3-14-2014

Exploring a Method to Quantitatively Measure Design Flexibility Early in the Defense Acquisition Life Cycle

Joseph S. Kim

Recommended Citation

Kim, Joseph S., "Exploring a Method to Quantitatively Measure Design Flexibility Early in the Defense Acquisition Life Cycle" (2014). *Theses and Dissertations*. 712.
https://scholar.afit.edu/etd/712

EXPLORING A METHOD TO QUANTITATIVELY MEASURE DESIGN FLEXIBILITY EARLY IN THE DEFENSE ACQUISITION LIFE CYCLE

THESIS

Joseph S. Kim, Captain, USAF

AFIT-ENV-14-M-32

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

AFIT-ENV-14-M-32

EXPLORING A METHOD TO QUANTITATIVELY MEASURE DESIGN FLEXIBILITY EARLY IN THE DEFENSE ACQUISITION LIFE CYCLE

THESIS

Presented to the Faculty

Department of Systems Engineering and Management

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Systems Engineering and Management

Joseph S. Kim, BS

Captain, USAF

March 2014

DISTRIBUTION STATEMENT A.
APPROVED FOR LIMITED DISTRIBUTION.

AFIT-ENV-14-M-32

EXPLORING A METHOD TO QUANTITATIVELY MEASURE DESIGN FLEXIBILITY EARLY IN THE DEFENSE ACQUISITION LIFE CYCLE

Joseph S. Kim, BS

Captain, USAF

Approved:

//signed//	17 Mar 2014
David Jacques, PhD (Chairman)	Date
//signed//	17 Mar 2014
Erin Ryan, Lt Col, USAF (Member)	Date
//signed//	17 Mar 2014
Kyle Oyama, Lt Col, USAF (Member)	Date

Abstract

The purpose of this research was to demonstrate a methodology using an Epoch-Era Analysis to quantify and estimate the value of design flexibility early in the Department of Defense's (DOD) acquisition life cycle. This method was implemented using a possible replacement to the Air Force's fighter-trainer aircraft as a baseline and a set of future requirements that would change the baseline. An existing Cost Estimating Relationship tool was utilized in conjunction with a decision tree modeling approach to accommodate uncertain future needs. Sensitivity analysis was performed to identify model parameters with dominant effects on the recommended design strategies. The results indicated that this methodology can quantitatively measure design flexibility using existing tools when key assumptions are made. The methodology exists as a proof of concept within the domain of aircraft to quantitatively measure design flexibility early in the acquisition life cycle. Further research is required to characterize the assumptions of this study and to test this methodology in other domains to validate its broader applicability.

Abstract

The purpose of this research was to demonstrate a methodology using an Epoch-Era Analysis to quantify and estimate the value of design flexibility early in the Department of Defense's (DOD) acquisition life cycle. This method was implemented using a possible replacement to the Air Force's fighter-trainer aircraft as a baseline and a set of future requirements that would change the baseline. An existing Cost Estimating Relationship tool was utilized in conjunction with a decision tree modeling approach to accommodate uncertain future needs. Sensitivity analysis was performed to identify model parameters with dominant effects on the recommended design strategies. The results indicated that this methodology can quantitatively measure design flexibility using existing tools when key assumptions are made. The methodology exists as a proof of concept within the domain of aircraft to quantitatively measure design flexibility early in the acquisition life cycle. Further research is required to characterize the assumptions of this study and to test this methodology in other domains to validate its broader applicability.

Acknowledgments

I would like to express my sincerest appreciation to my faculty advisor, Dr. David Jacques, and my committee members, Lt Col Erin Ryan and Lt Col Kyle Oyama, for their guidance and support throughout the course of this thesis effort. The patience, insight, and experience they provided were invaluable my endeavor. I would also like to thank Ms. Alicia Hartong from the Air Force Life Cycle Management Center for both the support and latitude provided to me throughout this study.

\- Capt Joseph S. Kim

Table of Contents

Page

List of Figures

List of Tables

Page

EXPLORING A METHOD TO QUANTITATIVELY MEASURE DESIGN FLEXIBILITY EARLY IN THE DEFENSE ACQUISITION LIFE CYCLE

I. Introduction

General Issue

In the world of DOD acquisition, flexibility is often touted as a valuable “ility.” However, effectively designing flexibility into systems and objectively measuring the outcome is exceedingly difficult. The added costs of designing flexibility early in the acquisition life cycle, as well as the future costs incurred, can be difficult to justify without a means of valuing said flexibility.

A developing example is the replacement aircraft for the Northrop T-38C Talon. It is the current airframe used for the fighter/bomber track of the United States Air Force’s Specialized Undergraduate Pilot Training (SUPT). First introduced in 1961, the T-38 received a host of upgrades over its life cycle to maintain the trainer’s relevance to newer generations of fighters and bombers culminating in the latest version, the T-38C [United States Air Force 2014]. While the T-38C has undergone a service life extension program, the Flight Training System Program Office located at Wright-Patterson Air Force Base projects the T-38C airframe will reach the end of its useful life in 2020 [United States Air Force 2014].

The McDonnell Douglas T-45 Goshawk is the current airframe used by the Navy as its aircraft carrier-capable jet trainer. First introduced in 1988, the T-45 received a glass cockpit upgrade and other modernizations for continued use as a contemporary jet trainer [United States Navy 2009]. Similar to the T-38C, the T-45 will likely see continued use as the Navy's jet trainer through continuous modernization efforts.

With the expiration of the T -38C airframe approaching in 2020 and the time-consuming nature of large acquisitions programs, the T-X FoS (Family of Systems), Advanced Pilot Trainer (APT) acquisitions process began in the fall of 2003 [United States Air Force 2014]. The T-45 Goshawk will also reach the end of its useful life, perhaps ten to fifteen years after the T-38C. If there were a method to quantitatively capture the value of designing flexibility into the T-38C replacement to accommodate the Navy's T-45 replacement, decision-makers could be better informed on whether or not the additional resources to design flexibility into the T-38C replacement would yield an acceptable return on investment. Similarly, additional future requirements could impact and possibly be accommodated by designing flexibility into the T-38C replacement trainer.

Problem Statement

Given the DOD's budget-constrained environment, there is further pressure to investigate methods to reduce life cycle cost. The Analysis of Alternatives completed by the T-X FoS ATP program offered a range of materiel solutions differing in the performance capabilities of the airframe being acquired relevant to the Air Force's jet trainer requirements. Rather than focus solely on the Air Force's fighter/bomber requirements, the concept of design flexibility and its quantitative measure was explored in order to accommodate other user's requirements. For this study, three additional requirements were considered: Navy trainers, Special Operations trainers, and Heavy airframe trainers.

Research Objectives/Questions/Hypotheses

The objective of this research was to demonstrate a method that models the life cycle cost (LCC) impacts associated with engineering design flexibility into a system early in the acquisition process. The T-X program served as a demonstration of this method which attempted to characterize the cost of adding flexibility to the baseline design and its impact (or lack thereof) on the LCC of the modified system.

Research Focus

There are a multitude of factors that can affect the LCC of an airframe. The scope of this research focused on how design changes driven by uncertain requirements in the early phases of acquisitions affected the LCC of the proposed airframes. LCC includes the following costs: research and development, investment, operating and support, and disposal [Defense Acquisition University 2013]. In this research, the calculation of life cycle costs were built into the cost estimating relationship (CER) tool provided by the Air Force Life Cycle Management Center (AFLCMC/XZE) and divided into development, production, operations and support (O&S), and disposal costs.

Investigative Questions

1. How can design flexibility, as a proxy measure for design flexibility, be quantifiably measured in the early stages of development of a system?

2. Can we measure the impact to expected LCC stemming from design changes to accommodate flexibility given uncertain future requirements?

3. Can a general method to quantify the value of design flexibility be developed and applied to other domains beyond airframes?

Methodology

A literature review examining the existing work on how to define flexibility and methods to measure flexibility was conducted. Based upon the information found, a definition and metric for design flexibility was established and utilized for this study.

An Epoch-Era Analysis approach was used to define discrete manifestations of the proposed system and evaluate the differences in LCC [Ross 2006]. By utilizing existing cost estimation relationship models developed by AFLCMC/XZE, separate epochs were created and examined to study the effects of design flexibility on the LCC of a proposed replacement to the T-38C trainer aircraft.

The baseline system was one of many proposed replacements to the T-38C trainer aircraft that met Air Force trainer requirements. Epochs were added to the baseline system by including three additional uncertain future requirements: Navy, Special Operations, and Heavy. Specific design changes to the baseline Air Force trainer requirements were considered to capture the requirements of the uncertain future requirements. Based on notional probabilities of occurrence, the expected LCCs of each epoch/era were compared to determine how the differing epoch variables impacted each era.

