the MDI values based on the type of facility (e.g., all air traffic control towers regardless of location have the same MDI value). Airfield pavements typically had MDI values from the high-80s to 99, with 99 being the highest possible MDI score. Starting in the fiscal year 2020, the USAF transitioned from a category code-based MDI system to a "tactical" MDI system (AFIMSC 2019). The tactical MDI system allows individualized MDI scores for each facility on its installation relative to the base's mission's dependency on the infrastructure and replicability of the function in the facility.

While there was a significant change across the USAF in MDI scores based on this subjective approach, airfield pavements still have among the highest MDI scores. The tactical MDI scores are in-place currently, but it is anticipated that there will be further adjudications and review of the new MDI scores as installations adapt to the new system.

MAJCOM priority, the second component of COF, is subjectively applied to individual projects based on the Commander's assessed priority of a given project to the mission. The second component, the POF, for airfield pavements is representative of the PCI value of the pavement section (although POF is not numerically equal to PCI). For pavements with a PCI value less than 50, the POF score is 100 (the maximum score); the POF for pavements with PCI values over 50 is calculated using Equation 5.1.

$$POF = 2 * (100 - PCI) \tag{5.1}$$

As shown in Figure 5.3, projects with a high consequence of failure and probability of failure are projects that would fall within the targeted funding area of the centralized portfolio, as the combined score would more than likely rise above the funding cut line. For airfield pavements, these two components combine to essentially ensure funding for failed airfield pavements (i.e., a "worst first" approach). Based upon this scoring methodology, a failing airfield pavement section would typically score well enough to be above the funding line; however, pavements in better conditions would not compete as well given the current scoring model. Furthermore, while pavements (and infrastructure in general) that are in poor and failing condition score better based on the USAF's scoring model, these projects typically cost more to repair, thereby creating a scenario where individual projects consume higher percentages of available resources. With a growing quantity of individual projects consuming large percentages of resources, it is inevitable that a growing quantity of other projects is not getting funded. This trend is part of a glide slope that would inevitably lead to a gradual and sustained degradation of all infrastructure over time, barring any sort of course correction.

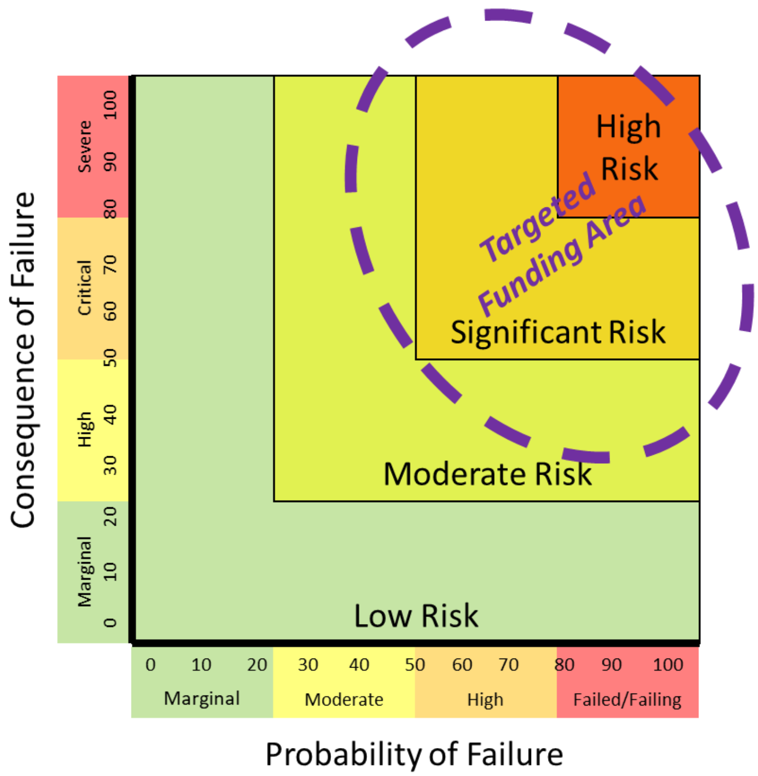


Figure 5.3 USAF Integrated Priority Listing Scoring Model

While targeting the "worst first" may seem like an intuitive choice to an individual unfamiliar with asset management principles, the "worst first" approach to maintenance and repair is often less optimal for resource efficiency. In resource-constrained environments, this approach, over time, locks an organization into a glide slope that leads to a gradual degradation of its infrastructure over time. Typically, the most efficient asset management approach is to utilize available (and limited) resources to keep good infrastructure good (i.e., spend resources on preventative maintenance actions that extend the life of the infrastructure and slow the rate of deterioration) first before utilizing resources to make bad infrastructure good (i.e., extensive corrective maintenance and reconstruction).

The USAF asserts that it has been investing in its infrastructure for years at a rate that is roughly half that of the private industry-standard (AFIMSC 2018). While this comment is based exclusively on the percentage of funding relative to the service's total infrastructure plant replacement value (PRV), it further speaks to the USAF's $33-billion deferred maintenance backlog. Overcoming this backlog requires one of two courses of action, but likely a combination of both: (1) meaningful increases in infrastructure funding; or (2) a meaningful reduction in the amount of maintained infrastructure. Both courses of action target maximizing the amount of funding available to sustain good infrastructure while buying down the backlog over time.

The USAF, throughout its existence, has averaged, in constant year dollars, an annual budget of around $170 billion (see Figure 5.4) (OUSD(C) 2018a). While the budget has varied depending on major historical and political events, the budget has remained relatively consistent when viewed in constant dollars. This total obligation authority (TOA) captures the total amount of funding the USAF was authorized by Congress for all its expenses, including major weapon system procurement, research and development, aircraft fuel and maintenance, military and civilian pay, and facility investment. With the USAF currently focusing on several major acquisitions programs while trying to increase its overall military personnel levels, it seems unlikely that the USAF could divert enough funding to overcome the maintenance backlog without a meaningful and sustained increase in TOA.

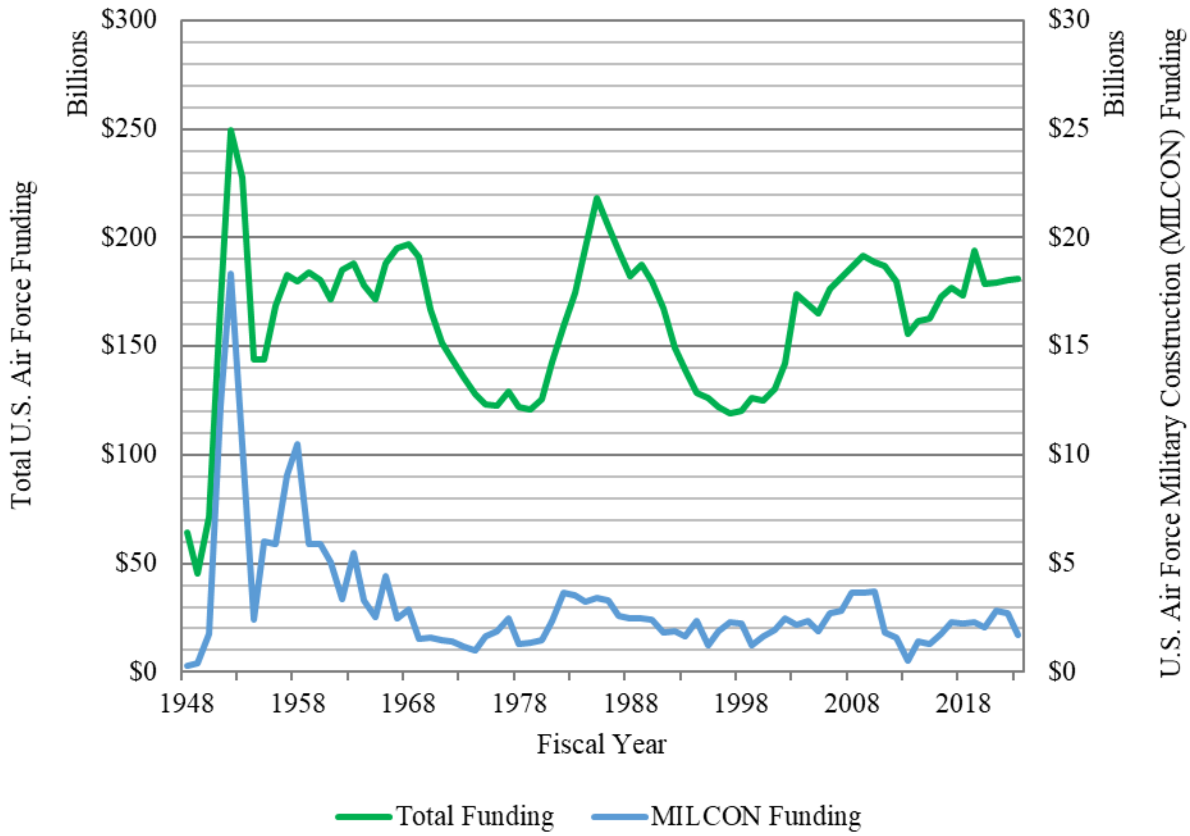


Figure 5.4 USAF Total Obligation Authority and Military Construction Funding from 1948-2023 in 2019 Constant Dollars (Created with data from OUSD(C) 2018a)

Congress has included language in the last several NDAAs specifically prohibiting further rounds of base closures, despite recommendations and requests from senior DoD officials. As a result, much of the DoD's effort to decrease the amount of maintained infrastructure is to consolidate and demolish excess infrastructure, while not reducing the overall number of installations (OUSD(C) 2018b). This strategy should inevitably provide some long-term savings; however, it is unlikely to produce savings at the level required to overcome the USAF's $33 billion maintenance backlog. That said, these savings could go further to slow the growth of the backlog with a revamped approach to asset management that no longer targets the worst infrastructure first.

A practical approach for revamping the asset management approach for airfield pavements might be to establish a minimum PCI value for investment to ensure that resources are going towards keeping good pavement good; pavements below this minimum PCI value would receive no investment. Over time, this approach should extend the lifespan and slow the rate of deterioration of the good pavements, thereby reducing the annual maintenance costs. As such, the reduction in annual expenses over time should begin to allow for investment in pavements below the minimum PCI level. The challenge with this approach is that it would inevitably lead to the closure of pavement sections. At airfields with multiple runways, an approach of this nature could likely be managed locally to mitigate any potential impacts; however, airfields with a single runway could potentially experience considerable impacts on flying operations and safety.

Another approach to addressing this problem would be to develop an optimization tool that seeks to identify the right projects to fund at the right time based on minimizing the total cost of ownership of the entire portfolio. Recognizing that, from an operational perspective, the USAF has some hard constraints that would need to be imposed in the formulation to prevent airfields from deteriorating to the point where the USAF would need to close an airfield. With this type of constraint, an optimization tool would be forced to include failing pavement sections in its investment strategy where otherwise the tool would likely forego recommending investment in these failing pavement sections. The difficulty with this constraint is that it would need to apply to approximately 60 percent of the USAF's airfields, as this represents the percentage of airfields in the USAF that are single-runway airfields.

While both of the previous strategies could help improve the USAF's centralized scoring model and align it better with asset management principles, neither strategy addresses the issues in the decentralized portfolio with preventative maintenance. As shown in Figure 4.11, the vast majority of the distresses present on USAF flexible pavements are climate and durability related distresses that require maintenance actions that qualify for decentralized funding and execution. A similar comment could be made for rigid pavements as well, as the majority of distresses, as shown in Figure 4.12, are climate and durability related. Furthermore, most of the high-density distresses shown in these figures are typically precursors to higher severity distresses that can degrade the structural capability of the pavement and require more extensive costly repairs. The challenge with addressing these high-density, low-severity distresses is it would require mandating action at the local level from higher headquarters through process or policy change. The process change could be absorbing these projects into the centralized portfolio, or the policy change could be to establish a focused fund that specifically fences resources to cover these preventative maintenance actions.

To summarize this section on USAF policies and operating procedures for maintaining, inspecting, and repairing airfield pavements, the centralized program (whether intentionally or not) is set up to repair the "worst first." While this may seem like an intuitive choice to an individual unfamiliar with asset management principles, the "worst first" approach to maintenance is, in fact, one of the least efficient uses of resources and locks an organization into a glide path that will see all of its infrastructure slowly degrade. Typically, the most efficient asset management approach is to utilize available resources to keep good infrastructure good (i.e., spend your resources on preventative maintenance actions that extend the life of the infrastructure) first before utilizing resources to make bad infrastructure good (i.e., corrective maintenance and reconstruction). The most practical approach to implementing an efficient asset management approach for airfield pavements is to establish a minimum PCI value for investment to ensure that resources are going towards keeping good pavement good; pavements below this minimum PCI value would receive no investment. The challenge with this approach is that it inevitably leads to the closure of pavement sections and potentially significant impacts to flying operations.

5.3 Approaches of Other U.S. Federal Agencies

To understand the various options and approaches to implement a lowest lifecycle cost approach for USAF airfield pavements, it is prudent to compare the USAF's current approach to that of other similar public sector agencies. Similar in the context of this research refers to public sector agencies that maintain large inventories of pavement sections (to include airfield or highway pavements) and not necessarily to other military organizations. The research focused on public sector organizations due to the difficulty of comparing a private sector organization that is principally motivated by maximizing its return on investment as it relates to profit margin. Public sector organizations, however, primarily focus on maximizing levels of service within available resources. Public sector organizations also commonly have multiple funding portfolios (similar to the USAF) that make infrastructure investment analysis and decisions more complicated (France-Mensah et al. 2019).

5.3.1 Federal Aviation Administration

The Federal Aviation Administration (FAA) prioritizes projects by the National Priority System (NPS). Similar to the USAF, the FAA funds projects across the multiple infrastructure categories. The NPS utilizes an equation-based scoring methodology that allows the FAA to evaluate projects or initiatives of various types (e.g., pavement, lighting, facilities, etc.). The scores are based on the project's alignment to the FAA's national goals and objectives and the importance of the airport to the nation's air transportation network (FAA 2000). These scores are used to prioritize projects from across the U.S. for funding in the Airport Improvement Program (AIP).

Projects that score well enough to receive funding based upon projected funding levels are then included in the semi-annual National Plan of Integrated Airport Systems (NPIAS). Based on several factors, the FAA may require certain projects to complete a cost-benefit analysis; however, the FAA does not generally use these results to determine a project's ranking as it relates to funding in the AIP (FAA 2018).

Furthermore, the FAA does not utilize pavement conditions to adjust NPS scores; rather, pavement conditions and timing are only used as barriers for entry to the competition for funding. For example, for a runway rehabilitation project to be eligible to compete, the runway would need to have a PCI value of 70 or less and not have been rehabilitated or constructed in the last 10 or 20 years, respectively (FAA 2019). Lastly, the FAA does not generally fund maintenance activities (e.g., crack sealing) through the AIP, as stipulated in 49 USC § 47102 (FAA 2019). Instead, airports would generally utilize other local sources (e.g., landing fees) to fund maintenance activities.

The FAA's published asset management framework includes performance goals to ensure the agency can measure whether it is achieving its stated objectives and goals. For pavements, performance goals relate specifically to runway conditions at airports included in the NPIAS. The FAA's stated goal is for at least 93 percent of the runways in the NPIAS to have a pavement condition of "fair" or better, which correlates to a PCI value of 55 or higher. Using the fiscal year 2017 data, the FAA estimates that 97.8 percent of the runways in the NPIAS achieve this performance standard (FAA 2018). In comparison, the USAF does not currently have published performance standards for its airfield pavements; however, it indicates that it intends to develop them in terms of condition, FOD potential, friction, and structural capacity (AFCEC 2014b).

As a general note, the AIP is a cost-sharing program in which the FAA covers the vast majority of the project cost. Depending on the airport size, the AIP covers between 75 and 95 percent of the total project cost (FAA 2020). The 2018 NPIAS included $35.1 billion for 3,321 airports across the U.S. for fiscal years 2019-2023. Figure 5.5 depicts the projected expenditures at each airport for the $35.1 billion NPIAS program.

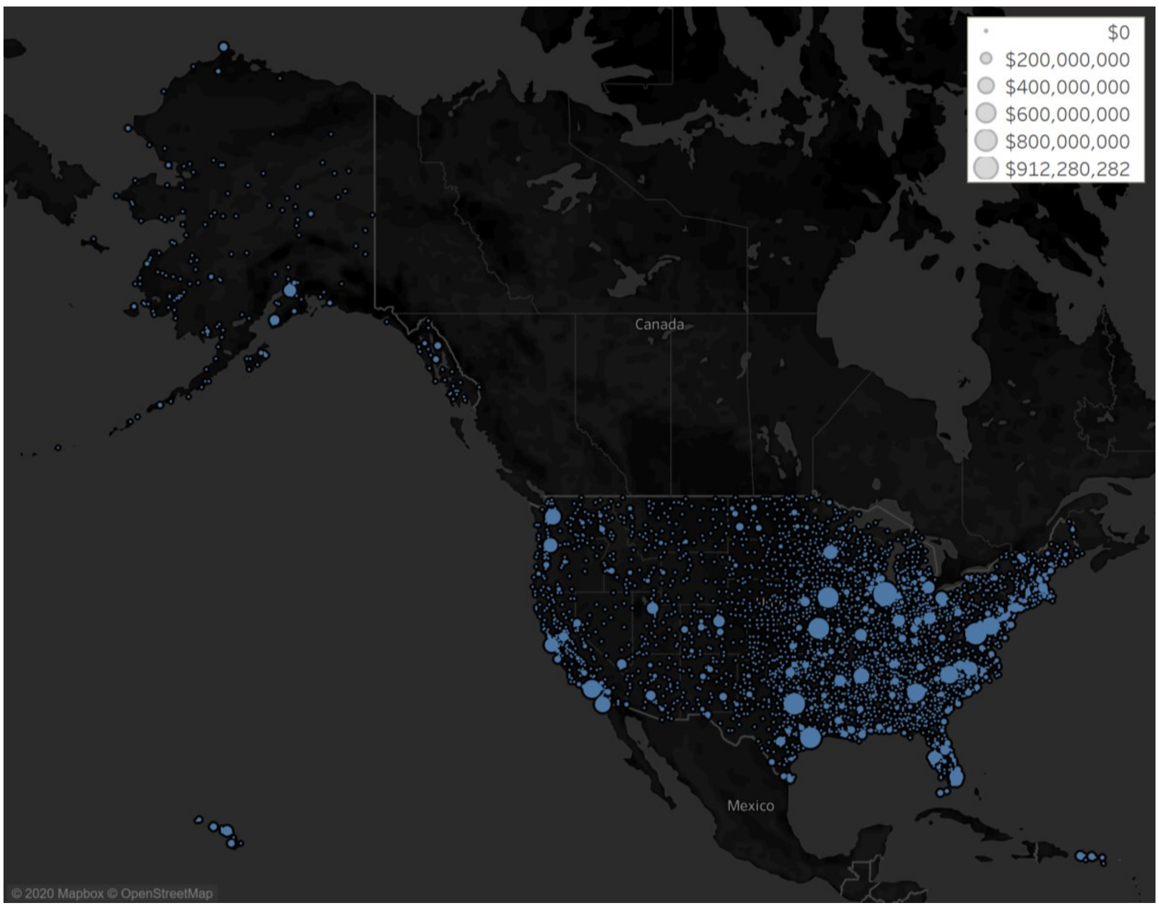


Figure 5.5 Fiscal Year 2019 to 2023 Projected Expenditures for the National Plan of Integrated Air Systems (Created with data from FAA 2018)

5.3.2 Federal Highway Administration

While the FAA maintains what is likely the most comparable national-level pavement portfolio to the USAF, it is important to look beyond the FAA to understand how other large public sector organizations manage their pavements. In accordance with the Moving Ahead for Progress in the 21st Century Act (MAP-21), each state DOT has been required to develop an asset management plan (FHWA 2012; 2019). According to the requirements of MAP-21, each state is required to include discussions on its full inventory, performance measures and objectives, performance gaps, lifecycle cost and risk management analysis, financial planning, and investment strategies (2012). The FHWA's Office of Asset Management has published numerous documents to support the implementation of a comprehensive approach to asset management (O'Toole et al. 2013; Zimmerman et al. 2019).

The FHWA discusses various investment strategies that could be utilized depending on the resource environment (unconstructed and constrained) as examples for state DOTs to consider. For preservation-focused strategies, the FHWA recommends developing triggers or rules to dictate when a particular maintenance action should be planned and accomplished (FHWA 2017b; O'Toole et al. 2013). These triggers should relate to the performance standards of the portfolio's overall asset management program. With established triggers and even in a resource-constrained environment, preservation focused investment strategy should slowly allow for reconstruction or major rehabilitation efforts to be accomplished on deteriorated pavement sections as more funding becomes freed up due to the increasing quantity of good pavements (Guevara et al. 2017; Zimmerman et al. 2019).

It is worth noting that the FHWA makes a clear delineation between network-level and asset-level planning. Network-level planning is referred to as lifecycle planning (LCP). It focuses on establishing a plan and sequence of actions to achieve desired performance objectives at the minimum practicable lifecycle cost (Zimmerman et al. 2019). LCP considers numerous assets of the same asset class simultaneously to make recommendations at the network-level. For example, LCP may determine that the default strategy for a given asset is to mill and overlay the pavement on a set interval. That said, a lifecycle cost analysis (LCCA), performed at the asset-level, may suggest that an alternative maintenance or rehabilitation action is more cost-effective for that specific pavement section at the time and deteriorated state.

