



NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

**OPTIMIZING THE COST-EFFECTIVENESS
OF EXTENDING EFFECTIVE MILITARY
AIRCRAFT SERVICE LIFE**

by

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September 2023

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REPORT DOCUMENTATION PAGE			<i>Form Approved OMB No. 0704-0188</i>	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC, 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE September 2023	3. REPORT TYPE AND DATES COVERED Master's thesis	
4. TITLE AND SUBTITLE OPTIMIZING THE COST-EFFECTIVENESS OF EXTENDING EFFECTIVE MILITARY AIRCRAFT SERVICE LIFE			5. FUNDING NUMBERS	
6. AUTHOR(S) Kevin P. Buchanan				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			10. SPONSORING / MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release. Distribution is unlimited.			12b. DISTRIBUTION CODE A	
13. ABSTRACT (maximum 200 words) Service life extension programs (SLEPs) are becoming increasingly required for United States military aircraft. Aircraft platforms are often expected to operate for longer than their intended operational life as new weapon systems become delayed in development and deployment. Traditionally, a SLEP extends service life via airframe structural modifications or parts replacements to combat fatigue. However, depending on the life extension timeline and required aircraft quantities, it may become more cost effective to meet operational requirements by purchasing newly produced aircraft. This study develops an integer quadratic program to identify optimal life extension decisions via repairing and replacing aircraft. The objective of the model is to minimize the costs incurred to meet fleet requirements over a planning time horizon. The model is used to determine an optimal repair and replace schedule for the F/A-18E/F fleet. Results indicate that a hybrid plan, including both repair and replace decisions, is optimal for the Super Hornets, driven by compounding operations and maintenance costs incurred on older aircraft. Sensitivity analysis on key parameters such as increased service life per repair and repair cost further influence costs incurred during SLEP. This work produces a platform-agnostic decision model that can be used to aid program managers and systems engineers in defining program requirements to meet operational needs until new development platforms can be fielded.				
14. SUBJECT TERMS SLEP, service life extension program, aircraft replacement, optimization			15. NUMBER OF PAGES 91	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UU	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18

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**OPTIMIZING THE COST-EFFECTIVENESS OF EXTENDING EFFECTIVE
MILITARY AIRCRAFT SERVICE LIFE**

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MASTER OF SCIENCE IN SYSTEMS ENGINEERING MANAGEMENT

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ABSTRACT

Service life extension programs (SLEPs) are becoming increasingly required for United States military aircraft. Aircraft platforms are often expected to operate for longer than their intended operational life as new weapon systems become delayed in development and deployment. Traditionally, a SLEP extends service life via airframe structural modifications or parts replacements to combat fatigue. However, depending on the life extension timeline and required aircraft quantities, it may become more cost effective to meet operational requirements by purchasing newly produced aircraft. This study develops an integer quadratic program to identify optimal life extension decisions via repairing and replacing aircraft. The objective of the model is to minimize the costs incurred to meet fleet requirements over a planning time horizon. The model is used to determine an optimal repair and replace schedule for the F/A-18E/F fleet. Results indicate that a hybrid plan, including both repair and replace decisions, is optimal for the Super Hornets, driven by compounding operations and maintenance costs incurred on older aircraft. Sensitivity analysis on key parameters such as increased service life per repair and repair cost further influence costs incurred during SLEP. This work produces a platform-agnostic decision model that can be used to aid program managers and systems engineers in defining program requirements to meet operational needs until new development platforms can be fielded.

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LIST OF ACRONYMS AND ABBREVIATIONS

A/C	Aircraft
COA	Course of Action
CONOPS	Concept of Operations
CY\$	Constant Year Dollars
DOD	Department of Defense
DON	Department of the Navy
FLL	Fatigue Life Limit
FMS	Foreign Military Sales
GAO	Government Accountability Office
JCIDS	Joint Capabilities Integration and Development System
LEO	Life Extension Optimization
MIP	Mixed Integer Program
NRE	Non-Recurring Engineering
O&M	Operations and Maintenance
PM	Program Manager
SLAP	Service Life Assessment Program
SLEP	Service Life Extension Program
SME	Subject Matter Expert
T/M/S	Type/Model/Series

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EXECUTIVE SUMMARY

This thesis investigates life extension practices for United States military aircraft and creates a decision-making aid for program office personnel to employ when determining the best way to safely and efficiently extend the operational life of an aircraft fleet. Although cost minimization may seem to be a purely programmatic problem, it relies heavily on the technical requirements and expertise from the engineering community, and those engineers, particularly systems engineers embedded within the program office team, should be integral to the decision-making process. This thesis leverages systems engineering, operations research, and program management principles working in tandem to help make a data-driven decision.

Traditionally, aircraft life extension is accomplished via a service life extension program (SLEP), in which increased maintenance, system modifications, and/or parts replacements are employed to keep existing aircraft in service past their original fatigue life limits (typically defined by a number of flight hours). However, the replacement of aging aircraft may also be a viable option, especially if that aircraft is still in production. Although replacement is usually a more expensive alternative on a per aircraft basis, it helps avoid some of the higher sustainment costs that older aircraft are likely to incur. While repair versus replace is not a novel concept, little research exists on how those options should apply to a large-scale, long-term problem such as that of maintaining operational capability of a fleet of aircraft.

Toward comparing repair-replace decisions, an integer quadratic program was formulated to determine the lowest cost course of action that meets fleet operational requirements. The model assumes parameters about a specific type/model/series (T/M/S) aircraft are given. Binary constraints are used to control decision variables such as the decision to SLEP or replace an aircraft at a given point in time, and other constraints are used to control when an aircraft can no longer be considered operational and to ensure operational quantity requirements are met over the specified time horizon. This model was then coded in Pyomo and used the Gurobi solver to determine the optimal solution that

minimizes life cycle costs. Simple, intuitive scenarios were run to validate and verify the model's performance before moving to a full-scale scenario.

The F/A-18E/F “Super Hornet” was specifically analyzed as a test case as it is a modern platform with an abundance of publicly available information that could be used to define the input parameters. For the Super Hornet fleet, the model recommended a combination of both traditional SLEP and replacement of aging aircraft as the optimal solution. The combined approach was largely driven by compounding maintenance costs on older aircraft, such that purchasing a nominal number of new aircraft ensured the reduced cost of the life extensions remained low over the planning horizon. Sensitivity analyses were conducted to identify the impact of uncertainty of certain parameters, and it was determined that the recurring costs of SLEP kit material and installation had the largest impact on the life cycle costs. However, the majority of costs incurred in all of the full-scale scenarios were due to general sustainment costs inherent in operating aging aircraft. Therefore, while outside the immediate scope of this thesis, as these costs do not directly pertain to life extensions, the best way to minimize life cycle costs is to reduce the annual sustainment costs driven by planned and unplanned maintenance and general operation.

While the Super Hornet fleet was selected to demonstrate the model's performance, the model should be capable of offering similar insights to any selected T/M/S for which programmatic and design parameters are available. Specific life limit, replacement cost, operational requirements, SLEP additional life and cost, and annual sustainment costs must be determined or estimated. The optimal solution for other platforms may vary significantly from the results of the Super Hornet, but the optimization function and constraints should be robust enough to handle a wide variety of possible scenarios.

ACKNOWLEDGMENTS

First and foremost, I'd like to thank my advisors, Dr. Daniel Eisenberg and Dr. Douglas Van Bossuyt, for all their insights, supporting me throughout my research, keen attention to detail, and helping to keep me on track. In particular, thanks to Dr. Eisenburg for all his assistance navigating the world of optimization and his expertise in Pyomo coding, previously unknown to me.

Next, I'd like to thank my command, the NAWCAD Air Systems Group, for allowing me the time away from my day job to complete this program and thesis as well as helping to fund my continued education. Also, to the PMA-299 team, I appreciate your understanding on the occasions I had to prioritize school over work.

To my SEM-PD21 cohort 221 members, thanks to you all for your comradery, both virtual and in person, as we struggled through together and came out the other side alive.

Finally, thanks to my family, friends, and loved ones for their support and understanding over the past two years as I had to forego spending time with them to work on my degree. I wouldn't be here without you, and owe my success to you.

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I. INTRODUCTION

While significant attention is often given to the development of new military systems, the complications of their sustainment are often overlooked or oversimplified. Maintaining continued airworthiness of military aircraft is a challenge that spans the life of the systems, especially during the operations and sustainment life cycle phases. This becomes even more challenging when systems are asked to remain in service longer than initially planned at program initiation. This thesis focuses on aircraft as a key military system and evaluates two alternatives to extending aircraft service life. The goal of this thesis is to compare programmatic and technical risks and offer a quantitative decision-making framework to optimize program costs that ensures the best use of limited funds.

The organization of this thesis is as follows: This chapter discusses the pertinent background to understand the basics of life extension programs, defines the problem statement, and outlines the overall methodology and scope of the optimization model. Chapter II outlines the fundamentals for each course of action (COA) and presents a summary of prior literature relevant to this thesis. Chapter III defines the mathematical model that is used to determine the optimal solution. Chapter IV details the model results from several scenarios and discusses them. Chapter V draws conclusions and offers recommendations for future programs.

A. BACKGROUND

A service life extension program (SLEP) is an important tool to allow sustained operation of Department of Defense (DOD) systems. While there is no universally accepted definition of what comprises a SLEP, it generally encompasses activities intended to extend the useful operational life by returning a system to as new a condition as possible (Stiffler and Wells 2022). Therefore, the required activities of a SLEP for any given system will be highly tailored to the specific needs of that system but may include component replacements, reliability or safety-driven modifications, maintenance requirement changes, and other such activities.

SLEPs may be particularly important for aircraft systems due to the safety implications of failures. Material failure, such as fatigue cracking and corrosion, will cause airframe structure to deteriorate as an aircraft ages and these issues may lead to structural failure, possibly resulting in the death of aircrew (Kim, Sheehy, and Lenhardt 2006, 2). Therefore, a structural life limit is established for a given aircraft system and is assessed at the airframe level; while other components and subsystems are likely to have their own, separately managed limits, they may be removed and replaced without affecting the integrity of the aircraft as a whole. This limit is generally formalized in maintenance publications for each applicable type/model/series (T/M/S) aircraft (e.g., the F/A-18A “Hornet” fleet may be assigned a different limit than the F/A-18E “Super Hornet”) and is usually measured in flight hours. When an individual aircraft reaches its flight hour limit, it is no longer considered airworthy unless an exemption is granted after engineering evaluation (DON 2022, 5).

There are a number of scenarios that may drive a requirement to extend the service life of an aircraft, but most tend to fall into one of two categories. The first scenario is that the rate at which an aircraft accrues flight hours over time (i.e., its utilization rate) is higher than was originally planned. For instance, if a fighter plane was designed with a 10,000-hour fatigue life limit (FLL) and was projected to accrue 500 flight hours per year, then it would notionally operate for 20 years before reaching this limit. If however, it actually flew 1,000 hours per year, then it would only be operational for 10 years. The second scenario driving a SLEP is that the originally forecasted program life was insufficient, often due to changing mission requirements. If a T/M/S was originally designed to operate for 20 years but no follow-on system is available to take its place at the end of that period, it must then remain in service as long as its mission remains relevant or else a capability gap will exist. The end result of these two scenarios is the same: the platform must outlast its original service requirements.

A traditional SLEP for aircraft will have elements categorized in one of three ways: inspection, repair, or replacement (He et al. 2016, 1747). When an aircraft reaches its published limit, a prescribed set of activities takes place based on requirements set by the cognizant engineering organization. Inspections may be required to assess the material

condition of critical components, the results of which would determine subsequent actions. Additionally, repairs may be required: either standard repairs to address conditions beyond allowable limits or modifications to the airframe design, such as incorporating doublers to increase strength. Lastly, components may be replaced with new ones of the same design, effectively resetting the fatigue clock for that component. It is possible that a SLEP for an aircraft may require a combination activities from each of these three areas to confidently extend the service life. The selection of these technical activities will be highly tailored based on the specific aircraft type, its history of failures, and forecasted future issues, based on either prior analysis or test.

An alternative to the traditional SLEP approach would be to replace aging aircraft with brand new ones of the same T/M/S. While a fundamentally different approach, this would still fulfill the ultimate objective of keeping legacy aircraft in service until they are no longer required, either because the mission is obsolete or are able to be replaced by a next-generation platform. One of the most critical factors in determining the viability of new production of an old T/M/S is whether or not the aircraft production line is still active. Often, foreign military sales (FMS) will require that production continues after the U.S. (domestic) program of record completes thereby keeping the production line in continuous operation. In this scenario, additional orders could be placed for new U.S. aircraft with minimal additional costs. However, if the production line is no longer active, additional costs are incurred to ensure tooling, qualified personnel, and materials are in place to restart production. This may not disqualify new production as a viable option but would increase the upfront costs.

A third possibility, which is outside the purview of maintenance and production lines, is to extend operation life by placing operational limitations on fleet operators. By restricting the rate at which flight hours are accrued or restricting the operational envelope to avoid known damaging maneuvers, aircraft may then operate over a longer time horizon before sufficient damage is accrued that would warrant airframe retirement. However, this would have numerous impacts that may limit the operational effectiveness of the system. These impacts possibly include a reduction of training flights, which would decrease overall pilot/aircrew proficiency or create a shortfall of qualified personnel and changing

the concept of operations (CONOPS) for system employment, which may have significant impacts to total mission effectiveness. Therefore, due to the complex interdependencies of these impacts, it is assumed that operational restrictions should not be considered viable.

B. PROBLEM STATEMENT

The goal of this thesis is to answer the following question for various military aircraft: which is a better option for life extension: SLEP, new production, or some combination of both? The decision to replace an aging aircraft platform with the next generation is made at the top levels of the DOD, following the Joint Capabilities Integration and Development System (JCIDS) processes in which a materiel development decision (MDD) is made to begin development on a new system (Joint Chiefs of Staff 2021, 88). However, this process does not typically apply to sustaining existing systems and there is no formal process in which life extension strategy decisions are made at the DOD level or the upper echelons of a specific service (Army, Navy Air Force, or Marine Corps); these decisions are generally left to the program manager (PM) responsible for the system.

Answering this question provides straightforward benefits to the DOD as it supports cost effective extension and maintenance of United States military aircraft service lives to meet minimum required military operational capabilities. This question can be decomposed to assess a number of factors that may affect the ultimate decision. The most obvious solely considers the costs involved in the extension effort. If all program planning assumptions are assumed to be valid, what is the least costly alternative that meets life extension goals: SLEP or new production? The question is significantly complicated once uncertainty and risks are introduced into the equation. If risks can be identified or planning assumptions change, to what extent might they impact overall SLEP costs or introduce technical risk into the continued operation of the system?

From an operations research and systems engineering perspective, this is a classic repair versus replace decision. Repair versus. replace decisions are not limited to aircraft systems nor the DOD, although the military context adds unique factors that must be considered. At what point is it no longer economically viable to sustain aging aircraft before they should be replaced?

C. OBJECTIVE AND METHODOLOGY

A mathematical model will be developed to create an objective framework to aid decision makers when determining a system's life extension strategy given the lack of existing, formalized processes. This will be accomplished via an integer quadratic program that optimizes the total life cycle cost associated with extending the effective life of a given aircraft platform.

When given program requirements and system operational parameters such as the life extension requirements, required number of operational aircraft, flight hour accrual rate, and other such factors, the model will identify the lowest cost solution to meet requirements, be it procuring and installing SLEP modification kits, procurement of new aircraft, or a combination of the two.

D. SCOPE AND ASSUMPTIONS

As with any model, generalizations must be made to remove details that may have little or no impact on the results and to simplify both the model generation and the users' understanding of the situation. The following are areas in which abstractions are made to simplify the model and its calculations without sacrificing significant realism.

One of the most significant assumptions relates to the ability to accurately define the true fatigue life limit of an airframe, eliminating conservatism that may actually allow for additional life. As briefly discussed previously, exemptions may be granted for aircraft once they reach their published limits to allow for continued operation. This "on-condition" sustainment philosophy, relies on the actual, inspected condition of a given aircraft to drive the decision to retire an aircraft or allow continued operations. On-condition life extensions make long-term forecasting and program planning extremely challenging as any required maintenance actions required to remain airworthy are unknown until each aircraft is inspected and its prior usage is assessed. Therefore, for the purposes of this model, it will be assumed that the published life limits are firm requirements and cannot be extended without incorporating pre-planned SLEP modifications or parts replacements. In reality, there would likely still be some level of limited life extensions pre-SLEP even if the true FLL is well-understood. For instance, if an aircraft is limited to an 8,000-hour FLL and

reached that limit but was due for a scheduled depot maintenance period in the next six months, it may be allowed to continue operating until its SLEP package may be installed in conjunction with the scheduled maintenance period for the sake of logistical efficiency.