The cost of design flexibility was compared to the cost of building separate discrete system that met the possible requirements of the Navy, Special Operations, and Heavy airframes. A comparison between designing for flexibility and developing separate discrete system shed light onto the value of early design for flexibility.

The current SUPT syllabus, the Initial Capabilities Document of the T-X program, and subject matter experts were utilized to create a rough baseline of Air Force requirements. The cost estimates developed for this research do not represent actual program estimates in order to allow the open distribution of the results. Separate baseline epochs adding requirements were created to examine the impact that design flexibility had on LCC. The additional capability required by each epoch variable is notional and the assumptions made are discussed in their appropriate sections.

The separate epochs are associated with variables that assumed a range of values that distinguished one from another. The ranges of values were captured in the CER tool and the outputs were recorded. This data served as inputs into a decision tree that calculated expected LCC for a wide variety of possible outcomes. For further insight, sensitivity analyses were conducted on several inputs to determine their impacts on the tradespace of expected LCC.

Assumptions/Limitations

Because the purpose of this study was to demonstrate a method, actual values for variable inputs and model outputs were not necessarily accurate compared to real-world values. Rather, they attempted to capture a range of reasonable values and suggest trends associated with design flexibility.

The cost model used in this study was limited by the manner of its inputs. This study worked around these input limitations which were noted in their appropriate sections. Other assumptions were noted as necessary in this research paper.

Implications

This exploratory model to quantify design flexibility was first created in the context of the T-X program. However, the model should be broad enough to accommodate other domains. With a general method to help quantify design flexibility, decision-makers at all levels could benefit from increased insight into adding, removing, or avoiding additional requirements. In the long run, the intent is to reduce total costs associated with acquiring new systems and modifying existing systems by providing a better understanding of the returns on investment inherent in design flexibility.

II. Literature Review

Chapter Overview

The purpose of this chapter is to establish a theoretical framework, define key terms, and identify studies and models that supported the modeling of design flexibility.

Literature

Multi-Attribute Tradespace Exploration with Concurrent Design (MATE-CON)

MATE-CON is a powerful tool to evaluate multiple architectures and their respective designs [Ross 2003]. For longer studies, the design-level analysis can be used to re-evaluate the architecture-level analysis to further improve the accuracy of the models used and the architectures selected.

MATE-CON can be broken down into five phases: need identification, architecture solution exploration, architecture evaluation, design solution exploration, and design evaluation. Developed and used extensively by Dr. Adam Ross at the Massachusetts Institute of Technology (MIT), he describes the process as such:

> "The Need Identification phase motivates the entire project, providing the needs, mission, and scope for the project. MATE-CON is the marriage of the architecture-level exploration and evaluation (MATE) with the design-level exploration and evaluation (CON). Architecture-level exploration and evaluation is accomplished using models and simulations to transform a large set of design vectors to attributes and then evaluating each set of attributes in utility-cost space. The set of modeled design vectors, or architectures, are analyzed in utility-cost space and the best architectures are selected for the design-level exploration and evaluation" [Ross 2003, 70].

With MATE-CON, Ross introduced a straightforward and powerful tool to examine a large set of designs and their impact to the value on the system known as an Epoch and Era Analysis (EEA).

Epoch-Era Analysis

EEA is an approach developed alongside MATE-CON that models several proposed designs and compares cost and utility metrics. EEA was originally created to be used with MATE; the original implementation modeled a vast number of space system designs and measures their respective cost and utilities [Ross, et al. 2004].

An Epoch "is a time period that bounds the change scenario during which utility functions, constraints, design concepts, available technologies, and articulated attributes are defined" [Ross 2006, 170]. Similar to economics analysis, EEA seeks to break down a complex problem into a series of simple problems. For both short and long run analyses, many system attributes and constraints are "fixed in the short run (Epoch), but variable in the long run (Era)" [Ross 2006, 170-171].

Each epoch has an identified beginning state and ending state. Each epoch has key variables that impact the defined value of the system that differentiates it from other epochs [Fitzgerald, Ross and Rhodes 2011]. A meaningful epoch variable also captures the uncertainty associated with the respective epoch. When multiple epochs are ordered together, an era that highlights a potential progression of system states over a period of time is created [Ross 2006]. The era allows an analyst to measure how changing epoch variables affect the system over a period of time based upon a metric of the analyst's choosing.

Defining and Measuring Flexibility

It is important to distinguish two types of flexibility, process and design:

> “The literature on flexibility in engineering design addresses two distinct problems: the first one focuses on the flexibility of the design process, and the second one on the flexibility of the design itself (not the process through which a product or a system is designed). This distinction between the flexibility of the process and flexibility of the design is not often made in the literature, and it sometimes adds to the confusion” [Saleh, Mark, and Jordan 2009, 313].

According to the distinction between the two types of flexibility, this research focused on a method to model design flexibility. Within the academic community, there are some inconsistencies that exist in the definition of design flexibility. A literature survey was conducted by Ryan examining 21 varying definitions of design flexibility spanning 1997-2010. The differences among the definitions included: does the system actually change, does the change happen quickly or cost-effectively, is the change foreseeable, does the change occur before or after fielding [Ryan, Jacques and Colombi 2013]. Many of these definitions attempt to capture value but this is accomplished in slightly different ways.

Adaptability is defined as the ability of a system that can modify its capabilities without external intervention [Ryan, Jacques and Colombi 2013]. Machine learning is a prime example of adaptability where an adaptable system can improve on its existing capabilities without the need for additional programming. Commonality seeks to create value by reducing unique parts requirements and establishing economies of scale with producing and maintaining shared parts [Simpson and D'Souza 2008]. With commonality, the certainty of additional requirements is implied with the effort to standardize parts between multiple systems. The F-35 Joint Strike Fighter is an example where commonality was implemented as a cost reduction measure.

Of particular interest is design flexibility, which is defined as a system designed with certain characteristics that may not optimize the immediate set of requirements, but easily allows the system to accommodate, via modifications, new requirements after the system has been fielded [Saleh, Mark, and Jordan 2009]. Design flexibility is also described as "the measure of how easily a system's capabilities can be modified in response to external change" [Ryan, Jacques and Colombi 2013]. In this definition, "easily" refers to the cost effectiveness and timely manner of the modification to the system.

In the literature, the definitions of design flexibility and design robustness are similar and often confused with one another, but are distinctly different. Design flexibility "implies an ability to satisfy *changing requirements* by *changing the system* after the system has been fielded" and "an ability of the design to be changed in order to track requirements changes" [Saleh, Mark, and Jordan 2009, 316]. Saleh used a spacecraft example to demonstrate his definition of design flexibility. He states that the spacecraft may require new functionalities as events and/or new data become available. The changing functionality is also quite likely due to the design lifetime of most spacecraft, which demands that the spacecraft incorporate design flexibility to accommodate these future changes [Saleh, Mark, and Jordan 2009]. This differs from design robustness which captures the ability of a design to "satisfy a *fixed* set of requirements, *despite* changes in the environment or within the system" [Saleh, Mark, and Jordan 2009, 316].

After defining flexibility, the next challenge is how to measure flexibility. Currently, the DOD's LCC includes research and development, investment, operating and support, and disposal costs over a system's life cycle [Defense Acquisition University 2013]. In addition to these costs, LCC estimates take into consideration potential program risks [Defense Acquisition University 2013]. Although comprehensive, DOD LCC estimates are ultimately a static measure assuming the program will not deviate from the acquisition program baseline [Defense Acquisition University 2013]. The DOD's method of estimating LCC does not attempt to measure flexibility in any way.

Ryan proposed a methodology that measured a cost coined as Current Expected Value Life Cycle Cost Curve (CEVLCCC) [E. Ryan, et al. 2013]. This methodology sought to capture cost impacts due to potential changes to the baseline. Of interest, this methodology accommodated the ability for the baseline system to respond to potential changes. If a system could respond cost-effectively to a change to its baseline it would drive down the associated cost penalty applied to that system in order to achieve design flexibility [E. Ryan, et al. 2013]. Ryan's methodology required that each system design candidate be of sufficient maturity that traditional life cycle cost estimates could be implemented. Unfortunately, this is not the case for this study. However, Ryan's approach to identify CEVLCCC as one proxy metric to capture value was used in a similar manner for this study.

Cost Estimating Tool

Engineers at AFLCMC/XZE have developed an Excel-based airframe LCC estimating tool that takes user inputs depending on the function and design features of the hypothetical aircraft and outputs LCC as a function of development, production, O&S, and disposal costs. Calculations are taken from past data with input from subject matter experts.