As part of lifecycle planning, the FHWA recommends that an organization first consider risk tolerances across its portfolio to inform investment and preservation strategies better (Zimmerman et al. 2019). Risk management can take many different forms, to include an assessment of a pavement section's consequence and probabilities of failure which mirrors the USAF's current strategy; however, the end goal of risk management should be the development of performance metrics to measure against the assessed risk tolerance (FHWA 2017a). For example, a state DOT may wish to maintain its interstate pavements at a high level due to its criticality to the state and nation's economy and transportation system while minimizing cost. As a result, the state DOT may establish a performance goal for 98 percent of its interstate pavements to achieve a PCI value of "fair" or better (Zimmerman et al. 2019). A pure lowest lifecycle cost approach could potentially achieve this performance objective; however, simulations would be needed to validate. This caveat is in large part due to the recognition that a pure lowest lifecycle cost assessment is effectively an exercise in engineering economics and does not directly consider performance or risk (i.e., singular objective optimization). A state DOT would potentially need to make adjustments to its investment and preservation strategies to ensure that it could achieve its performance objectives, which may drive an increase in lifecycle cost to buy down risk at high-performance standards or levels of service. Balancing cost and performance in this manner is a form of a multi-objective optimization, which typically requires additional computation time and complexity. Furthermore, research suggests that optimization models, particularly multi-objective approaches, are not suitable for analysis of large networks without a variety of workarounds (Chen et al. 2015; France-Mensah and O'Brien 2018).

5.4 Recently Published Research

The infrastructure crisis facing the USAF is not unlike the situation facing transportation authorities around the country, and it is a challenge requiring deliberate planning and decision-making to make cost-effective budgetary investments (Alberti and Fiori 2019; ASCE 2017; Arif et al. 2016; Bush 2019; Chi et al. 2013; France-Mensah and O'Brien 2018; Luhr et al. 2019). In operations management literature, the infrastructure challenges facing the USAF and many other transportation authorities are described as a capability trap. In this context, the combination of constrained resources and a growing infrastructure backlog can cause decision-makers to focus on short-term decisions rather than looking for long-term solutions (Guevara et al. 2017). Prior research sought to mitigate this capability trap through the development of numerous mathematical formulations to include variations of multiobjective optimization and genetic algorithms.

These formulations aimed to optimize numerous factors impacting highways and roads, such as operations and maintenance costs, environmental impacts, user costs, safety, and mobility (Aleadelat et al. 2020; France-Mensah and O'Brien 2019; Gao and Zhang 2008; Hafez et al. 2019; Li and Sinha 2004; Medury and Madanat 2013). The vast majority of recent research on work planning recommends utilizing optimization techniques (Aleadelat et al. 2020; Denysiuk et al. 2017; Hafez et al. 2019; Khiavi and Mohammadi 2018; Saha and Ksaibati 2018; Zhang et al. 2017). Additionally, prior research has typically focused on either work planning or budget allocation utilizing small populations over a limited period. Increasing the scope of these optimization techniques would require significant increases in computing time and power, potentially driving a requirement for additional dedicated personnel to support the additional computational demand (Ahmed et al. 2017; de la Garza et al. 2011; Duncan and Schroeckenthaler 2017; France-Mensah and O'Brien 2018; Harrison et al. 2019; Woldesenbet et al. 2016; Wu et al. 2012; Zhang et al. 2017).

Research also suggests a gap exists as it relates to optimizing budget allocation from multiple funding portfolios, as is common practice in the public industry (France-Mensah et al. 2019). As such, transportation authorities have been slow or hesitant to adopt these techniques, with the majority of transportation authorities not using pavement management systems to their full potential (Chen et al. 2015; France-Mensah and O'Brien 2018; France-Mensah et al. 2019; Wu et al. 2012). Furthermore, close to half of the agencies surveyed indicated they had not used their pavement management systems to evaluate the cost-effectiveness of various treatment options (Zimmerman 2017).

Noticeably missing from past research on the subject are optimization techniques aimed at addressing airfield pavements, which typically experience a more significant proportion of non-load related distresses compared to highway pavements (Rushing et al. 2014). Research on utilizing optimization techniques for airfield pavements is limited, and the available research on the subject has not highlighted strategic-level (i.e., large portfolios of airfields) budget allocation and planning (Di Mascio and Moretti 2019; Hajek et al. 2011). While there is a research gap in airfield pavement maintenance, there also exists a gap in pavements research, generally, concerning optimizing budget allocation for large portfolios (i.e., state, national, or international-level) utilizing multiple funding portfolios over an extended period.

5.5 Summary

The literature discussed in this chapter provides a few main takeaways to shape this research effort. First, there are likely several policy decisions that could be investigated to help improve the USAF's pavement portfolio. However, the scope of this research is to ultimately investigate how the lowest lifecycle cost approach could be determined and potentially implemented within the current business rules and policies of the USAF. The comment follows that the USAF needs practical and implementable solutions to its growing infrastructure challenge. Theoretical solutions that exist outside of the realities of USAF rules, regulations, and processes would likely prove insurmountable to implement. As such, the models and algorithms developed as part of this research effort assumed business rules and policies remained the same. Additionally, keeping the focus on implementable solutions within the current USAF construct allows for better evaluation of the proposed solution or methodology (i.e., if too many variables are changed, it becomes difficult to ascertain the relative impact of each change).

Second, unlike highway transportation authorities, the USAF does not have performance objectives for its pavement portfolio. Therefore, it is likely the USAF is content on some level with its current pavement performance, and it is primarily interested in reducing the total cost of ownership. Airfield pavements do not typically deal with many of the other decision factors seen with highway pavements (e.g., driver safety, smoothness emissions, user costs, etc.). As a result, multiobjective optimization is unnecessary, provided that appropriate constraints are applied to bound the solutions.

Third, optimization techniques require a significant amount of computing power and time to solve complex problems. Based on a review of recent research, it is likely impractical to directly optimize an entire pavement network over a long period of time. To successfully optimize a problem set this large would likely require a specialized computer and software, and is ultimately not a practical solution for the USAF or most transportation authorities. Therefore, it appears that the most efficient method of optimization is to optimize the whole by optimizing the parts. In this analogy, the whole is the USAF's pavement portfolio, and the parts are the individual pavement sections. As such, the potential solution would focus on optimizing maintenance strategies for individual pavement sections to reduce the total cost of ownership. Collectively, these optimized solutions would equate to an optimized pavement portfolio. This optimization strategy focuses on the work planning aspect of asset management, and further attention is necessary to develop a complementary budget allocation method.

Fourth, the static critical PCI values that the USAF uses to demark the point at which a pavement should receive a major M&R treatment are likely not the most economical choice for a significant portion of the pavement portfolio. Furthermore, standardized preventative maintenance approaches for each pavement section are similarly not the most economical choice. Both observations speak to the work planning aspect of an asset management strategy. To help the USAF shift to a lowest lifecycle cost approach, thereby reducing the total cost of ownership, work planning should be individualized as much as practical to identify the economically optimal solution. Most recent research efforts utilized complex, multiobjective optimization techniques to accomplish this outcome. However, a simulation-based approach could provide a similar solution using less computing power and time.

Lastly, the USAF's budget allocation strategy is likely exacerbating its infrastructure challenges. As discussed in this chapter, the USAF's centralized scoring model is structured to prioritize failed pavements over pavements in "good" or "fair" condition. Pavement repairs typically increase in cost as the condition decreases; therefore, the centralized scoring model is effectively prioritizing projects near their highest cost point. Over time, this "worst first" approach inevitably leads to a growing maintenance backlog in a fiscally constrained environment. Providing a course correction for the USAF's airfield pavement portfolio requires a rethinking of its budget allocation strategy, as well as its work planning methodology.

CHAPTER VI

DEVELOPMENT OF THE BEHAVIORAL AND ECONOMIC AIRFIELD SIMULATION TOOL AND ANALYSIS OF THE U.S. AIR FORCE'S CURRENT PAVEMENT MANAGEMENT STRATEGY

This chapter contains portions of two technical papers submitted to two peer-reviewed journals. The first paper (Synovec and Howard Forthcoming) and the second paper (Synovec et al. Forthcoming) are in their peer-review process with journals as of the completion of this dissertation. While there are similarities between the two articles and this chapter, the content has been substantially reorganized, reformatted, and edited to meet Mississippi State University's dissertation formatting guidelines and the flow of the overall dissertation.

6.1 Introduction

This chapter presents a methodology to model the long-term implications of short-term decisions or behavioral trends for an entire pavement portfolio. Previous research efforts simulating portfolio-level decision-making and outcomes have typically constrained their focus to shorter-term simulation periods or small sample sizes (Ahmed et al. 2017; de la Garza et al. 2011; Duncan and Schroeckenthaler 2017; France-Mensah and O'Brien 2018; Harrison et al. 2019; Woldesenbet et al. 2016; Wu et al. 2012; Zhang et al. 2017). Research in the area is also limited on modeling multiple funding portfolios (France-Mensah et al. 2019). Furthermore, recent research has predominantly focused on highway pavements, with few research efforts focusing on airfield pavements (Di Mascio and Moretti 2019; Hajek et al. 2011). While pavement management concepts are broadly similar between airfield and highway pavements, it is important to recognize that the distresses experienced by each pavement type tend to vary significantly. Airfield pavements tend to experience a greater proportion of environmental-related distresses compared to highway pavements (Rushing et al. 2014; Synovec et al. 2019). The portfolio simulation described in this chapter helps to address portions of these current research gaps.

To develop the portfolio simulation, several algorithms, described herein, were developed to model the behaviors of approximately 109 decision-makers. The primary algorithm running the simulation is known as the BEAST. While the BEAST and its sub-algorithms are purpose-built to model behaviors and policies of the USAF, this chapter details its development in a manner that other organizations could utilize this research to develop a similar simulation for other networks of data. Additionally, this chapter summarizes the outputs from the BEAST utilizing the USAF's current airfield pavement management strategy. As described in the chapter, the USAF's current pavement management practices will continue to worsen the growing maintenance backlog and create an increased risk to its global flying operations.

6.2 BEAST Formulation

This section summarizes the components in the portfolio-level simulation developed and utilized throughout this research. The simulation is known as the BEAST. Figure 6.1 to Figure 6.5 are referenced throughout this section for clarity on how the various components work together to build the simulation. This section is broken up into three subsections: (a) inputs; (b) modeling building; and (c) simulation programming.

For perspective, the simulation includes the USAF's entire airfield pavement portfolio of 11,287 pavement sections across the world at 108 airfields. With 108 airfields maintained locally through the decentralized funding portfolio and centrally through the centralized portfolio managed by the AFIMSC, there are effectively 109 different decision-makers influencing the outcomes of the USAF's pavement portfolio (see Figure 5.2). The simulation models these 109 decision-makers and the two portfolios utilizing the USAF's current guidance and historical decisions. After detailing simulation development, this chapter concludes with an analysis of the simulation's modeling of the current pavement management strategies and practices.

It is important to note that these 109 decision-makers are not necessarily individual people. Within each of these organizations, there is clearly one senior decision-maker; however, there is also an underlying team of engineers and managers that collectively work to make decisions. Additionally, over the course of thirty years, the personnel in these organizations will change due to normal personnel hiring and retiring cycles. In comparison, state transportation authorities typically make similar decisions at the district (or comparable) level, where there are usually considerably less than 108 districts.

6.2.1 Inputs

As shown in Figure 6.1, simulation inputs can broadly be divided into three categories: (a) financial data; (b) regulations, instructions, and policies; (c) PAVER data. Due to the author's role in the USAF, the research was able to utilize actual financial data of historical expenditures and allocations within the centralized and decentralized portfolios. Due to the sensitivity of this information, the financial data was sanitized to a certain extent while still providing a realistic perspective on spending, budgeting, and allocations for airfield pavements.

As discussed previously, the USAF funds all preventative, corrective, stopgap, and major maintenance and repair from its overall facility sustainment account, officially known as the FSRM program. The FSRM program funds infrastructure maintenance of all real property in the USAF, including airfield pavements, roads, dorms, operations buildings, utilities, and structures.

As such, $1 billion in FSRM funding does not directly translate into $1 billion in funding for airfield pavement maintenance. Airfield pavements comprise about 19 percent of the USAF's overall sustainment requirements. While the actual expenditures vary annually, 19 percent is a good estimate for approximating allocations from a simulation perspective relative to recent historical expenditures. Year-to-year variation is a result of the centralized scoring model and decentralized prioritization discussed earlier that compete pavements with infrastructure requirements from other real property categories.

Applying the 19 percent assumption to the centralized portfolio is fairly straightforward; however, application is complicated to the decentralized portfolio. The decentralized portfolio, at the installation-level, funds more than preventative maintenance and small repair projects (e.g., service contracts, work order supplies, training, tools, etc.). As a result, the amount of decentralized funding that could potentially be utilized for airfield pavements is effectively a percentage of a percentage. With these factors in mind, an annual budget of $296 million was utilized to replicate USAF historical expenditures. Of the $296 million, approximately $223 million is allocated to the centralized portfolio. This $296 million budget involves decision making and prioritization by 109 organizations (108 USAF installations/airfields and the AFIMSC), and all of these organizations need to be appropriately modeled to build the most realistic simulation of current USAF airfield pavement investments and strategy (see Figure 6.1).

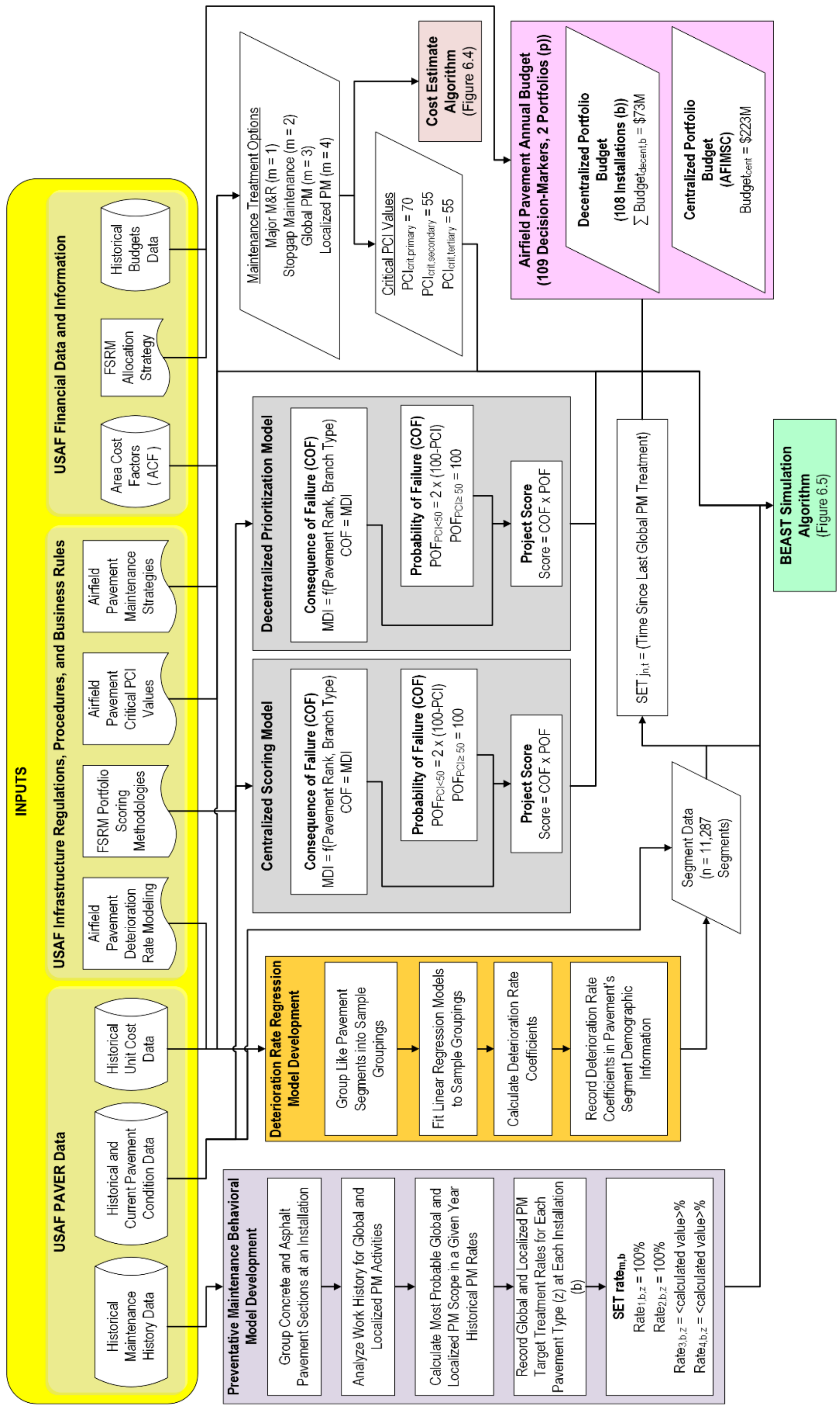


Figure 6.1 Overview of Status Quo Simulation

The USAF outlines its policies, procedures, and assumptions on pavement maintenance, economic analysis, area cost factors, inflation factors, centralized scoring model, and investment timing in a series of AFI, UFC, ETLs, and AFMAN (AFCEC 2014b; USAF 2015; USAF 2018; USAF 2019a; USAF 2019b; USACE 2004; USACE 2020). Historical unit costs used in the simulation are presented in a paper by Synovec and Howard (Synovec and Howard Forthcoming). Collectively this information forms the basis for decision-making, constraints, assumptions, and programming used to build the simulation and algorithms discussed in the next section.

The primary source of input data for the simulation was the USAF's PAVER database containing 11,287 pavement sections at 108 airfields around the world. While guided by the same previously discussed overarching asset management strategy, each installation manages its pavements differently based on competing priorities locally from other real property categories. For example, one installation may be disproportionately impacted by harsh summers and failing heating, ventilation, and air condition systems. The resulting outcome is this installation likely prioritizes its limited, decentralized funding towards mechanical systems as opposed to pavements. Conversely, an installation with fairly good infrastructure may be better able to fund pavement preventative maintenance. The underlying issue, in either case, is that each installation has different historical tendencies that would impact how much funding it expends on performing preventative maintenance on its airfield pavements. This historical behavior is crucial to model to appropriately understand how 108 different decision-makers spend their funding, and it is discussed in the next section.

The PAVER database contains the entire USAF's airfield pavement maintenance and condition records. The database includes multiple data points (current and historical) for its airfield pavements at the section-level of the network hierarchy. Within the USAF, a network (e.g., the airfield at Columbus AFB) is comprised of branches (e.g., Taxiway Alpha), which are comprised of smaller, distinctive areas or lengths of pavement known as sections (e.g., the first thousand feet of Taxiway Alpha) (AFCEC 2014b; Shahin 2005). While PAVER tracks multiple data points for each pavement section, the primary metric for tracking pavement deterioration is the PCI rating. The PCI rating is predicted over time by developing deterioration models based on fitting a regression model to historical PCI ratings and extrapolating the results over time. PAVER does not directly track or predict structural capacity over time.

6.2.2 Model Building

An essential step in building the simulation was forecasting pavement deterioration as impacted by various types of maintenance treatments and deferred maintenance. To mirror USAF approaches, the author utilized the process for developing the regression models outlined in ETL 14-3. The approach developed linear-regression deterioration models for each installation and subsequently further divided each installation into subgroups of similar pavement sections (e.g., all primary asphalt taxiway sections at Shaw AFB). The regression models were subsequently adjusted, using the methodology outlined in ETL 14-3, to account for changes in annual deterioration due to maintenance treatments and repairs (AFCEC 2014b). To allow the simulation to adjust PCI values based on maintenance treatments, a decision algorithm (that is part of RAMPSS) was created to apply the rules from ETL 14-3 to pavements based on decisions made by the simulation's course of action selection algorithm (see Figure 6.2).

Modeling the decentralized program relies upon characterizing the decision-making behaviors of the individual installations. While the hope is that all preventative maintenance is accomplished annually, the limited budgets, competing priorities, and unknown externalities influencing decisions often cause preventative maintenance for airfield pavements to be deferred.

A review of PAVER's historical maintenance data confirms this assumption. As such, the installation's historical behaviors were modeled in the context of a probability. In this sense, probabilities were established to predict whether each installation would perform localized preventative maintenance and global preventative maintenance on its asphalt and concrete pavements (categories include composite pavements based on exposed surface type), resulting in four probabilities per installation. The probabilities were applied to predict the level of preventative maintenance each installation performed with its decentralized budget, assuming each installation would prioritize primary pavements over secondary and tertiary (see Figure 6.1 and Figure 6.3). It was assumed, that an installation would perform 100 percent of its stopgap maintenance requirements, which is corrective maintenance to ensure flight safety on pavements that have already deteriorated beyond a critical PCI value.

The cost estimate algorithm estimates a course of action based upon area cost factors, historical costs, and USAF maintenance strategies. The latter two components were used to estimate unit costs related to PCI rating for asphalt and concrete pavements based on the USAF's recommended maintenance strategies. This methodology was used to estimate PCI-derived unit costs for each of the four USAF maintenance treatments: (1) major maintenance and recapitalization (M&R); (2) stopgap maintenance; (3) global preventative maintenance; and (4) local preventative maintenance. The unit costs associated with each strategy were adjusted for locality using area cost factors (see Figure 6.4). Note that conditions-based unit cost estimation techniques are not without fault, though, these techniques have been successfully utilized in several similar investigations (Alberti and Fiori 2019; Gao and Zhang 2013; Khiavi and Mohammadi 2018; Menendez et al. 2013).