This analysis also assumes that the requirement for number of operational aircraft does not exceed the quantity that was originally purchased – the requirement may vary year over year provided the value is always less than or equal to the number of aircraft procured. In other words, it is expected that the program of record quantities originally identified were sufficient to meet the operational need if the aircraft were never retired. If this were not true, the only solution would be to procure additional aircraft, which does not require a repair/replace decision to be made. For example, if the program of record procurement completes with 100 aircraft, the required number of operational aircraft in any given year may not exceed 100.

It is also assumed that neither a traditional SLEP nor procurement of new aircraft would offer any capabilities not already in the fleet; these life extension activities are solely sustainment-focused and are not further complicated by the risks and costs associated with system development. This assumption also allows prior (actual) costs to be used without having to adjust for increasingly complex systems, which may be likely to be more expensive.

Additionally, the analysis uses constant-year dollars (CY\$) when evaluating courses of action, removing complications due to inflation, either forecasted or realized. This makes figures more easily comparable year over year without the user having to perform additional calculations to manually adjust costs. The user may still apply assumed inflation rates to the CY\$ after the model is run if required to forecast actual projections for budgeting or other purposes.

E. RELEVANCE TO SYSTEMS ENGINEERING

The classic “V” model, shown in Figure 1, illustrates a simplified view of systems engineering processes throughout system development. While a SLEP is not quite the same as the development of a new system, the same general principles apply. The work done in this thesis primarily aligns to the requirements and design phases, on the bottom-left side

of the “V.” The operational need must already be defined – in this case if and for how long the aircraft’s service life must be extended. At that point, the optimization model developed here may be used to determine the most appropriate SLEP course of action, essentially the top-level architecture of the solution. Obviously, the decision to repair or replace aircraft could be considered as viable options. However, multiple versions of a traditional SLEP, if available, may also be evaluated for both technical adequacy and affordability. For instance, if a SLEP option exists that is less costly but offers less additional fatigue life than a more intensive alternative, it may not be evident which is more cost effective since a higher quantity of the less expensive option are likely required to achieve the same end result. The selected SLEP architecture should then be traceable back to the operational needs to show that the required fleet capabilities may be maintained. This work is also applicable in the later stages of the life cycle as the SLEP solution is being implemented. As military policy and/or operational concepts change over the years or if additional data becomes available to prove that original assumptions were incorrect, it is important to reassess the originally selected SLEP solution to ensure it will still meet the operational need.

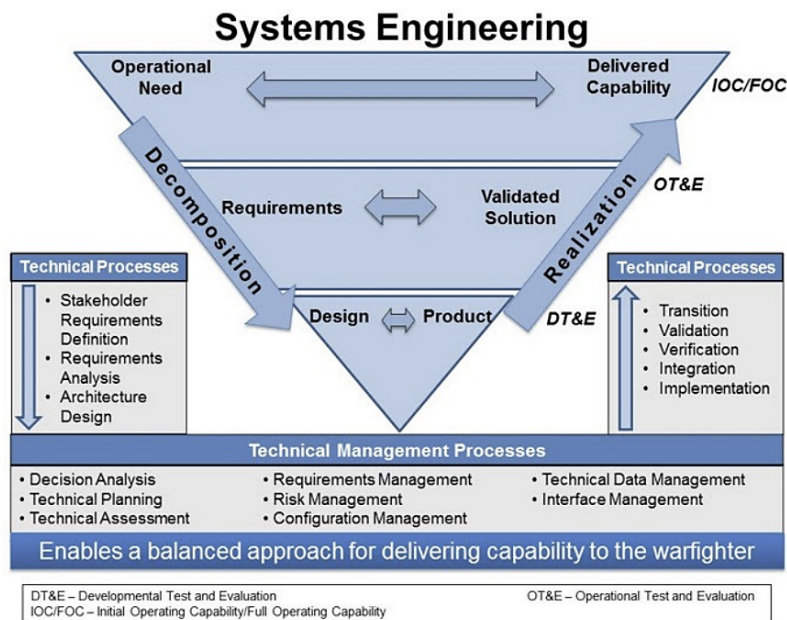


Figure 1. The Systems Engineering “V” Model.
Source: DOD (2022, 13).

Ultimately, it is not the role of the systems engineer to decide which SLEP course of action to pursue (provided all meet the technical requirements) due to the budgetary responsibility held by the program manager. However, as DOD engineering organizations are responsible for the airworthiness of the aircraft and other technical requirements, certain courses of action may be inherently riskier than others and the systems engineers for the platform should therefore be deeply involved in identifying and evaluating all SLEP alternatives, and provide a recommendation to the PM. Additionally, to make an informed decision, even with the use of an optimization model, systems engineers will be required to help determine many of the model inputs and evaluate the results. One such example is working in conjunction with the structural engineers, the subject matter experts (SMEs) for airframe fatigue, to define and estimate the associated costs for a potential SLEP solution (especially the design and qualification aspects). So while a minimized program cost is not the primary concern of the systems engineer, any negative technical consequences of the selection will undoubtedly fall to the engineering community to mitigate. Therefore, it is critical that systems engineers understand and are fully integrated in the COA development and selection process that this thesis analyzes.

II. BACKGROUND OF ALTERNATIVES AND REVIEW OF PRIOR WORK

This chapter provides the relevant background for aircraft life extension alternatives, including research into actual extension programs for military systems, to provide context for the optimization model that is presented later on in Chapter III. Additionally, this chapter summarizes the literature review that was conducted to leverage preexisting work and to identify gaps that will be explored in greater detail in this thesis.

A. BACKGROUND OF ALTERNATIVES

In order to develop a decision-making model for life extension alternatives, the costs associated with SLEPs and aircraft replacement must be understood. This section describes the basics of each course of action as well as where costs would be incurred and how they may be categorized.

1. Traditional SLEP

A traditional SLEP would proceed similarly to any developmental program in that the generic life cycle model is followed, shown in Figure 2. The requirements for life extension are defined and drive the concept. The system, in this case an aircraft modification kit, is then designed and realized (produced and fielded).

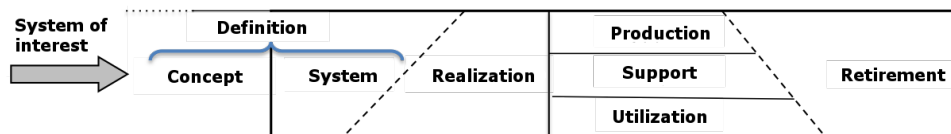


Figure 2. Generic Life Cycle Model.
Source: Forsberg, Turner, and Adcock (2023)

Since the requirements for a SLEP are specific to a particular type of aircraft with unique mission requirements, it is unlikely that the activities and costs associated with them can be generalized to define a reliable relationship between the additional life offered by a SLEP and the costs. However, to determine if this is the case, five SLEPs previously

undertaken for military aircraft were considered in greater detail. For each scenario, first the baseline, pre-SLEP life of the aircraft was determined. Then, the additional expected life post-SLEP was found so as to be able to compare it to the baseline. With the top-level technical goals of the SLEPs documented, the costs of those SLEPs (on a per-aircraft basis) and the flyaway costs for a new aircraft were found. Since these SLEPs did not occur concurrently, all cost data was adjusted to 2023 dollars for comparability. The summary of these prior SLEPs is shown in Table 1.

Table 1. Summary of Historical Aircraft Life Extension Programs

Platform	Original Life (hours)	Additional Life (hours)	Flyaway Cost (per A/C)	Cost of SLEP (per A/C)
C-2A Greyhound	10,000 ¹	5,000 ¹	\$49.4M (\$39.0M 2016\$) ¹	\$6.4M (\$4.6M 2010\$) ²
F/A-18E/F Super Hornet	6,000 ³	4,000 ⁴	\$83.9M (\$83.9M 2023\$) ⁵	\$36.3M (\$26.0M 2010\$) ²
F-16 Fighting Falcon	8,000 ⁶	4,000 ⁶	\$71.8M (\$64.0M 2021\$) ⁷	\$2.9M (\$2.4M 2018\$) ⁶
A-10 Thunderbolt II	6,000 ⁸	10,000 ⁸	\$22.5M (\$18.6M 2018\$) ⁹	\$11.5M (\$8.1M 2009\$) ⁹
P-3C Orion	24,000 ¹⁰	15,000 ¹¹	\$96.4M (\$36M 1987\$) ¹²	\$23.2M (\$15.8M 2007\$) ¹¹

¹ Data from USNA (2016); ² Data from Keating et al. (2010, 10–33); ³ Data from Global Security (2018); ⁴ Data from Eckstein (2022); ⁵ Data from DON (2023a, 46); ⁶ Data from Garbarino (2018); ⁷ Data from Venckunas (2021); ⁸ Data from Davis (2009, 2–3); ⁹ Data from Smith (2018); ¹⁰ Data from Global Security (2016); ¹¹ Data from Lockheed Martin (2007); ¹² Data from Aero Corner (n.d.)

Note: then-year dollars were converted to current-year dollars (adjusting for inflation) using <https://www.officialdata.org/>. Original costs are depicted beneath the corrected costs for reference.

From this data, percentages were calculated for the amount of additional life expected from a SLEP (where 100% would represent a doubling of the service life). Similarly, percentages were calculated for the per aircraft SLEP costs as compared to the cost of a new, replacement aircraft (where 100% would indicate that the SLEP costs are equal to the replacement costs). This normalized data for each aircraft was then plotted to determine if there was a trend between the additional life and cost, the results of which can be seen in Figure 3.

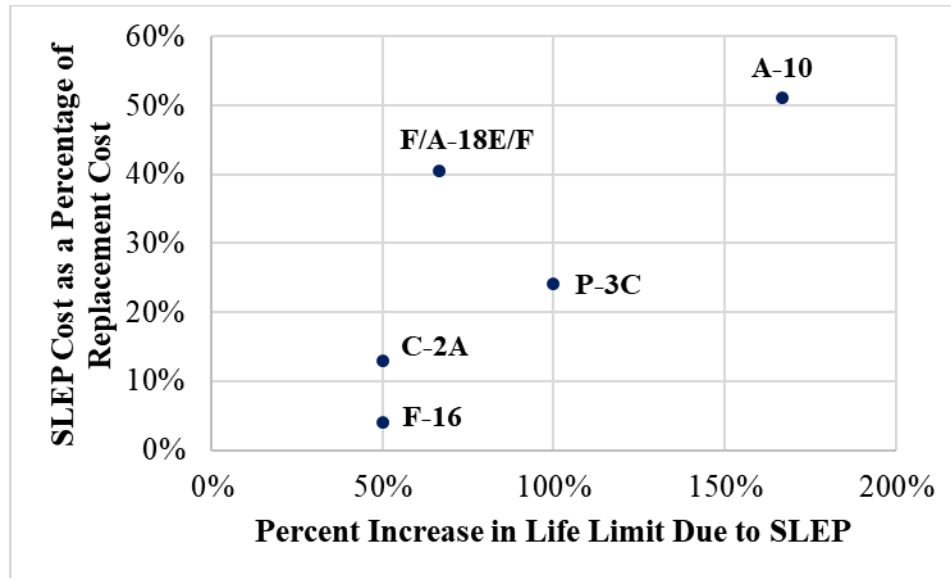


Figure 3. Comparison Between Expected Life Extension and Cost

From the plotted data, there is no consistent trend between the cost incurred and additional life gained from a SLEP. Therefore, subject matter experts should be used to determine cost estimates for non-recurring and recurring activities.

In order to consider how costs associated with a traditional SLEP could be incorporated into an optimization model, they must be categorized; activities associated with a traditional SLEP may be sorted into one of two groups: non-recurring and recurring. Non-recurring activities are those required to be performed only once over the course of the program. In the case of SLEP, these non-recurring costs may include damage tolerance analyses, modification design, ground or flight testing, formal certification of the design, and other such activities (Defense Acquisition University n.d.). Recurring activities are those that will be typically repeated for each SLEP being performed. These recurring cost elements primarily include material procurement and labor for manufacture, installation, and related efforts (Boger and Liao 1990, 14–16). Recurring versus non-recurring is an important distinction since while the number of aircraft receiving SLEP modifications will vary with the operational requirements, the non-recurring activities must still be fully funded whether modifying a single aircraft or the entire fleet.

2. Replacement Aircraft

Aircraft replacement is a more straightforward alternative than a traditional SLEP, especially if the production line is still active, primarily due to the higher certainty of understanding how the aircraft will perform once delivered. While possible supply chain interruptions, quality escapes, and other risks certainly exist, they are largely managed by the contractor responsible for production. Additionally, it is likely that decision makers would have much more accurate cost estimates for new aircraft production given years of prior procurement history, thereby avoiding some level of cost risk.

Establishing and managing an aircraft production line is an extremely complicated process; material procurement, labor, quality, stock, and obsolescence must all be managed during production (Mertins, Krause, and Schallock 1999, 63). However, this research will not discuss the specifics of establishing and managing production as including aircraft replacement as a life extension alternative assumes that this process is either already ongoing or has been successfully established in the past.

Similar to the previous discussion for a traditional SLEP, required activities for aircraft replacement may be categorized as either non-recurring or recurring. The non-recurring activities in this case would be mostly driven by those costs associated with restarting the production line. Recurring costs would include the material and labor costs required to physically produce the new aircraft, tooling replacement (as required), and production support functions such as engineering and quality assurance (Birkler et al. 1993, 60). Restarting a production line, while no small undertaking, is still much cheaper and more efficient than establishing a brand-new line; the non-recurring labor costs are approximately 10% of the original labor costs and the time to produce the first units is a year or two less than the original production start (Birkler et al. 1993, 14).

In another study, the RAND Corporation considered the F-22A “Raptor” as its production line was shutting down and sought to estimate the potential cost to re-open the line if required by the United States Air Force (Graser et al. 2011, 1–30). This study considered the costs associated with facilities, tooling, personnel, requalification, and major subcontractors. It also considered the main advantages and disadvantages of

restarting production, including how production tooling may be required for a future SLEP. Additionally, it found that, unsurprisingly, the cost to restart production to procure an additional 75 aircraft would be more costly (by approximately \$900 million) if a complete line shutdown were to occur (Graser et al. 2011, 22).

As with the cost estimates for a traditional SLEP, production line restart and procurement costs will be highly sensitive to the specifics of the program being considered. Therefore, there is no “one size fits all” figure that can be used to approximate the required funding, and SME inputs along with historical actual costs should be used to develop estimates.

3. General Sustainment Costs

Regardless of how a program opts to address service life issues, sustainment costs are unavoidable, and while not wholly a part of a SLEP effort, should be considered when deciding which course of action to pursue. Presumably, as aircraft age, it would become more expensive to continue to maintain them, which if true would result in higher sustainment costs for older airframes that undergo SLEP modifications than those that are replaced by newly procured aircraft.

The Congressional Budget Office (CBO) conducted a study specifically to determine how aging affects the operations and maintenance (O&M) costs for military systems (Kiley and Skeen 2001, 11–37). This study, considering U.S. Navy and Air Force aircraft, determined that there was a significant relationship between age and cost. It was originally estimated that O&M costs would increase between 1% and 3% each year (Kiley and Skeen 2001, 36). A later study from the CBO, revisiting the prior analysis, suggests that the actual increase may be between 3% and 7% after removing the effects of inflation (Trunkey 2018, 1). The summary of this updated study can be seen in Figure 4.

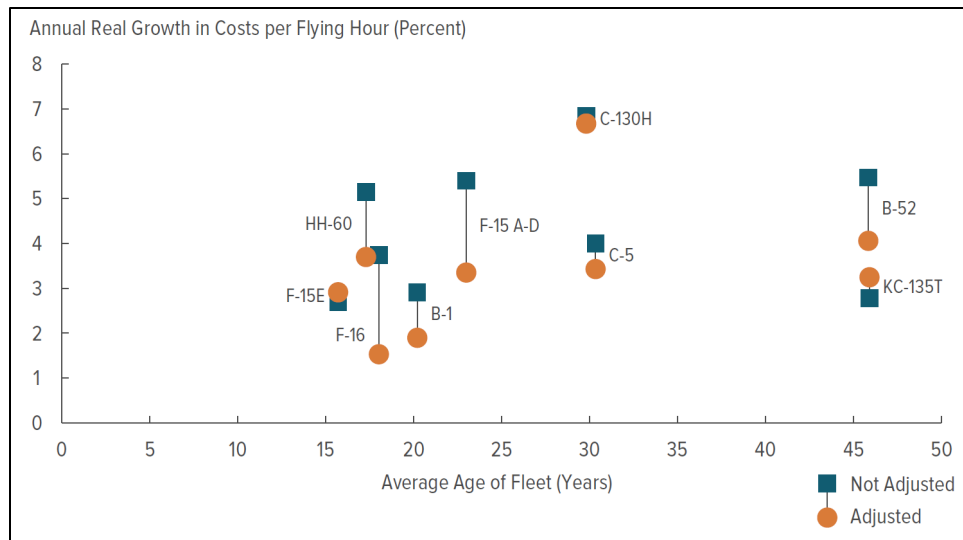


Figure 4. Operating Costs of Aging Aircraft.
Source: Trunkey (2018, 9)

While this cost increase over time may seem relatively insignificant at first glance, the Navy’s fiscal year 2021 budget for air operations O&M was over \$12 billion (Department of the Navy [DON] 2021, 2) and the Air Force’s O&M budget for air operations in the same year was nearly \$35 billion (Department of the Air Force 2021, 8). So even small percentage increases each year will likely have a significant impact on the overall cost requirement.