An example of one input is the type of aircraft being developed. The options within the tool allow for fighter, bomber, cargo, and trainer aircraft. Based upon this selection, the tool draws upon information from past airframes of that type to estimate several costs which include, but are not limited to: annual operation costs, maintenance costs, and development costs.

Although a powerful tool, the estimating tool has limitations as well. Unless a specific component is coded into the tool, the only method to account for an additional feature is to incorporate it into an existing input. For example, if a user wanted another estimate of an airframe with a larger landing gear, no explicit input for landing gear type exists. The way around this limitation is to adjust the total empty aircraft weight to accommodate a reasonable value for the modification. Typically, only major components such as engines and avionics have dedicated input values [AFLCMC/XZE 2013].

Conclusion

There are many models and techniques that improve the analysis of multiple alternatives, define flexibility, measure flexibility, and compare flexibility. This research intends to take these models and incorporate them into a unified method that better predicts and analyzes the cost associated with design flexibility using the T-X program as a source of data. Although based off data from the T-X program, the steps to implement this method should be applicable to other disciplines as well.

III. Methodology

Chapter Overview

The purpose of this chapter was to describe the research methodology of this study, explain the sample selection, describe the procedures used in designing the instrument and collecting the data, and provide an explanation of the procedures used to analyze the data.

Based on the literature review, design flexibility was measured based upon the ability for an airframe in development to accommodate future potential requirements. The metric used to measure design flexibility was the expected LCC, a proxy measure of design flexibility [Ryan, Jacques and Colombi 2013].

A quantitative and predictive research methodology was used for this study. Epochs and their associated variables were established based upon the four different aircraft requirements: Air Force, Navy, Special Operations, and Heavy (transport). Next, the cost estimating relationship (CER) tool developed by AFLCMC/XZE was used to generate LCC estimates based on the different aircraft design requirements. A separate LCC estimate was generated to compare the cost of an Air Force system with additional requirements incorporated versus the cost of a new dedicated system. To examine impact the additional requirement had on the system, Ross' epoch and era analysis was used to observe the differences and trends across all the eras. In addition to the existing tools, general assumptions towards the requirements of different users were made to model the different aircraft configurations based on the intended user. Multiple sensitivity analyses were conducted to examine the impact of uncertain parameters on the output of the method.

Although modeling past behavior and trends is important for a decision-maker, future behavior of a system is more important than explaining past observations [Shmueli 2007]. Ultimately, the method developed in this study should be of use to decision-makers attempting to quantify the cost associated with designing flexibility into their systems regardless of the cost models used.

Sample

Reiterating the previous point on Ross' MATE-CON, the process can be broken down into five phases: need identification, architecture solution exploration, architecture evaluation, design solution exploration, and design evaluation [Ross 2003]. At the time of this study, the Air Force had already accomplished the need identification, architecture solution exploration, and architecture evaluation for the T-X program. The need identification requirement was established first as the T-X FoS ATP's Initial Capabilities Document and later as the Capability Development Document. Both architecture solution exploration and evaluation were completed as identified by the "family of systems" approach to acquisitions [Ross, et al. 2004]. The Air Force expanded its acquisition focus beyond just the airframe and recognized the importance of capturing all aspects of a new trainer.

This study continues with design solution exploration and design evaluation. The design solution exploration considered the impact of adding three additional requirements to the replacement; a Navy, Special Operations, and Heavy (transport) requirements. The design evaluation was the result of this study.

Testing

The first step in examining the impact of additional requirements to a T-X baseline design was to establish separate epochs. The Air Force epoch costs reflected the baseline design while the additional epochs captured the cost to add additional requirements. Ideally, the additional epochs would capture only their respective requirements rather than include the AF requirements. But due to the limitation of the CER tool and the notional nature of the additional requirements, this was a necessary assumption. The epoch variables represented the future possibility that the requirements and/or the design parameters demanded of the baseline system could change.

For this study, the epoch variables and their possible range of values represented realizations of requirements that were not originally identified in the Acquisition Program Baseline (APB). However, the inclusion of the epoch variables was assumed to occur before production costs were incurred. This point is further clarified in Chapter 4.

It is important to note that AFLCMC/XZE developed multiple baseline Air Force only requirement (AF) epochs for their own estimating purposes. This study utilized their estimate of a single-engine supersonic aircraft as the baseline AF estimate. The different epoch variables were notional and chosen based on discussions with subject matter experts at AFLCMC/XZE as well as the modeling limitations of the CER tool. This was deemed reasonable as the purpose of the model was to explore a new method to measure design flexibility and the accuracy of the epoch variables was deemed less important for this initial demonstration of the methodology. Table 1: CER Tool Assumptions, summarizes the assumptions related to the CER tool that were made for this study. These assumptions were reiterated as appropriate in the latter sections.

Table 1: CER Tool Assumptions

CER Tool Assumptions
Disposal costs were omitted from LCC calculation
Additional epoch requirements were added to the baseline AF estimate
N and H epoch variables were converted to aircraft weight
Timeline for development, production, and retirement remained constant
Annual production of aircraft remained constant

Separate epochs capturing Navy requirements (N), Special Operations requirements (SO), and Heavy requirements (H) were created based upon the identified epoch variables. Ideally, unique requirements for each epoch would be used to capture their respective LCCs. However, AF specific requirements were the only requirements available. Therefore, the N, SO, and H requirements were additions to the AF baseline and assumed to fully encompass AF requirements. Sensitivity analysis helped address the unrealistic assumption that N, SO, and H epochs fully encompassed AF requirements.

In regard to the number-of-engines variable, rather than an addition to the AF baseline, the number of engines represented a potential change to the AF baseline and was implemented as such in this study. In hindsight, a more appropriate approach could characterize the number of engines as a design decision rather than a stochastic event. Additional epochs and eras could be created to capture the decision to incorporate one or two engines. To scope the possible number of eras to a reasonable total, the number of engines was treated as a stochastic event and the costs associated with a one-or-two engine design were averaged into the appropriate epoch costs. A summary of the epochs and their variables are listed in Table 2: Epoch Summary.

Table 2: Epoch Summary

Epoch	Epoch Variables
Air Force Requirement (AF)	N/A
Navy Requirement (N)	Number of Engines Reinforced Landing Gear Tail Hook # of Combat-Coded A/C
Special Operations (SO)	Improved Avionics # of Combat-Coded A/C
Heavy Requirements (H)	Number of Engines Cockpit Interface Interchangeability # of Combat-Coded A/C

The N epoch variables are meant to represent features similar to the existing T-45 Goshawk. Two features included a tail hook and a stronger structure supporting the landing gears to accommodate carrier landings [United States Navy 2009]. The addition of these requirements was reflected in the CER tool as additional aircraft weight. The option for one or two engines was also a potential requirement due to the Navy's affinity for two engines as seen on their current F-18 and past F-14 fighter aircraft. This option was explicitly specified in the CER tool. The purpose of the epoch variables and their combinations with a one or two engine design was to generate discrete LCC points in order to calculate the mean LCC of the epoch. It was assumed the range of LCC across the range of epoch variables was a uniform distribution in the absence of specific distribution data. This assumption was extended to the SO and H epochs as well. The method could easily accommodate other LCC distributions such as triangle and normal.

The SO epoch variable of improved avionics captured the clandestine nature of special operations. This can be manifested as avionics that allow for low-level flying at night or a sophisticated communications/electronics package similar to those equipped in the EC-130 that support special operations [United States Air Force 2005]. The avionics weight was an explicit input in the CER tool that was utilized to capture this SO requirement.

The H epoch translated cockpit interface interchangeability into aircraft weight in the CER tool. Without an explicit input in the CER tool to capture this epoch variable, aircraft weight was chosen as a proxy input that best represented the addition of cockpit interface interchangeability. This epoch variable was meant to capture the ability for the AF aircraft to accommodate a different cockpit layout more appropriate for a heavy trainer aircraft vs a fighter-bomber trainer aircraft. Notionally, this could include location of throttle, joystick type, joystick position, and instrument layout. Like the N epoch, a one-or-two engine design was combined with each possible weight configuration to calculate the mean LCC of the H epoch.

For the N, H, and SO epochs, the number of combat coded aircraft was another epoch variable they shared and was directly input into the CER tool. This variable captured the uncertainty in fleet size representative of any aircraft acquisition. Along with the other epoch specific variables, the number of combat-coded aircraft was input with every combination of aircraft weight, avionics weight, and number of engines as appropriate to create a range of LCCs and ultimately calculate the average LCC of the epoch.