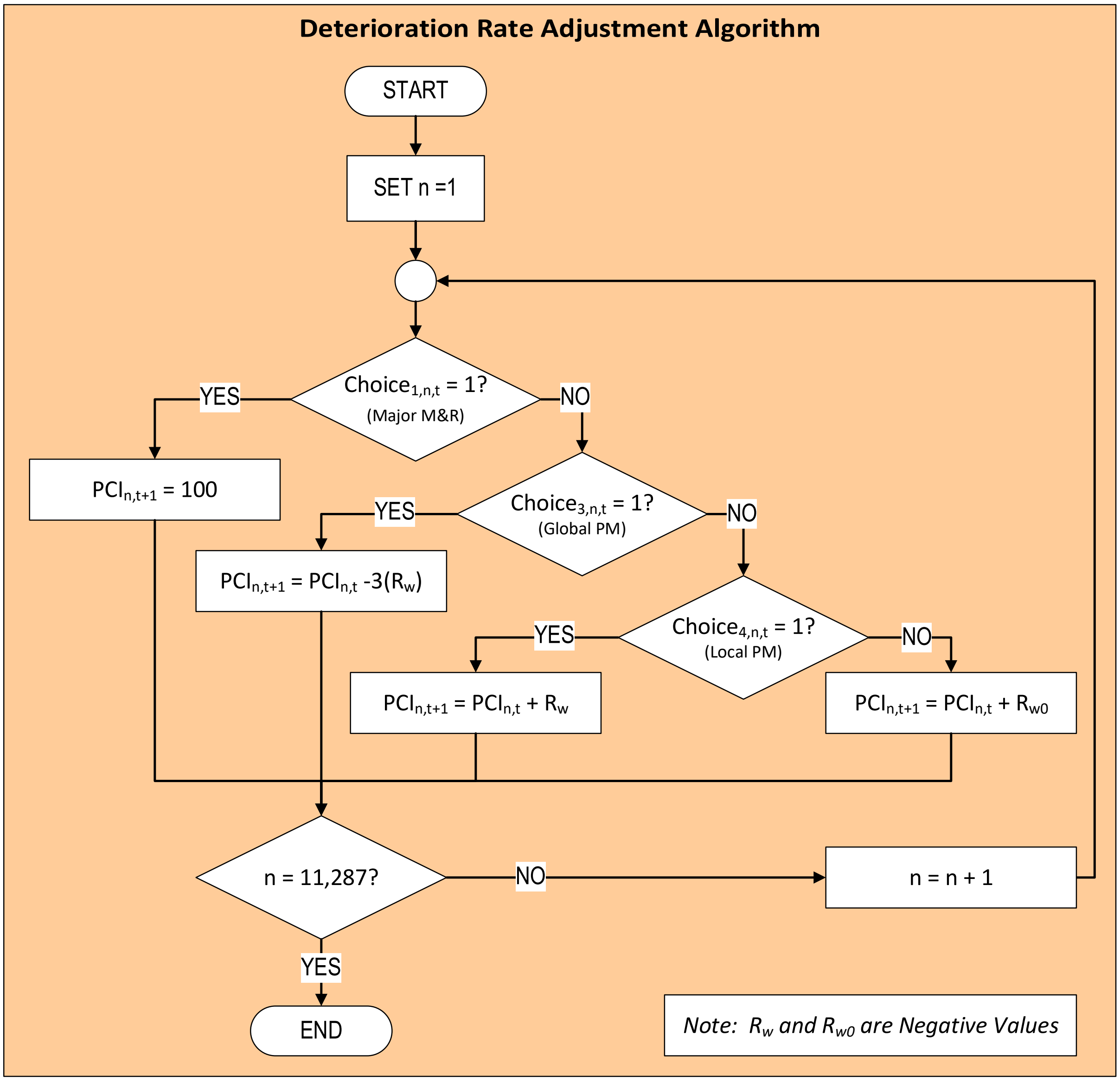


Figure 6.2 Deterioration Rate Adjustment Algorithm

To identify and prioritize annual requirements for each pavement section, Figure 6.3 works in conjunction with the BEAST to annually select treatments for every pavement in the portfolio. As shown in Figure 6.5, the BEAST identifies the appropriate maintenance strategy for a given PCI based on its PCI value and calculates a score for the given maintenance action in accordance with the scoring models shown in Figure 6.1. The BEAST then utilizes Figure 6.4 to calculate the cost of the maintenance action. Using the project score and cost estimate, the course of action selection algorithm then selects which requirements to fund based on available funding (see Figure 6.3). Projects are funded in a sequential manner (highest score first) until all yearly funding is depleted.

Within the decentralized portfolio, the course of action selection algorithm is utilized in the manner presented above but only considers similar projects at the same installation. The algorithm funds projects based on a combination of available funding and historical preventative maintenance probability. Due to probability considerations, some installations do not spend all of their decentralized funding. Decentralized funding is likely spent on maintenance other than paving, which matches the PAVER data and personal experiences by the author.

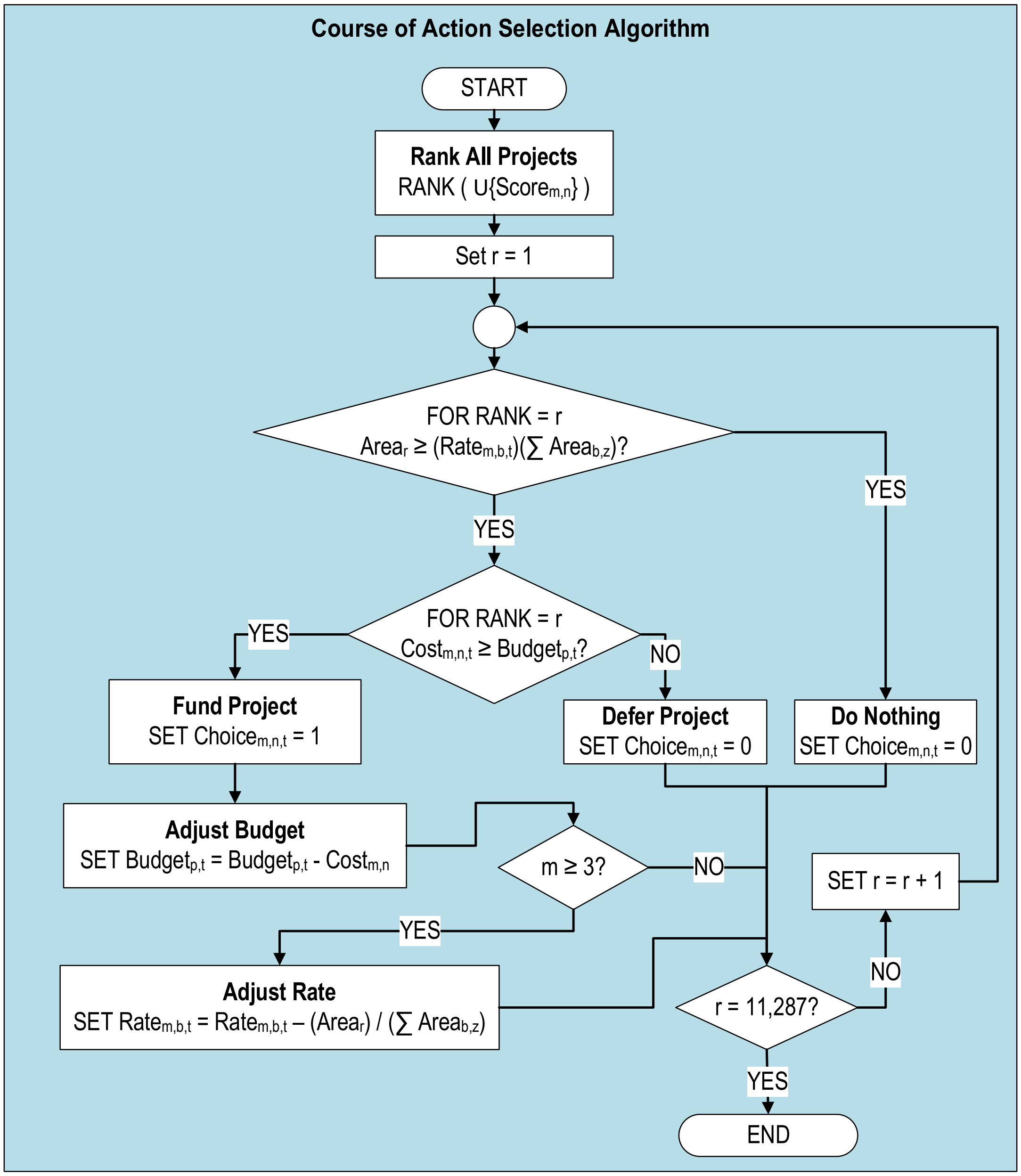


Figure 6.3 Overview of Course of Action Selection Algorithm

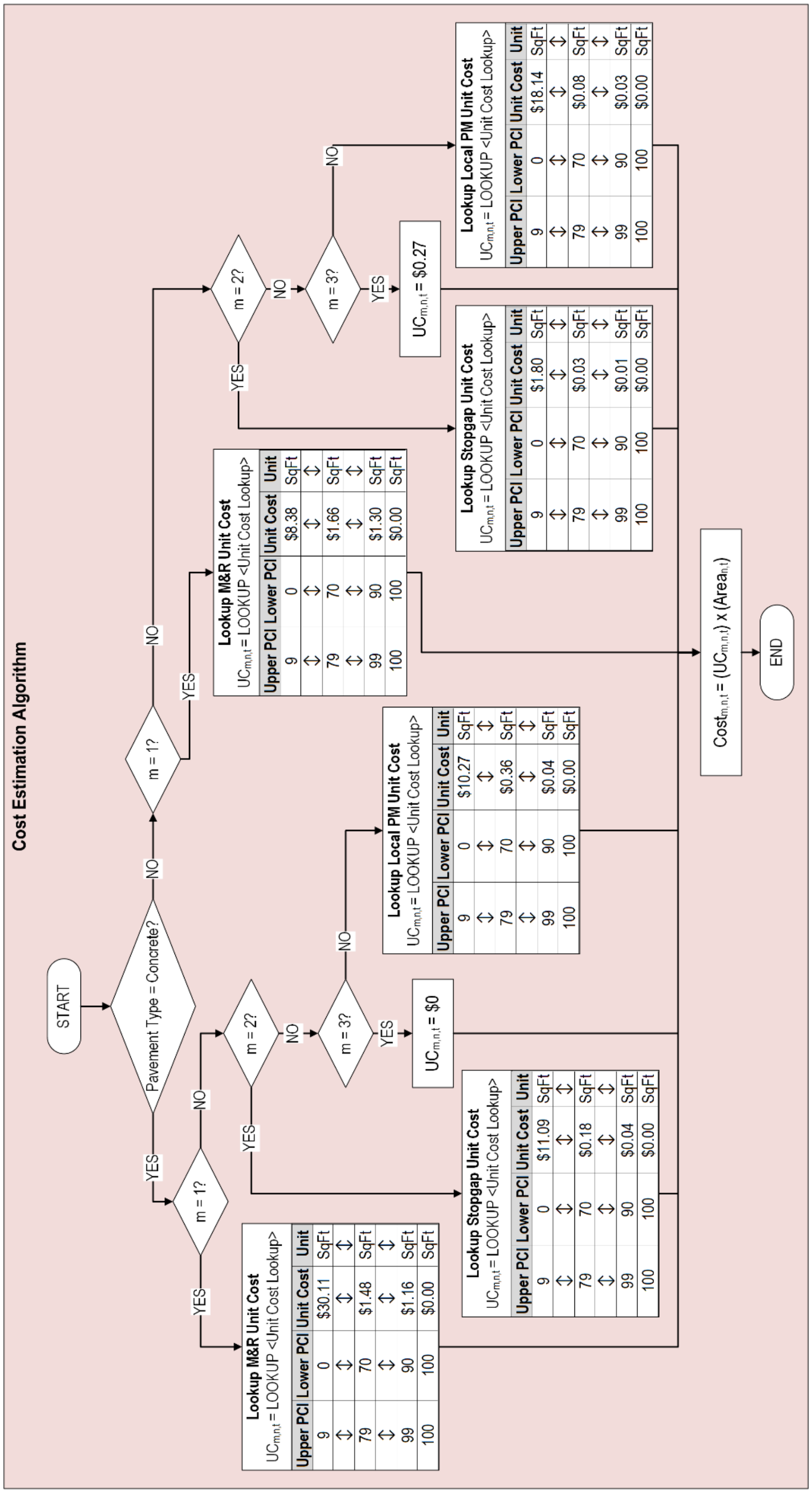


Figure 6.4 Overview of Cost Estimation Algorithm

6.2.3 Simulation Programming

BEAST (Figure 6.5) considers maintenance actions in sequential order to avoid double treatments in the same year and to more closely reflect reality. For example, stopgap maintenance is considered after major M&R actions, since repairing a failing section precludes the need for stopgap maintenance. However, if a failing section is not repaired, stopgap maintenance is considered and funded first ahead of all preventative maintenance actions to avert any flying operations safety-related issues.

After the simulation runs for a given year, the choices determined for that year through the four modules provide positive and negative impacts to pavement condition through their impacts on deterioration rates. The deterioration rate adjustment algorithm individually adjusts pavement section deterioration rates based upon the choices selected for that particular section by the simulation for a given year (Figure 6.2). The simulation continues this process for a thirty-year period to assess the long-term outcomes of current maintenance strategies. This simulation could be extended for longer periods with additional programming and computing time.

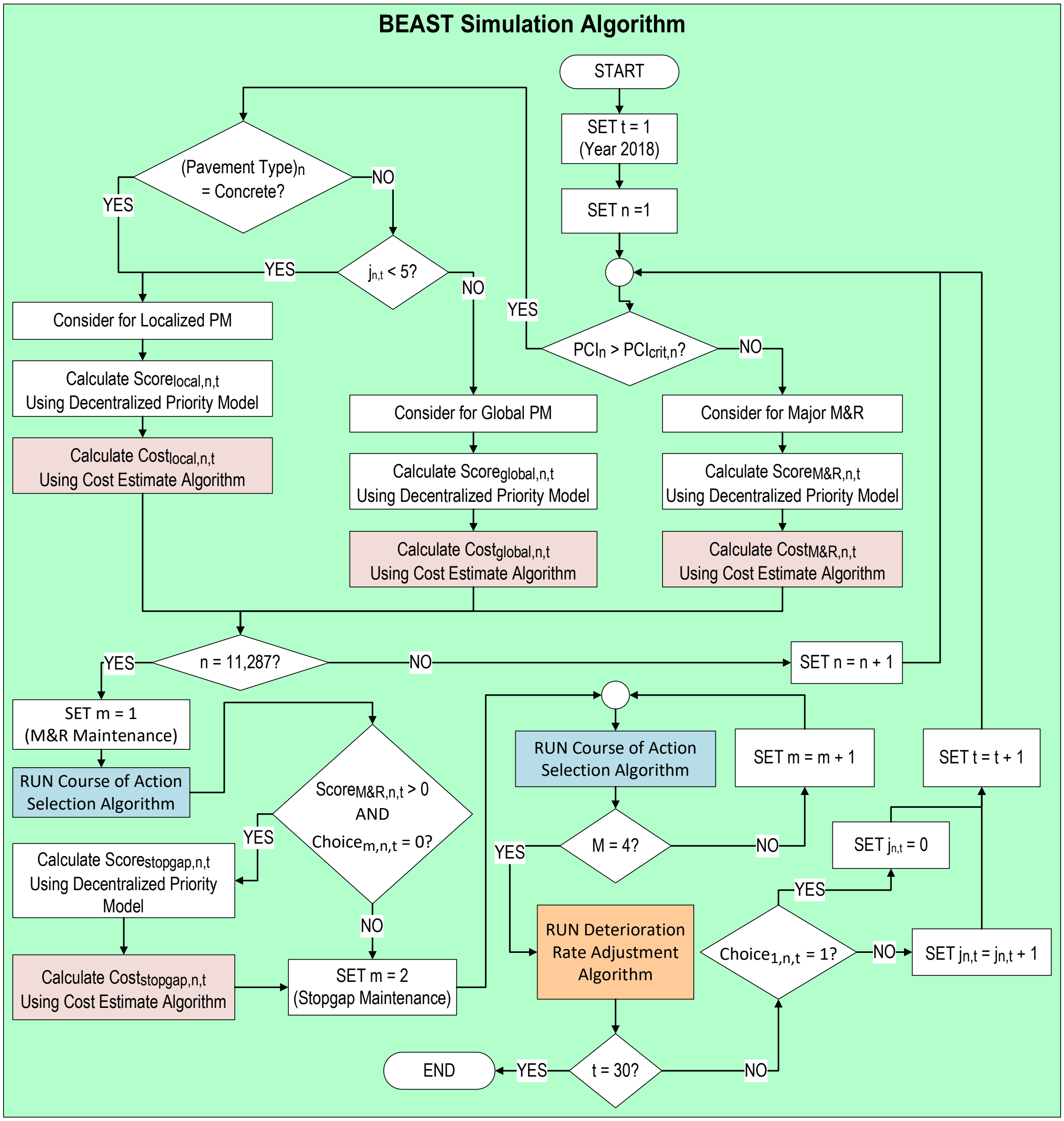


Figure 6.5 Overview of BEAST Simulation Algorithm

At the end of a yearly simulation, the model typically exhausts all available funding within the centralized portfolio and funds decentralized options up to the allocated funding at each installation. Within the decentralized portfolio, the simulation exhausts available funding at most installations; however, some installations with low or near zero probabilities associated with preventative maintenance would typically see a balance at the end of the simulated year. This balance, as it relates to an installation's maintenance probabilities, is representative of an installation electing locally to fund other non-pavement priorities (e.g., facility renovations).

6.3 Simulation Observations

Outputs from the BEAST for the status quo are shown in Figure 6.6 through Figure 6.8. As shown in Figure 6.6, the USAF's current investment strategies and business practices are likely to lead the continual degradation of its airfield pavements. The estimated backlog in the fiscal year 2018 is approximately \$2.3 billion; by 2048, the simulation indicates that this backlog will grow to approximately \$5.8 billion measured in constant-year 2018 dollars. The weighted average PCI rating for the USAF's airfield pavement declined from 83 to 64 over the same period. The primary driver for this trend is the current centralized scoring model that tends to target a "worst first" investment strategy. As pavement sections deteriorate, the cost of a major M&R project to recapitalize the section typically increases, as does the POF score. High POF scores (low PCI's) are prioritized under the current USAF business rules. Figure 6.7 shows as the percentages of airfield pavements with worsening PCI ratings increase, costs associated with deferred major M&R projects and maintenance actions grow.

Figure 6.8 compares timing between intended PCI values for major M&R actions and the simulation predicted PCI values. The USAF's pavement portfolio is routinely executing major M&R treatments at a median value of 18 points below the critical PCI value. The resulting cost of major M&R actions is close to an order of magnitude higher than it would be at or near the currently used critical PCI values. Increasing costs of major M&R actions reduce the number of pavement sections able to be treated annually. The result is a pavement portfolio that sees significant decreases in its overall condition (Figure 6.6) and a significant increase in pavements in poor, very poor, and failed conditions (Figure 6.7).

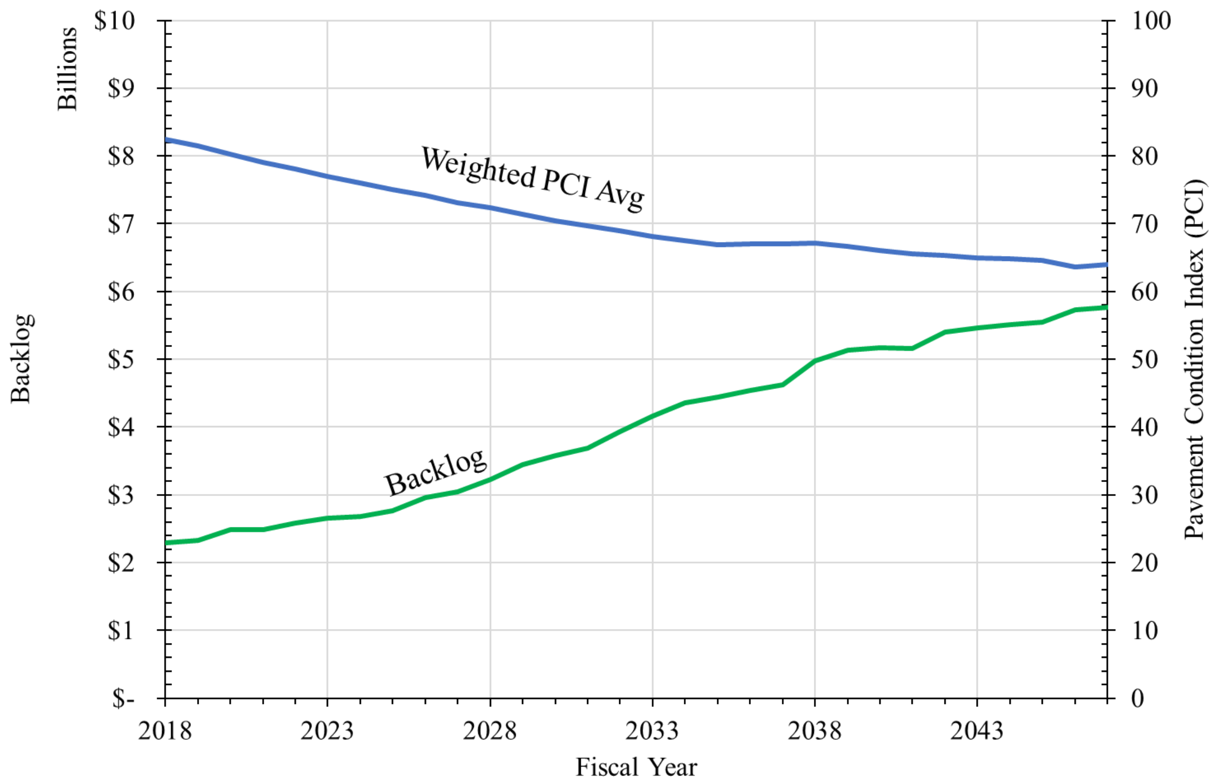


Figure 6.6 Status Quo Simulation Output Depicting Infrastructure Backlog and Weighted Average Pavement Condition Index Over Thirty Years

The simulation demonstrates that the current investment strategy is unsustainable at the current funding levels; however, a funding inflection point potentially exists that would make the current investment fiscally sustainable. Trials from this simulation estimate that the centralized portfolio needs roughly three times current levels to reverse growing trends of airfield pavement maintenance backlogs (i.e., 75 percent of the overall sustainment portfolio instead of 19 percent). Worsening conditions in other infrastructure categories would impact funding to airfield pavements (i.e., worsening facilities could wind up requiring larger percentages of funding from the centralized portfolio).