B. REVIEW OF PRIOR WORK

There has been significant prior research into the successes and failures of SLEP on aircraft programs and the repair versus replace decision, which is something that is applied to nearly all systems. This section summarizes prior research performed in the areas this thesis seeks to explore and identifies gaps that warrant further discussion and investigation.

In a case study written on behalf of the Air Force Institute of Technology, the SLEP for the A-10 Thunderbolt II was discussed (Jacques and Strouble 2010, 54–60). Based on full scale fatigue testing on the A-10’s airframe and wings (multiple tests were conducted at different system/subsystem levels), various SLEP alternatives were identified, including both repair and replacement of the wings, the primary life-limiting components.

Additionally, the study specified the quantities required to meet an operational requirement to fly until 2028 (Jacques and Strouble 2010, 54–60). This analysis did not detail any comparative analysis on the specifics of the wing replacement/repair, only the total costs, so it is unclear exactly how these costs were determined.

Although predominantly focusing on the technical aspects of the P-3C “Orion” SLEP and the accompanying costs, James Tran’s 2014 analysis did consider the alternative of procuring the next generation P-8 “Poseidon” to the traditional SLEP approach. However, the real strengths of this study were in highlighting the inability of the P-3C program to identify the full technical requirements to execute an effective SLEP due to inadequate life assessment, as confirmed by inspections on fleet aircraft (Tran 2014). However, as this assessment was conducted after the traditional SLEP decision had already been made, detailed analysis into considering a replacement was not performed. Additionally, this only considered replacement of a different airframe than that being repaired, so cost any comparisons would be different than those considered in this thesis. Tran’s research may be used to help identify risk areas for a traditional SLEP approach.

As service life extensions are not unique to aircraft systems, work outside of the aerospace industry may be relevant to this thesis. For instance, Liu et al. (2021, 1–15) consider the most cost-effective means of life extension for ships. Like aircraft, ships’ design lives are primarily driven by material fatigue. It provides a detailed look into the technical side of a SLEP and considers not only the style and cost of repairs, but also the installation timing (Liu, Yang, and Frangopol 2021, 1–15). However, this treated repair as the only option and did not consider replacement as a viable alternative. This paper illustrated the importance of the time phasing of a SLEP and how it is just not a binary decision of whether to repair a system, but also when to make the repair to maximize the utility of the repair, given the investment.

Conversely to the ship life extension work which sought to make the most of repairs, there has been a great deal of research into the optimal time to replace systems to minimize cost by predicting failures. In one such study by R. Jiang (2018, 303–306), classic replacement models are analyzed and used to develop optimization models. Jiang’s work also considers when each model should be used, such as in determining replacement

intervals and how often to conduct preventative maintenance (Jiang 2018, 308). However, while informative to help add context and an understanding of the SLEP decision, these classic models are not directly applicable; because aircraft already have a calculated fatigue life limit, it is assumed that those limits cannot be exceeded without a SLEP. Components or subsystems that fail prior to the life limit would be subject to a separate repair or replace decision, but that is a reactive process unlike the proactive process to install SLEP modifications or procure replacements. Additionally, Jiang's research does not explicitly address the cost of repairs to extend life, though it could be argued that preventative maintenance falls into this category.

A 2010 Government Accountability Office (GAO) report was conducted to assess how well the services' (Air Force, Navy, and Marine Corps) plans to upgrade, retire, or replace current tactical aircraft measured against inventory requirements (Sullivan 2010, 1–29). Some extremely relevant data to this thesis was discussed, such as a cost comparison for an F/A-18E/F “Super Hornet” service life extension versus procurement of replacement aircraft. In this analysis, it was deemed to be more cost effective to replace the aging aircraft given the specifics of the Super Hornet program at the time, especially considering that the production line was still active (Sullivan 2010, 22). Unfortunately, however, there was no discussion as to how these costs were specifically calculated nor how the program requirements could be traced to the operational requirements. This report highlights the trade space that exists between sustainment and replacement and can be used to help frame the decision-making process.

Complimentary to Sullivan's report, a 2010 RAND Corporation report performed multiply analyses in evaluating whether a SLEP for the F/A-18E/F fleet would be more cost effective than replacing them with the next generation F-35C (Keating et al. 2010, 1–29). Unlike other repair versus replacement cost comparisons, this study also accounted for the increased sustainment costs that aging aircraft are more likely. Additionally, rather than simply provide an answer as to which course of action is less expensive, the report assesses how the answer varies as certain parameters change, such as the cost of the SLEP (illustrated in Figure 5), the amount of additional life a SLEP provides, or the cost of the replacement aircraft (Keating et al. 2010, 20–24). These analyses were then repeated

considering the C-2A “Greyhound” fleet (Keating et al. 2010, 33–40). Unfortunately, the granularity of the cost estimates is still relatively coarse and relies on a single value (normalized to the requirement per aircraft) to represent the cost of a SLEP, rather than breaking into non-recurring and recurring costs (which would allow the quantity of aircraft undergoing SLEP to be variable without double bookkeeping the non-recurring costs). Regardless, this work offers many valuable insights into life cycle cost estimation for both replaced and SLEP aircraft.

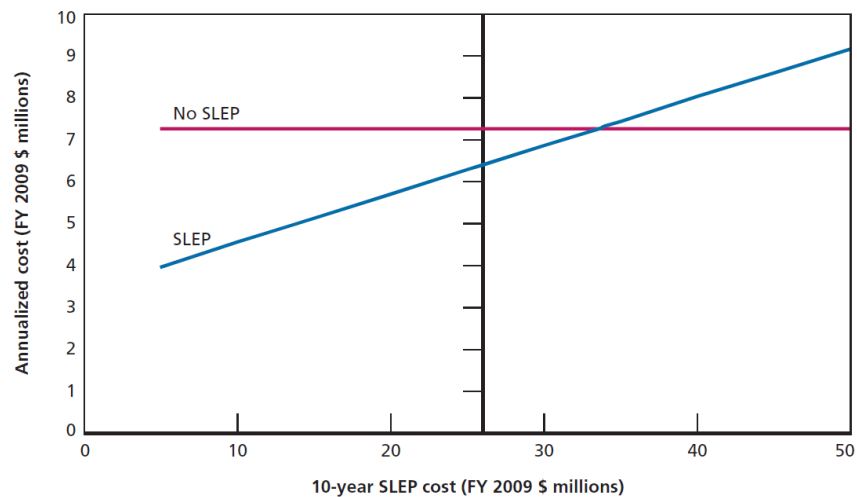


Figure 5. Estimated Cost Implications of a SLEP to the F/A-18E/F.
Source: Keating et al. (2010)

While several of the previous works cited sought to optimize the cost, there was little discussion on whether a formal optimization model was formulated and solved or if costs for known alternatives were simply calculated and compared. Since the relationships between decision variables and the resultant total cost may not always be intuitive, it is important to understand the exact methodology used so decision makers are able to make properly informed decisions. To that end, the following research is focused on creating and implementing mathematical models which optimize cost for either the repair or replacement of existing systems.

A 1968 study sought to minimize the cost in purchasing a mix of different types of Marine Corps aircraft to satisfy training requirements (Bracken and Burnham 1968, 81–

96). The authors created a linear program in which costs for procurement and operating the aircraft were summed while considering the attrition rate for each aircraft type as well as constraining by the required quantity to meet training needs over a five-year period (Bracken and Burnham 1968, 81–96). As this was conducted in the late 1960s, computing power was likely a limiting factor in the complexity of the model. No life extension alternatives were considered, only new procurement; therefore, this model is not directly comparable to the one developed in this thesis. However, the basic principles employed by Bracken and Burnham serve as a foundation for this thesis.

A more recent example of procurement optimization is demonstrated by an effort to minimize the cost of equipment replacement, validated using data for vehicles owned by the Texas Department of Transportation (Fan, Machemehl, and Gemar 2012, 160–170). In this study, an integer linear program was formulated over a twenty-year time horizon which predicted substantial cost savings could be achieved as compared to current practices. Additionally, and interestingly, the authors opted to use a recursive approach that factored previous decision into the results (Fan, Machemehl, and Gemar 2012, 160–170). Unfortunately, this report did not explicitly consider whether a SLEP-type approach could be applied as an alternative (which may not even be a realistic approach for a land-based vehicle), and therefore still only considers half of the decision space discussed in this thesis.

Another study considers new production, modernization, and retirement of U.S. military owned systems when developing a cost optimization model (Ameyugo 1996, 1–33). This report considers inventory quantity, system age, budget, and production line constraints in the optimization model and uses integer constraints and binary decision variables to control the results (Ameyugo 1996, 29–33). However, like the previous models, this does not account for the possibility of a SLEP extending system life. The general form of the objective function, summing all possible costs using binary decision variables to determine whether certain costs will be incurred, is a very useful baseline to have when considering the repair versus replacement decision in the context of SLEP.

Bradley Meeks' thesis (1999, 1–41) considers the optimizing depot maintenance for the EA-6B “Prowler” fleet. This depot maintenance required replacing and modifying major aircraft structure to extend life, and despite not explicitly using the term “SLEP,” is

a SLEP, nonetheless. The model considers a number of aircraft over multiple time periods and seeks to minimize the time aircraft are removed from the active inventory while undergoing modification (Meeks 1999, 1–41). Despite solving for minimized time rather than cost, the optimization function mirrors the basic format employed previously by Ameyugo; all possible outcomes are summed, and binary decisions variables are used to ignore those that are not applicable by setting the variable’s value equal to zero (Meeks 1999, 20–24).

So while SLEP, system replacement, and cost optimization are not new concepts, there exists a gap in prior research that this thesis seeks to fill. This thesis will consider the most optimal way to minimize life cycle costs when both repair (SLEP) and replacement are viable options (in the context of military aircraft). Table 2 summarizes the relevant prior research and illustrates where each study applies to the topics discussed herein.

Table 2. Literature Review Summary

Source	Aircraft-Centric	Repair-Based SLEP	Replacement	Repair vs. Replace	Cost Optimization
Jacques and Strouble (2010)	X	X	O	O	-
Tran (2014)	X	X	O	O	-
Liu, Yang, and Frangopol (2021)	-	X	-	-	X
Jiang (2018)	-	-	X	O	X
Sullivan (2010)	X	X	X	X	-
Keating et al. (2010)	X	X	X	X	O
Bracken and Burnham (1968)	X	-	X	-	X
Fan, Machemehl, and Gemar (2012)	-	-	X	-	X
Ameyugo (1996)	O	-	X	-	X
Meeks (1999)	X	X	-	-	X

X = Detailed Discussion O = Limited Discussion - = No Discussion

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III. MODEL METHODOLOGY AND DEFINITION

This chapter details the model developed in this thesis and provides explanations for its use to determine optimal aircraft sustainment via SLEP and new production. Additionally, the basics of the selected solver software is summarized to provide background on the optimization methods. Sample, simplified data sets are used to demonstrate model output. This simplified scenario verifies and validates model performance before larger-scale, real-world scenarios are considered.

A. OPTIMAL AIRCRAFT LIFE EXTENSION MODEL

This section provides the formulation of the life extension optimization (LEO) mathematical model, including the optimization function, all constraints, and other relevant calculations. The basic model elements are defined in Tables 3 through 6. Table 3 describes the objective function for which the model solves. Table 4 identifies the indices used throughout the model that define the dimensions of variables and parameters. Table 5 identifies all variables used in the model that the solver may adjust to achieve an optimal solution. Finally, Table 6 identifies all parameters that require preassigned values and do not change as the model is solved. The full definitions of these elements are provided later in this section.

Table 3. Objective Function Definition

Objective	Description [units]
C	Total program cost of the life extension [\$]

Table 4. Index Definitions

Index	Description
i	Set of aircraft in the fleet
t	Each year under consideration

Table 5. Variable Definitions

Variable	Description [units]
A_{it}	Age of aircraft i in year t [years]
D_{it}	Binary variable defining whether aircraft i has been purchased yet in year t [1 if no, 0 if yes]
L_{it}	Fatigue life limit of aircraft i in year t [years]
M_{it}	Decision to modify (SLEP) aircraft i in year t [1 if yes, 0 if no]
P_{it}	Decision to procure a new aircraft to replace aircraft I in year t [1 if yes, 0 if no]
S_{it}	Sustainment cost of aircraft i in year t [\$]
X_{it}	Binary variable defining whether aircraft i has exceeded its life limit in year t [1 if yes, 0 if no]
Y	Binary variable determining if SLEP kit NRE costs are required [1 if yes, 0 if no]
Z	Binary variable determining if production restart costs are required [1 if yes, 0 if no]

Table 6. Parameter Definitions

Parameter	Description [units]
b	Y-intercept of the linear regression line approximating sustainment costs [\$]
B	Baseline (no-SLEP) fatigue life limit of aircraft i [years]
d	Additional life gained if an aircraft is SLEPed [year]
E	Non-recurring engineering (NRE) costs for SLEP mod kit development [\$]
F_i	First year aircraft i was in service [years]
H_{it}	Flight hours accrued by aircraft i in year t [hours]
J	Year in which life extension requirements become available [years]
k	Kit and installation cost for traditional SLEP (per aircraft) [\$]
m	Slope of the linear regression line approximating sustainment costs [\$]
N	Cost of a new aircraft [\$]
O	Operational flight hours accrued per year [hours]
Q	Maximum production capacity in each year [aircraft]
R	Cost to re-start production line [\$]
r_t	Required number of authorized aircraft in year t [aircraft]
U	Maximum SLEP modification capacity in each year [aircraft]
W	Cost to sustain an aircraft in its first year [\$]

1. Objective Function Definition

The model objective is to minimize the total life cycle costs, C , directly associated with SLEP and new production. This function is comprised of three factors: the cost to implement a traditional (modification based) SLEP, the cost to replace aging airframes with new ones, and the general sustainment costs. This objective function is represented by Equation (1). The structure for the modification and replacement portions of the objective function are essentially mirrors of each other. There is an upfront cost for either modification kit development or production line restart, as applicable and discussed later, which is added to the total cost of either the total kit procurements or the total new aircraft procurements. The general sustainment costs are simply the total sum of the cost to sustain each aircraft in each year.

$$\min C = \left(Y * E + k * \sum_{i=1}^I \sum_{t=1}^T M_{it} \right) + \left(Z * R + N * \sum_{i=1}^I \sum_{t=1}^T P_{it} \right) + \sum_{i=1}^I \sum_{t=1}^T S_{it} \quad (1)$$

2. Index Definitions

Two indices are used in the model: i and t . These are defined by Equations (2) and (3). In the model, i represents an aircraft in the inventory while I represents the total quantity. So, for example, if 100 total aircraft were procured, I would equal 100. Similarly, t represents the first year under consideration while T represents the last year under consideration. So, for example, if the model is being run from years 2000–2020, $t = 1$ corresponds to the year 2000 while T would equal 21, corresponding to the year 2020.

$$i = \{1, \dots, I\} \quad (2)$$

$$t = \{1, \dots, T\} \quad (3)$$

3. Binary Decision Variable Definitions

Two primary, binary decision variables are used in the optimization model: M_{it} and P_{it} . M_{it} is the decision to install a SLEP modification kit on a given aircraft in a given year

and P_{it} is the decision to procure a replacement aircraft for a given aircraft in a given year. If an aircraft receives a modification kit in a year, M_{it} will equal 1; otherwise, M_{it} will equal 0. Similarly, if an aircraft were replaced by a new one in a year, P_{it} would equal 1; otherwise, P_{it} would equal 0. These are defined and constrained by Equations (4) and (5).