Eight eras were evaluated in this study:

1. AF = AF epoch only
2. AFN = AF and N epochs
3. AFSO = AF and SO epochs
4. AFH = AF and H epochs
5. AFNSO = AF, N, and SO epochs
6. AFNH = AF, N, and H epochs
7. AFSOH = AF, SO, and H epochs
8. AFNSOH = AF, N, SO, and H epochs

The eras evaluated in this study were not collectively exhaustive as a whole, but collectively exhaustive of the eras that included AF epochs. Each era represented a possible future reality. A design strategy represented the decision-maker's choice to pursue or forgo design flexibility. Among the possible design strategies involving the AF epoch, the AFNSO and AFSOH eras were omitted from the analysis.

The design strategies evaluated in this study were:

1. AF = AF epoch only
2. AFN = AF and N epochs
3. AFSO = AF and SO epochs
4. AFH = AF and H epochs
5. AFNH = AF, N, and H epochs
6. AFNSOH = AF, N, SO, and H epochs

The two omitted design strategies were not considered because the six design strategies selected were representative of multiple epoch eras. The additional design strategies would not demonstrate any additional insight to the methodology than those chosen to be evaluated.

Once a design strategy was selected, each of the eight eras became a possible realization. Palisade's Precision Tree add-in for Excel was used to visualize and calculate expected LCCs based upon probabilities of an era occurring. Figure 1: Partial Decision Tree illustrates a portion of the decision tree used in this study. The green square represents a decision node for the possible choices that a decision-maker could make. In this study, the decision node represents aircraft design strategies that could be pursued. The design strategy is the decision-maker's choice to design flexibility (or not) into the baseline AF epoch. Red circles represent chance nodes with branches that capture a set of mutually exclusive and collectively exhaustive outcomes.

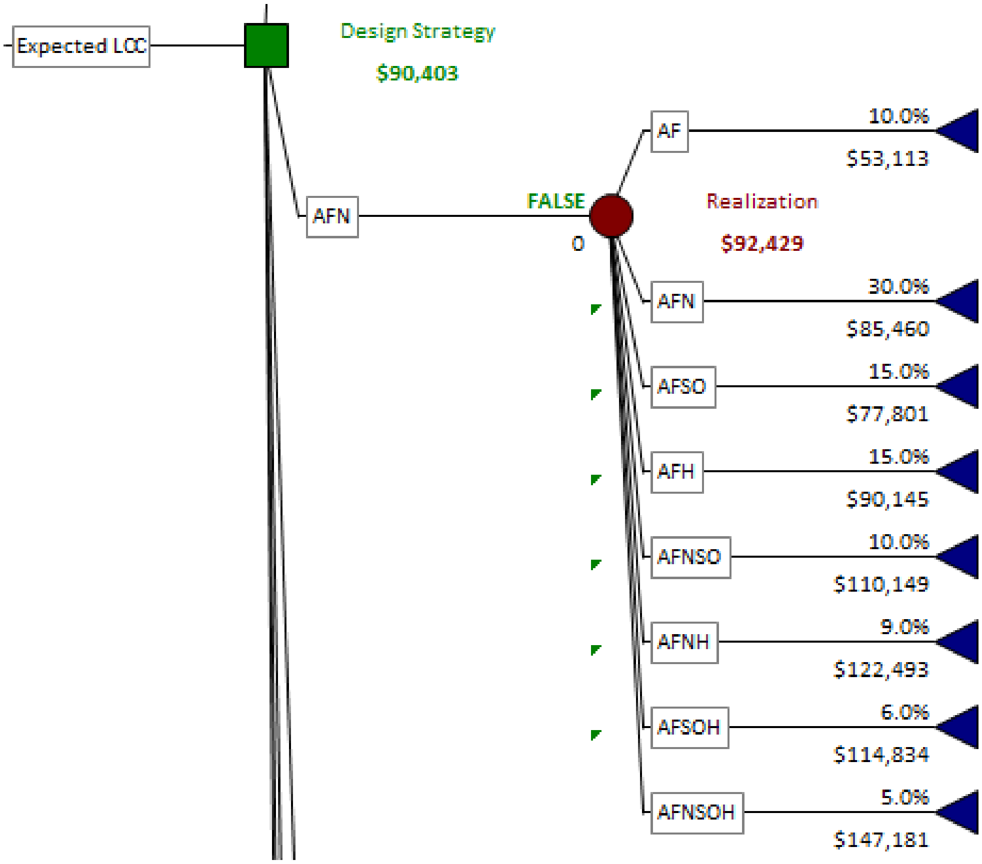

Figure 1: Partial Decision Tree

The probability associated with each era represent the probability that the era will be realized for a given design strategy. Because the eight eras including an AF epoch are mutually exclusive and collectively exhaustive, the sum of the probabilities must equal 100%. It's feasible that the probabilities among the possible eras could change depending on the design strategy chosen. However, with no good method to capture how a chosen design strategy would impact the probabilities of its outcomes, it was assumed that the probabilities of each outcome across all design strategies were equal. The probabilities of the eight eras are listed in Table 3: Era Summary.

Table 3: Era Summary

Era	Epochs	Probability of Occurring
AF	AF	10%
AFN	AF + N	30%
AFSO	AF + SO	15%
AFH	AF + H	15%
AFNSO	AF + N + SO	10%
AFNH	AF + N + H	9%
AFSOH	AF + SO + H	6%
AFNSOH	AF + N + SO + H	5%

The probability of occurrence for each era was determined based upon the foreseeable need for a new trainer aircraft. Due to the introduction of 5th generation fighter aircraft and improvements in avionics, modern day trainers must prepare pilots to become familiar with these improved capabilities. The T-45 Navy trainer entered service in 1991 and primarily prepared Navy aviators for the F-18 Hornet [United States Navy 2009]. With the introduction of the F-35 as the Air Force and Navy's next fighter, it was deemed that the eras that captured Navy requirements had a higher probability of occurrence than the other comparable eras. Given that the probability of one era occurring impacted the probabilities of the remaining eras, the probabilities were treated as dependent. Due to the dependent nature of the probabilities, there are conditional probabilities that are implied by the probability distribution among the possible eras.

The trainer aircraft used to prepare SUPT pilots for many of the platforms that support special operations entered service in the 70's [United States Navy 2012]. The aircraft used to train SUPT pilots for Heavy missions was adopted in 1992 but has not seen significant upgrades since its adoption [United States Air Force 2005]. Based upon the age of the trainer aircraft used to satisfy the Special Operations and Heavy requirements, these eras were assigned the next highest probability of occurrence. The AF only era was considered the next probable era followed by AFNSOH due to the small chance that all additional requirements would be realized.

The additional requirements of each epoch variable in this study, other than the number of combat-coded aircraft, were meant to be design changes to the existing Air Force baseline. For example, the N epoch variable of a tail hook would be a flexible design addition to the Air Force baseline. This design consideration would require some modification to the Air Force design to cost effectively accommodate a tail hook in the future if the need arose. This design flexibility approach was used in contrast to simply adding the full design requirement of a tail hook to the AF baseline because there was no certainty that an era such as AFN would be realized. Also, the additional requirements levied on the baseline AF system would have negative impacts on the cost and performance of the system.

Designing flexibility into any system comes at a cost. To calculate the impact to LCC of the additional requirements to the baseline design, a subjective impact value from 0.0 – 1.0, was added to the production and operation and sustainment (O&S) cost of the relevant era. The subjective impact was a penalty that design flexibility imposed on the AF baseline that resulted in higher production and O&S costs. In regards to development costs, the difference in additional development cost to accommodate flexible design was added to the AF development cost. The nature of the epoch variables was consistent with Saleh's definition of design flexibility that a system could be modified more easily if additional requirements were levied on the baseline system [Saleh, Mark, and Jordan 2009].

The values of each epoch variable were limited by the CER tool. Explicit design changes could not be directly added as inputs into the CER tool for N and H requirements. These requirements were translated into aircraft weight, an input the CER tool could accommodate. The breakdown of the epoch variables, their baseline values, and their possible values are listed in Table 4: Epoch Variables below.

Table 4: Epoch Variables

Epoch Variables	Baseline Value	Possible Values
Number of Engines	1 Engine	1 Engine 2 Engines
Reinforced Landing Gear	A/C Weight 9900 lbs (+0 lbs)	Additional A/C Weight 200 lbs 300 lbs 400 lbs 500 lbs 600 lbs 700 lbs 800 lbs
Tail Hook	A/C Weight 9900 lbs (+0 lbs)	Additional A/C Weight 400 lbs 500 lbs … 1300 lbs 1400 lbs
Avionics	Avionics Weight 360 lbs (+0 lbs)	Additional Avionics Weight 100 lbs 200 lbs … 600 lbs 700 lbs
Cockpit Interface Interchangeability	A/C Weight 9900 lbs (+0 lbs)	Additional A/C Weight 100 lbs 200 lbs 300 lbs 400 lbs
# of Combat Coded A/C	350 A/C	# of A/C N: 200, 250, 300 SO: 150, 200, 250 H: 150, 200, 250, 300

The range of values for each epoch variable was notionally selected. Certain considerations were made to ensure that the maximum epoch variable values remained reasonable. For example, the addition of a reinforced landing gear and tail hook should not increase total aircraft weight by 50%. Similar considerations were taken to determine the minimum values for each epoch variable. Landing gear and tail hook considerations were deemed to have a larger impact to aircraft weight than the ability for the cockpit to accommodate separate configurations. The values for the number of combat-coded aircraft were chosen based on the total number of trainer aircraft produced for each respective epoch.