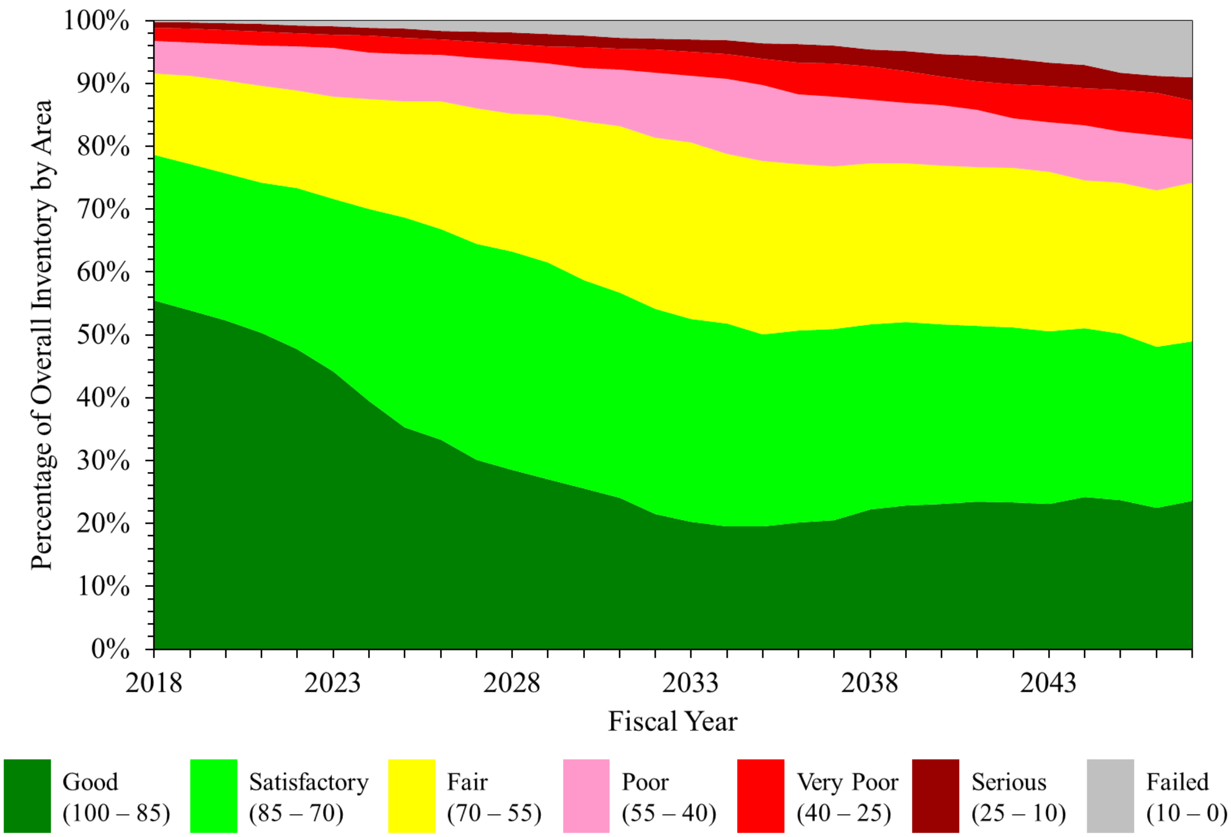
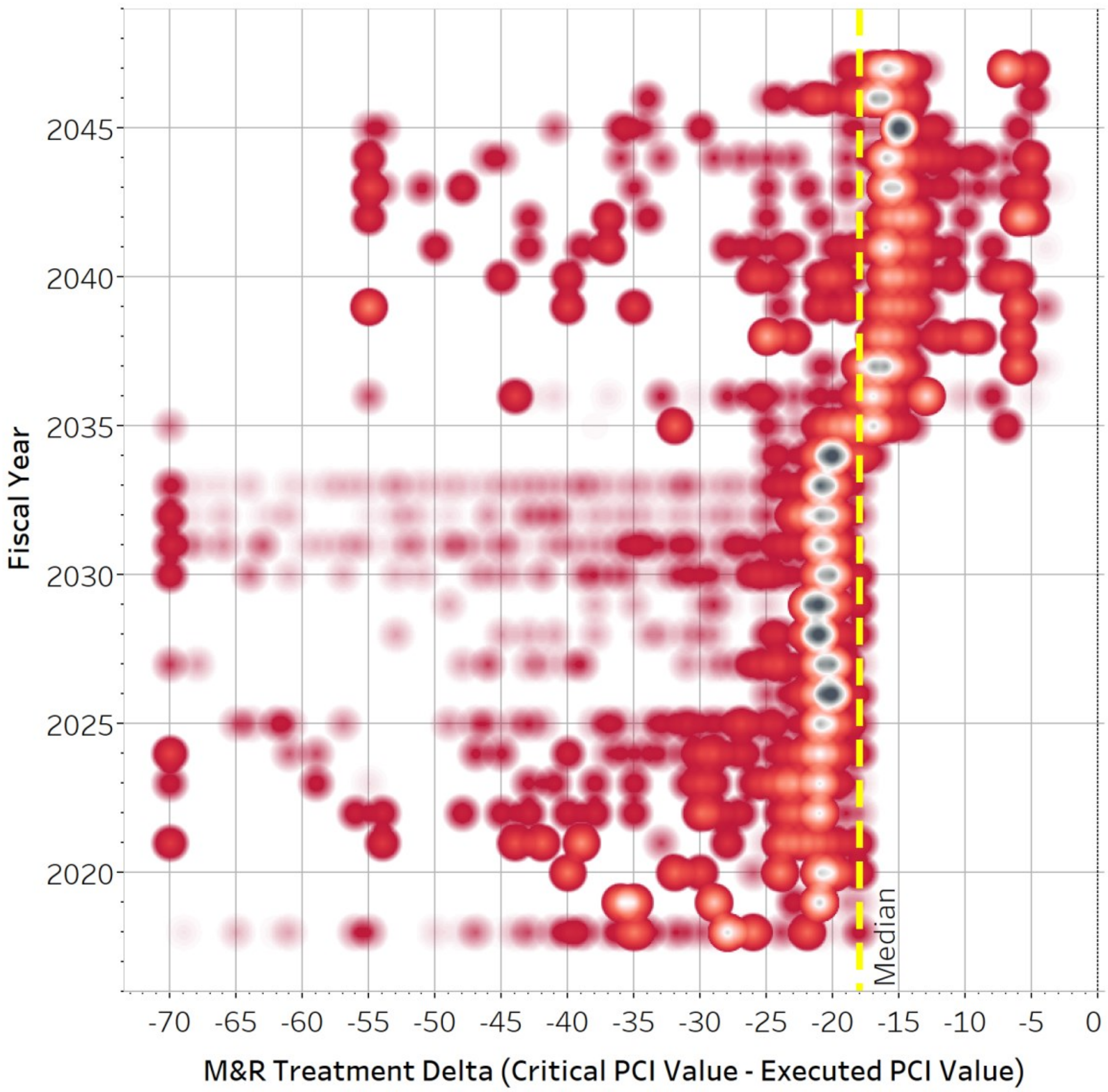


Figure 6.7 Status Quo Simulation Summary of Pavement Condition Index as a Percentage of the Overall Airfield Pavement Inventory by Area over Thirty Years



Notes: The Density Plot Above Depicts Funds Expenditute on Airfield Pavement Maintenance and Repair Actions Corresponding to the Pavement's PCI Rating at the time of Expenditure Relative to its Critical PCI Value. The Results are Based on the Simulation of the Current Status Quo Maintenance Strategies. Negative Values are Indicative of a Project that was Executed Below the Critical PCI Value. Scale Above is from Red to White to Black Corresponding to Low, Medium, and High Frequencies of Occurrences Respectively. A Yellow Dashed Line is Shown to Represent the Median Delta for all Years Combined.

Figure 6.8 Comparison of the Executed PCI Values for Major Maintenance Repair Projects Compared to the Critical PCI Value for the USAF's Status Quo Maintenance Strategy

6.4 Summary

The USAF operates and maintains a global infrastructure portfolio with a plant replacement value of approximately $263 billion located at 1,707 sites worldwide having 1.6 billion square feet of paved surfaces; its airfield pavement portfolio alone is 169 times larger than Hartsfield-Jackson Atlanta International Airport (AFCEC 2020b; DUSD (I&E) 2017; Wilson and Goldfein 2019). The USAF infrastructure portfolio is facing a crisis due to its growing backlog of deferred maintenance requirements that already exceeds $33 billion, with a sustainment budget that has remained consistently stagnant and underfunded (Mills et al. 2017; Wilson and Goldfein 2019).

While the USAF has invested in asset management for almost two decades, given the current infrastructure crisis, it appears evident that its strategy is not producing the intended results. A large part of the issue is its centralized portfolio (used by the USAF to fund maintenance and repair projects over $2 million across all infrastructure categories) effectively utilizes a worst-first resource allocation strategy, due to the scoring model that typically awards the highest project scores to pavements with the lowest PCI ratings (Synovec et al. 2019). The result of this construct is an asset management strategy that routinely invests in pavements with significant deterioration and defers maintenance on pavements in less deteriorated states. As shown in Figure 6.9, over time, this strategy leads to a scenario in which the USAF's airfield pavement portfolio condition (as measured by weighted average PCI rating) is projected to collectively decline approximately 19 points. While the USAF's current infrastructure investment strategy is billed as a "risk-based" approach that seeks to reduce risk to operations, it does so by trading investment in deteriorated assets that produce immediate-term benefits for repairs in assets with less deterioration and long-term benefits (Menendez et al. 2013; Mills et al. 2017). As projected by the BEAST, the USAF's current maintenance strategy (i.e., status quo) is unsustainable and would likely lead to significant operational impacts.

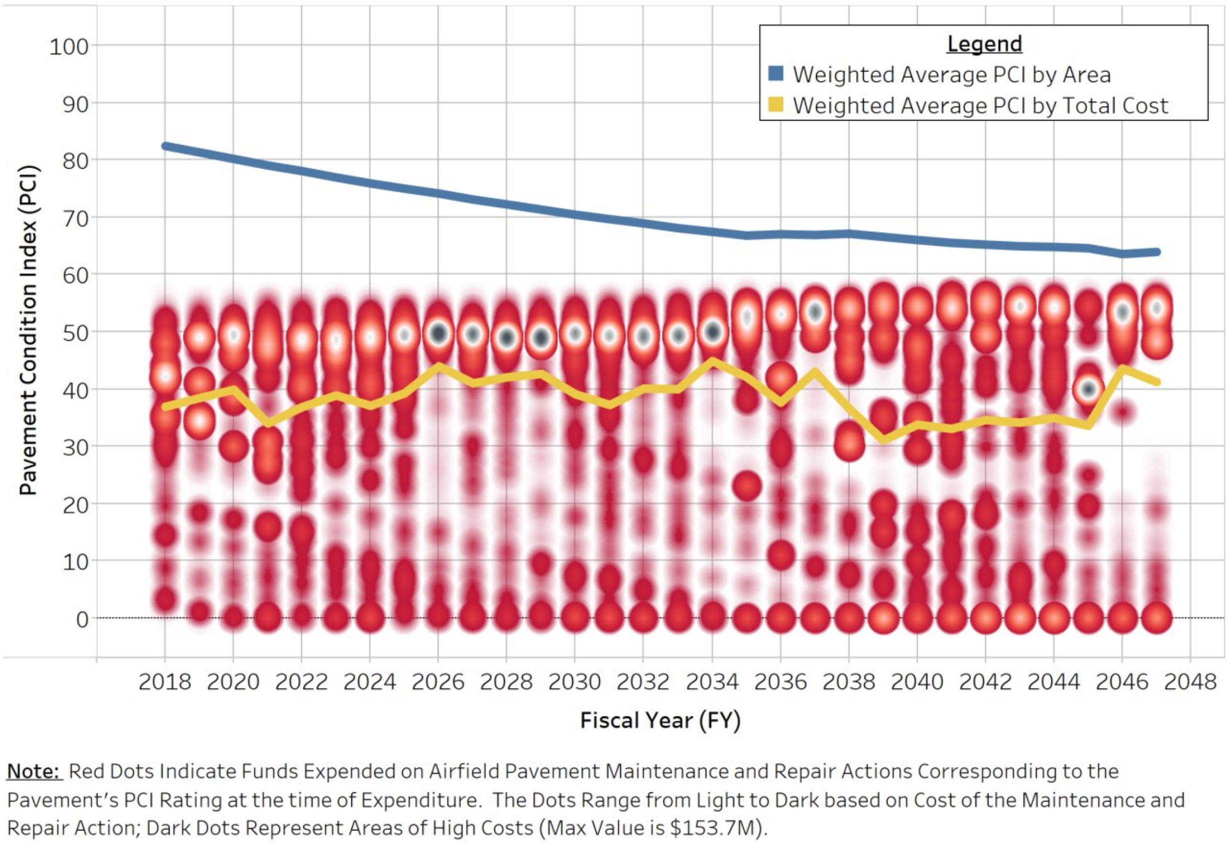


Figure 6.9 Simulation Output Summary of the USAF's Stats Quo Maintenance Strategy

CHAPTER VII

DEVELOPMENT OF THE RAPID ASSET MODELING OF PAVEMENT SUSTAINMENT STRATEGIES ALGORITHM AND RECOMMENDATIONS TO REDUCE THE TOTAL COST OF OWNERSHIP FOR THE U.S. AIR FORCE

This chapter contains portions of a technical paper that was submitted for publication to a peer-reviewed journal. As of the date of this dissertation, the manuscript (Synovec and Howard Forthcoming) is still in review. While there are similarities between the journal article and this chapter, the content has been substantially reorganized, reformatted, and edited to meet Mississippi State University's dissertation formatting guidelines and the flow of the overall dissertation.

7.1 Introduction

The objective of this chapter is to detail the development of an automated methodology to individualize maintenance strategies for a global (or comprehensive) pavement portfolio. This research addresses gaps in the literature on optimizing large-scale pavement portfolios and airfield pavements, which is discussed more comprehensively later in the chapter. While this methodology is heavily focused on the USAF and airfield pavements, this research could be used more broadly by other transportation authorities with large pavement portfolios. As such, every effort was made, where possible, to provide the information herein to recreate this research in other scenarios.

The research presented herein is part of a larger research effort to help address this research gap and develop an asset management strategy that the USAF can utilize to implement the lowest life-cycle cost approach throughout its entire global airfield pavement inventory. While the larger research effort focuses on reducing the cost of ownership and increasing the overall condition within its current budgetary constraints, directly optimizing such a large portfolio would be impractical due to operational and budgetary complexities and the formidable computing time and power required. As such, this chapter presents a methodology to utilize simulation techniques to optimize the maintenance recommendations of the "parts" to optimize the "whole." While the discussion and analysis are heavily focused on the USAF, the concepts and methodologies presented herein can be beneficial to other agencies that are looking for ways to implement the lowest life-cycle cost strategies.

7.2 Objective, Scope, and Methodology

The problem facing the USAF's airfields was not developed overnight, and it will not be solved overnight. The problem is not insurmountable, but it will take a deliberate reassessment of the entire infrastructure investment program (see Figure 5.2), particularly as it relates to work planning and budget allocation. This research effort document herein is specially focused on the work planning component. As such, the objective of this research as noted earlier in this chapter is to develop individualized maintenance strategies for all pavement sections in the USAF's airfield inventory that reduce the cost of ownership of the section by utilizing cost-effective maintenance strategies and timing for major M&R actions (i.e., critical PCI values). The intent behind the decision to individualize maintenance strategies was to develop a methodology that allowed individual sections to be assessed to provide specific recommendations to achieve the lowest life-cycle cost-driven strategy. The aggregation of all the individual recommendations would, in theory, produce the lowest life-cycle cost strategy for the USAF's airfield pavement portfolio. In subsequent chapters in this dissertation, the aggregated maintenance strategies are used to revise the budget allocation strategy and simulate long-term outcomes of the USAF's pavement portfolio.

The vast majority of recent research on work planning recommends utilizing optimization techniques (Aleadelat et al. 2020; Denysiuk et al. 2017; Hafez et al. 2019; Khiavi and Mohammadi 2018; Saha and Ksaibati 2018; Zhang et al. 2017). As previously discussed, these optimization techniques have limitations that make them potentially impractical or difficult to implement within the USAF's infrastructure investment strategy. Furthermore, with 109 decision-makers and airfields around the world, the pavement portfolio, with its multiple funding sources, business rules, and varying prioritization approaches, is a rather complicated and complex environment that is better suited for a simulation environment. This is particularly relevant as the USAF is more interested in understanding long-term outcomes as it relates to decisions over time, impacting its entire pavement portfolio. As such, simulation techniques appeared to be the most appropriate methodology for achieving the research objective.

The simulations were able to model every possible combination of maintenance strategies and critical PCI values (within the range of variables used in the simulation) for every pavement section in the USAF's portfolio over a fifty-year evaluation period. Given the range of variables used in the simulation, there were 184 potential solutions for each pavement section (four maintenance strategies and 46 critical PCI values; described in the next section). The algorithm (described in the next section) selects the solution with the lowest EUAC as the recommended maintenance strategy and critical PCI value for the trial pavement section. The remaining sections of this chapter describe the simulation framework, outcomes, findings, and recommendations.

7.3 Simulation Framework

This section is divided into three subsections detailing the three main components of the simulation framework used herein. The main components are inputs, deterioration rate regression modeling, and the RAMPSS algorithm. The RAMPSS algorithm is ultimately the engine that drives the simulation, decision-making process, and maintenance strategy selection. These components and framework are presented visually in Figure 7.1 and Figure 7.2 to depict the processes and relationships on the components and subcomponents of the framework.

7.3.1 Inputs

As shown in Figure 7.1, inputs to the simulation framework fall into three broad categories: PAVER data, financial data, and USAF rules, procedures, and regulations. PAVER is the DoD's sustainment management system of record for pavements (AFCEC 2014b). Furthermore, PAVER is widely used by transportation authorities outside of the DoD, particularly for airfield pavements (Hajek et al. 2011). While airfield pavements are fully inventoried in PAVER and contain available historical records for each pavement section, the USAF is still working on fully utilizing PAVER for road sustainment. Airfield data is collected and included on a recurring five-year cycle through a service contract, with the recommendation that each installation should continue to update its PAVER data between the five-year contract assessments (USAF 2017c).

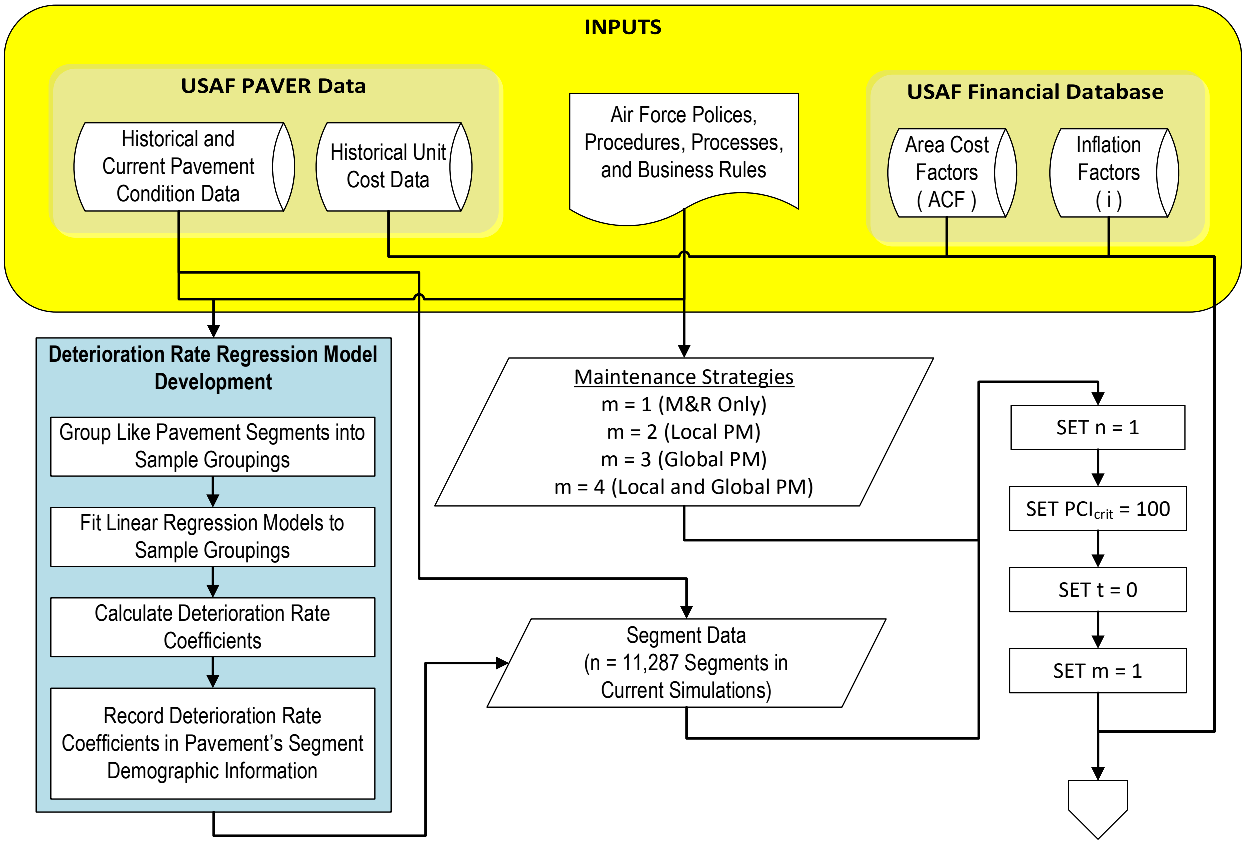


Figure 7.1 Lowest Life-cycle Cost Maintenance Strategy Determination (Part 1)

The recurring five-year assessments consist of a PCI survey of the entire airfield, updates to the work history and distresses in PAVER, and utilization of tools within PAVER to generate recommended work planning actions that are published in a survey report. The work history and distress data are recorded in PAVER for the current assessment and, when available, for prior assessments. This historical documentation provides an ability to look back over the available history to track deterioration rates and comparable trends. The recommended maintenance actions in the report are typically short-term in nature and assume an unconstrained budgetary environment. PAVER estimates the cost of these recommended maintenance actions using historical unit cost data. At the network-level, these costs (as shown in Table 7.1) are presented as a unit cost per square foot as a function of PCI value, surface type, and maintenance treatment option (see Table 5.1 for a description of the maintenance options). While this type of conditions-based unit cost technique is not without fault, it has been successfully used in other studies aimed at optimizing pavement maintenance (Alberti and Fiori 2019; Gao and Zhang 2013; Khiavi and Mohammadi 2018; Menendez et al. 2013).