$$M_{it} \in \{0,1\} \quad \forall i,t \quad (4)$$

$$P_{it} \in \{0,1\} \quad \forall i,t \quad (5)$$

Additionally, four other binary decision variables are used which are fully controlled by the value of M_{it} , P_{it} , and model parameters: D_{it} , X_{it} , Y and Z . D_{it} represents whether an aircraft has already been procured at a given point in time by comparing the year it was purchased and the current year. If the current year is later than the year in which that aircraft was procured, D_{it} will equal 0; otherwise D_{it} will equal 1. X_{it} represents whether an aircraft is still operational based on the current point in time and its accrued flight hours as compared to its life limit. If an aircraft has already been procured and its total flight hours to-date do not exceed the life limit, X_{it} will equal 1 (meaning it is operational); otherwise, X_{it} must equal 0 (meaning it is non-operational). Y and Z are effectively used to trigger the funding requirement for modification development and production restart costs, respectively. If either variable equals zero, then the corresponding cost in the objective function is \$0. Y represents whether any aircraft will receive SLEP modification kits and therefore whether kit development and qualification must be funded. If any aircraft receive a SLEP modification, Y will equal 1; otherwise, Y will equal 0. Z represents whether any aircraft will be replaced by newly procured aircraft and therefore whether production line restart costs must be incurred. If any aircraft are replaced, Z will equal 1; otherwise, Z will equal 0. These are defined and constrained by Equations (6), (7), (8), and (9).

$$D_{it} \in \{0,1\} \quad \forall i,t \quad (6)$$

$$X_{it} \in \{0,1\} \quad \forall i,t \quad (7)$$

$$Y \in \{0,1\} \quad (8)$$

$$Z \in \{0,1\} \quad (9)$$

4. Non-Recurring Cost Decision Variable Constraints

In order to drive the value of Y and Z to the desired results, additional constraints must be applied. To set Y or Z equal to 1 in the event any modifications or replacements are undertaken, the value of Y or Z must be greater than or equal to the sum of all aircraft modifications or replacements, respectively, over the considered timeframe for all aircraft. This is shown in Equations (10) and (11). In order to drive the value of Y or Z to equal 0 in the event no modifications or replacements are undertaken, Y or Z must be less than or equal to the sum of all modifications or replacements, respectively, over the desired timeframe and aircraft inventory. This is shown in Equations (12) and (13).

$$Y \geq \sum_{t=1}^T M_{it} \quad \forall i \quad (10)$$

$$Z \geq \sum_{t=1}^T P_{it} \quad \forall i \quad (11)$$

$$Y \leq \sum_{i=1}^I \sum_{t=1}^T M_{it} \quad (12)$$

$$Z \leq \sum_{i=1}^I \sum_{t=1}^T P_{it} \quad (13)$$

5. Fatigue Life Limit and Flight Hour Accrual Constraints

Before driving the value of X_{it} to the desired value, additional information related to an aircraft's life limit must be determined. It is assumed that over the life of the program, an aircraft can either be modified or replaced (but not both), though neither is necessarily required. This assumption is captured by Equation (14). First, the life limit for each aircraft

in each period, L_{it} , must be defined. Since each aircraft will have a baseline life limit (prior to any extension actions), defined by the parameter B , the life limit is initialized at the $t = 0$ time period for all aircraft, shown in Equation (15). Then, to calculate the life limit for a given aircraft in a given year, an additional parameter for the amount of additional service life provided by a SLEP modification must be considered, referred to as d . Therefore, L_{it} must equal the life limit from the previous period plus either the additional life, if a modification kit is installed, or the baseline life, if a replacement aircraft is procured. Since only a single modification or replacement is authorized for each aircraft, the new life limit cannot exceed the baseline plus the additional life or twice the baseline limit (functionally meaning the new aircraft would not be used until the one it replaces retires). This life limit calculation is captured in Equation (16).

$$\sum_{t=1}^T (M_{it} + P_{it}) \leq 1 \quad \forall i \quad (14)$$

$$L_{i,0} = B \quad \forall i \quad (15)$$

$$L_{it} = L_{i,t-1} + (M_{it} * d) + (P_{it} * B) \quad \forall i, t \quad (16)$$

A parameter for the utilization rate (the number of operational flight hours accrued per year), O , is used to calculate the total number of flight hours, H_{it} , that have been accrued by an aircraft (including its replacement, if applicable) by a given year. This also requires a known parameter set, F_i , of the first year an aircraft was available (the year in which it was first procured). It is assumed that an aircraft flies O hours in the first year in addition to all subsequent years. Therefore, the total number of hours accrued is represented by Equation (17). It should be noted that this calculation does not yet consider whether an aircraft has been procured, so the value of H_{it} may take on zero or negative values if procurement has not yet occurred; this illogical scenario is accounted for later in the model.

$$H_{it} = O * (t + 1 - F_i) \quad \forall i, t \quad (17)$$

6. Aircraft Operational Availability Variable Constraints

Having calculated the previous information, it is now possible to fully constrain the value of the aircraft availability variable, X_{it} , discussed previously. By selecting an arbitrarily large value, 100,000 in this case, and multiplying it by X_{it} , the resultant value must be greater than or equal to the difference between the life limit and the number of hours accrued. This allows X_{it} to equal 1 but not 0 when an aircraft's life limit has not yet been surpassed, as shown in Equation (18). Contrarily, to drive X_{it} to equal 0 but not 1 when the life limit is surpassed, as shown in Equation (19), the same arbitrarily large value is multiplied by the difference between 1 and X_{it} and must be greater than or equal to the difference between the hours accrued and the life limit. To account for the fact that these constraints are inequalities, a 1 is added to the current life limit, allowing an aircraft that has met but not yet exceeded its limit to register as "available."

$$100,000 * X_{it} \geq (L_{it} + 1) - H_{it} \quad \forall i, t \quad (18)$$

$$100,000 * (1 - X_{it}) \geq H_{it} - (L_{it} + 1) \quad \forall i, t \quad (19)$$

Mirroring the way X_{it} is constrained, since an aircraft cannot count towards the inventory if it not yet been procured, Equations (20) and (21) are used to drive the value of the D_{it} , which is also a binary variable. This uses the same arbitrary, large number (100,000) and compares the difference between the year in which the aircraft was first procured, F_i , and the current year. Again to account for the inequalities, a 1 is added to the current year. Unlike X_{it} , D_{it} takes on a value of 0 when the aircraft is considered available and 1 when it has not yet been procured.

$$100,000 * D_{it} \geq F_i - (t + 1) \quad \forall i, t \quad (20)$$

$$100,000 * (1 - D_{it}) \geq (t + 1) - F_i \quad \forall i, t \quad (21)$$

7. Fleet Quantity Requirement Constraints

Next, to ensure the operational demand is met, another set of constraints must be established to require the total number of operational aircraft to be greater than or equal to the fleet required quantity each year, r_t , as shown in Equation (22). Since the demand may vary over time based on a number of external factors, this must be applied to each time period. The number of operationally available aircraft is determined by subtracting the aircraft that have not been procured from the number of aircraft that have not yet exceeded the life limit.

$$\sum_{i=1}^I (X_{it} - D_{it}) \geq r_t \quad \forall t \quad (22)$$

8. SLEP and Replacement Capacity and Timing Constraints

Capacity for both production and SLEP modifications should also be considered, as it is unrealistic to assume an infinite number of aircraft could be built or modified in a single year. These constraints are represented by equations (23) and (24) in which the sum of any aircraft modified or procured in each year may not exceed its respective maximum value, parameter U or Q .

$$\sum_{i=1}^I M_{it} \leq U \quad \forall t \quad (23)$$

$$\sum_{i=1}^I P_{it} \leq Q \quad \forall t \quad (24)$$

More constraints must then be defined to ensure neither replacement nor SLEP modification may occur before a given aircraft is procured. This is accomplished by requiring the sum of D_{it} and M_{it} or P_{it} to be less than or equal to 1. This ensures that if D_{it} equals 1, meaning it has not yet been purchased, then neither M_{it} nor P_{it} may take on a value of 1, meaning a SLEP modification or replacement would occur for that aircraft in that year. These constraints are represented by Equations (25) and (26).

$$D_{it} + M_{it} \leq 1 \quad \forall i, t \quad (25)$$

$$D_{it} + P_{it} \leq 1 \quad \forall i, t \quad (26)$$

Additionally, assuming the original procurement program was structured appropriately, there will be no need to modify or replace aircraft until a requirement is formalized that necessitates life extension. Therefore, the model results may not allow any extension activities to occur before that point, represented by parameter J , the year in which life extension was deemed necessary. The constraints are captured by Equations (27) and (28), in which the sum of all modifications or replacements from the first year through year J must be equal to zero.

$$\sum_{i=1}^I M_{it} = 0 \quad \forall t \in \{1, \dots, J\} \quad (27)$$

$$\sum_{i=1}^I P_{it} = 0 \quad \forall t \in \{1, \dots, J\} \quad (28)$$

9. General Sustainment Cost Calculations and Constraints

To calculate the general sustainment costs each year, which will increase exponentially as an aircraft ages, the age of each aircraft must be determined. The age would be linear for each aircraft if no replacements could occur. However, since replacement is a viable course of action, this would result in a step function when the replacement occurs. Therefore, the replacement decision variable needs to be considered. First, the age value for each aircraft is initialized at $t = 0$, as shown in Equation (29). Then, the age in all subsequent years is equal to the age in the prior year plus 1 unless that aircraft was replaced (if P_{it} equals 1), in which case the age then resets back to 1. This is shown in Equation (30).

$$A_{i,t=0} = 1 - F_i \quad \forall i \quad (29)$$

$$A_{it} = A_{i,t-1} * (1 - P_{it}) + 1 \quad \forall i, t \quad (30)$$

Calculating the sustainment costs would realistically take on the form of Equation (31), where % represents the annual cost increase percentage, since the costs to perform general in-service repairs increase exponentially for every year in service, as discussed in Chapter II.A.3.

$$S_{it} = (X_{it} - D_{it}) * W * (1 + \%)^{A_{it}} \quad \forall i, t \quad (31)$$

However, this creates a non-linear and non-quadratic equation, which could not be solved using available solvers. Therefore, a linear approximation for the increase of sustainment costs over time is used instead. Performing linear regression, values for the slope and intercept (m and b , respectively) must be calculated and are included in the parameter list. This is accomplished using Equation (32) for the slope and Equation (33) for the intercept (Zach 2020), where x and y are values for the two variables being considered, and n is the number of data points.

$$m = \frac{n * \sum(x * y) - \sum x * \sum y}{n * \sum x^2 - (\sum x)^2} \quad (32)$$

$$b = \frac{\sum y * \sum x^2 - \sum x * \sum(x * y)}{n * \sum x^2 - (\sum x)^2} \quad (33)$$

Assuming a thirty-year time horizon and a cost per year increase of 5% (based on the previous discussion in Chapter II.A.3), the R^2 value is 0.97. Hence, a linear approximation should be sufficient to estimate exponential growth. Once m and b are calculated, the updated equation for sustainment costs, replacing Equation (31), is shown in Equation (34). Since non-operational aircraft would not incur any costs, the difference between X_{it} and D_{it} is used to include only those aircraft already procured that have not exceeded the fatigue life limit. This difference is then multiplied by the sustainment cost for a new aircraft and then multiplied by the result from the linear regression at a given point in time.

$$S_{it} = (X_{it} - D_{it}) * W * (m * A_{it} + b) \quad \forall i, t \quad (34)$$

With these constraints defined, the objective function may be calculated and optimized to minimize the total cost as described previously.

B. SOLVER DESCRIPTION

The LEO model is an integer quadratic program that can have a significant number of binary constraints and has bilinear terms for calculating sustainment costs. For this reason, a commercial solver or specialized algorithm is necessary to solve the model when instantiated with data. Several optimization software solutions were considered to solve the model before finding one that worked. Originally, COIN-OR's "CBC" solver, a branch and cut linear program solver capable of handling mixed integer programs (COIN-OR n.d.), was considered. However, due to the non-linearity caused by the calculation of the sustainment costs, this was not viable for this application. Next, COIN-OR's Ipopt, a large-scale nonlinear solver (COIN-OR n.d.), was considered. While this solver would have been capable of handling the exponential sustainment cost increase originally formulated in Equation (31), it unfortunately is not capable of processing binary constraints, which are fundamental to the model's formulation. Therefore, Ipopt was also ruled out as a viable option.

Ultimately, the Gurobi solver (version 10.0.1.0) was selected. The Gurobi optimization software is compatible with linear, mixed integer linear, and mixed integer quadratically constrained programs. It pre-solves the problem to reduce size (and therefore the computational resources required) then employs a branch and cut algorithm to determine the optimal solution (Gurobi 2016). A top-level block diagram of Gurobi's algorithm is shown in Figure 6. Branch and cut algorithms are a combination of two other optimization methods: branch and bound and cutting planes. In this method, a relaxation of the program is created, and as the program iterates, suboptimal and infeasible solutions are eliminated. If a cutting plane is found, it is incorporated to further reduce the possible solution space. This iteration continues until a solution converges within a specified tolerance (Siegmundt et al. 2020).

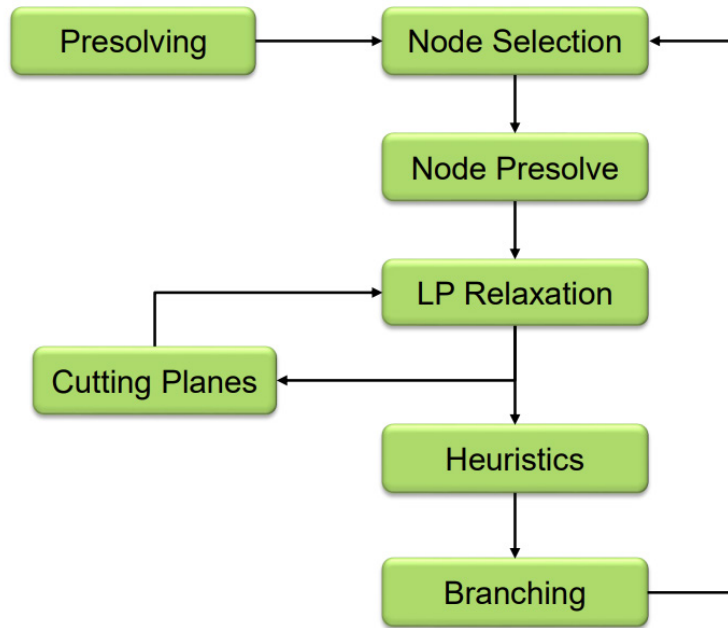


Figure 6. Gurobi's Branch and Cut Algorithm.
Source: Gurobi (2016)

The mathematical model for life extension optimization, described in Chapter III.A, was created with Pyomo, a software package designed to formulate and solve optimization problems (Pyomo n.d.). The Pyomo code is written in Python, an open-source general programming language (Python n.d.). The full Pyomo code can be found in the appendix.

C. MODEL VERIFICATION AND SAMPLE SCENARIOS

Two simplified aircraft sustainment scenarios were developed to demonstrate model output. Since a real-world scenario could involve tens or hundreds of aircraft operating over several decades, the model's accuracy cannot be intuitively verified or validated. Therefore, simplified sets of inputs were generated such that the optimal sustainment plan produced by the model could be validated with simple calculations.

For the simplified scenarios, only five aircraft over a five-year time period were considered. Arbitrary values for the input parameters were created for two scenarios: one in which aircraft replacement would occur and one in which SLEP modification would occur. These parameters are shown in Table 7.

Table 7. Sample Scenario Parameter Definitions

Parameter	Parameter Description	Scenario 1	Scenario 2
b	Regression intercept	0.1841	0.1841
B	Baseline FLL	100 hours	100 hours
d	Additional SLEP life	100 hours	100 hours
E	SLEP NRE cost	\$10,000,000	\$1,000
F_i	First years in service	{1, 2, 3, 4, 5}	{1, 2, 3, 4, 5}
J	Life extension decision year	1	1
k	SLEP kit and installation cost	\$1,000	\$100
m	Regression slope	0.1457	0.1457
N	Replacement aircraft cost	\$1,000	\$10,000
O	Hours flown per year	50	50
Q	Maximum production capacity	5	5
r_t	Quantity required in each year	{1, 2, 3, 4, 4}	{1, 2, 3, 4, 4}
R	Production restart cost	\$0	\$10,000
U	Maximum SLEP capacity	5	5
W	New aircraft sustainment cost	\$100	\$100

By varying the costs for SLEP NRE, SLEP kits, replacement aircraft, and production line restart, between the two scenarios, it is obvious that Sample Scenario 1 would force aircraft replacement and Sample Scenario 2 would force SLEP modifications.