Each epoch must have a beginning and ending state identified. Clearly, the beginning and ending state of the AF baseline was before LCC was incurred as only eras involving the AF epoch were considered. Any additional epochs began after development costs were incurred but prior to production costs. The decision to pursue a design strategy must be made prior to DOD acquisition Milestone A. The described timeline is illustrated in Figure 2: Era Timeline Assumption using the AFN design strategy and AFN era occurrence as an example.

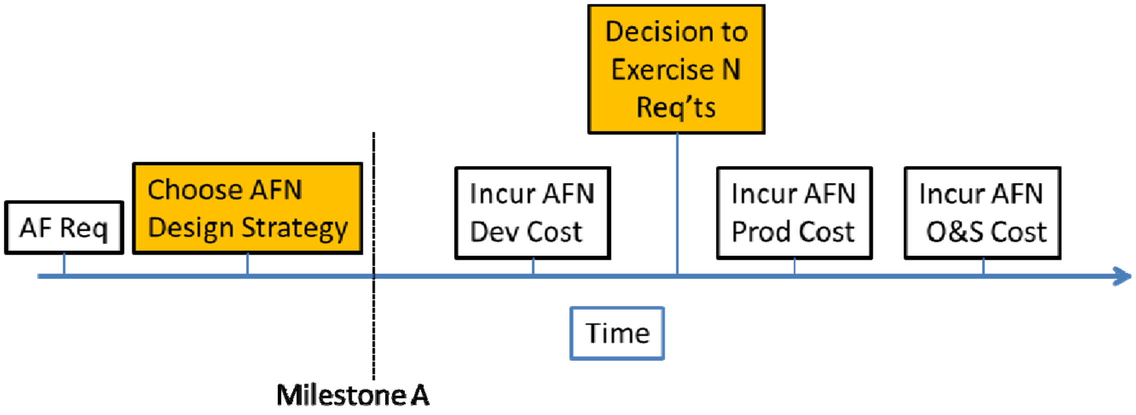

Figure 2: Era Timeline Assumption

Once the AFN design strategy is chosen, AFN development costs are incurred regardless of N epoch occurring or not occurring. The decision whether to exercise the N epoch must occur after development cost is incurred but before production cost is fully incurred. For example, if the decision to not exercise N epoch was made before development costs were incurred, then no further investments to the AF baseline should be made and therefore, no additional costs to the AF baseline would be incurred. Eras with three or more epochs would look similar to Figure 2: Era Timeline Assumption with the chosen design strategy occurring before Milestone A and the decision to exercise the additional epochs occurring between development and production costs.

If the decision to exercise an epoch were to occur after production costs were incurred, another "penalty" factor would be required to account for the extra cost of restarting production or extending the production timeline beyond original estimates. This is illustrated in Figure 3 using AFN as an example.

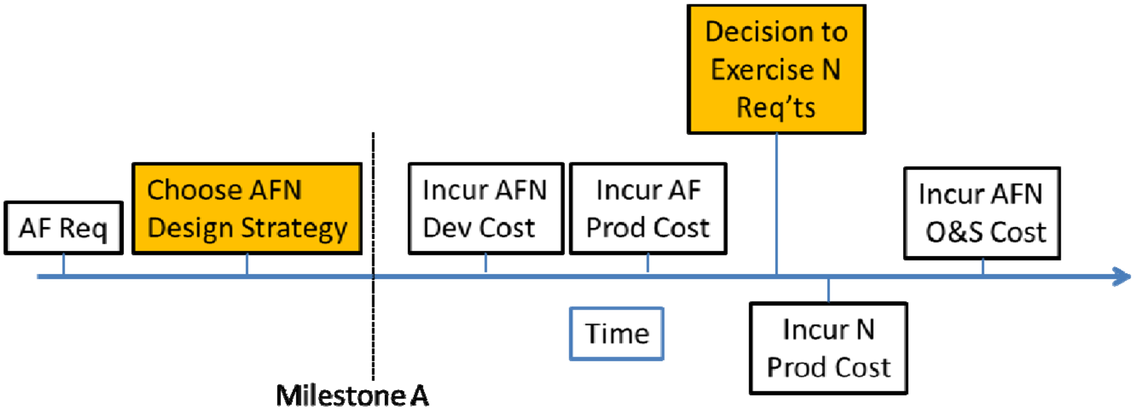

Figure 3: Possible Era Realization

Other penalties such as loss of expertise, additional staff support costs, lack of bulk orders are some of the additional costs that would be incurred. This research assumed a timeline as shown in Figure 2: Era Timeline Assumption due to the inability of the CER tool to calculate the aforementioned penalty to LCC and avoid unnecessary speculation.

Another necessary assumption was once a design strategy was chosen, there are no “off ramps” available. For example, after AFN’s development cost occurs and if the decision to not exercise N epoch’s requirements was made, there was no option that allowed the acquisition to revert back to a baseline AF design and produce AF aircraft, effectively avoiding any future cost penalties associated with design flexibility.

The expected cost of flexibility was measured by comparing a given era’s expected LCC against the expected LCC of the era’s respective epochs. The expected LCC of AFN was measured against the sum of the LCC of AF and N epochs to determine if there was cost savings associated with design flexibility. All cost figures were calculated in Base Year 2013 (BY2013) dollars.

Finally, one and two-way sensitivity analyses were conducted in order to analyze how changes in some of the major inputs would affect expected LCC. Specifically, era LCC estimates, probability of occurrence, and subjective impact sensitivity analyses were conducted. Due to the greater uncertainty associated with subjective inputs, a sensitivity analysis was deemed necessary to establish trends associated with those inputs. The goal was to view the impact that the subjective inputs had on the output.

Summary

The goal of this study is to demonstrate a method to quantitatively measure the value of design flexibility. Reasonable assumptions were made to overcome limited information, CER tool functionality, and to properly scope this research. Other notional assumptions such as probability of occurrence and subjective impact were the subject of sensitivity analyses to identify the trending impact these inputs had on the method's output.

IV. Analysis and Results

Chapter Overview

This chapter covers the implementation of the methodology and the associated outcomes. The goal of this analysis was to demonstrate the method proposed in Chapter 3 and to quantify the cost of design flexibility in the context of the T-X acquisition scenario.

Analysis

The first step of analysis was to generate the proper data points and establish cost averages for each epoch. Using the CER tool provided by AFLCMC/XZE, estimates of development, production, and O&S costs were recorded across the range of values established by the epoch variables. The disposal cost was another output of the CER tool; however, disposal costs were less than a tenth of a percent of the total LCC for each epoch. Therefore, disposal costs were omitted from this analysis. Using H as an example, for 200 aircraft, four cost estimates were generated adding 100 lb increments to the AF baseline and four additional cost estimates were generated using a two engine design. This process was repeated twice more at fleet sizes of 250 and 300 aircraft. The average across all the H cost estimates was recorded with an assumed uniform distribution. The averages of each epoch are summarized in Table 5: Epoch Cost Averages.

Table 5: Epoch Cost Averages

Epoch	**LCC**	**Total Dev Cost**	**Unit Prod Cost**	**Unit O&S Cost**	**# of A/C**
AF	$48,236	$2,916	$39.72	$89.76	350
N	$37,625	$2,949	$48.36	$90.02	250
SO	$30,592	$2,994	$48.86	$89.13	200
H	$37,033	$2,805	$46.71	$89.89	250
NOTE: All $ figures BY13 in millions					

These averages were based upon inputs in the CER tool that estimated development beginning in 2016, production beginning in 2020, and aircraft retirement in 2047. The total estimated program timeline from development to retirement was 32 years. This notional timeline was based upon the baseline AF estimate provided by AFLCMC/XZE.

Based upon the generation of this data, several observations were made. Development cost was independent of fleet size. Regardless of how many aircraft were input into the CER tool, development costs would hold constant. As indicated in SO’s unit production cost average, avionics weight played a larger factor in production due to a high unit production cost. Likewise, SO’s unit O&S cost was slighter lower than the larger fleet epochs due to avionics weight having very little impact on O&S which overcame the diseconomies of scale associated with a smaller fleet size. This was compared to N and H where additional aircraft weight had a lesser impact on production cost than avionics weight, but a slightly larger negative impact to unit O&S cost compared to the AF baseline.