Table 7.1 Summary of Unit Cost Data Used by RAMPSS in Cost per Square Foot

PCI Value	Asphalt			Concrete		
	Local PM	Global PM	Major M&R	Local PM	Global PM	Major M&R
0	$18.14	$0.27	$8.38	$10.27	$0.00	$30.11
10	$12.25	$0.27	$8.38	$5.81	$0.00	$30.11
20	$6.62	$0.27	$8.38	$3.10	$0.00	$30.11
30	$1.85	$0.27	$8.38	$1.70	$0.00	$30.11
40	$0.59	$0.27	$8.38	$1.00	$0.00	$30.11
50	$0.40	$0.27	$1.98	$0.71	$0.00	$5.20
60	$0.17	$0.27	$1.75	$0.49	$0.00	$2.74
70	$0.08	$0.27	$1.66	$0.36	$0.00	$1.48
80	$0.03	$0.27	$1.30	$0.14	$0.00	$1.26
90	$0.03	$0.27	$1.30	$0.04	$0.00	$1.16
100	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00

The USAF outlines its work planning guidance for airfield pavements in a series of documents with the primary guidance documents being an ETL 14-3 and UFC 3-270-08, *Pavement Maintenance Management*. ETL 14-3 provides USAF-specific guidance on developing a preventative maintenance plan and deterioration models (AFCEC 2014b). UFC 3-270-08 provides broad-DoD guidance on performing economic analysis of M&R alternatives and the use of PAVER's internal reports and features (USACE 2004).

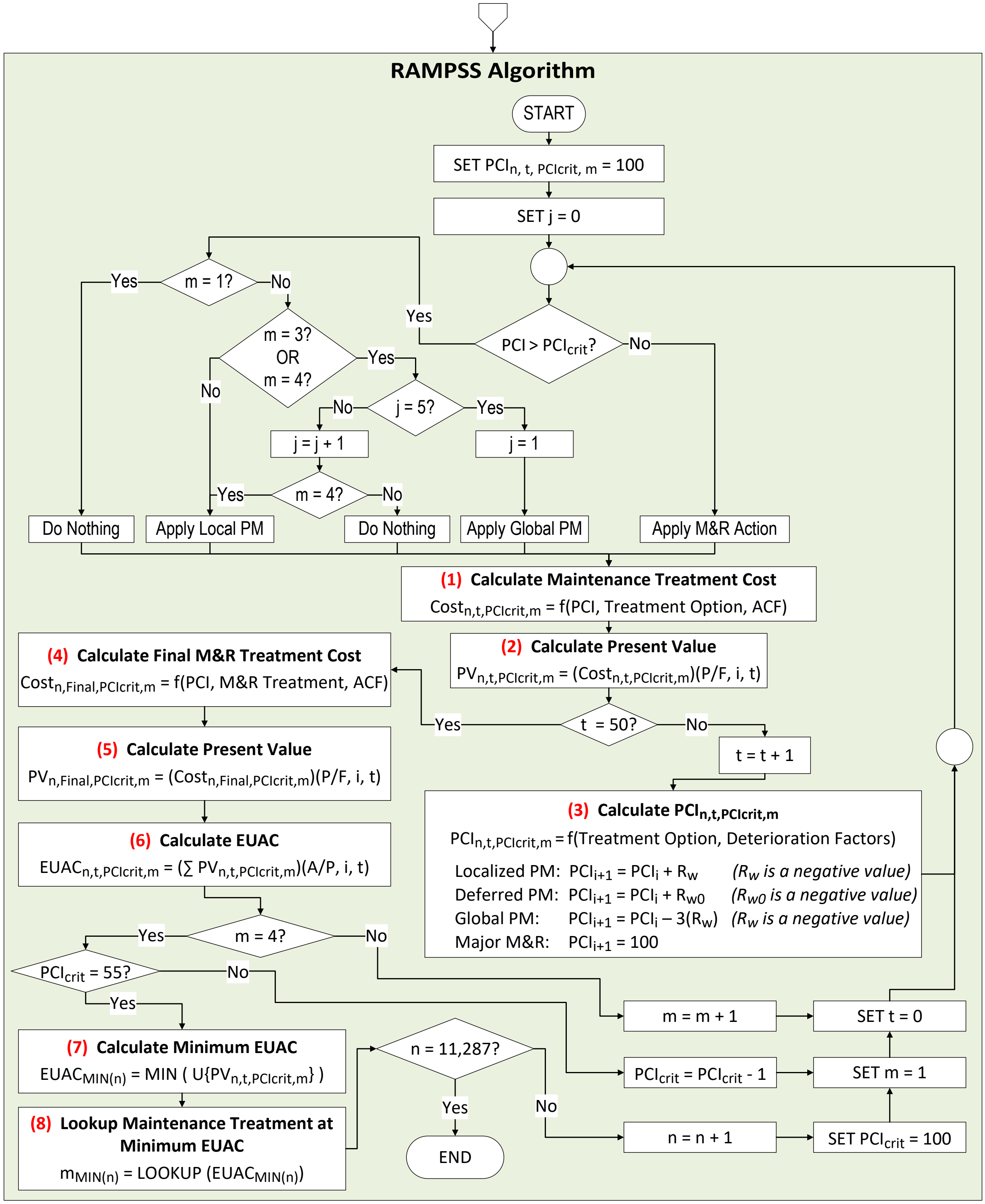


Figure 7.2 Lowest Life-Cycle Cost Maintenance Strategy Determination (Part 2)

In addition to the discipline-specific guidance documents referenced in the previous paragraph, the simulation referenced several financial regulations and manuals to ensure the economic analysis complied with USAF and DoD standards (USAF 2018; USAF 2019a; USACE 2020). These documents provided information on official area cost factors and inflation factors. For this research, an inflation rate of two percent was used for converting current-year dollars to past-year dollars and vice versa; two percent is a standard rate prescribed for infrastructure-related economic analysis.

7.3.2 Deterioration Rate Modeling

Deterioration rates for each pavement section were calculated using the USAF's current methodology, which utilizes linear regression modeling to estimate deterioration rates for a given pavement family (AFCEC 2014b). Pavement families combine like pavement sections together for analysis based on shared characteristics. For example, a pavement family could be all primary asphalt pavements at a given airfield. As part of the analysis, all pavement sections were assigned to families specific to each airfield. Based on sample sizes, some airfields were able to be divided into multiple families; however, the smaller airfields typically were only able to be divided into two families (i.e., asphalt and concrete pavements).

Using the methodology prescribed by the USAF in ETL 14-3, the deterioration modeling module in PAVER was used to develop a series of linear regression deterioration models that were incorporated into a lowest life-cycle cost algorithm. The slope of the linear regression model represents the annual deterioration rate (R_w) in terms of PCI points lost per year with recommended localized preventative maintenance actions completed. ETL 14-3 outlines a process to adjust R_w based upon deferred localized preventative maintenance actions. This revised annual deterioration rate (R_{w0}) is primarily a function of climate zone. It is intended to replicate an increased deterioration rate associated with the deferral of service life-extending preventative maintenance. For global preventative maintenance actions, the USAF assumes treatment actions provide a three-year service life extension over the service life predicted using the R_w deterioration rate (AFCEC 2014b). From a modeling standpoint, the service life extension was incorporated by adding an equivalent value of three times the R_w rate to the PCI rating at the time of treatment during the simulation. The deterioration models assume that major M&R actions would restore the pavement to a 100 PCI rating due to the typical scope of these projects. The equations used to adjust PCI values based on applied maintenance treatments are shown in Box 3 of Figure 7.2.

7.3.3 RAMPSS Algorithm

The RAMPSS algorithm is a series of logic decisions, data tables, and Visual Basic for Applications (VBA) code based in Microsoft Excel that automates the simulation and analysis processes. An overview of the RAMPSS algorithm is shown in Figure 7.2, which is a continuation of Figure 7.1; the reference point between the two figures, indicating the transition between the two figures, is the pentagon shape. Additionally, red numbers are used in Figure 7.2 to identify key equations and processes; these numbers are referenced throughout the narrative (generally as Box 1, Box 2, and so forth) discussion to help link the discussion and the RAMPSS algorithm. Excel was chosen as the analysis platform due to its widespread and approved use throughout the USAF, which supports implementation. With the simulation environment and inputs ready, RAMPSS, which is housed in a single file, runs the simulations for the entire USAF airfield pavement portfolio in about 15 minutes on a standard computer.

As a general note, the inputs are formatted as a data table and copied to the inputs tab in the spreadsheet containing the RAMPSS algorithm and its VBA code. As the VBA code runs, it pulls data from this inputs tab to run through the RAMPSS algorithm and outputs the results into an outputs tab. The primary inputs to the RAMPSS algorithm from the inputs tab are pavement type (construction, feature class, and rank), section size, deterioration rates (as discussed in the previous section), and location (see Table 7.2). As a general note, the author included additional fields in his inputs tab, but these fields additional fields are primarily descriptive in nature and used in conjunction with the RAMPSS output for analysis purposes. That said, the data shown in Table 7.2 is fictionalized as an example to represent the minimum data required to run the RAMPSS algorithm. The RAMPSS algorithm is programmed to calculate additional fields it needs from this minimum data set. As an example, the RAMPSS algorithm uses R_w and the location to calculate R_{w0}, as previously discussed. To save computing time, R_{w0} could be added directly as an input variable. Whether an organization uses PAVER or not, these inputs could be generated by most pavement management systems to recreate or utilize the RAMPSS algorithm for another organization.

Table 7.2 Example RAMPSS Algorithm Minimum Input Data

Unique Identifier (UID)	**Location**	**Feature Class**	**Pavement Rank**	**Pavement Construction Type**	**Section Size** ***(Sq Ft)***	**Historical Deterioration Rate (R_w)** ***(PCI Points/Yr)***
1508	Shaw AFB, SC	Runway	P *(Primary)*	Concrete	100,000	-0.89
5680	Luke AFB, AZ	Taxiway	S *(Secondary)*	Asphalt	80,000	-1.96

The first part of the RAMPSS algorithm is work planning. The algorithm automatically selects the appropriate maintenance action based upon the PCI value of the pavement and the maintenance strategy being used for this particular trial. As shown in Figure 7.1, the four preventative maintenance strategies used in the simulation were: (a) no preventative maintenance; (b) annual localized preventative maintenance actions only; (c) global preventative maintenance actions only accomplished on a five-year frequency (default frequency in PAVER); and (d) global and annual localized preventative maintenance. It is important to note that all four strategies rely on major M&R actions once the pavement has deteriorated beyond the PCI_{crit}. As such, the first decision the RAMPSS algorithm makes for each pavement during a trial run is to determine whether the pavement's PCI is beyond the PCI_{crit} value. If the PCI is still above PCI_{crit} value, the algorithm then works through a series of logic statements to determine which maintenance treatment is required. PCI_{crit} values for the simulation were assessed varying values from 100 to 55 (46 possible PCI_{crit} values). 55 was selected as the lower bound, as it is the dividing line on the PCI rating scale between "fair" and "poor" pavements (ASTM International 2018). It is also the current PCI_{crit} value used by the USAF for secondary and tertiary airfield pavements (AFCEC 2014b).

Each combination of PCI_{crit} value and maintenance strategy (represented in Figure 7.2 by the variable "m") (184 combinations) for each pavement (represented in Figure 7.2 by the variable "n") was evaluated for a fifty-year simulation period. Time was represented in Figure 7.2 by the variable "t." As a general note, the variable "j" was used for a special time counter within the algorithm to monitor the recurring interval for global preventative maintenance treatments. Once "j" reached a value of five, the RAMPSS algorithm would execute a global preventative maintenance treatment commensurate with the five-year interval stipulated in the maintenance strategy.

With regard to the decision to use a 50-year simulation period, various evaluation period lengths were evaluated and, ultimately, 50 years was determined to provide a suitable assessment period for understanding how the maintenance strategies impact the pavement and EUAC over time. While the DoD utilizes a 20-year design life for its pavements, approximately 58 percent of USAF airfield pavements have exceeded their design life without major M&R actions (Synovec et al. 2019; USACE 2001). As such, this type of analysis needs to model an evaluation period that is long enough to simulate at least one or two major maintenance and rehabilitation actions per maintenance strategy. When considered with the individualized deterioration rates, a fifty-year evaluation period seemed reasonable in the RAMPSS algorithm to accomplish this goal. For comparison, the FHWA recommends modeling highway pavements for some time between 20 to 40 years (Zimmerman et al. 2019).

Additional simulation period lengths were evaluated for comparison to a 50-year duration. For the vast majority of pavement sections, the EUAC curve over time tended to flatten around the fifty-year point, such that the results and outcomes saw insignificant changes (i.e., the EUAC value decreased slightly, but the recommended PCI_{crit} value and maintenance strategy remained unchanged). Between 20 to 40 years, the outcomes were subject to the most change, and depending on which simulation period length was used, the recommended PCI_{crit} value and maintenance strategy typically changed.

After the RAMPSS algorithm identified the maintenance action, it calculated the cost of the maintenance action using the historical unit cost data from PAVER (see Table 7.1) and area cost factors from UFC 3-701-01 (USACE 2020). This step is identified in Box 1 in Figure 7.2. Using the USAF's prescribed inflation factors, the RAMPSS algorithm converted the past-year maintenance cost to a present value in current-year dollars (Box 2 in Figure 7.2). The present value was then saved and used to calculate the EUAC after the fifty-year simulation period had finished for the given trial. With the simulated maintenance action executed, the RAMPSS algorithm used deterioration modeling information for the given section to adjust the PCI value for the subsequent simulation year (Box 3 in Figure 7.2). This process continued for fifty years until the trail was complete for the section with the combination of PCI_{crit} value and maintenance strategy. Lastly, as prescribed in UFC 3-270-08, the RAMPSS algorithm incorporated the major M&R cost to restore the pavement at the end of the 50 years to a 100 PCI rating into the EUAC calculation for the given trial (Box 4 in Figure 7.2). This step was accounted for the unrealized cost that would eventually occur outside the simulation period. The final major M&R cost calculation is converted to a present value (Box 5 in Figure 7.2) to allow it to be incorporated into the EUAC calculation (Box 6 in Figure 7.2).

The RAMPSS algorithm performed this analysis repeatedly for a given section until it evaluated all possible combinations, producing 164 possible solutions. Subsequently, the RAMPSS algorithm would then select the recommended maintenance strategy and PCI_{crit} value for the pavement section based upon the solution with the lowest EUAC (Box 7 and Box 8 in Figure 7.2). In cases where the RAMPSS algorithm encountered a tie in EUAC values, the algorithm used the highest PCI_{crit} value as the tiebreaker. The logic for this tiebreaker rule was to reward a maintenance strategy for producing the same cost savings at a higher PCI rating and pavement condition. Once these steps were complete for a given pavement section, the RAMPSS algorithm repeated the evaluation process for all 11,287 pavement sections in the network.

7.4 Analysis and Findings

Figure 7.3 shows typical outputs from the RAMPSS algorithm for a given pavement section. This particular section is a primary asphalt pavement located on the secondary runway of a major USAF airfield in a wet-freeze climactic region. As shown in the right graph of Figure 7.3, the RAMPSS algorithm recommends a recurring global preventative maintenance approach to maintain this section with a PCI_{crit} value of 67. The global preventative maintenance curve becomes flat at this PCI_{crit} value, which is indicative of a tie for the lowest EUAC. As previously mentioned, the RAMPSS algorithm breaks ties by selecting the lowest EUAC at the highest PCI_{crit} value.

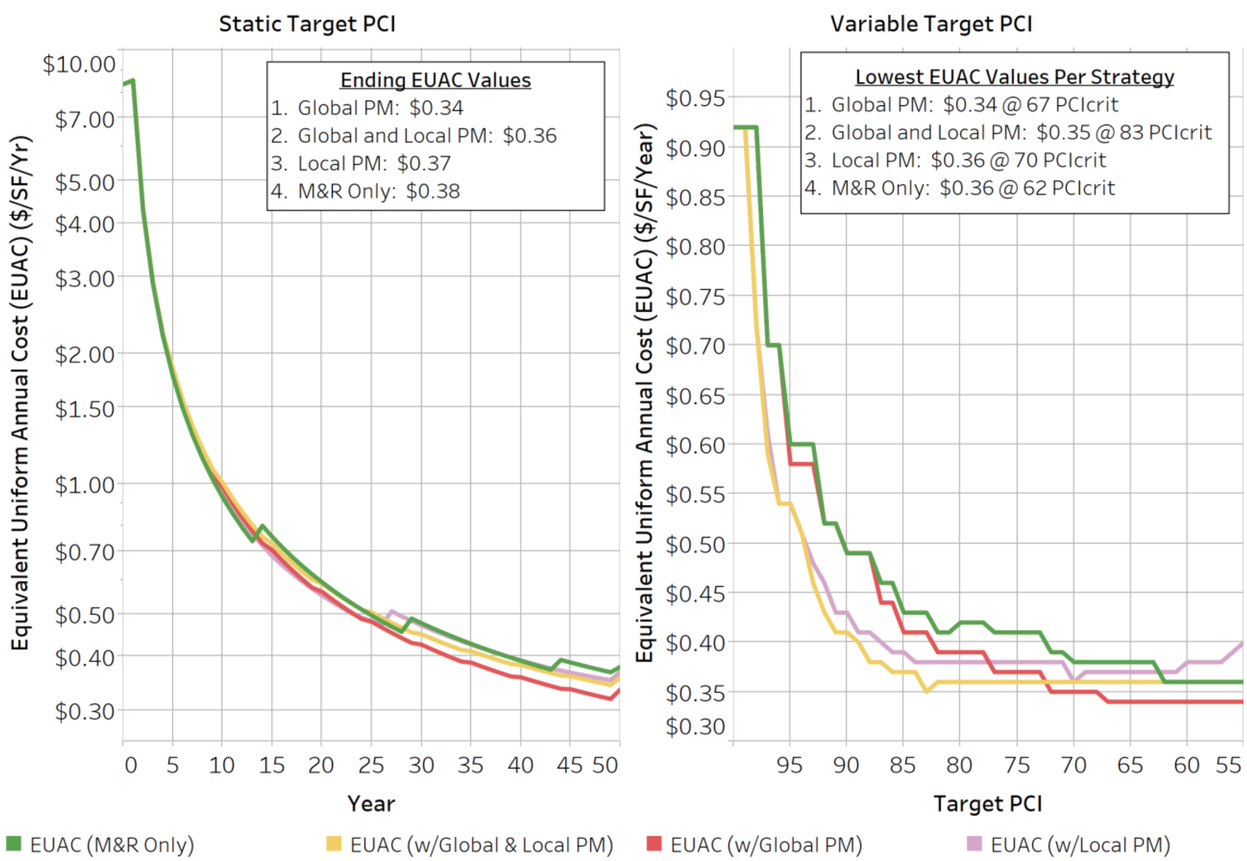


Figure 7.3 Lowest Life-Cycle Cost Maintenance Strategy Determination Output for Individual Airfield Pavement Section

While the right graph in Figure 7.3 depicts the lowest EUAC at fifty-years for each maintenance strategy at the various PCI_{crit} values, the left graph shows the time-dependent curve of the same pavement section and maintenance at a static PCI_{crit} value of 67. The left graph allows for the visualization of how the maintenance recommendations are impacted by time (i.e., if the simulation period were shorter, a different maintenance strategy may become the most cost-effective). In the case of this particular pavement section at PCI_{crit} value, the global preventative maintenance strategy is not the most cost-effective until year 27. As a general note, the spike observed in the left graph of Figure 7.3 at the 50-year mark is a result of the simulation restoring the pavement with a major M&R action, as discussed in the previous section.

When the new recommended maintenance strategy is compared to the status quo strategy for this particular pavement section, at the 50-year mark, the recommended strategy results in an estimated cost savings of $0.02 per square foot per year (approximately six percent savings) (see Figure 7.4). For reference, a primary runway pavement in the USAF would receive localized preventative maintenance and have a PCI_{crit} value of 70. For the size of the pavement section in question, this would equate to an estimated $9,400 in annualized savings. While this may seem insignificant at face value, the cumulative annual effect of the savings from this pavement section and any additional savings from sections across the portfolio has the potential to free up significant resources to support reversing the maintenance backlog. The total value of the savings across the entire portfolio, as calculated by the RAMPSS algorithm, was $126 million in annualized savings.

The analysis provided for the runway section described above could be documented for the remaining pavement sections within the USAF's portfolio; however, in the interest of space, the remaining results are summarized for the entire portfolio in Figure 7.5 to Figure 7.7. The left graph in Figure 7.5 shows the change in the recommended PCI_{crit} compared to the status quo value. For secondary and tertiary pavements (PCI_{crit} value of 55), the algorithm recommended 95 percent of the pavement sections have an increased PCI_{crit} value; the median value for these pavements was 70. Conversely, only 68 percent of primary pavements (PCI_{crit} value of 70) were recommended for increased PCI_{crit} value; the median value for these pavements was 74.