Even with the simplified inputs, the model still contains 178 variables (102 of which are binary) and 308 constraints but takes only approximately 0.1 seconds to solve. The results from each scenario are discussed in the following sections.

1. Sample Scenario 1 Output: Aircraft Replacement

As expected, Sample Scenario 1 resulted in no aircraft receiving SLEP modifications and two aircraft being replaced, as shown in Table 8 and Table 9. The optimal objective value given the input parameters was \$2,505.43 over the entire five-year time period.

Table 8. *M* Values: Sample Scenario 1

$i \backslash t$	1	2	3	4	5
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0
5	0	0	0	0	0

Table 9. *P* Values: Sample Scenario 1

$i \backslash t$	1	2	3	4	5
1	0	0	0	0	0
2	0	0	0	1	0
3	0	0	0	1	0
4	0	0	0	0	0
5	0	0	0	0	0

Once it was confirmed that the correct course of action was taken, the quantity requirements were then verified since the model would be useless if the fleet operational needs were not met. This is shown in Figure 7.

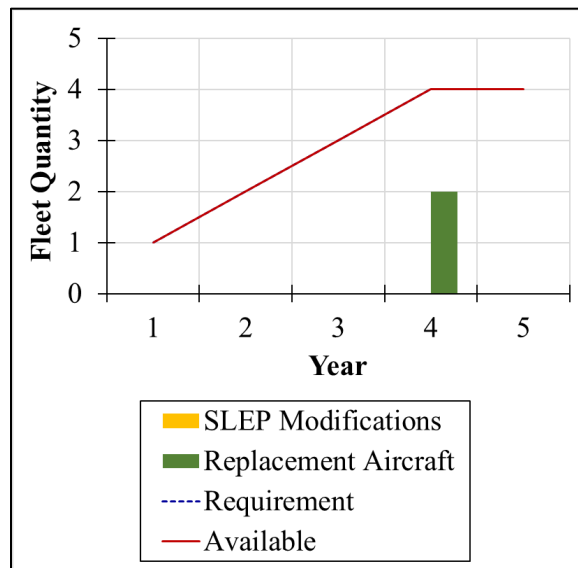


Figure 7. Fleet Quantity and Actions Taken Over Time: Sample Scenario 1

Considering the optimal solution, replacing two aircraft in the fourth year makes intuitive sense. As the requirement and aircraft available curves are coincident, it is difficult to see the requirement curve. This indicates that the minimum requirements are exactly met incurring no unnecessary costs. Aircraft 1, 2, and 3 would exceed their baseline life limits in years 3, 4, and 5, respectively. However, since the requirement in year 5 is only 4 aircraft, one of those would not require its life extended; in this case, aircraft 1 is allowed to be retired since replacing it would incur higher sustainment costs than aircraft 2 or 3.

The total costs for Sample Scenario 1 are therefore only driven by the one-time production line restart costs (which is \$0), the cost of the replacement aircraft, and the sustainment costs, as illustrated in Figure 8. Since no SLEP modifications occurred, no NRE nor modification kit costs were incurred.

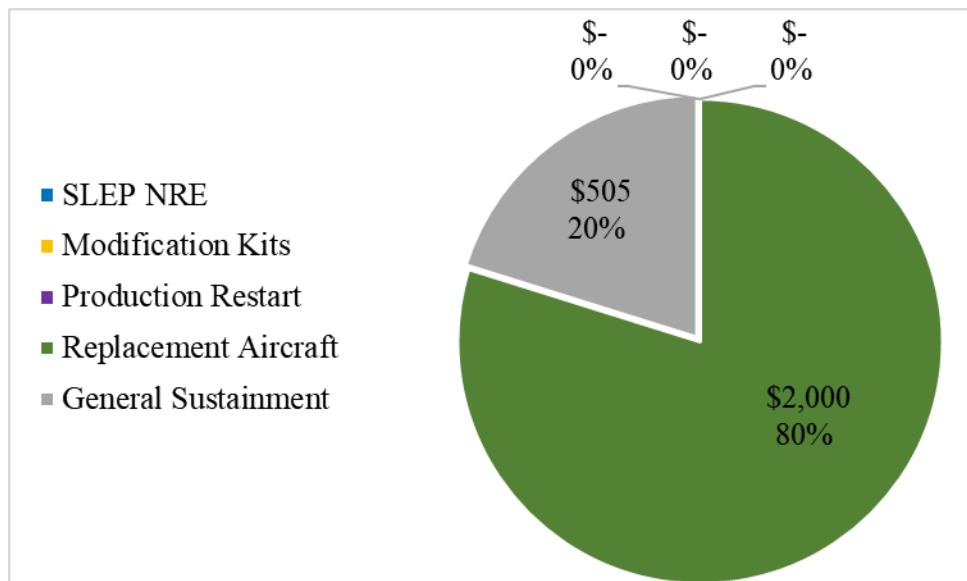


Figure 8. Total Cost Breakdown: Sample Scenario 1

2. Sample Scenario 2: SLEP Modifications

The results for Sample Scenario 2 were also as expected; two aircraft received SLEP modifications and none were replaced, as shown in Table 10 and Table 11. The optimal objective value given the input parameters was \$1,792.85 over the entire five-year time period.

Table 10. *M* Values: Sample Scenario 2

$i \backslash t$	1	2	3	4	5
1	0	0	0	0	0
2	0	0	0	1	0
3	0	0	1	0	0
4	0	0	0	0	0
5	0	0	0	0	0

Table 11. *P* Values: Sample Scenario 2

$i \backslash t$	1	2	3	4	5
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0
5	0	0	0	0	0

After again confirming the appropriate course of action was selected, the operational requirements were assessed, shown in Figure 9.

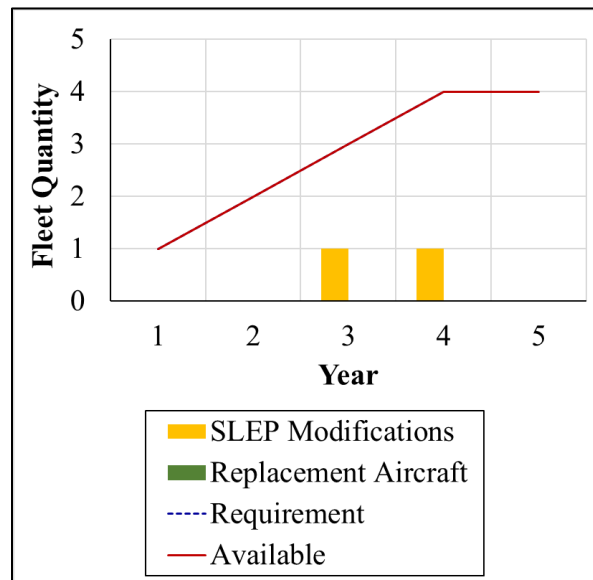


Figure 9. Fleet Quantity and Actions Taken Over Time: Sample Scenario 2

Similar to Sample Scenario 1, the quantity requirement was exactly met in each time period, showing compliance. Unlike Sample Scenario 1, in this case the SLEP modifications were performed in years 3 and 4 instead of only in year 4. This makes sense, however; since they are not being replaced, the aircraft's sustainment costs do not reset when a SLEP kit is installed. Therefore, there are multiple optimal solutions all resulting in the same objective value. These aircraft could receive their modifications in years 2, 3, or 4 (and are not required to occur in the same year) without impacting the total cost.

The total costs for Sample Scenario 2 are therefore only driven by the one-time SLEP NRE costs, the cost of the SLEP modification kits, and the sustainment costs, as illustrated in Figure 10. Since no replacements occurred, no production line restart nor replacement aircraft costs were incurred.

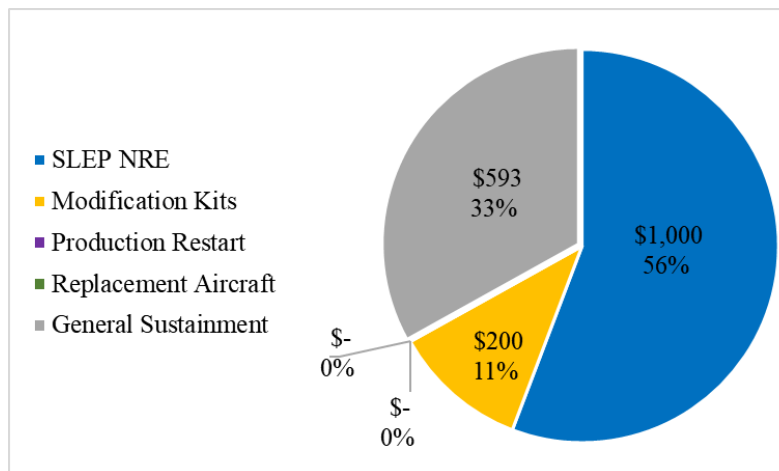


Figure 10. Total Cost Breakdown: Sample Scenario 2

3. Model Verification Conclusions

Additional sample scenarios were evaluated to further test the model and solver, varying the number of aircraft, years under consideration, and specific parameter values. In each case, the results were as expected and not unlike those reported in Sections III.C.1 and III.C.2 (though specific optimal values for decision variables and the objective changed in each scenario). Hence, it is then the conclusion that the model performs as desired and is ready to be implemented with actual data.

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IV. MODEL RESULTS AND ANALYSIS

This chapter details the LEO model results with input parameters considering the F/A-18E/F Super Hornet to demonstrate how the model may be used in a real-world scenario. Additional model runs were then performed modifying parameters to assess the sensitivity of the optimal life extension plan.

A. NOMINAL F/A-18E/F LIFE EXTENSION OPTIMIZATION MODEL

1. Model Data

To run the model for the F/A-18E/F fleet, publicly available information was used to determine the values for each of the required parameters. While many of these values were readily available, others had to be derived from related data or non-primary sources. Tables 12, 13, and 14 show each parameter and its value and provides a brief explanation if any calculations or assumptions were made to determine those values.

Table 12. Nominal F/A-18E/F Model Parameters

Parameter	Parameter Description	Value	Notes
b	Regression intercept	0.6266	Derived from a 5% increase each year. ¹
B	Baseline FLL	6,000 hours ²	
d	Additional SLEP life	4,000 hours ³	
E	SLEP NRE cost	\$449,202,000	Calculated based on \$283.5M SLEP plus \$165.7M for other deficiencies across current fleet quantity. ⁴
F_i	First years in service	See Table 13.	This set of parameters represents the initial, full production run, but not aircraft later procured in response to operational changes and low readiness metrics (after 2010)
J	Life extension decision year	17 (2013)	One year prior to first development funding. ⁵

Parameter	Parameter Description	Value	Notes
k	SLEP kit and installation cost	\$12,743,957.62	Calculated based on \$11.3M SLEP kit/labor costs plus \$1.4M cost for other deficiency modification kits/labor. ⁶
m	Regression slope	0.1096	Derived from a 5% increase each year. ¹
N	Replacement aircraft cost	\$83,883,125 ⁷	
O	Hours flown per year	300 ⁸	
Q	Maximum production capacity	48	Assumed maximum value during original production period. ⁸
r_t	Quantity required in each year	See Table 14.	A steady-state value was assumed for the outyears. Initial years based on procurement profile. ⁹
R	Production restart cost	\$0 ⁶	
U	Maximum SLEP capacity	102	Assumed nominal depot maintenance quantity based on 4.5-year cycle. ¹⁰
W	New aircraft sustainment cost	\$2,406,850	Calculated from total Air Operations O&M ¹¹ divided by total fleet quantity. ¹²

¹ Data from Trunkey (2018, 1); ² Data from Global Security (2018); ³ Data from Eckstein (2022); ⁴ Data from DON (2018, 185–265); ⁵ Data from DON (2015, 228); ⁶ Data from DON (2023b, 87–120); ⁷ Data from DON (2023a, 246); ⁸ Data from Keating et al. (2023, 6); ⁹ Data from Gertler (2009, 4–5); ¹⁰ Data from Morrison (2011, 6); ¹¹ Data from DON (2021, 39); ¹² Data from Trevithick (2021)

Table 13. F/A-18E/F Procurement Timeline.
Adapted from Gertler (2009, 4–5).

Year	Quantity Procured
1997	12
1998	20
1999	30
2000	36
2001	39
2002	48

Year	Quantity Procured
2003	45
2004	42
2005	42
2006	38
2007	37
2008	37
2009	23
2010	9

Table 14. Annual Inventory Requirement Profile

Year(s)	Inventory Requirement
1997	12
1998	32
1999	62
2000	98
2001	137
2002	185
2003	230
2004	272
2005	314
2006-2035	338

Given these inputs, the full model comprised 125,037 variables (71,450 of which were binary) and 197,976 constraints, and it took approximately 10 to 15 minutes to solve each time using Pyomo and Gurobi as described in Chapter III.B. Comparing this data set to that presented in Chapter III.C, the model was then over 600 times larger than the simplified scenarios.

2. Model Results

The optimal solution results for the nominal Super Hornet scenario are shown in Figure 11 and Figure 12. In Figure 11, the left vertical axis shows the total fleet quantity for the operational requirement and available aircraft (relating to the requirement and available lines), the right vertical axis shows the number of actions taken as either SLEP modifications or replacements in a given year (relating to the SLEP modifications and

replacement aircraft bars). Figure 12 provides a summary the different costs incurred across the entire planning horizon for aircraft life extension and provides a means to estimate which costs are driving decisions for SLEP or replacement.

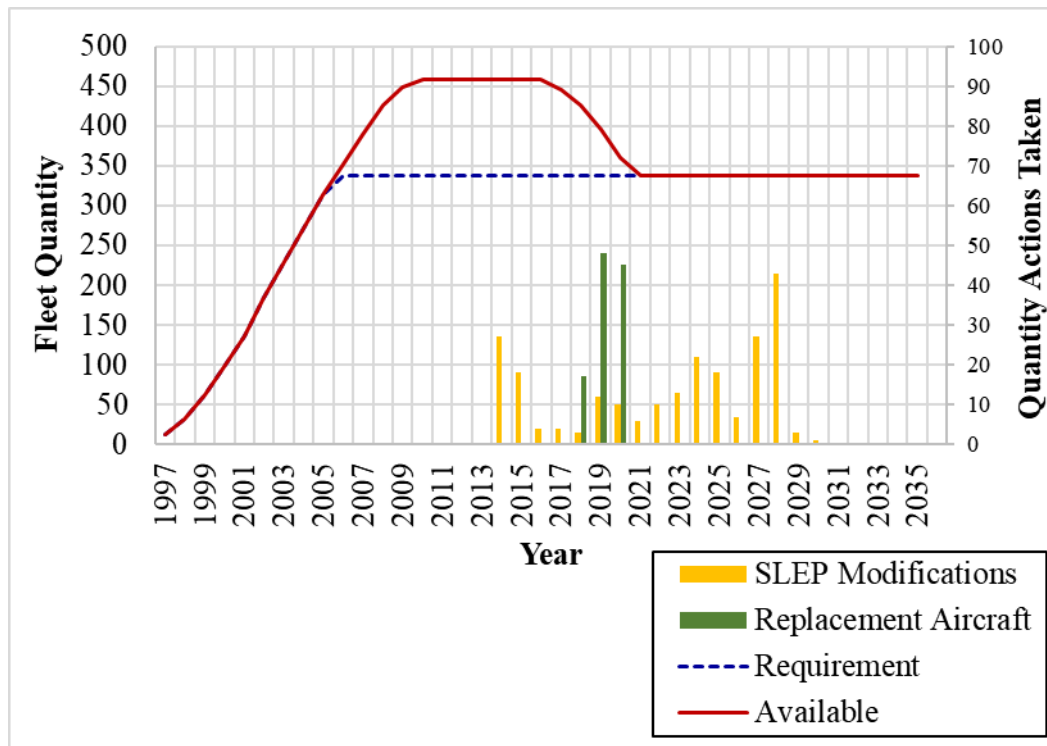


Figure 11. Nominal F/A-18E/F Model Results

From Figure 11 and similar to the sample scenarios presented in Sections III.C.1 and III.C.2, the operational requirement is met or exceeded for all time periods. In this case, the operational requirement is exceeded from 2006 through 2020. This is because the number of aircraft originally purchased exceeded the steady-state operational requirement. However, once some of the older aircraft began to reach their life limits and the available quantity began to decrease, actions were taken (as early as 2014) to allow the minimum fleet quantity requirement of 338 to be exactly met in 2021 and in all subsequent years.