As discussed in Chapter 3, cost estimates for each epoch were generated by adding or changing requirements to the AF baseline. Average development cost for H was lower than the AF development cost. Although initially odd, closer examination revealed that while all other inputs were held constant in the CER tool, switching from a one engine design to a two engine design would decrease development costs by approximately $300 million. According to the CER tool, the one and two engine designs are modifications to existing engines. A possible explanation for the reduced development costs for a two engine design could be due to an existing two engine design that is closer to the modified engine requirements than the one engine design. Because the range of additional weight for H was relatively small (100 lbs – 400 lbs), the cost to develop the additional weight did not exceed the decreased development cost when averaged across all possible H cost estimates. A two engine design was not without its own penalties. Although development costs associated with a two engine design would decrease development cost, an increase in the production cost was incurred.

Before calculating expected LCCs, key terms were defined. Flexible investment cost was the cost to design flexibility into the AF baseline design and was determined by the design strategy chosen by the decision-maker. Flexible investment cost impacted the baseline development, production, and O&S costs, and was incurred regardless of whether the option to implement the additional capabilities was exercised. The flexible investment development cost was equal to the AF baseline development cost plus the additional development cost to accommodate a given era’s requirements. The exception to this was AFH where the development cost was set equal to AF rather than using a development cost lower than the baseline. The two epoch era equations listed used Navy requirements as an example in Equation 1.

$$\text{AFN Flexible Investment Development Cost} = \text{AFN Dev Cost} \tag{1}$$

The total of AF unit production cost plus the product of N unit production cost and N subjective impact was multiplied by the number of AF aircraft to calculate the AFN flexible investment production cost. The subjective impact captured the additional cost associated with producing AF aircraft with design flexibility that could accommodate a potential future N requirement is demonstrated in Equation 2.

$$\begin{aligned}&\text{AFN Flexible Investment Production Cost} =\\&\text{\# of AF A/C} * ((\text{AF unit Prod Cost}) +\\&(\text{N unit Prod Cost} * \text{ N subjective impact}))\end{aligned} \tag{2}$$

Figure 4: Flexible Investment Production Cost, illustrates Equation 2 where the baseline unit production cost was more expensive when considering the design flexibility required of the potential future requirement of N. The unit production cost impact due to flexible design was a small percentage of the unit production cost of N.

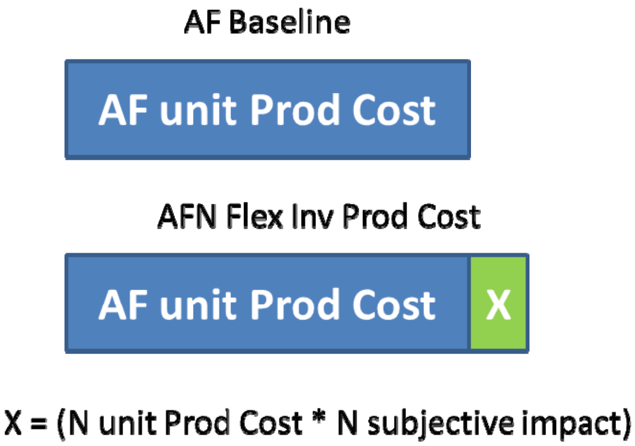

Figure 4: Flexible Investment Production Cost

The subjective impact was a notional value between 0 – 1.0 that represented how design flexibility negatively affected the cost of producing each AF aircraft. A value of zero indicated no impact to AF production costs. The purpose of the subjective impact was to model the penalty of design flexibility on the baseline AF system. The subjective impact captured the design change to AF that allowed the aircraft to be easily modified to accommodate future epoch requirements if the need arose.

Notional subjective impact values are listed in Table 6: Subjective Impacts. The Navy epoch was considered to have the greatest cost impact to unit production costs due to the nature of accommodating a reinforced landing gear and a tail hook. This could result in a heavier frame compared to the AF baseline which would translate into increased production and O&S costs. The special operations epoch was considered to have a moderate negative impact due to the considerations of improved avionics. Although a stronger frame than the AF baseline may not be necessary, the space necessary to accommodate larger avionics could have a moderate impact on the baseline design. Finally, the Heavy epoch was considered to have the least negative impact as supporting a separate control scheme within the cockpit might require relatively minimal changes between the interfaces of the cockpit and airframe.

Table 6: Subjective Impacts

Epoch	Subjective Impact
N	0.10
SO	0.07
H	0.05

Flexible investment O&S cost was treated in the same manner as flexible investment production cost. The AF baseline O&S cost incurred a penalty for the additional flexibility requirements that must be accommodated throughout the life cycle of the now modified AF system as shown in Equation 3.

$$\text{AFN Flexible Investment O\&S Cost } = \text{\# of AF A/C} * ((\text{AF unit O\&S Cost}) + (\text{N unit O\&S Cost } * \text{ N subjective impact})) \tag{3}$$

The flexible investment cost of the extended eras AFNH and AFNSOH followed the same convention as their shorter counterparts with a small exception to AFNSOH's flexible investment production cost as demonstrated in Equations 4 - 5. The flexible investment development cost of AFNSOH aggregated the development cost delta of the additional epochs. As previously mentioned, the negative cost delta between AF and H development cost was ignored.

$$\text{AFNSOH Flexible Investment Development Cost} = \text{AFN Dev Cost } + (\text{AFSO Dev Cost - AF Dev Cost}) \tag{4}$$

$$\text{AFNSOH Flexible Investment Production Cost} = \#\text{ of AF A/C} * ((\text{AF unit Prod Cost}) + (\text{N unit Prod Cost} * \text{N subjective impact}) + 0.9 * [(\text{SO unit Prod Cost} * \text{SO subjective impact}) + (\text{H unit Prod Cost} * \text{H subjective impact})]) \qquad (5)$$

The two epoch eras have assumed an additive nature of accommodating the flexible design of additional requirements. The general convention for flexible investment costs for AFNSOH was modified by the inclusion of multiplying 0.9 to the sum of the flexible design impact of SO and H. This was designed to capture some of the non-additive properties of producing flexible design changes to roughly the same area of the AF aircraft. It can be argued that production efficiencies could exist when modifying AF's baseline avionics as demanded by SO's requirements and cockpit interchangeability as demanded by H's requirements. A relatively high value of 0.9 was chosen to capture a minor efficiency because the avionics in an A/C are not necessarily limited to the general proximity of the cockpit. The further the distance flexible design work occurs away from the cockpit, the less production efficiencies would be realized between SO and H requirements. The non-additive attribute exists only in the AFNSOH and AFSOH flexible investment production cost and is unique to these two eras.

$$\text{AFNSOH Flexible Investment O\&S Cost} = \#\text{ of AF A/C} * ((\text{AF unit O\&S Cost}) + (\text{N unit O\&S Cost} * \text{N subjective impact}) + (\text{SO unit O\&S Cost} * \text{SO subjective impact}) + (\text{H unit O\&S Cost} * \text{H subjective impact})) \qquad (6)$$

The AFNH era arguably did not realize the same production efficiencies as AFNSOH and AFSOH due to the separate areas of the AF aircraft being modified as demanded by N and H requirements. Therefore, both AFNH flexible investment production and O&S costs followed similar convention to the shorter eras as shown in Equations 7 - 8.

$$\text{AFNH Flexible Investment Production Cost} = \text{\# of AF A/C} * ((\text{AF unit Prod Cost}) + (\text{N unit Prod Cost} * \text{N subjective impact}) + (\text{H unit Prod Cost} * \text{H subjective impact})) \tag{7}$$

$$\text{AFNH Flexible Investment O\&S Cost} = \text{\# of AF A/C} * ((\text{AF unit O\&S Cost}) + (\text{N unit O\&S Cost} * \text{N subjective impact}) + (\text{H unit O\&S Cost} * \text{H subjective impact})) \tag{8}$$

The AFNSO era followed the same convention as AFNH to calculate flexible investment cost. Eras with three or four epochs suffered greater penalties. For example, the AFNH era required that all AF aircraft accommodate design flexibility for N and H requirements while the AFN era required the accommodation of only N requirements. A summary of the flexible investment LCC of the six design strategies is listed in Table 7: Flexible Investment Summary.