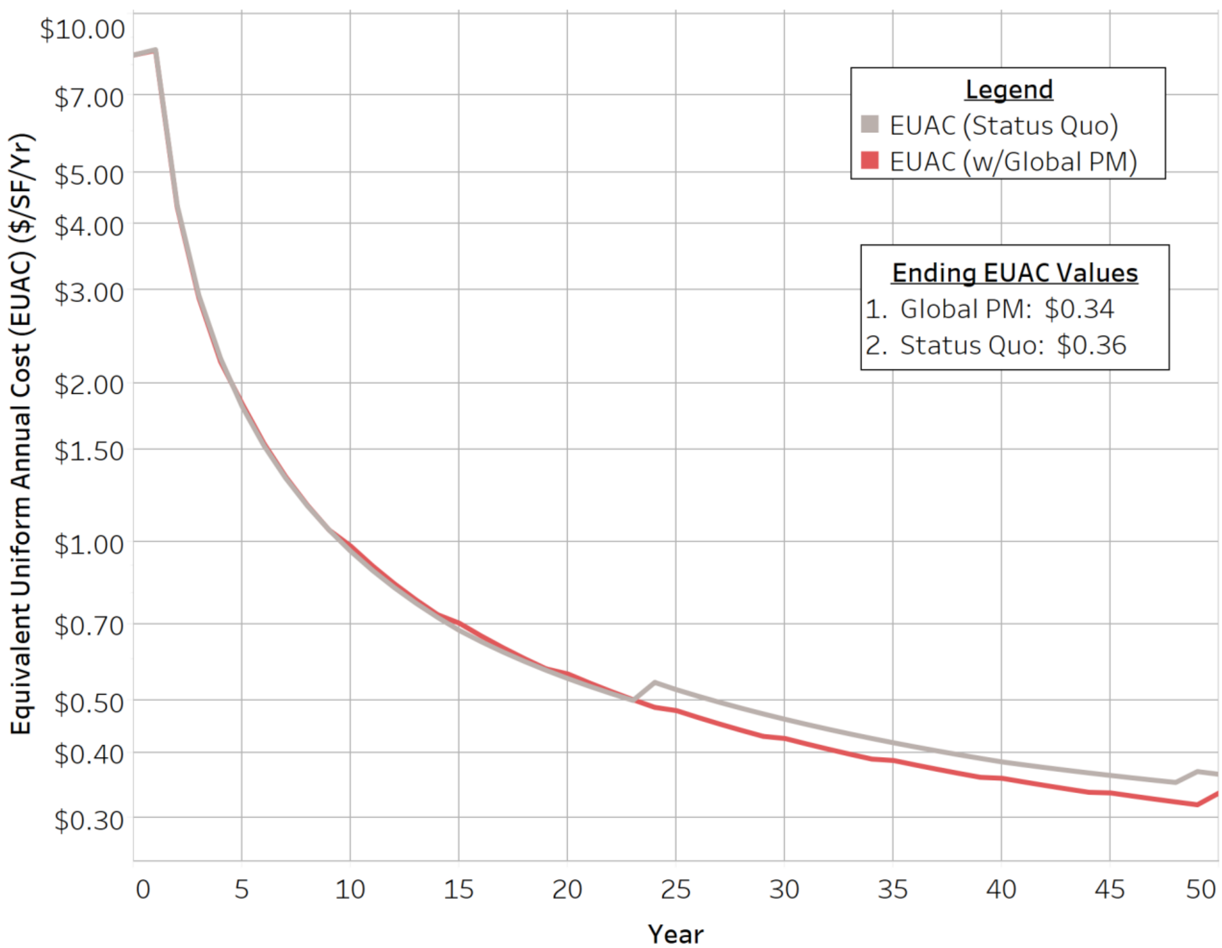


Figure 7.4 Comparison of Lowest Life-Cycle Cost Maintenance Strategy and Status Quo Maintenance Strategy

While not shown explicitly in Figure 7.5, further analysis of the recommended PCI_{crit} values revealed a potential correlation between surface types and recommended PCI_{crit} values; generally speaking, concrete pavements tended to have higher PCI_{crit} values. As a general note, there were a handful of pavements with recommended PCI_{crit} values over 85, as shown in the graph. These concrete pavements also have abnormally low annual deterioration rates (R_w) compared to the rest of the portfolio, which likely produce an outlier effect. Looking at the actual

PAVER historical data for these pavements, the majority of the pavements are at least 40 years old, with PCI ratings of at least 85 and located in favorable climate zones. Due to the outlier effect surrounding these particular pavement sections, the PCI_{crit} may need to be manually adjusted down to be more comparable with similar pavements.

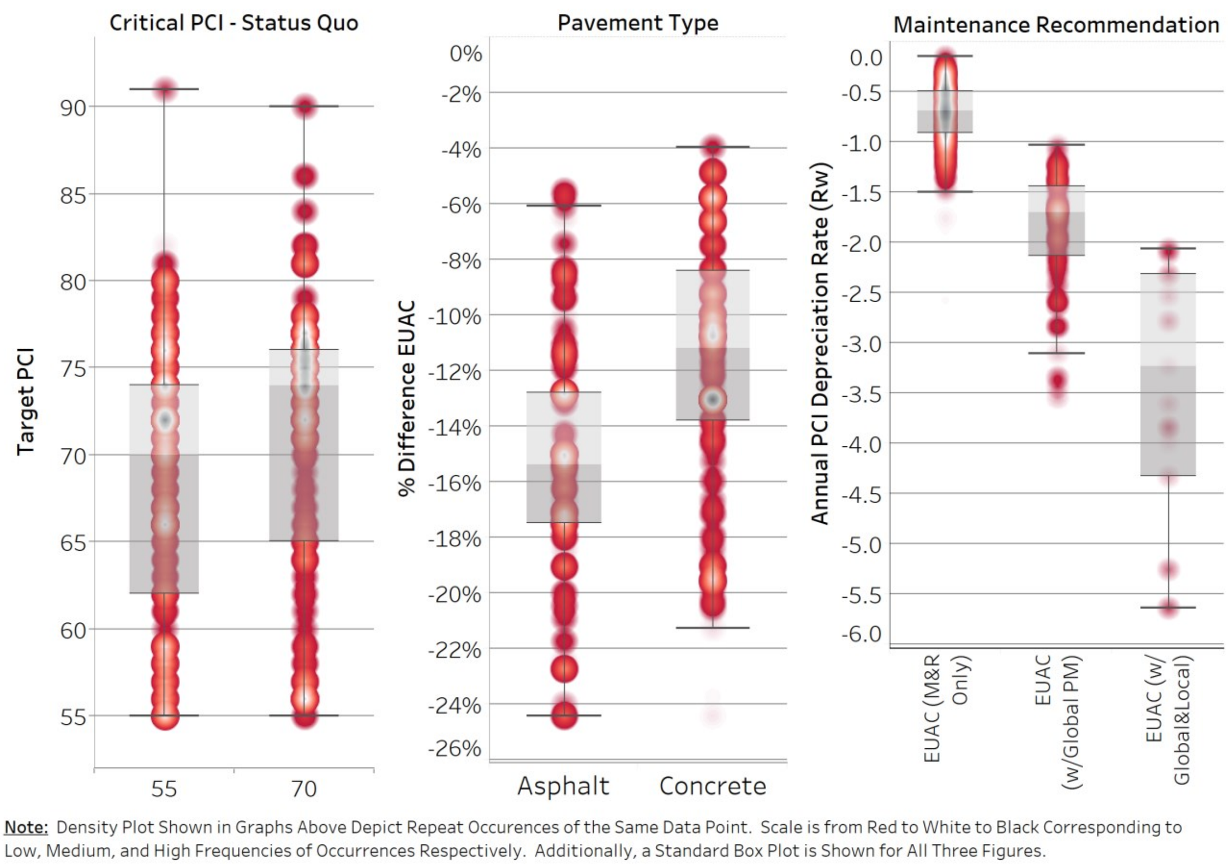
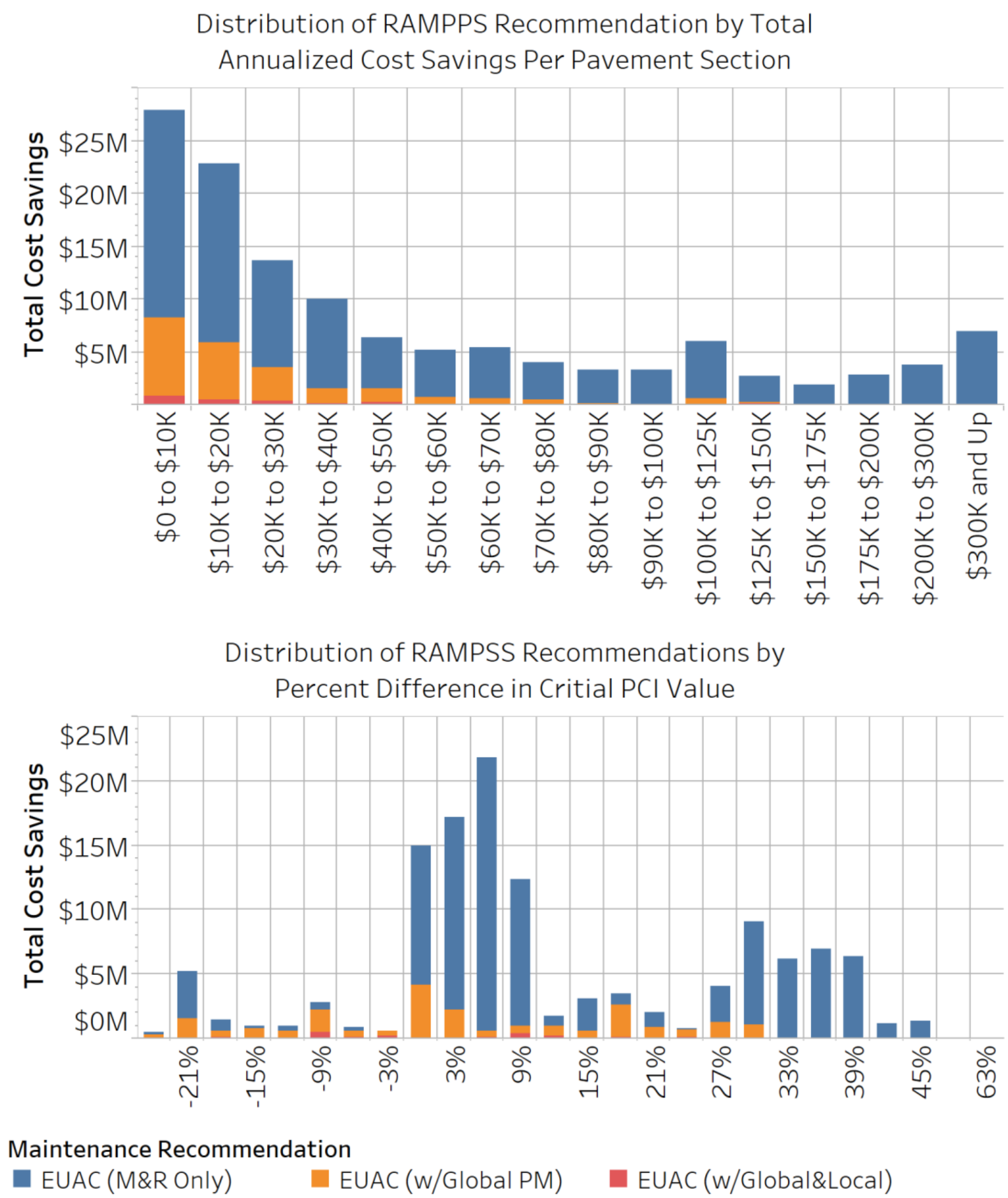


Figure 7.5 Lowest Life-Cycle Cost Maintenance Strategy Determination Outputs from RAMPSS for All USAF Airfield Pavements

The middle graph of Figure 7.5 summarizes the range in percent difference between the EUAC associated with the recommended and status quo maintenance strategies; negative values are indicative of projected cost savings. As shown in the graph, the RAMPSS algorithm predicts that the recommended maintenance strategies would produce cost savings over the entire pavement portfolio, albeit to varying degrees. The median percent difference in EUAC for asphalt and concrete pavements was -15 and -11 percent, respectively. This observation, coupled with the analysis from the primary runway section discussed previously, lend support to the theory that the cumulative effect of incremental cost savings across the entire portfolio has the potential to help reverse the growing backlog trend. Displayed graphically in Figure 7.6, the total estimated annualized cost savings across the entire pavement portfolio can add up fairly fast, even with relatively small savings per pavement section.

As shown in the right graph of Figure 7.5, the recommended maintenance strategy was highly correlated with the annual deterioration rate (R_w). As the annual deterioration rate increased, the RAMPSS algorithm tended to favor additional preventative maintenance actions; however, the algorithm favored global over localized preventative maintenance. Localized preventative maintenance was only recommended by the RAMPSS algorithm when used in conjunction with global preventative maintenance for pavements with high annual deterioration rates. Preventative maintenance (global or localized) is certainly beneficial to extending the service life of pavements; however, it does appear that, in a fair amount of cases, it may not be the most cost-effective strategy (see Figure 7.6 and Figure 7.7). It is important to note that this finding is based on the assumption that each pavement section receives an appropriate major M&R action at the recommended critical PCI value, which on average, is earlier than the USAF currently recommends. Routinely missing the critical PCI value (as is the case currently as shown in Figure 6.9) would potentially warrant consideration of a different maintenance strategy, as the recommended maintenance strategy from the RAMPSS algorithm could potentially be more costly at a lower critical PCI value.



Note: The Graphs Above Depict Histograms of the RAMPSS Recommended Maintenance Strategies Compared to the Status Quo. The Top Graph Reflects the EUAC Multiplied by the Total Area of the Pavement Section to Provide Context on the Cumulative Effect of Decreases in EUAC. The Bottom Graph Shows the Percent Difference Between the Recommended and Status Quo Critical PCI Value. In Both Graphs, the Total Cost Savings Reflect the Sum of the Annualized Pavement Section Savings.

Figure 7.6 Histogram Plots of Outputs from RAMPSS for All USAF Airfield Pavement Sections Depicting Cost Savings and Critical PCI Value Differences Per Section by Total Savings

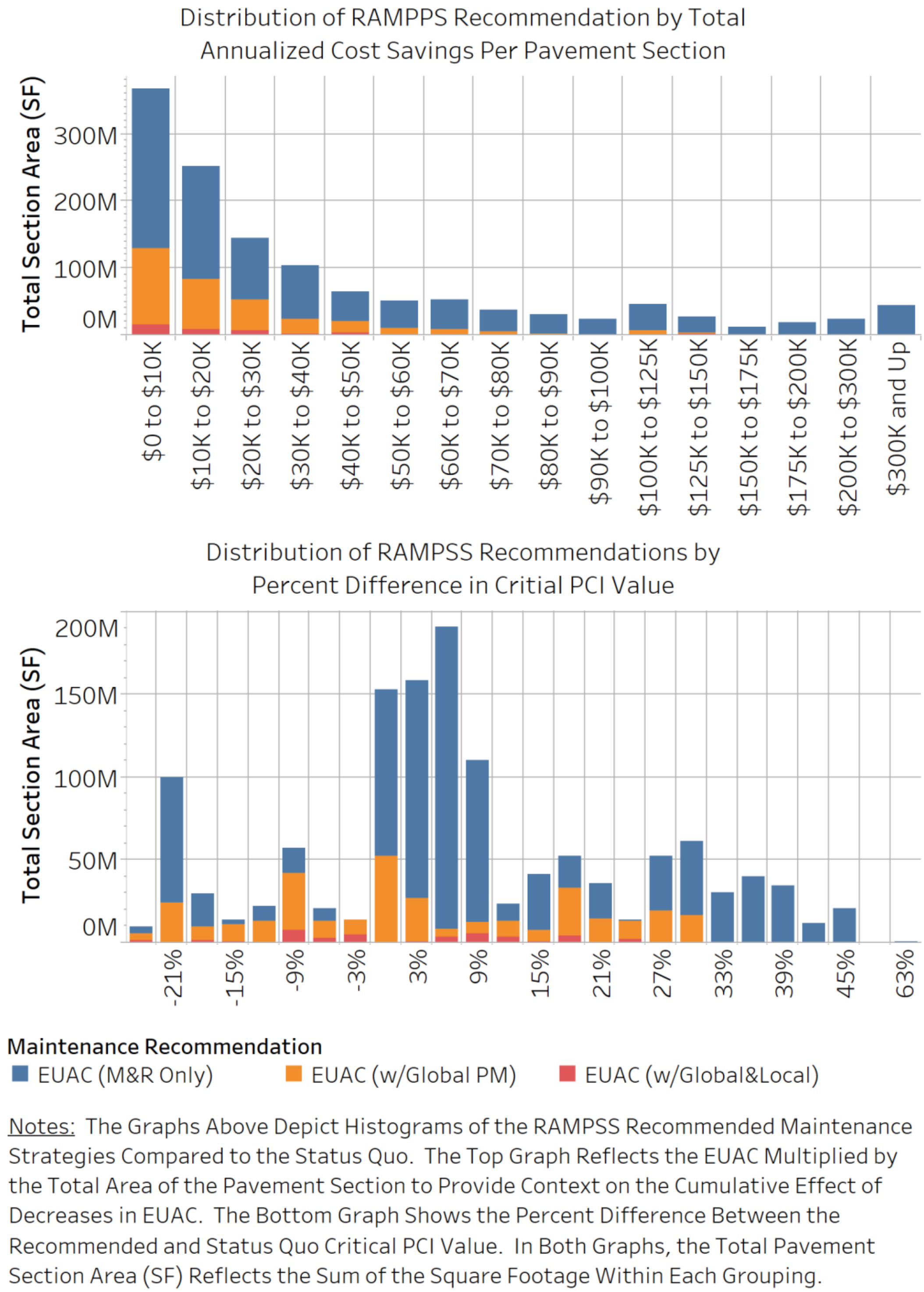


Figure 7.7 Histogram Plots of Outputs from RAMPSS for All USAF Airfield Pavement Sections Depicting Cost Savings and Critical PCI Value Differences Per Section by Total Area

Summarizing Figure 7.6 and Figure 7.7, the analysis of the RAMPSS outputs for the USAF's airfield pavement portfolio shows that pavements maintained at a higher critical PCI value are generally more cost-effective to maintain, thereby lowering the overall cost of ownership of these pavements. Furthermore, localized preventative maintenance (i.e., spot treatments) are not cost-effective, except in a small percentage of pavement sections, compared to global preventative maintenance or major M&R only strategies. When applied together, these two findings provide the USAF with a promising solution to lower total cost of ownership of its pavement portfolio and provide a better service to the service's operational requirements.

For context, the lower graph in Figure 7.7 can generally be interpreted as follows. If, for example, one views the 9 percent bin, it shows that the overwhelming majority of the roughly 110 million square feet of this category are optimized cost-wise with M&R only, but where treatments are applied at a critical PCI value roughly 9 percent higher than is currently used (i.e., a PCI of 70 increases to roughly 76). This finding generally aligns with many perspectives in the highway industry that, for example, champion concepts such as keeping good roads good. In this analysis, this finding is comprehensively supported with over 11,000 sections assessed that represents a worldwide network. RAMPSS is suggesting that USAF could save considerable money over time by doing globally applied M&R earlier at many locations (not all locations), which would also have the benefit of pilots and other servicemen and women using an airfield runway that is not only cheaper to own, but also in modestly better condition at most worldwide installations.

It is important to recall that the USAF, from an airfield pavement perspective, is primarily concerned with environmental-related distresses (Rushing et al. 2014; Synovec et al. 2019). Approximately 95 percent by surface area of the identified pavement distresses in the USAF's pavement inventory are non-load related distresses. Of the load-related distresses, the vast majority are low-severity or are present alongside non-load related distresses (Synovec et al. 2019). In this scenario, pavement preservation techniques are likely well suited since structural failures are not a significant concern based on the probability of occurrence.

Lastly, the USAF is an organization that contends with an infrastructure portfolio that lacks reasonable alternatives, as approximately 60 percent of its airfields have only one runway (Synovec et al. 2019). Additionally, single-runway airfields typically have only one primary, parallel taxiway. As a result, accomplishing major reconstruction or repair work could potentially require the airfield to be shut down, thereby requiring aircraft, personnel, and support equipment to be relocated for an extended period. While the analysis presented herein is indifferent to the operational impacts, these impacts represent a meaningful organizational risk that would likely be a factor in a decision to undertake major maintenance or repair work on a pavement section. If operational considerations were to defer maintenance, it is likely that the estimated savings from RAMPSS would be reduced. Further research would be necessary to account for operational constraints; however, this operational impact may best be accounted for within the USAF's centralized investment strategy and scoring models (i.e., budget allocation).

7.5 Summary

Within its $263 billion infrastructure portfolio, the USAF maintains an airfield pavement inventory of over 1.6 billion square feet of paved surfaces around the world. The sheer scope of this infrastructure portfolio, coupled with its growing $33-billion maintenance backlog, dictates that the USAF take action to reverse this trend or continue to take a risk in its ability to project combat airpower. As shown in this analysis, shifting to the lowest life-cycle cost strategies appears to reduce the cost of ownership and produce cost savings that could potentially help reverse the growing maintenance backlog. Furthermore, this research finds that military airfield pavements are generally more cost-effective to maintain at higher critical PCI values and with maintenance strategies other than localized preventative maintenance. Using estimates from the RAMPSS algorithm developed and presented herein, the cumulative economic impacts of the recommended strategies equate to an annualized savings of approximately $126 million. Subsequent research on the topic, coupled with the findings from this effort, could validate this theory and produce positive and actionable outcomes for the USAF.

The USAF's infrastructure maintenance backlog has created a challenging environment; however, this challenge is not unlike the realities faced by other local government and public-sector agencies. The methodology presented herein was developed to make recommendations using data from the USAF's pavement sustainment management system (i.e., PAVER). A similar analysis could be performed utilizing this methodology with other agencies' data to provide individualized lowest life-cycle cost recommendations.

CHAPTER VIII

COMBINING THE BEAST AND THE RAMPSS ALGORITHMS TO EVALUATE A NEW AIRFIELD PAVEMENT MANAGEMENT STRATEGY FOR THE U.S. AIR FORCE

This chapter contains portions of a technical paper that was submitted for publication to a peer-reviewed journal. The paper (Synovec et al. Forthcoming) is in the peer-review process as of the date of this dissertation. While there are similarities between the journal article and this chapter, the content has been substantially reorganized, reformatted, and edited to meet Mississippi State University's dissertation formatting guidelines and the flow of the overall dissertation.