Interestingly, the optimal solution for this scenario is to pursue both traditional SLEP modifications and replacement aircraft. In total, the model recommends that 228

aircraft receive SLEP modifications and 110 be replaced. This is due to the breakdown of costs incurred from SLEP and replacement (Figure 12). While the recurring costs for SLEP modifications are only approximately 15% of the cost to purchase a replacement (for two thirds the amount of additional life), SLEP modifications do not reset the sustainment costs to that of a new aircraft, unlike replacement. Figure 12 demonstrates that sustainment costs make up the majority of the total costs due to the long planning horizon. Hence, it is less expensive to replace some aircraft rather than to pursue a solution that solely incorporates cheaper SLEP modifications.

Shown in Figure 12, the magnitudes of the costs incurred from an optimal plan are also somewhat surprising. The nominal scenario incurs a total of over \$74.7 billion dollars across the 39-year time period, of which 83% is due to the sustainment costs. This dwarfs the seemingly high non-recurring SLEP kit developmental costs (SLEP NRE) of just under half of a billion dollars. Prior to this analysis, one might assume SLEP kit development costs to be a significant factor in choosing whether to repair or replace. The remainder of the costs are the recurring purchase and installation of the modification kits (4%) and the procurement of replacement aircraft (12%).

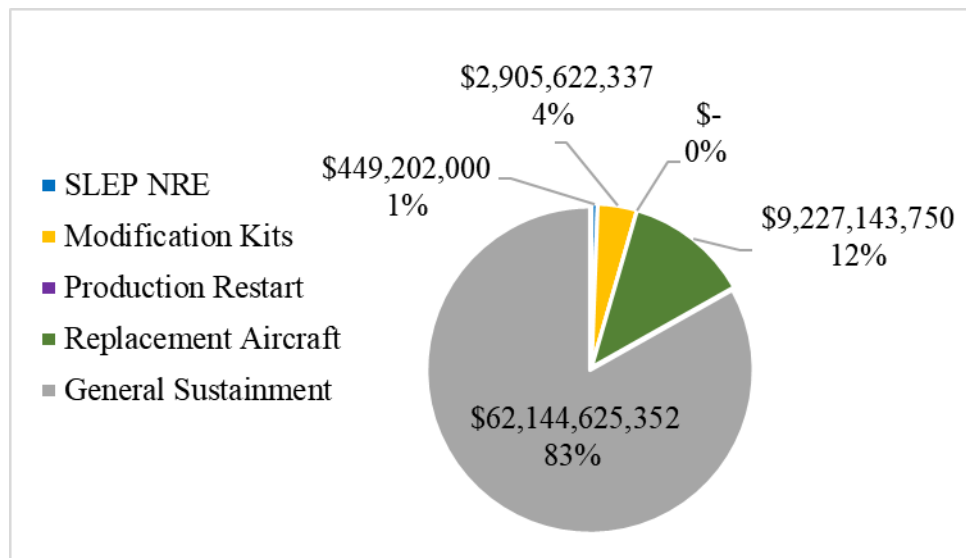


Figure 12. Nominal F/A-18E/F Scenario Optimal Cost Summary

The results somewhat correspond to the real-world Super Hornet fleet, as planners also opted to pursue both additional aircraft procurement and traditional SLEP. However, these results may not be directly comparable due to the Super Hornet's actual low availability rates during the operations and sustainment life cycle phase (Keating et al. 2023, 1–7). Therefore, reactive activities were undertaken to rectify the situation, rather than pursuing a solely proactive strategy such as the one that the LEO model recommends.

B. SENSITIVITY ANALYSIS

To study the sensitivity of the model results to modifications in key parameters, d , the amount of additional life gained from a traditional SLEP, and k , SLEP modification kit procurement and installation costs per aircraft, are varied to determine the impact on the total life cycle costs.

1. Additional Life from SLEP (d)

After running the model several additional times, beginning with a d value of 1,000 hours, increasing in increments of 500 hours up to 6,000 hours, sensitivity results for modifying parameter d are presented in Figure 13 and Figure 14. For values less than 2,000 or greater than 4,000 the optimal objective cost was unchanged. For low values, a pure production approach is optimal, while a mix of traditional SLEP and replacement is optimal for higher values of d . Therefore, many of the repetitive results were omitted from the plots shown later.

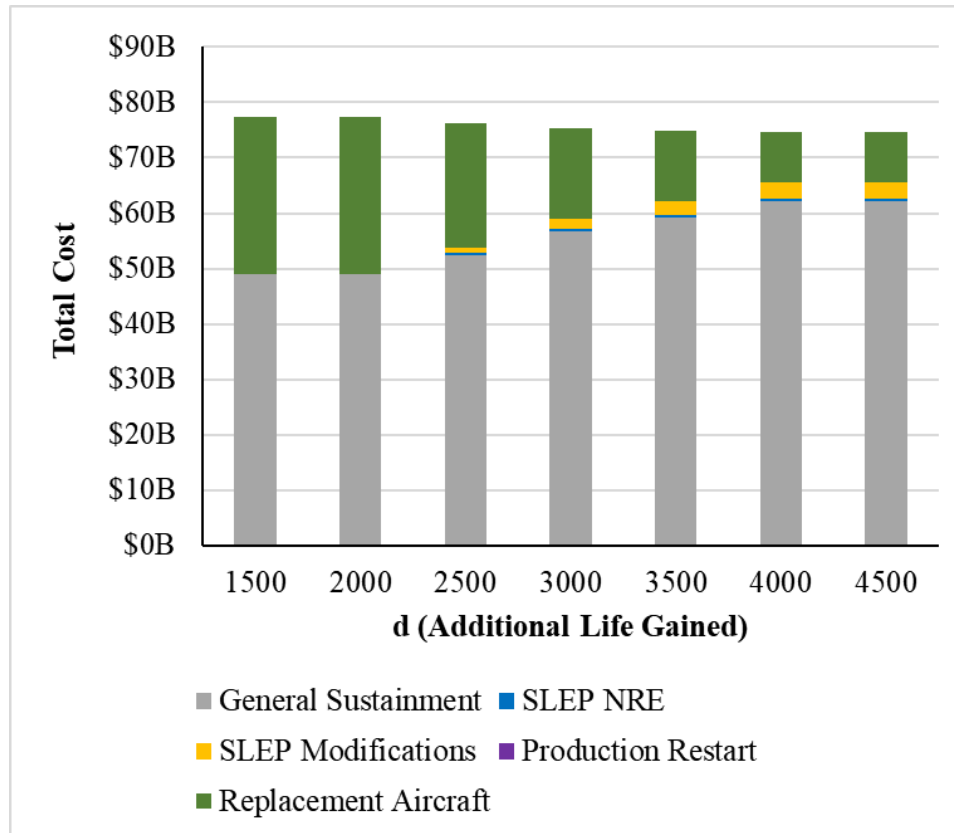


Figure 13. Total Cost as Parameter d Varies

From the results in Figure 13, as d increases (above 2,000 hours), the number of replaced aircraft decreases and the number of SLEP modified aircraft increases (until 4,000 hours). For low values of d , only procurement and general sustainment costs are incurred. For values of d greater than or equal to 2,500, the SLEP NRE and kit procurement costs are also incurred. Since the production restart costs are still zero, none of these scenarios incur any additional costs for that category. Figure 14 shows that the total cost appears to exponentially decay as d increases (once d crosses the threshold that allows any number of traditional SLEP modifications to be cost effective). An opportunity to avoid a total of \$2.6 billion life cycle costs exists if d can be maximized without impacting any of the other parameters (such as the kit development costs or kit procurement and installation costs).

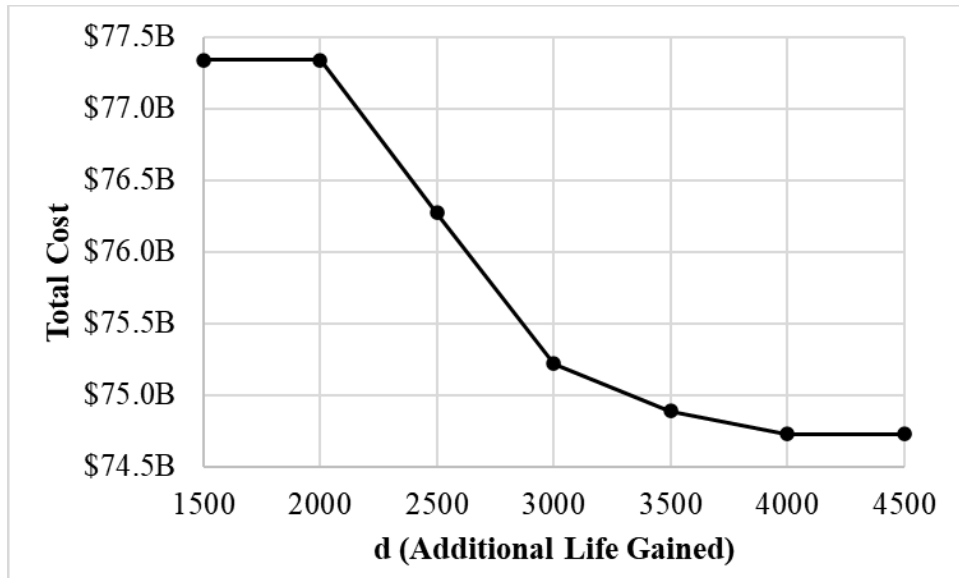


Figure 14. Total Cost as a Function of Parameter d

2. Recurring SLEP Costs (k)

After running the model several additional times, with k varying from 50% of the nominal value (\$6.4M) in increments of 25% of the nominal value (\$12.7M) up to 200% nominal (\$25.5M), results for the sensitivity analysis are presented in Figure 15 and Figure 16. Unlike the sensitivity analysis for d , the total cost differed for each value of k in this data set. This makes sense since unless the optimal solution solely consisted of replacement aircraft, a different value of k would impact the total cost.

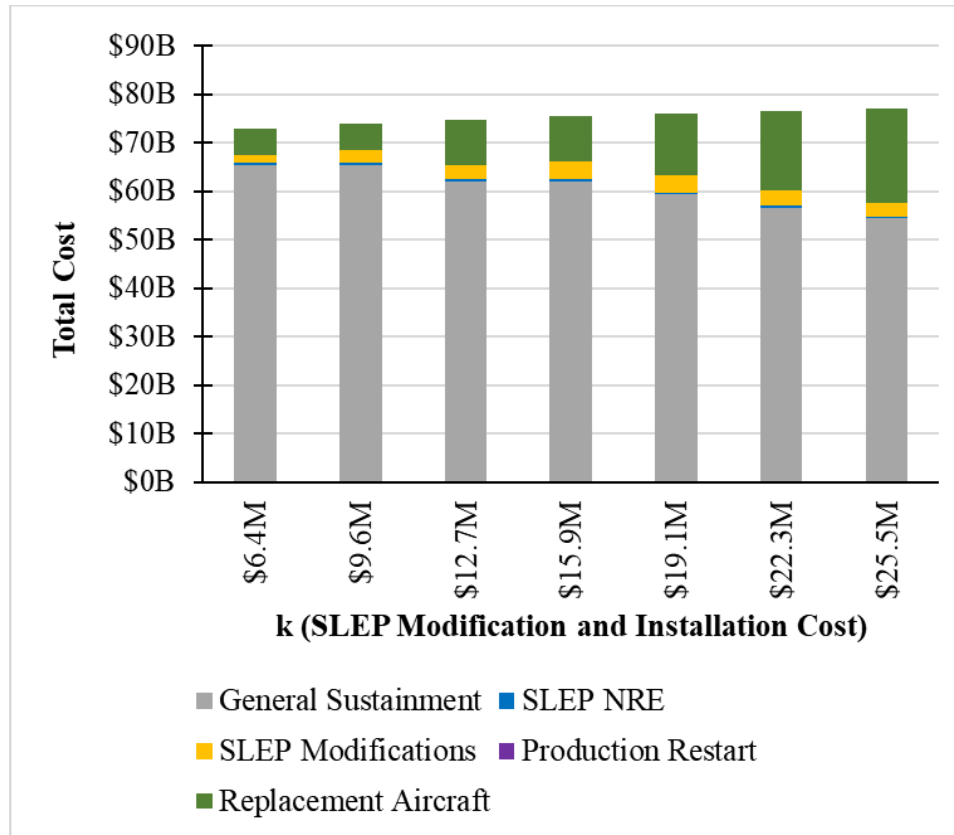


Figure 15. Total Cost as Parameter k Varies

From the results in Figure 15, the number of SLEP modified aircraft was the same (quantity of 273) for the lowest two data points (50% and 75% of nominal), and for $k = 200\%$ of nominal, only 106 would receive SLEP modifications. At some point, the optimal solution would be purely replacement (no SLEP modifications), but it seems unreasonable to assume values of k that are over double the nominal value. For all these data points, general sustainment, SLEP NRE, SLEP modifications and installation, and replacement aircraft costs are incurred. As with all previous model results, no production restart costs are incurred as the line is still assumed to be open and the costs are therefore zero. Figure 16 shows that the total costs appear to logarithmically increase as k increases. The difference between the 200% and 50% of nominal k values (representing an underestimation or overestimation of these recurring costs) is \$4.0 billion over the 39-year life cycle.

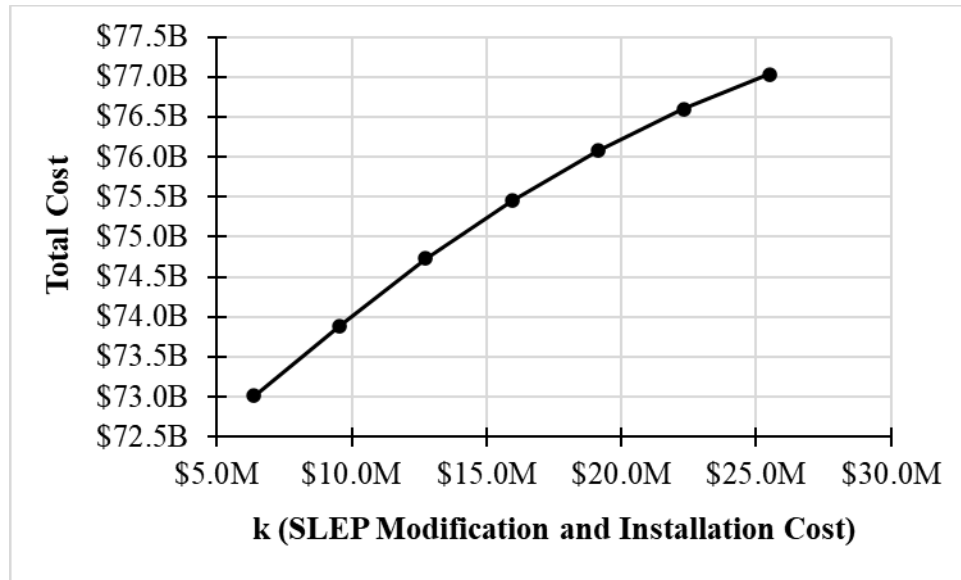


Figure 16. Total Cost as a Function of Parameter k

3. Comparison of d and k

The previously evaluated parameters d and k represent two of the areas with the highest uncertainty before an aircraft life extension program is pursued, as they are based on technical and programmatic experts' assessments. Since the intent of this optimization model is to help decision makers pursue the most cost-effective course of action, the relationship between those parameters should be explored further. To do so, the model ran a total of 49 times (including the runs used for the previous sensitivity analyses) to consider all possible combinations of these d and k values. The results of these runs are shown in a heat map in Figure 17, in which lower costs are shown as green and higher costs are shown as red. For reference, the cell with nominal inputs is shown in bold with a double line border ($d = 4,000$, $k = \$12.7M$).