Table 7: Flexible Investment Summary

Design Strategy	Era	Flexible Investment LCC	Delta
AF	AF	$48,236	$0
AFN	AF	$53,113	$4,877
AFSO	AF	$51,695	$3,459
AFH	AF	$50,627	$2,391
AFNH	AF	$55,533	$7,297
AFNSOH	AF	$58,787	$10,551
NOTE: All $ figures BY13 in millions			

Implementation cost was the cost of an era if a given era occurred. There were a few key assumptions to implementation cost which were driven by the limitations in the CER tool. If an era was realized, it was assumed that the additional aircraft produced occurred concurrently with AF production. For example, in one realization of an era, the option to exercise an era may happen years after the AF baseline has finished production. For the purposes of this study, an era is exercised immediately and both the AF aircraft with design flexibility and the epoch specific aircraft (e.g. AFN) with implemented capabilities began production at the same time and shared identical service life and retirement dates (see Figure 2: Era Timeline Assumption and Figure 3: Possible Era Realization). If this were not the case, cost penalties associated with discordant epoch timelines within the era would be required.

Implementation development cost was equal to flexible investment development cost. The Implementation production and O&S cost, and ultimately LCC, were dependent on the chosen design strategy. In Figure 5: AF Design Strategy, given an AF design strategy, or the decision to forgo any sort of design flexibility, implementation cost was equal to the sum of the separate epoch LCCs. All dollar figures are in BY13 in millions.

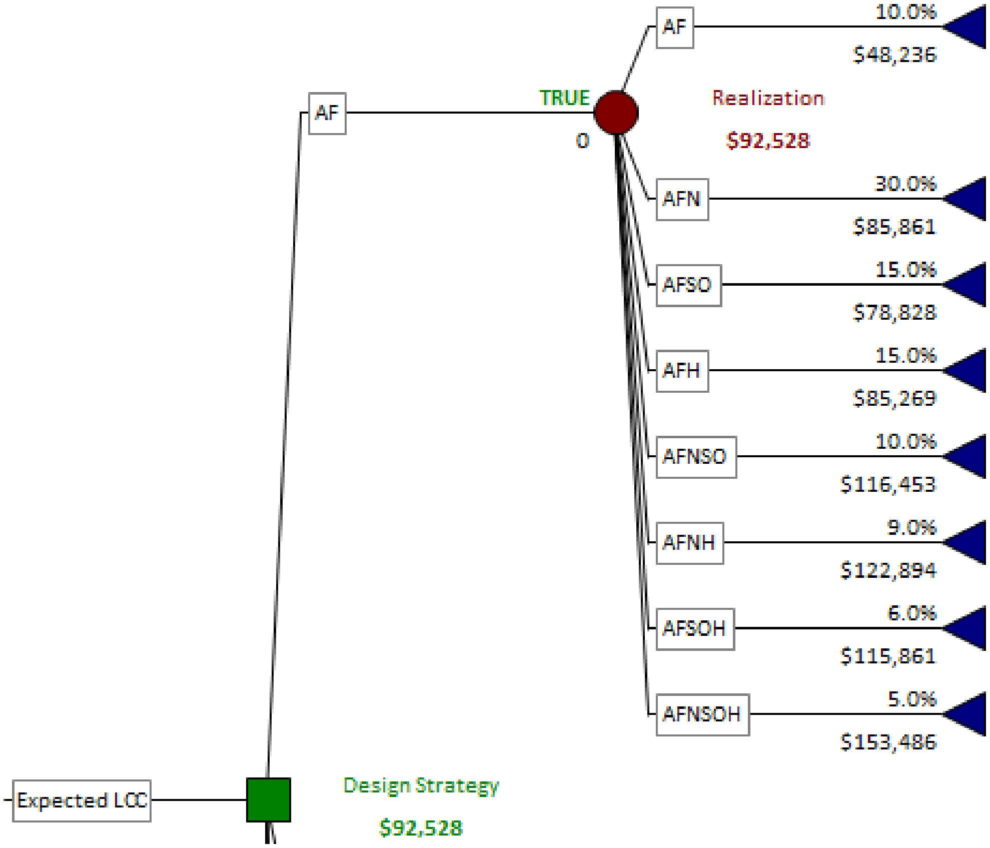

Figure 5: AF Design Strategy

Equation 9 shows the implementation LCC of AFN given an AF design strategy is:

$$\text{AF} \rightarrow \text{AFN Implementation LCC} = \text{AF LCC} + \text{N LCC} \qquad (9)$$

Figure 6**:** AFN Design Strategy summarizes the implementation LCC of each era given an AFN design strategy.

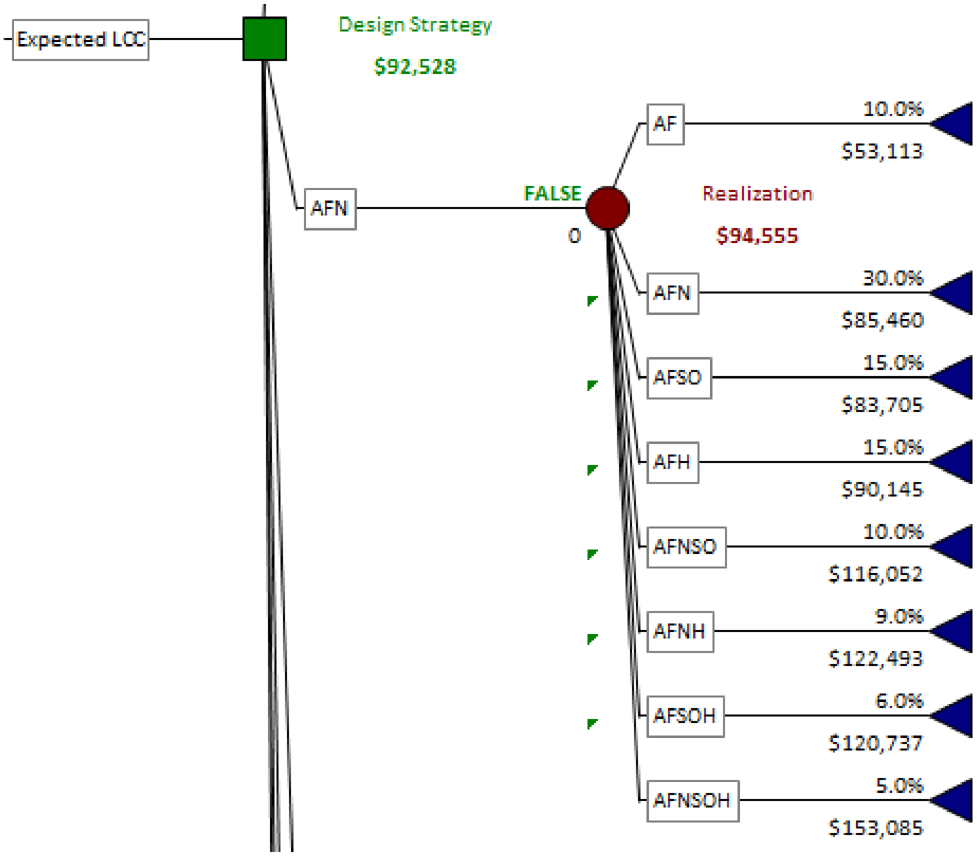

Figure 6: AFN Design Strategy

The implementation LCC of each era included the AFN flexible investment cost. The flexible investment cost captured the cost penalty to the AF aircraft for accommodating design flexibility. To demonstrate in Equation 10, the implementation LCC for AFH given an AFN design strategy (AFN → AFH denotes an AFN design strategy and an AFH era realization) is:

$$\text{AFN} \rightarrow \text{AFH Implementation LCC} = \text{AFN Flex Inv LCC} + \text{H LCC} \qquad (10)$$

AFN → AFN was an aligned scenario where flexibility was designed for and the need to capitalize on the flexible design occurred. Implementation LCC for this was divided into development, production, and O&S cost shown in Equations 11 - 13:

$$\text{AFN} \rightarrow \text{AFN Implementation Dev Cost} = \text{AFN Dev Cost} \tag{11}$$

$$\text{AFN} \rightarrow \text{AFN Implementation Prod Cost} = 1 * (\text{AFN Flex Inv Prod Cost} + (\text{\# of N A/C} * \text{N unit Prod Cost})) \tag{12}$$

$$\text{AFN} \rightarrow \text{AFN Implementation O\&S Cost} = 0.96 * (\text{AFN Flex Inv O\&S Cost} + (\text{\# of N A/C} * \text{N unit O\&S Cost})) \tag{13}$$

These equations captured the 350 AF aircraft with N requirement design flexibility and the cost to produce and operate the additional 250 N aircraft at their respective costs. In equations 12 and 13, a modifier was applied to the total production and O&S cost. This modifier represented economies of scale based on the production and sustainment of a larger fleet of aircraft. The modifier was calculated by averaging the percent increase or decrease in unit production and O&S cost across the four epochs when the number of aircraft was increased from the baseline 350 aircraft to the epoch's respective additional aircraft averages. The purpose of this modifier was to realize any efficiencies or inefficiencies associated with a larger fleet of aircraft as estimated by the CER tool. A summary of all the production cost modifiers are represented in Table 8: Summary of Production Cost Modifiers.