8.1 Introduction

This chapter builds upon the research from the previous chapters to provide an evaluation of the larger research aimed at reducing the total USAF airfield pavement ownership cost. The previous chapters focused on addressing two key decision points in the development of asset management strategies: (a) what work is required (i.e., work planning); and (b) how should requirements be prioritized (i.e., budget allocation). The RAMPSS algorithm provides individualizes maintenance strategies for airfield pavement sections and provides an automated methodology to determine cost-effective strategies to maintain pavements. This research demonstrated it is more cost-effective to maintain airfield pavements at higher critical PCI values and with maintenance strategies other than localized (i.e., targeted) preventative maintenance (Synovec and Howard Forthcoming). Furthermore, this work highlighted several revealing observations from a strategic-level view of a pavement portfolio and addressed the first of the broader research's two key decision points (i.e., work planning). The research described in this chapter builds upon this research and focuses on addressing budget allocation decisions through the use of portfolio-level simulations to model the impact of work planning, budget allocation, decision-making behaviors, and USAF policy on its pavement portfolio over a thirty-year period.

While Chapter VI focused on using the BEAST to analyze the status quo, this chapter adapts the BEAST to model the RAMPSS recommendations. As described in Chapter VI, the USAF's current pavement management practices will continue to worsen the growing maintenance backlog and create an increased risk to its global flying operations. Implementing a lowest lifecycle cost approach with individualized maintenance strategies, as recommended by RAMPSS, appears to provide a solution to change course and help avoid this outcome.

8.2 Simulating the Individualized Maintenance Approach

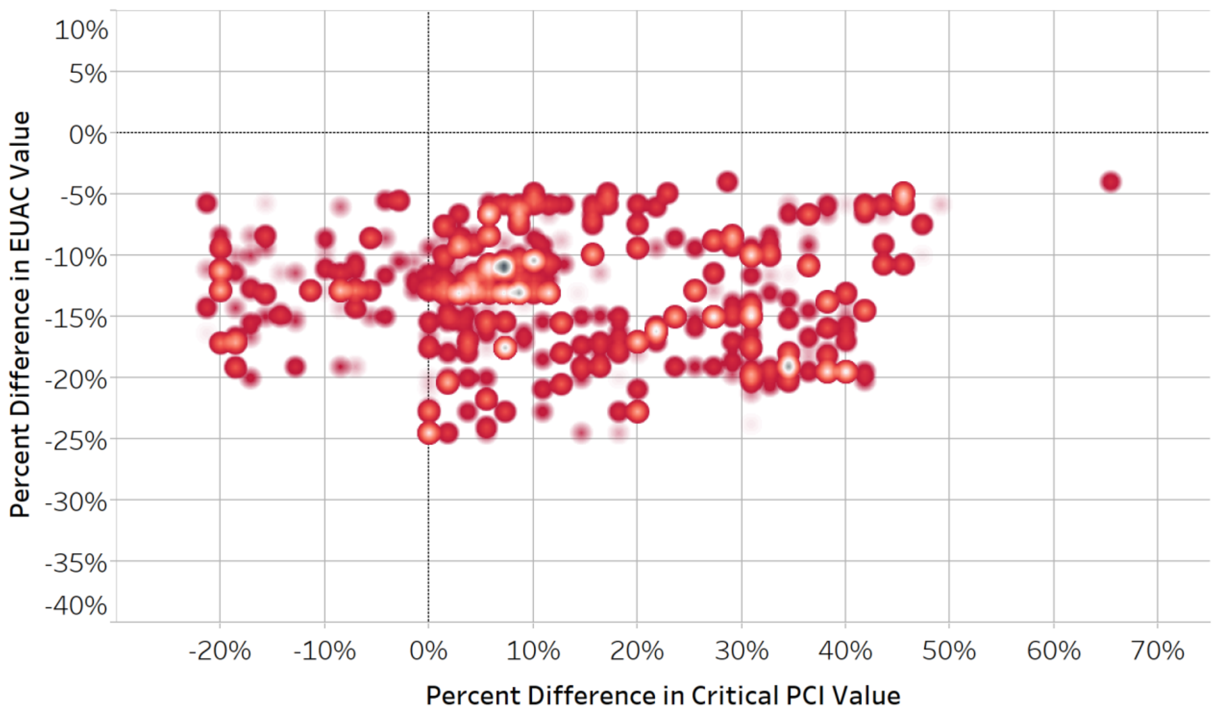
The USAF currently targets major M&R actions at static trigger points; critical PCI values of 70 trigger primary pavements deemed essential to flying operations, and critical PCI values of 55 trigger all other pavements. While these critical PCI values are easily applied, they are not specific enough to identify the optimal time to recapitalize a specific pavement section because they do not: account for local deterioration rates, account for local operational environments, and adjust based on recommended preventative maintenance actions (Synovec and Howard Forthcoming).

The RAMPSS algorithm models a pavement section over fifty years, simulating the application of dozens of different maintenance options and strategies. RAMPSS automatically recommends an individualized maintenance strategy for a given pavement section based on minimizing the EUAC. RAMPSS for the USAF's entire pavement portfolio (Figure 8.1) showed maintaining pavements at a higher critical PCI value and utilizing maintenance strategies other than localized preventative maintenance (i.e., targeted maintenance) is more cost-effective (i.e., a lower cost of ownership). To model the long-term impacts of these recommendations, the RAMPSS recommendations were inserted into the BEAST algorithm.

8.2.1 Simulation Framework

Incorporating RAMPSS required major changes to the BEAST. Several elements could be carried over, but the BEAST's maintenance decision-making process and scoring models had to be rebuilt to prioritize investment at the lowest lifecycle cost recapitalization point (see Figure 8.2 and Figure 8.3). Adapting the BEAST required developing a new scoring model for the centralized portfolio that prioritized targeted major M&R actions at the lowest lifecycle cost point. Achieving an economically optimal solution requires prioritizing investment timing, so a scoring model was developed that prioritized projects at the recommended critical PCI value (determined from RAMPSS). To achieve this prioritization concept, the author elected to build the scoring method by using a normal probability density function as the basis for assigning prioritization points. For each probability density function, the target PCI was assigned as the mean value, and a standard deviation of five was used. This standard deviation ensured that every pavement section had at least two opportunities to achieve a relatively high project score compared to the maximum value. If the standard deviation was set too narrow for this type of scoring model, it could create a situation in which a pavement section's PCI rating may never fall within one standard deviation of the target PCI value (highest scoring region considered) simply due to higher rates of annual deterioration relative to the other pavements in the inventory.

The score for a recapitalization project became a ratio of two probability density functions associated with the current PCI and the target PCI serving as the value of interest, subsequently multiplied by ten thousand (the maximum score currently used by the USAF in its centralized infrastructure investment portfolio). After some simplification, the end equation used to calculate project scores for the centralized portfolio is shown in Equation 8.1 in Figure 8.2. To avoid prematurely funding recapitalization too early relative to the target PCI, a logic statement was applied to not score projects more than five PCI points above the target value (see Figure 8.3).



Note: Density Plot Shown in Graph Above Depict RAMPSS Algorithm Outputs Compared to Status Quo Maintenance Strategy. Scale is from Red to White to Black Corresponding to Low, Medium, and High Frequencies of Occurrences Respectively. Positive Percent Differences in Critical PCI Values are Indicative of a Higher Recommended Value by RAMPSS than Status Quo. Negative Values of Percent Difference in EUAC are Indicative of Estimated Lower Annualized Costs with RAMPSS Recommended Maintenance Strategy Compared to Status Quo.

Figure 8.1 Comparison of Recommended Maintenance Strategy from RAMPSS to Status Quo for the USAF's Airfield Pavement Portfolio

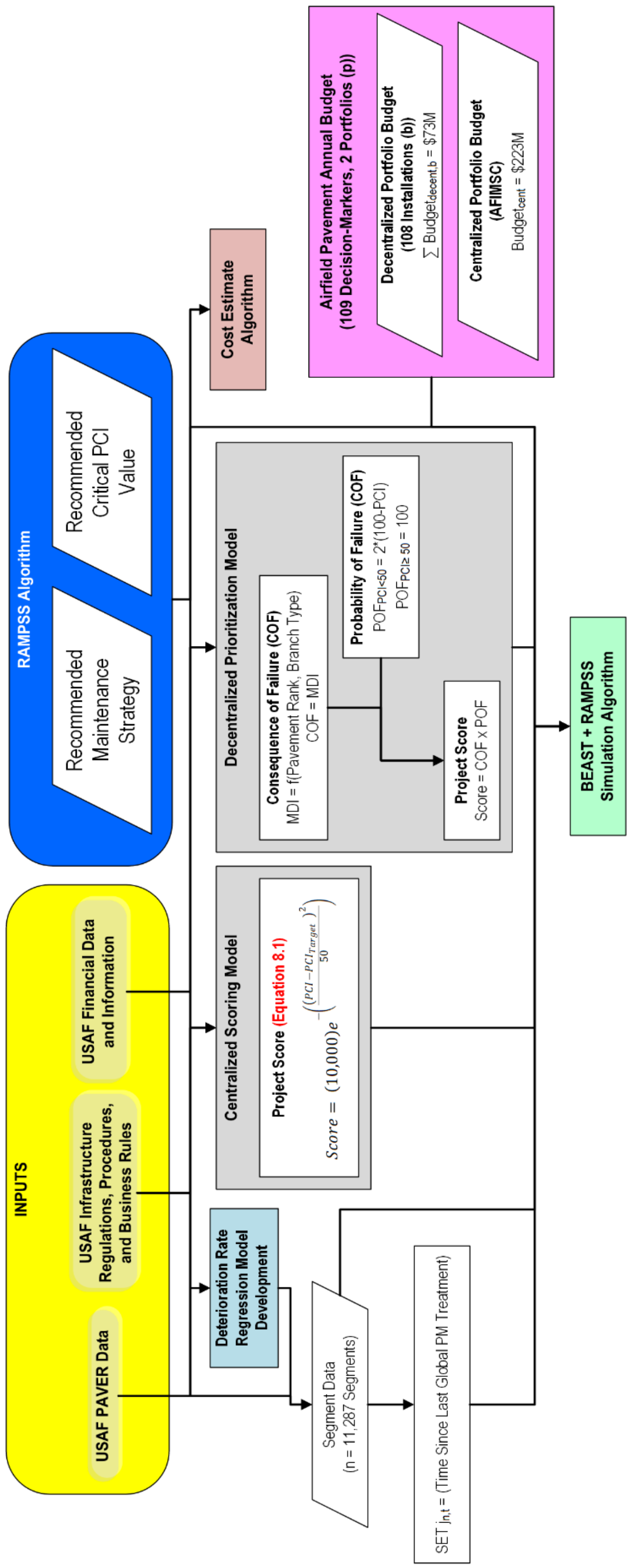


Figure 8.2 Overview of Lowest Lifecycle Cost Simulation

It is important to note that this equation values reducing the cost of ownership above other factors (i.e., mission dependency or operational impacts), such that a pavement section with a PCI rating equivalent to its target PCI value for a major M&R action would receive the maximum score regardless of the pavement section's relative importance to flying operations. This is a deviation from the USAF's status quo scoring model that prioritizes deteriorated pavements with a high impact on flying operations. Equation 8.1 could be further modified to capture the operational impacts by incorporating the MDI value for each pavement section into the scoring model. While this would decrease the value of the cost of ownership reduction, it would potentially provide a balance between operations and budgetary considerations.

While the centralized portfolio required a new scoring model to target investment at the recommended recapitalization points, it was assumed that the decentralized portfolio could still be modeled using the current risk-based scoring model that utilizes COF and POF. As such, the decision-making algorithm assumed that local pavement engineers would follow the recommended maintenance strategies as their budgets allowed and would prioritize pavements with higher impacts on flying operations.

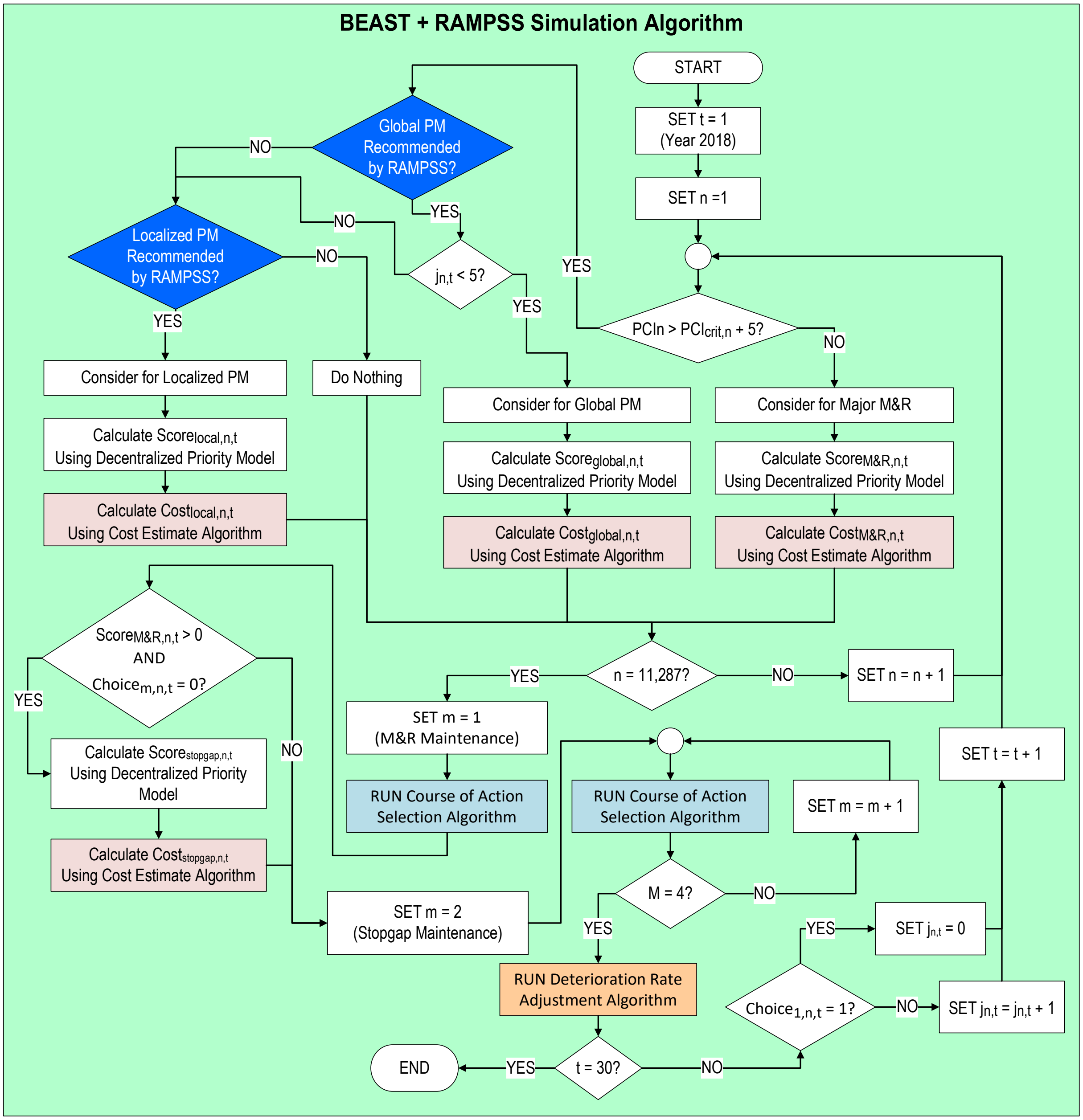


Figure 8.3 Overview of BEAST Algorithm with RAMPSS Incorporated

8.2.2 Simulation Observations

The simulation was conducted again for thirty years to model the long-term implications of switching to the lowest lifecycle cost strategy recommended by RAMPSS (outputs are shown in Figure 8.4 to Figure 8.6). As shown in Figure 8.4, the simulation shows that over thirty years, the growing maintenance backlog trend observed during the status quo simulation (as shown in Figure 6.6) reverses and decreases each year of the simulation. Starting with a backlog of $2.6 billion, over thirty years, the backlog decreases to $159 million measured in constant year 2018 dollars; furthermore, the average weighted PCI rating increases from 82 to 87 over the same period. When comparing the status quo to RAMPSS simulations, note that the infrastructure backlog starts in the first year approximately $300 million higher than the status quo simulation. The reasoning for this backlog increase is due to a considerable percentage of pavement sections that have target PCI values more than the reinvestment points used previously in the status quo business rules (approximately 81 percent). Even with a higher starting backlog, the change in investment strategy still managed to produce positive outcomes. This change is primarily driven by the shift in prioritizing recapitalization projects closer to the lowest lifecycle cost reinvestment point, which in-turn allows investment at lower price points, thereby allowing investment to target larger quantities of pavement sections each year. While this strategy inevitably defers projects significantly below its optimal recapitalization point, these projects over time incrementally get funded as the backlog decreases as evidenced by the decreases in the percentages of poor, very poor, serious, and failed pavements over time is shown in Figure 8.5.

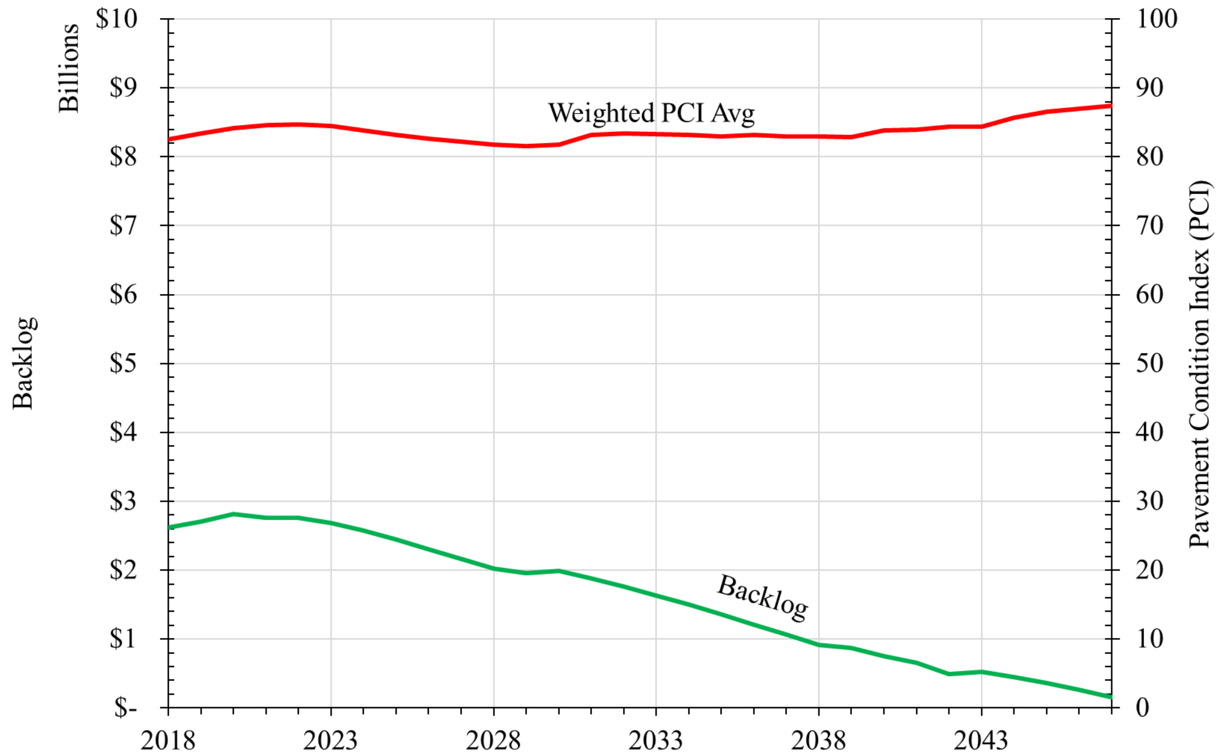


Figure 8.4 Lowest Lifecycle Cost Simulation Output Depicting Infrastructure Backlog and Weighted Average Pavement Condition Index Over Thirty Years

A major change between the status quo and the lowest lifecycle cost strategy recommended by RAMPSS is highlighted in Figure 8.6. The recommended RAMPSS strategy routinely executes major M&R actions slightly above the RAMPSS recommended critical PCI value. This is ultimately a reflection of the programming built into the revised scoring model that allowed major M&R projects to be considered within five PCI points of the critical PCI value. Since the scoring model prioritizes timing, projects near the critical PCI value receive high project scores. While this could be addressed by adjusting the scoring model and programming rules, the overall outcomes are shown in Figure 6.7 and Figure 6.8, which are certainly desirable. One key finding is that closing the timing gap between intended and actual execution points is critical to reversing the maintenance backlog growth, as the timing ultimately reduces the number of projects and requirements that continue to grow in value. As a result, Figure 8.6 is likely a leading indicator of portfolio performance that would be observed over time in Figure 8.4 and Figure 8.5 (i.e., lagging indicators).