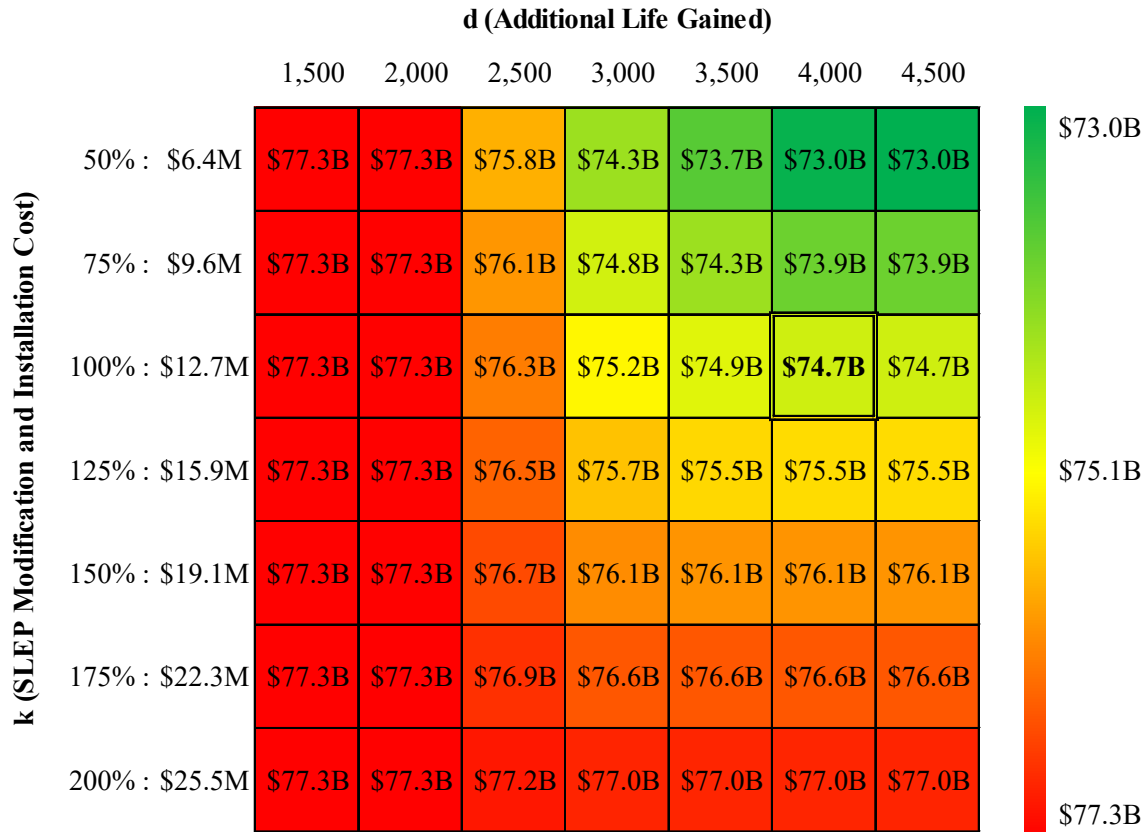


Figure 17. Impact on Total Cost by Varying Parameters d and k

The same general trends exist as when these parameters were considered independently. Unsurprisingly, the lowest possible cost is achieved when d is maximized and k is minimized; costs generally increase as one moves down and to the left on the matrix. No matter the value of k , the total costs are the same if d is 1,000 or 1,500, but then decrease as d increases (and more aircraft receive SLEP modifications as opposed to being replaced). Also similar to the prior analysis with varied k and fixed d , the cost will increase as k does (for all values of d greater than 2,000).

However, the matrix is not diagonally symmetric. For one “step” increase of both d and k from the nominal values (gaining 500 extra hours of life for an 25% higher kit costs), an additional \$726.4M dollars would be required over the life cycle. On the other hand, if a step decrease for both nominal values of d and k were pursued (500 fewer additional hours for 25% lower kit costs), then \$426.8M could be avoided. Therefore, in

the case of the F/A-18E/F fleet, k has a more substantial impact on the total life cycle costs than d . This means that program managers and engineers should focus their efforts on developing cheaper SLEP kits with less additional life than those that may provide additional life at a higher cost.

C. EFFECTS OF OTHER PARAMETERS

Since parameters d and k have already been shown to have a significant impact on the total cost, other parameters were also investigated but ultimately determined to be less impactful for program office decision makers. This section discusses many of the other parameters, some of which are uncontrollable by the cognizant program office, and their impact on the optimal life extension course of action.

1. Life Extension Decision Year (J)

When developing the model, it seemed logical that the year in which it was deemed necessary to extend the life of the fleet, parameter J , would have a significant impact on the results; since there would be a larger time period in which to take actions, those actions may be more optimally timed to reduce cost. However, while varying J allowed for SLEP modifications to be made earlier, there was actually no impact on the total life cycle cost. The total number of SLEP modifications and replacements were identical to the nominal case (228 and 110, respectively), and the total cost over the 39-year period was still \$74.7B. The results of the most drastic variation, in which $J = 1$ (1997), can be seen in Figure 18. If J becomes too large, eventually it reaches a point where no feasible solution exists as the fleet quantity would drop below the requirement before any actions may be taken.

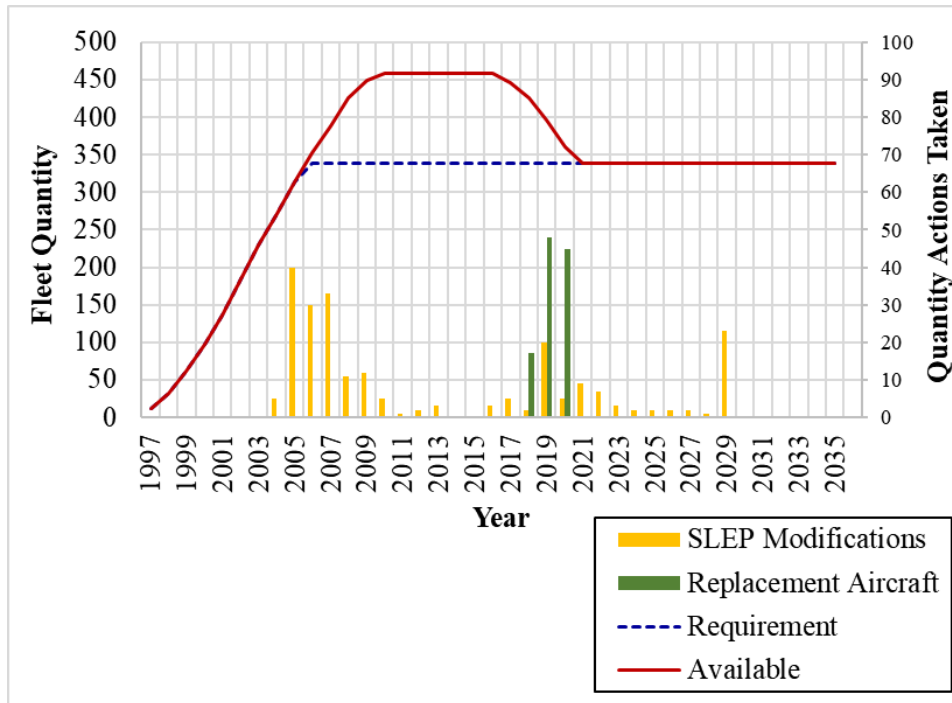


Figure 18. Model Results when $J = 1$

From the results in Figure 18, it is apparent that the model then allowed early SLEP modifications to occur, but since a traditional SLEP does not reset the age of the aircraft, the sustainment costs still increase year over year. It should be noted that while the timing of the SLEP modifications may vary without impacting cost, the timing of the replacement aircraft is the same as the nominal scenario since those decisions are made to minimize the average age of the affected aircraft over the time horizon (thereby minimizing the sustainment costs).

This independence of J may not be a fully realistic scenario, depending on the technical specifics of the SLEP modifications. If a modification must be made within a certain time period to fully gain the additional life offered by SLEP (e.g., within some number of flight hours from reaching the baseline life limit), then additional model constraints should be implemented to further control the SLEP timing. However, this does not seem important to the results since it is proven that the modification installation timing does not impact total cost, only the quantity of those modifications. Therefore, the model results would still be valid and program planners may manually schedule the SLEP

modifications to align with the actual engineering requirements while still incurring the minimum total cost.

This relationship of J to total cost is also interesting to note as it allows for a smoother modification installation profile to be undertaken to reduce the quantity variation year over year and allow for more consistent workload planning (for personnel labor, material procurements, etc.), which is likely to be desirable.

2. Procurement (N) and Production Restart Costs (R)

Considering the LEO model's objective function, production restart costs and aircraft procurement costs are essentially treated the same in calculating the total as the SLEP NRE and SLEP modification costs, respectively. Therefore, varying parameters R (production restart cost) and N (new aircraft cost) would have an inverse effect on the model results of varying E (SLEP NRE) and k (SLEP kit cost). As replacement costs become higher, it becomes less expensive to pursue a higher quantity of SLEP modifications, and as replacement costs decrease, it becomes less expensive to pursue more replacements.

However, since the cost estimates for N are generated from actual previous procurements, they are likely to be much more accurate and have less uncertainty than the estimates for k . Additionally, since the F/A-18E/F production line remains open, there are no estimates currently available for how expensive a production restart would be. Furthermore, since production restart is a one-time cost, it is suspected that it would not have an overly significant impact on the life cycle cost (similar to how E represented less than 1% of the total cost in the nominal scenario). There is therefore little value added in varying R and E to determine their sensitivities on the model results.

3. Operational Parameters: Flight Hour Accrual (O) and Fleet Quantity (r_t)

Some of the parameters used in the model are generated based on operational requirements, which are handed down to the program office responsible for SLEP and thus not controllable by program office decision makers. In particular, parameters O (the rate at which flight hours are accrued) and r_t (the quantity requirement in a given year) are still

very important to the model results. Both of these parameters are driven by force structuring needs and are generally assumed to be non-negotiable for the purposes of SLEP decision-making at the program office level.

Parameter O determines how quickly an aircraft will reach its life limit. While different for every aircraft, a constant rate is assumed that accounts for the fleet as a whole which accounts for higher utilization during operational deployments, lower utilization for non-deployed flights, and time when the aircraft is not operational for maintenance. The nominal rate of 300 flight hours per year indicates that a Super Hornet would reach its baseline life limit of 6,000 hours in 20 years. Therefore, if this average rate increases, then aircraft must either be extended or retired sooner than the nominal scenario and costs would increase. On the other hand, if O decreases, later or fewer extension actions would be required causing life cycle costs to decrease.

Arguably the most important parameter to the life extension decision process is the requirement, r_t , for how many aircraft are required and for how long. While the model is capable of handling any (feasible) variation for the fleet quantity over time, the inputs have a massive impact on the total life cycle cost. To illustrate this, two additional scenarios were considered. In the first, the same nominal requirement of 338 aircraft is maintained, but that quantity is only required over a 25-year time period (as compared to the nominal 39-year period); these results are shown in Figure 19. The second scenario maintains the nominal 39-year time period but increases the steady-state requirement to 375 aircraft; these results are shown in Figure 20.

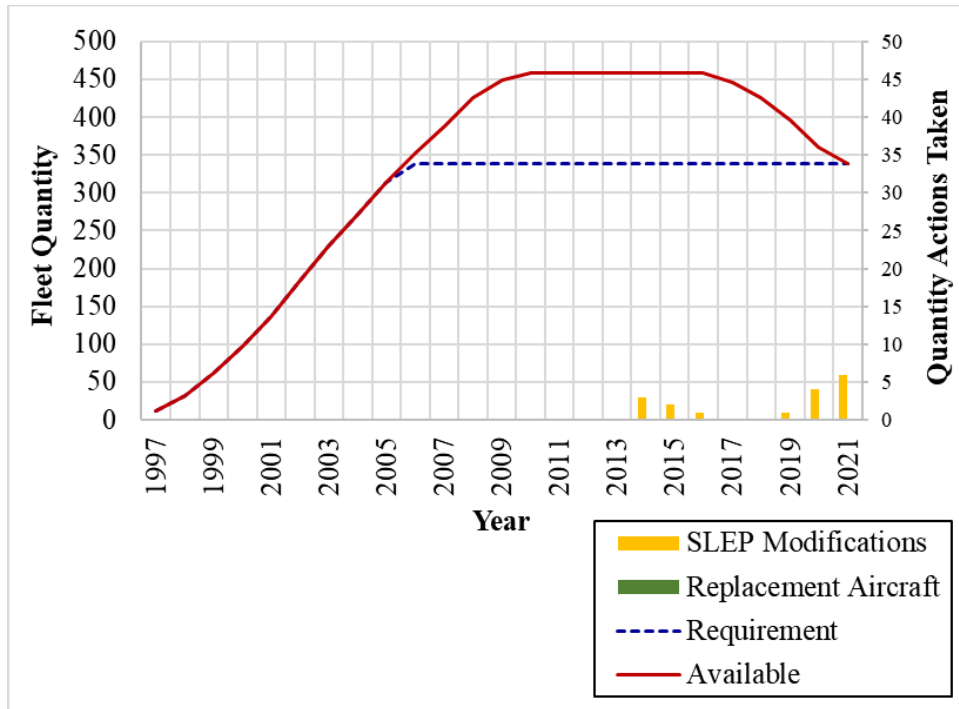


Figure 19. 25-Year Requirement Model Results

In the 25-year scenario, unsurprisingly, fewer extension activities were required to meet the updated requirements. Only 17 aircraft require SLEP modifications and none require replacement. This resulted in a total life cycle cost of only \$33.4B. Due to this low level of intervention, nearly all (98%) of the costs are due to general sustainment with the remainder accounted for by SLEP NRE and the procurement and installation of modification kits.

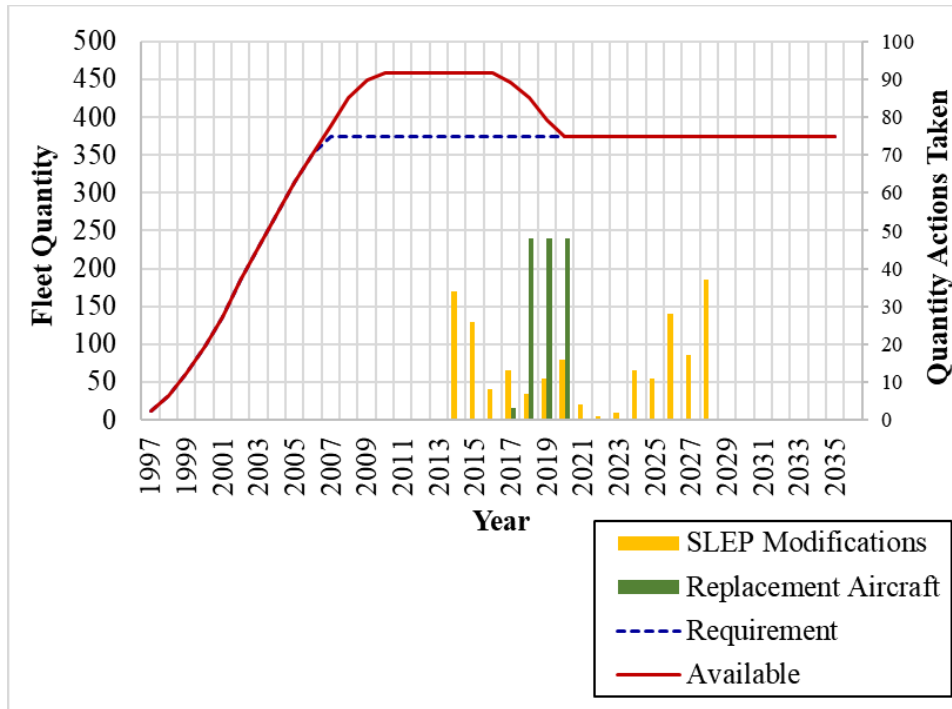


Figure 20. Fleet Quantity of 375 Model Results

In the 375 aircraft scenario, the same quantity of SLEP modifications is recommended as in the nominal case (228), but the number of replacements increased from 110 to 147. The total life cycle cost in this scenario increased to \$79.9B, due to the increased procurement quantity and the cost to sustain those additional aircraft.

If the quantity were to vary year over year (and not reach and sustain a steady-state value), the model is still able to recommend the optimal course of action, though the results do not look much different than those shown previously since the model does not allow an aircraft to retire if it will be needed in the future. Therefore, no additional results for those scenarios will be discussed.

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V. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

The motivation behind this thesis was to consider both traditional SLEP and aircraft replacement as viable alternatives to extend the effective life of U.S. military aircraft and to develop an optimization model to help program managers and systems engineers to make better-informed decisions to maximize the use of funds when life extension becomes necessary. In this thesis, a T/M/S agnostic model was developed that may be used to recommend the optimal course of action when provided parameters specific to a given aircraft type. Using the F/A-18E/F fleet as an example, full-scale results were obtained and assessed to not only determine the least cost approach to life extension but also understand the sensitivity of the results to certain parameters.

A. GENERAL CONCLUSIONS AND RECOMMENDATIONS

Overall, the optimization model was able to successfully identify an optimal solution for each of the scenarios with which it was presented. Although the specific parameters were for one type of aircraft, the Super Hornet, the objective function and constraints were developed such that the model may be used for any type of aircraft (and possibly other systems which operate under comparable fatigue life limited circumstances).

As this model is intended to be used in the planning stages of life extension programs, enough emphasis cannot be placed on the importance of accurate cost and engineering estimates. The most recently available data should be used for inputs and if early assumptions are later proven to be false, the model should be re-run with updated parameters. For this reason, subject matter experts should be heavily involved in the development of technical requirements, cost estimations, and the verification of known parameters. As demonstrated in the F/A-18E/F examples, relatively small changes in estimates for some parameters can have significant impacts on not only the projected cost but also the determination of which life extension COAs to pursue. Just a 25% reduction in the Super Hornet's SLEP kit and installation costs resulted in a life cycle cost avoidance

of nearly \$1B and the recommendation to install SLEP modification kits on aircraft that would have otherwise been candidates for replacement.

Aside from the specific purpose this thesis seeks to accomplish, it also led to interesting insights about the general sustainment costs, which are incurred even if no life extension activities are required. For all variations of the Super Hornet life extension scenario, the general sustainment costs accounted for the majority of the life cycle costs, ranging from 63% to 83% of the total. It was somewhat surprising that these costs consisted of such a large portion of the total considering that the parameter for new aircraft sustainment costs was only \$2.4M per aircraft (roughly 3% of the cost of a new aircraft). Therefore, and while outside the immediate scope of this thesis, programs should continue to focus on improving the reliability of the aircraft and other activities that have an ability to reduce the annual O&M costs.

B. LIMITATIONS OF THIS WORK

While the model performs as intended, there are several limitations that should be discussed in greater detail before it is used to inform real-world decisions.

Most notably, for the majority of the model solutions, particularly those in which any amount of traditional SLEP is recommended, multiple solutions exist which have the same minimized life cycle cost. This is not erroneous since the timing of a SLEP kit installation does not impact the overall cost since it does not reset the aircraft's life. By design, once the solver identifies an optimal solution, the program ends without seeking additional optimal solutions. This is important for those using the model to understand as it means there may be an ability to adjust the time phasing of certain events without actually increasing the projected costs. Therefore, the provided solution should still be carefully examined, and modified as appropriate, to make the best use of other program and outside resources required to accomplish the work.

Additionally, due to limitations of the Gurobi solver discussed in Chapter III.B, the calculation of general sustainment costs uses a linear approximation rather than the more accurate exponential equation. While this is unlikely to have a significant impact on the optimal solution, it should be recognized that some years may have underestimated or

overestimated sustainment costs. However, since those sustainment costs would typically be funded via a separate appropriation than a SLEP or replacement aircraft (O&M funds versus procurement funds), the estimates generated here would not likely be used to directly influence actual budget proposals and therefore slight inaccuracies for these costs are acceptable.

Furthermore, the only outputs from the model are the optimal values of the decision variables and the total (minimized) life cycle cost. The sensitivity analyses conducted in Chapter IV.B were performed manually after running multiple, serial iterations of the model. This would be possible for future use as well, but this should be known ahead of time without the expectation that any uncertainty analysis would be automatically generated. While the Super Hornet scenarios indicated that the SLEP kit costs had a more significant impact on total life cycle cost than the amount of additional life gained via a traditional SLEP, that may not be the case for every type of aircraft. Relationships such as these should therefore be considered before taking any actions.

C. RECOMMENDATIONS FOR FUTURE WORK

The work presented in this thesis may be extended to pursue research in adjacent areas or expanded to improve the scope and/or accuracy of the LEO model developed herein.

Since the intent of the LEO model is to aid planners with life extension decisions, increasing its ability to aid in data-driven decision making would be beneficial. To do so, one could create more formalized metrics to develop policies for when certain life extension courses of action should be used. As discussed by Eisenberg, Fish, and Alderson (2022, 10–12), metrics used to prioritize and add transparency to government spending decisions, such as the Mission Dependency Index, should be objective and parameter sensitivities should be understood by those feeding the data generation. To create these metrics, existing data on prior and current life extension and acquisition programs may be used to determine the historical accuracy of forecasted versus actual cost and other parameter estimates. This data may then be used to establish variability ranges to be used

in sensitivity analyses, the results of which should inform the decision process. This work may also have the added benefit of further validating and verifying the LEO model's performance depending on whether data is available to determine the realized results as compared to the planned life extension strategy.

Alternatively, a mission engineering analysis could be completed to consider the effects of scenarios in which fleet quantity requirements are not met. This may be of particular interest if the optimal solution (while meeting all requirements) is unaffordable or if users desire to validate the given requirements to ensure the best use of funds (and not waste resources on unnecessary life extension activities). While it is assumed that falling below the required fleet quantity will result in a true capability gap, a probabilistic mission analysis, such as that presented by Short et al. (2018, 565–588), could be used to predict the likelihood of mission success. While this prior work considered space systems on Mars, the same principles could be used to consider a system of systems environment for a selected aircraft platform. By changing the LEO model's requirement parameters, r_i , the model could be rerun to consider alternate scenarios that may be more affordable.

The LEO model may also be improved to offer better accuracy or additional capabilities. One such improvement would be the ability to account for planned down time in which an aircraft is non-operational, as would be the case when receiving extensive maintenance or when placed into long-term preservation (which may be done if the amount of aircraft in a given year exceeds requirements so as not to unnecessarily expend life). Another potential improvement would be to increase the accuracy of procurement costs. As the current formulation assumes fixed values for both aircraft replacement and SLEP kits, the model may be modified to incorporate variable pricing to account for economies of scale; in reality, the per aircraft cost is more likely to be lower if purchasing higher quantities. Lastly, the Pyomo code could be expanded to automate sensitivity analysis; multiple runs could be pre-programmed, varying certain parameters by specified amounts and generating outputs for comparative analysis. This would alleviate much of the tedium and manual post-processing required in the model's current state.

APPENDIX. PYOMO CODE

```
In [1]: import pyomo.environ as pyo
        from pyomo.opt import SolverFactory
        import pandas as pd
        import os
```

SLEP vs. Replace Solver

```
In [2]: ## Loading data
        # the following code will locate all csv files from the current working directory
        # and store them as data frames in the dictionary data

        # get current working directory
        mydir = os.getcwd()

        # locate all files ending with .csv and store their names in filepaths and filenames
        filepaths=[]
        filenames=[]
        for path, subdirs, files in os.walk(mydir):
            for file in files:
                if file.endswith('.csv'):
                    filenames.append(file)
                    filepaths.append(os.path.join(path, file))

        # loop over all filenames and load as dataframes
        # key = filename, returns pandas dataframe
        data = {}
        number_of_files=len(filenames)
        for i in range(number_of_files):
            data[filenames[i]] = pd.read_csv(filepaths[i])

        print('Number of CSV files found: ', number_of_files)
        print('')
        print('List of all filenames: ', filenames)
```

```
In [3]: ## the following code converts the F_i and r_t dataframes into a dictionary for input into pyomo

        # get the f_i dataframe
        f_i_df = data['0_ALL_first years, F_i .csv']
        # convert columns into key:value pairs and convert to dict
        f_i_dict = pd.Series(f_i_df.F_i.values, index = f_i_df.i).to_dict()

        # get the r_t dataframe
        r_t_df = data['0_ALL_Required aircraft, r_t.csv']
        r_t_dict = pd.Series(r_t_df.r_t.values, index = r_t_df.t).to_dict()

        ## Extract specific values from non-indexed parameters

        # define the mostParams dataframe and use .loc method to get values
        mostParams = data['0_nominal_most params.csv']

        B = mostParams.loc[mostParams['Parameter'] == 'B', 'Value'].values[0]
        slope = mostParams.loc[mostParams['Parameter'] == 'slope', 'Value'].values[0]
        intercept = mostParams.loc[mostParams['Parameter'] == 'Intercept', 'Value'].values[0]
        d = mostParams.loc[mostParams['Parameter'] == 'd', 'Value'].values[0]
        E = mostParams.loc[mostParams['Parameter'] == 'E', 'Value'].values[0]
        k = mostParams.loc[mostParams['Parameter'] == 'k', 'Value'].values[0]
        N = mostParams.loc[mostParams['Parameter'] == 'N', 'Value'].values[0]
        O = mostParams.loc[mostParams['Parameter'] == 'O', 'Value'].values[0]
        R = mostParams.loc[mostParams['Parameter'] == 'R', 'Value'].values[0]
        W = mostParams.loc[mostParams['Parameter'] == 'W', 'Value'].values[0]
        J = mostParams.loc[mostParams['Parameter'] == 'J', 'Value'].values[0]
        U = mostParams.loc[mostParams['Parameter'] == 'U', 'Value'].values[0]
        Q = mostParams.loc[mostParams['Parameter'] == 'Q', 'Value'].values[0]
```

```

In [4]: model = pyo.ConcreteModel()

# define input values
numAircraft = len(f_i_dict.keys())
numTime = len(r_t_dict.keys())

## define sets
model.i = pyo.RangeSet(numAircraft)
model.t0 = pyo.RangeSet(0,numTime)
model.t1 = pyo.RangeSet(numTime)

## define parameters
# non-indexed parameter definition
model.B = pyo.Param(initialize = B)
model.d = pyo.Param(initialize = d)
model.E = pyo.Param(initialize = E)
model.k = pyo.Param(initialize = k)
model.N = pyo.Param(initialize = N)
model.O = pyo.Param(initialize = O)
model.R = pyo.Param(initialize = R)
model.W = pyo.Param(initialize = W)
model.L0 = pyo.Param(model.i, initialize = model.B)
model.BigM = pyo.Param(initialize = 100000)
model.slope = pyo.Param(initialize = slope)
model.intercept = pyo.Param(initialize = intercept)
model.J = pyo.Param(initialize = J)
model.U = pyo.Param(initialize = U)
model.Q = pyo.Param(initialize = Q)

#Indexed parameter definition
model.F = pyo.Param(model.i, initialize = f_i_dict)
model.r = pyo.Param(model.t1, initialize = r_t_dict)

# define model calculated params
# model.H - hours accrued
h_it = dict()
for i in model.i:
    for t in model.t1:
        val = model.O*(t+1-model.F[i])
        h_it[i,t] = val
model.H = pyo.Param(model.i, model.t1, initialize=h_it)

# model.A0 - initial age
A0_i = dict()
for i in model.i:
    A0_i[i] = 1 - f_i_dict[i]
model.A0 = pyo.Param(model.i, initialize=A0_i)

## define variables
# binary decision variables
model.M = pyo.Var(model.i, model.t1, within=pyo.Binary)
model.P = pyo.Var(model.i, model.t1, within=pyo.Binary)
model.X = pyo.Var(model.i, model.t1, within=pyo.Binary)
model.Y = pyo.Var(within=pyo.Binary)
model.Z = pyo.Var(within=pyo.Binary)
model.D = pyo.Var(model.i, model.t1, within=pyo.Binary)

# continuous decision variables
model.L = pyo.Var(model.i, model.t1, within=pyo.NonNegativeReals)
model.A = pyo.Var(model.i, model.t1, within=pyo.Reals)
model.S = pyo.Var(model.i, model.t1, within=pyo.NonNegativeReals)

## model constraints
# binary on/off constraints
def any_slep(model, i):
    return model.Y >= sum(model.M[i,t] for t in model.t1)
model.any_slep_constraint = pyo.Constraint(model.i, rule = any_slep)

def any_purchased(model, i):
    return model.Z >= sum(model.P[i,t] for t in model.t1)
model.any_purchased_constraint = pyo.Constraint(model.i, rule = any_purchased)

def total_slep(model):
    return model.Y <= sum(sum(model.M[i,t] for i in model.i) for t in model.t1)
model.total_slep_constraint = pyo.Constraint(rule = total_slep)

def total_purchase(model):
    return model.Z <= sum(sum(model.P[i,t] for i in model.i) for t in model.t1)
model.total_purchase_constraint = pyo.Constraint(rule = total_purchase)

def slep_or_purchase(model, i):
    return sum(model.M[i,t] + model.P[i,t] for t in model.t1) <= 1
model.slep_or_purchase_constraint = pyo.Constraint(model.i, rule = slep_or_purchase)

```

```

# Life limit constraints
def update_life_limit(model, i, t):
    if t == 1:
        return model.L[i,t] == model.L0[i] + model.M[i,t]*model.d + model.P[i,t]*model.B
    elif t > 1:
        return model.L[i,t] == model.L[i,t-1] + model.M[i,t]*model.d + model.P[i,t]*model.B
model.update_ll_constraint = pyo.Constraint(model.i, model.t1, rule = update_life_limit)

# Life limit availability constraints
def aircraft_avail1(model, i, t):
    return model.X[i,t]*model.BigM >= (model.L[i,t] + 1) - model.H[i,t]
model.aircraft_avail1_constraint = pyo.Constraint(model.i, model.t1, rule = aircraft_avail1)

def aircraft_avail2(model, i, t):
    return (1 - model.X[i,t])*model.BigM >= model.H[i,t] - (model.L[i,t] + 1)
model.aircraft_avail2_constraint = pyo.Constraint(model.i, model.t1, rule = aircraft_avail2)

# purchase date availability constraints
def purchase_avail1(model, i, t):
    return (model.D[i,t])*model.BigM >= model.F[i] - (t + 1)
model.purchase_avail1_constraint = pyo.Constraint(model.i, model.t1, rule = purchase_avail1)

def purchase_avail2(model, i, t):
    return (1 - model.D[i,t])*model.BigM >= (t + 1) - model.F[i]
model.purchase_avail2_constraint = pyo.Constraint(model.i, model.t1, rule = purchase_avail2)

# no false start constraints
def no_early_SLEP1(model, i, t):
    return model.D[i,t] + model.M[i,t] <= 1
model.no_early_SLEP1_constraint = pyo.Constraint(model.i, model.t1, rule = no_early_SLEP1)

def no_early_replace1(model, i, t):
    return model.D[i,t] + model.P[i,t] <= 1
model.no_early_replace1_constraint = pyo.Constraint(model.i, model.t1, rule = no_early_replace1)

# fleet quantity reqs
def operational_reqs(model, t):
    return sum(model.X[i,t] for i in model.i) - sum(model.D[i,t] for i in model.i) >= model.r[t]
model.operational_reqs_constraint = pyo.Constraint(model.t1, rule = operational_reqs)

```

```

# aircraft age
def aircraft_age(model, i, t):
    if t == 1:
        return model.A[i,t] == model.A0[i]*(1 - model.P[i,t]) + 1
    elif t > 1:
        return model.A[i,t] == model.A[i,t-1]*(1 - model.P[i,t]) + 1
model.aircraft_age_constraint = pyo.Constraint(model.i, model.t1, rule = aircraft_age)

# No early action constraints, based on decision timeframe
def no_early_SLEP2(model, i, t):
    if t <= J:
        return model.M[i,t] == 0
    elif t > J:
        return model.M[i,t] == model.M[i,t]
model.no_early_SLEP2_constraint = pyo.Constraint(model.i, model.t1, rule = no_early_SLEP2)

def no_early_replace2(model, i, t):
    if t <= J:
        return model.P[i,t] == 0
    elif t > J:
        return model.P[i,t] == model.P[i,t]
model.no_early_replace2_constraint = pyo.Constraint(model.i, model.t1, rule = no_early_replace2)

# SLEP capacity constraint
def SLEP_capacity(model, t):
    return sum(model.M[i,t] for i in model.i) <= model.U
model.SLEP_capacity_constraint = pyo.Constraint(model.t1, rule = SLEP_capacity)

# production capacity constraint
def production_capacity(model, t):
    return sum(model.P[i,t] for i in model.i) <= model.Q
model.production_capacity_constraint = pyo.Constraint(model.t1, rule = production_capacity)

# Sustainment costs -- Linear approximaioin
def sust_cost(model, i, t):
    return model.S[i,t] == (model.X[i,t] - model.D[i,t])*model.W*(model.slope*model.A[i,t] + model.intercept)
model.sust_cost_constraint = pyo.Constraint(model.i, model.t1, rule = sust_cost)

```

```

## model objective function
def objective(model):
    return model.Y*model.E + model.k*sum(sum(model.M[i,t] for i in model.i) for t in model.t1) + \
        model.Z*model.R + model.N*sum(sum(model.P[i,t] for i in model.i) for t in model.t1) + \
        sum(sum(model.S[i,t] for i in model.i) for t in model.t1)
model.objective = pyo.Objective(rule = objective, sense = pyo.minimize)

```

```

In [5]: # solve the model
opt = SolverFactory('gurobi')

results = opt.solve(model)

```

```

In [6]: # create output file with model solution details (number variables, solve time, etc.)
result_series = pd.Series(data = results)
result_series.to_excel('0_model_run_admin_file.xlsx')

```

```

In [7]: # create model output file with optimal solution
import csv

with open('0_nominal model solution.csv', 'w', newline='') as f:
    thewriter = csv.writer(f)

    # print optimal objective solution
    thewriter.writerow(["Objective","",model.objective()])

    # print decision variable values
    for v in model.component_objects(pyo.Var, active=True):
        thewriter.writerow(["NEW VARIABLE",v,"NEW VARIABLE"])
        for index in v:
            thewriter.writerow ([v,index, pyo.value(v[index])])

```

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