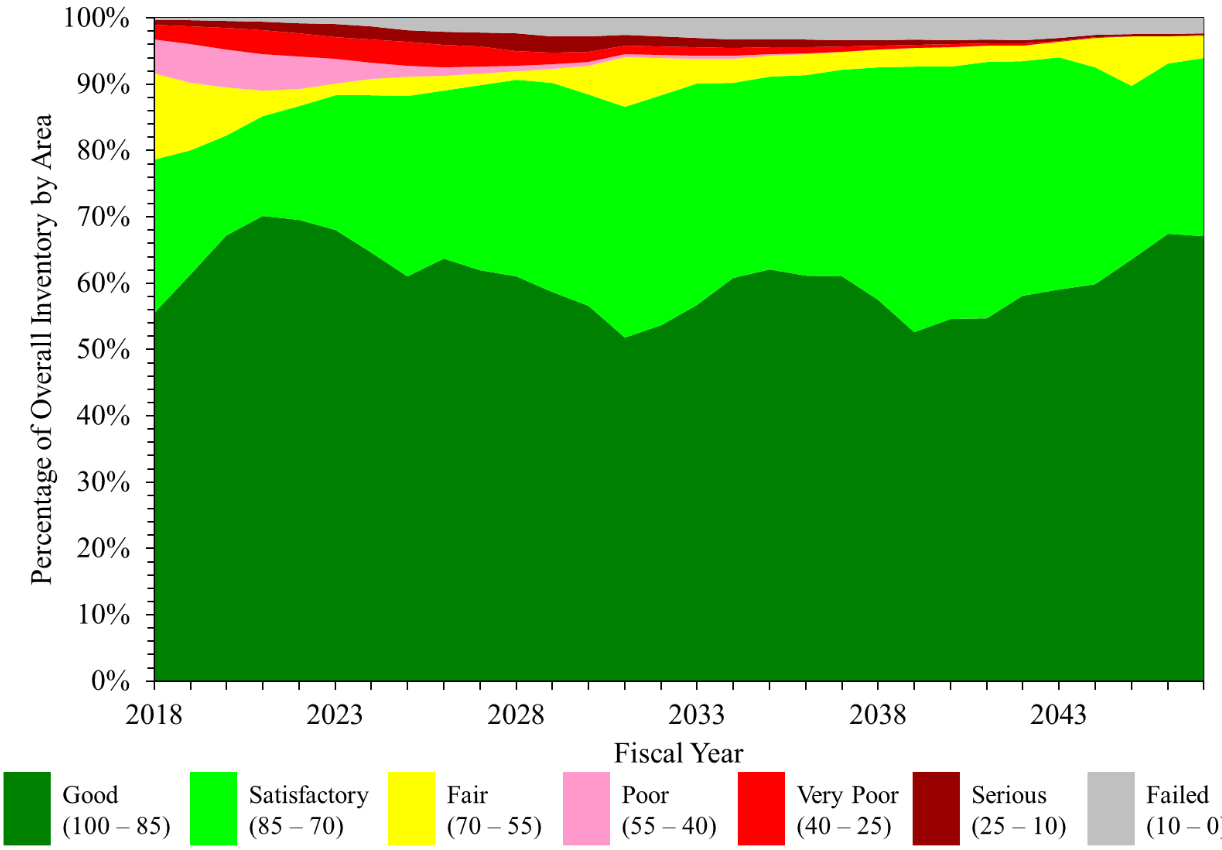
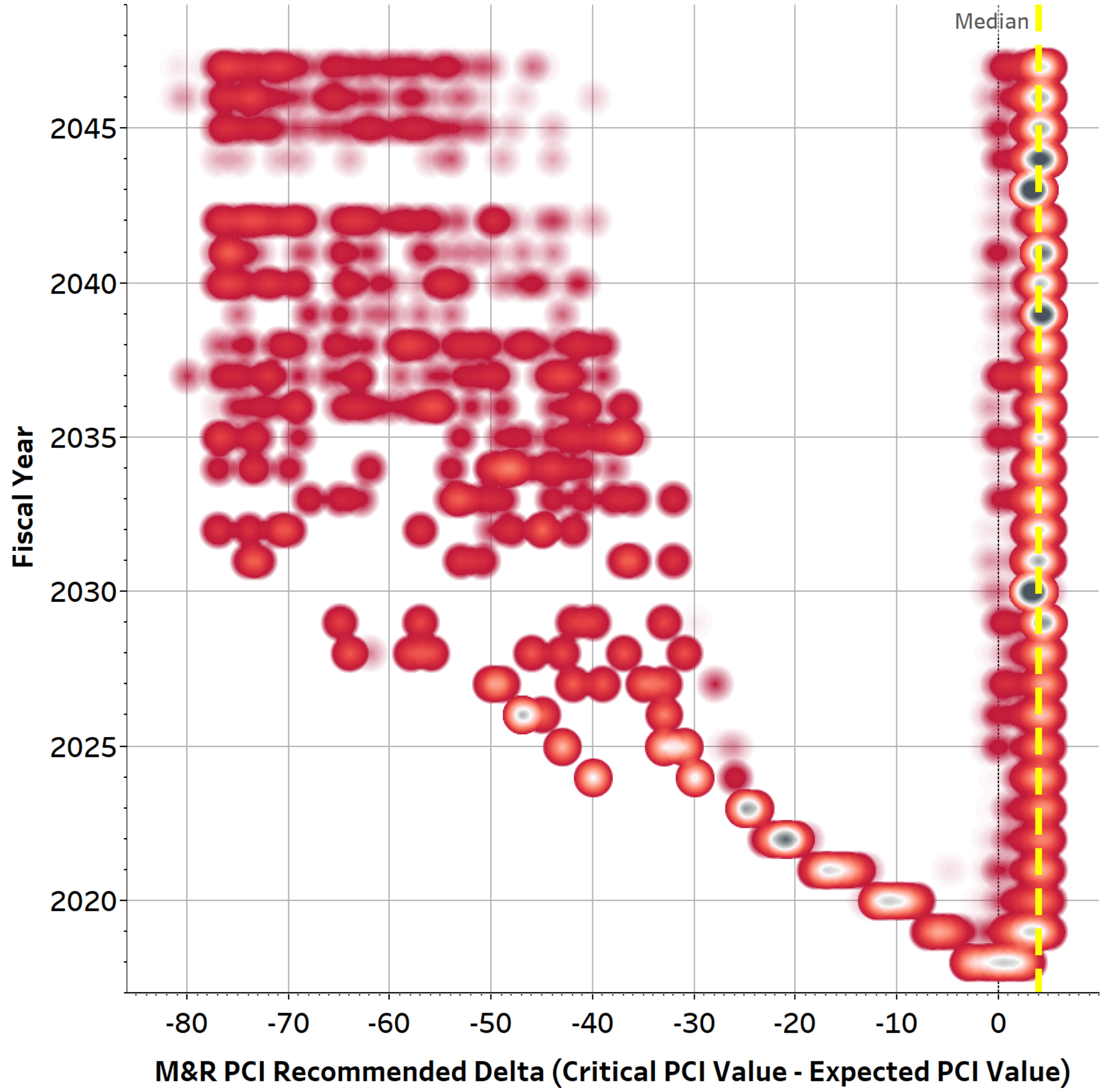


Figure 8.5 Lowest Lifecycle Cost Simulation Summary of Pavement Condition Index as a Percentage of the Overall Airfield Pavement Inventory by Area over Thirty Years



Notes: The Density Plot Above Depicts Funds Expenditute on Airfield Pavement Maintenance and Repair Actions Corresponding to the Pavement's PCI Rating at the time of Expenditure Relative to its Critical PCI Value. The Results are Based on the Simulation of the Lowest Lifecycle Cost Maintenance Strategies. Negative Values are Indicative of a Project that was Executed Below the Critical PCI Value. Scale Above is from Red to White to Black Corresponding to Low, Medium, and High Frequencies of Occurrences Respectively. A Yellow Dashed Line is Shown at 4 to Represent the Median Delta for all Years Combined.

Figure 8.6 Comparison of the Executed PCI Values for Major Maintenance and Repair Projects Compared to the Critical PCI Value for the Lowest Lifecycle Cost Strategy

8.3 Analysis and Findings

While both strategies investigated (status quo and lowest lifecycle cost) could benefit from additional funding, the simulations show that an investment strategy change alone can help reverse the trend observed in the status quo scenario. On the surface, the status quo funding model is a risk-based approach to infrastructure investment; however, further analysis of the model during the simulation demonstrates that this model is predominantly recapitalizing pavements in poor or worse condition. The result over time of this strategy is a pavement inventory that trends increasingly towards lower PCI ratings.

The lowest lifecycle cost strategy recommended by RAMPSS appears to be a positive shift towards a more sustainable portfolio; however, it is not without its faults. As shown in Figure 8.7, when only primary pavements are considered, the status quo funding model eliminates all backlog associated with primary pavements at PCI ratings of very poor, serious, and failed. Conversely, the lowest lifecycle cost funding model still leaves approximately 0.6 percent of primary pavements in these conditions after thirty years, with the vast majority being in a serious or failed condition. With primary pavements' significance to sustaining flying operations, is 0.6 percent (4.6 million square feet) acceptable? Granted, the RAMPSS strategy, overall, trends both the USAF's overall portfolio and primary pavements in positive directions, it does so by deferring action on pavement sections beyond their recapitalization point, thereby allowing these sections to continue to degrade. Over time, as the backlog dwindles and eventually is eliminated, these deteriorated pavement sections would be recapitalized (see Figure 8.6); however, the length of time for this deferred action could cause operational impacts. For example, if a runway section was allowed to deteriorate to the point of failure because it was past its recapitalization point, the decision to defer action could eventually (under the right conditions) cause the airfield to close before the section is recapitalized. One potential solution to this issue is to diversify investments between the two investment models (i.e., a hybrid model).

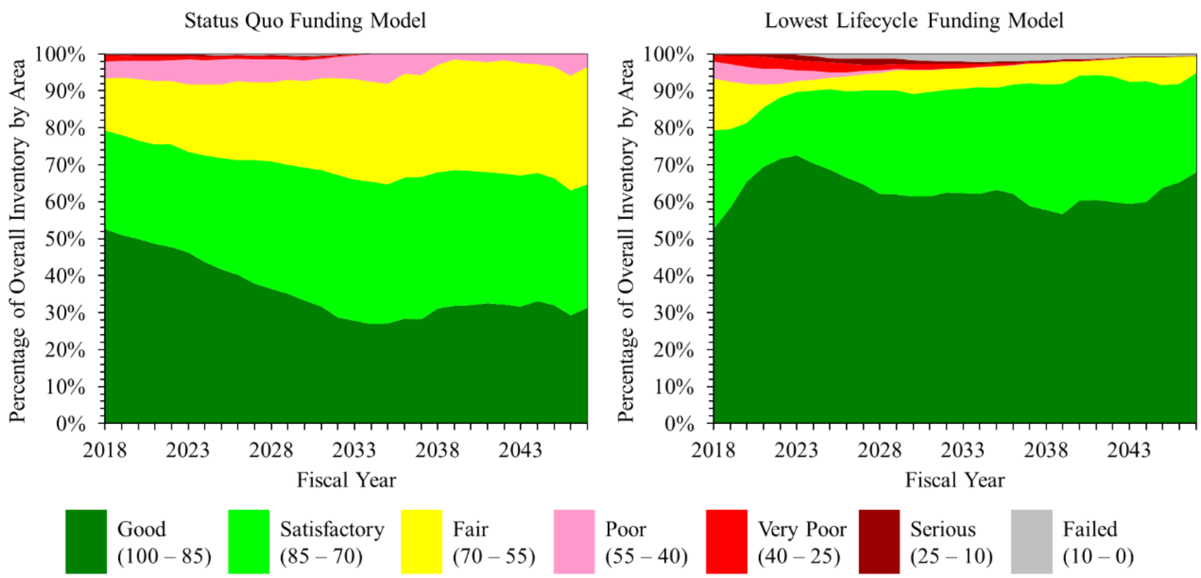


Figure 8.7 Comparison of Status Quo and Lowest Lifecycle Cost Funding Models as a Percentage of the USAF's Pavement Inventory (Primary Pavements Only) by Area over Thirty Year

Due to the nature of the status quo and the RAMPSS models, there is considerable distance between these two strategies. There does exist a middle ground that could leverage components of both investment strategies. For example, the RAMPSS strategy appears to demonstrate strong evidence that it can reverse the USAF's maintenance backlog and improve the overall conditions of its pavement portfolio. However, it achieves these outcomes at the expense of pavements already in a severely deteriorated state. Conversely, the status quo investment strategy prioritizes risk reduction, which effectively promotes a worst-first investment strategy that prioritizes severely deteriorated pavements. It stands to reason that a hybrid approach that utilizes facets of both investment strategies could produce satisfactory outcomes.

The author looked at several hybrid investment strategies, and the most promising was a 75-25 hybrid model that splits the centralized portfolio and allocates 75 percent of the funds to the lowest lifecycle cost approach, with the remaining 25 percent allocated to the status quo investment strategy. The hybrid approach facilitates investment to the USAF's severely deteriorated pavements, such that all primary pavements are rated as fair or better before the end of the simulation period (see Figure 8.8). While the hybrid model achieves some positive outcomes, it does come at a cost. Compared to the lowest lifecycle cost strategy, the hybrid strategy results in an opportunity cost of approximately $654 million in additional maintenance backlog.

The appeal of the hybrid model for the USAF is two-fold. First, the USAF has a lack of alternatives at most airfields (i.e., an airfield with one runway or one main parking apron) that instills a higher degree of apprehension towards an investment strategy that explicitly recommends deferring major M&R actions on severely deteriorated pavements, thereby allowing these pavements to continue to deteriorate (Synovec et al. 2019). Second, approximately nine percent of the USAF's airfield pavement portfolio is currently rated as poor or worse, leaving the service to attempt to recapitalize these pavements at great cost in a stagnant budget environment by deferring needed maintenance actions on other equally important pavements. The hybrid approach is an attempt to address these factors by acknowledging that the status quo investment model is unsustainable. In contrast, a purely lowest lifecycle cost approach is potentially impractical, given the current condition of its portfolio. A hybrid approach is likely not a long-term solution; it is essentially a "bridge" to help transition a portfolio to the lowest lifecycle cost approach recommended by RAMPSS. As such, once the portfolio condition improves such that the maintenance backlog is eliminated, the portfolio should transition its investment strategy to minimize the cost of ownership with a purely lowest lifecycle cost approach.

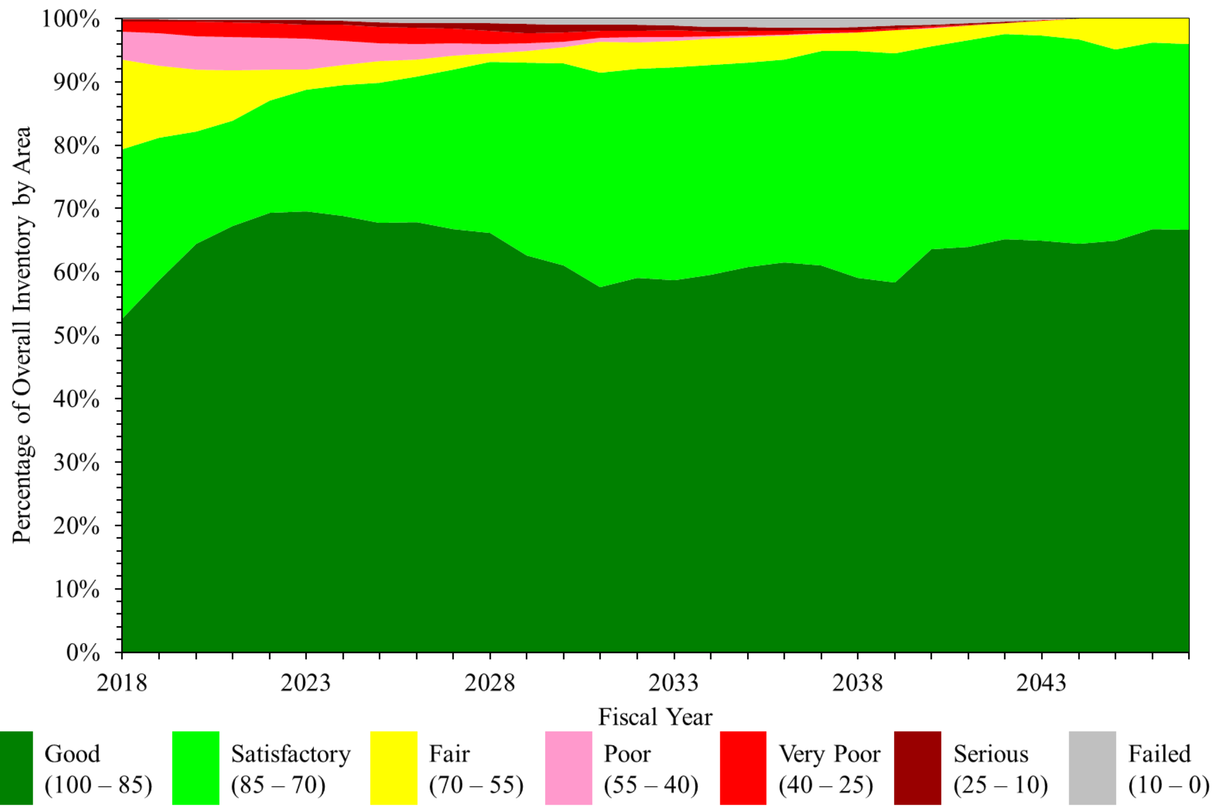


Figure 8.8 75-25 Hybrid Funding Model as a Percentage of the USAF's Pavement Inventory (Primary Pavements Only) by Area over Thirty Years

8.4 Summary

This chapter documents features of the BEAST and the analysis of the USAF's current pavement strategy. As projected by the BEAST in Chatper VI, the USAF's current maintenance strategy (i.e., status quo) is unsustainable and would likely lead to significant operational impacts. When the maintenance strategy proposed by RAMPSS are incorporated, the BEAST estimates that the RAMPSS-based strategy can reduce the backlog by approximately $2 billion, while increasing the USAF's weighted average PCI rating by approximately five points. Due to the nature of USAF operations and its current backlog, the service may need to adopt a hybrid strategy until its airfield pavement portfolio's maintenance backlog is eliminated. Lastly, modeling the difference between the planned strategy and the executed strategy (as shown in Figure 8.6) can provide a meaningful leading indicator of potential future portfolio pitfalls (e.g., growing maintenance backlog).

CHAPTER IX

CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

The overall objective of this dissertation was to develop a comprehensive and practical asset management approach to reduce the total cost of ownership of airfield pavements for the USAF. While this research is heavily focused on the USAF and its airfield pavement portfolio, the methodologies and findings are presented in the dissertation in a manner to allow other transportation authorities to leverage this research to analyze its own portfolio. Additionally, this research helps address several research gaps. While there is a research gap in airfield pavement maintenance, there are also gaps in pavements research, generally, concerning optimizing budget allocation for large portfolios (i.e., state, national, or international-level) utilizing multiple funding portfolios over an extended period.

The primary contribution of this dissertation is a practical means to developing a comprehensive asset management approach that helps transform a global pavement portfolio from a worst-first approach to one that utilizes a lowest lifecycle cost approach, thereby reducing the total cost of ownership of the portfolio. Furthermore, this approach does not rely on significant increases in funding levels or new technologies and methods: it merely requires policy changes. With these policy changes, this research shows that the USAF could both reduce its airfield pavement specific maintenance backlog (as a result of reducing the total cost of ownership) and increase the overall average condition of its pavement portfolio.

The research described in this dissertation identified several conclusions that help address the current research gaps, advance the civil engineering body of knowledge, and address the research objectives. These conclusions are summarized below.

- As detailed in Chapter IV, the DoD's airfield pavement design appears to be effective at achieving the desired results (i.e., preventing structural failure in the mode of interest). Based on the analysis of USAF's PAVER database, the USAF's airfield pavements predominantly experience non-load related distress. The overwhelming majority of distresses are climate and durability related distresses. These types of distresses can tend to become structural distresses over time due to deferred maintenance in the right conditions.

- Using the BEAST to model the behaviors and economic decisions of the USAF's current pavement strategy, the research demonstrates that the status quo is unsustainable and would likely lead to significant operational impacts. According to the BEAST, the estimated backlog in the fiscal year 2018 is approximately $2.3 billion; by 2048, the BEAST indicates that this backlog will grow to approximately $6.6 billion measured in constant-year 2018 dollars. The weighted average PCI rating for the USAF's airfield pavement declined from 83 to 63 over the same period. The primary driver for this trend is the current centralized scoring model that tends to target a "worst first" investment strategy.

- Shifting to the lowest life-cycle cost strategies recommended by RAMPSS appears to reduce the cost of ownership and produce cost savings that could help reverse the growing maintenance backlog. Furthermore, pavements are generally more cost-effective to maintain at higher critical PCI values and with maintenance strategies other than localized preventative maintenance. As estimated by the RAMPSS algorithm, the cumulative economic impacts of the recommended strategies equate to an annualized savings of approximately $126 million.

- When the maintenance strategies proposed by RAMPSS are incorporated into the BEAST, the BEAST estimates that the RAMPSS-based strategy can reduce the backlog by approximately $2 billion, while increasing the USAF's weighted average PCI rating by approximately five points.

- The BEAST provides a methodology to analyze a pavement portfolio over an extended period of time to forecast outcomes of decisions and strategies taken in the present. The outcomes of the BEAST demonstrate that comparing planned and actual execution of a pavement maintenance plan provides a good leading indicator of portfolio alignment and future health. This conclusion is based on an observation that the failure to monitor the actual execution of a pavement maintenance plan could provide a transportation authority a false impression of its ability to achieve its stated performance objectives or asset management goals.

- As discussed throughout the dissertation, the USAF is an organization that is constrained by Federal statute and regulation in its decision-making abilities. Additionally, the majority of USAF installations are single-runway airfields. As a result, the USAF is often faced with a lack of practical alternatives when it comes to fully embrace asset management or reducing its infrastructure portfolio (i.e., divestment or BRAC). A significant part of its decision scenario involves the concept of continuity of operations (COOP) and avoidance of large-scale airfield projects leading to airfield closures. Implementing a lowest lifecycle cost strategy may prove difficult given these realities and constraints. Therefore, the USAF should consider adopting a hybrid approach that provides a balance between risk reduction (i.e., status quo) and lowest lifecycle cost (i.e., RAMPSS). Analysis of this hybrid approach demonstrates an ability to support objectives while reducing the overall airfield maintenance backlog.

9.2 Recommendations

The research presented in this dissertation addresses the primary research objective of developing a practical asset management approach to reduce the total cost of ownership of the USAF's airfield pavements. Based on observations and conclusions presented herein, the following recommendations are made.

- The USAF should consider adopting the RAMPSS tool in some capacity and leverage it to individualize maintenance recommendations for its airfield pavements. Furthermore, the USAF should consider leveraging the methodology used in RAMPSS to develop similar tools for other infrastructure categories using data from its sustainment management systems.

- The USAF should consider leveraging the BEAST's methodology to simulate the impact of decisions and changes in strategy prior to implementation. Furthermore, this methodology could likely model similar outcomes for infrastructure categories and components with well-defined maintenance actions and plans (e.g., HVAC systems).

- Future research should focus on further objectifying the operational impacts of pavement maintenance, particularly as it relates to maintenance on primary pavements that potentially lead to airfield closures.

- The USAF should assess the cost-benefit analysis of adding redundant infrastructure to critical, single-runway airfields. This assessment would need to consider the cost of relocating mission sets for airfield closures (caused by large-scale maintenance projects) relative to the cost of constructing redundant infrastructure (e.g., secondary runway).

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