Table 8: Summary of Production Cost Modifiers

Era	# of A/C	Production Cost Modifier
AF	350	1.00
AFSO	500	1.17
AFN, AFH	600	1.20
AFNSO, AFSOH	700	1.24
AFNH	850	1.37
AFNSOH	950	1.41

A summary of all the O&S cost modifiers are represented in Table 9: Summary of O&S Cost Modifiers.

Table 9: Summary of O&S Cost Modifiers

Era	# of A/C	O&S Cost Modifier
AF	350	1
AFSO	500	0.98
AFN, AFH	600	0.97
AFNSO, AFSOH	700	0.94
AFNH	850	0.89
AFNSOH	950	0.85

Counter-intuitively, unit production cost increased as the number of aircraft produced increased. To investigate this, the annual rate aircraft production rate was set at 48 aircraft. As fleet size increased and annual aircraft production rate stayed equal, a longer production run would increase unit production cost. Higher annual production rates associated with larger fleet sizes decreased unit production cost; however, without any additional information on annual production rates, the default value remained. The production cost modifier was set to a value of one to avoid diseconomies of scale in the unit production cost for larger fleet sizes.

Figure 7: AFNSOH Branch Summary summarizes the Implementation LCC given an AFNSOH design strategy.

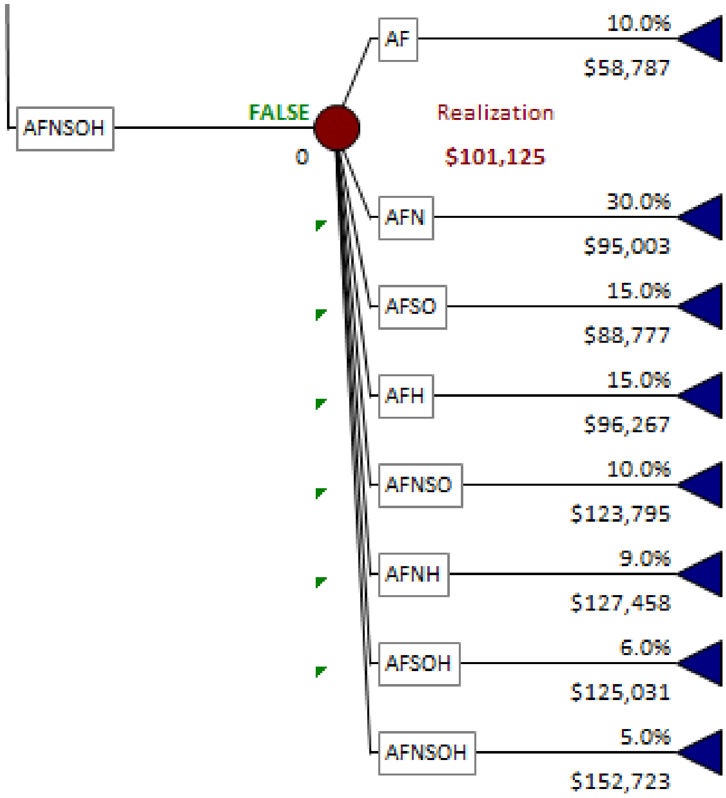

Figure 7: AFNSOH Branch Summary

Like the smaller design strategies, all the eras within the AFNSOH design strategy included AFNSOH flexible investment cost to capture the AF aircraft accommodating flexible design requirements for N, SO, and H. Because this design strategy accommodates all potential requirements, any additional epochs realized will also incur the subjective impact penalty associated with flexible design. For example, given AFNSOH → AFNH, all the AF aircraft suffer penalties for accommodating N, SO, and H flexibility, all the N aircraft suffer penalties for accommodating SO and H flexibility, and all the H aircraft suffer penalties for accommodating N and H flexibility. In addition to the subjective impact penalties, the production and O&S costs were modified by the appropriate values from Table 8: Summary of Production Cost Modifiers, and Table 9: Summary of O&S Cost Modifiers.

Table 10: Design Strategy and Era Realization Summary, summarizes all LCCs of the six design strategies and eight possible eras.

Table 10: Design Strategy and Era Realization Summary

	Design Strategy					
Era	**AF**	**AFN**	**AFSO**	**AFH**	**AFNH**	**AFNSOH**
AF	$48,236	$53,113	$51,695	$50,627	$55,533	$58,787
AFN	$85,861	$85,460	$89,320	$88,252	$89,482	$95,003
AFSO	$78,828	$83,705	$77,772	$81,219	$92,565	$88,777
AFH	$85,269	$90,145	$88,728	$82,482	$90,746	$96,267
AFNSO	$116,453	$116,052	$115,397	$118,844	$120,074	$123,795
AFNH	$122,894	$122,493	$126,353	$120,107	$118,553	$127,458
AFSOH	$115,861	$120,737	$114,804	$113,074	$121,338	$125,031
AFNSOH	$153,486	$153,085	$152,429	$150,699	$149,145	$152,723
NOTE: All $ figures BY13 in millions						

For each design strategy where the era occurred (e.g. AFN→AFN, AFNH→ AFNH, etc.), the lowest LCC was realized compared to the other possible LCCs associated with that design strategy. The AFNSOH design strategy was the exception to this pattern. This suggests that diminishing returns is associated with design flexibility. As the number of cost penalties due to a flexible design increased and afflicted a larger fleet of aircraft, the diminishing returns increased until, the AFNSOH's case, it incurred negative value to design for flexibility.

The values in Table 10: Design Strategy and Era Realization Summary, were populated in a decision tree using Palisade's Precision Tree add-in as well as the probabilities of occurrences listed in Table 3: Era Summary. Based upon this baseline information, Precision Tree recommended that choosing an AF design strategy would net the lowest expected LCC. The differences in design strategy expected LCC were compared to the AF design strategy and are summarized in Table 11: Expected LCC Differences.

Table 11: Expected LCC Differences

	Design Strategy					
Design Strategy	**AF**	**AFN**	**AFSO**	**AFH**	**AFNH**	**AFNSOH**
AF	$0	$2,027	$1,833	$579	$4,781	$8,597
NOTE: All $ figures BY13 in millions						

A positive value for any of the design strategies other than AF indicates higher expected LCC associated with design flexibility. These results state that given the assumptions and input values made in this study, design flexibility provides no expected return on investment. Figure 8: Design Flexibility Model Visualization, illustrates one of the major reasons the expected LCC differences suggested a design strategy against design flexibility given the baseline values assumed in this study. The AFN era was used as an example.

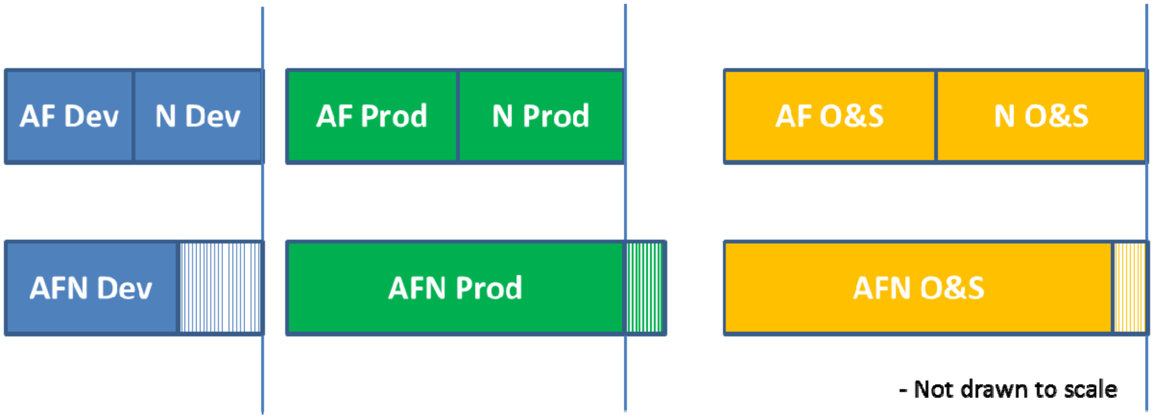

Figure 8: Design Flexibility Model Visualization

The top row in Figure 8: Design Flexibility Model Visualization, illustrates the LCC to procure a separate AF and Navy system which is compared to the bottom row which depicts the LCC of the AFN era. The AFN implementation equation captured the cost savings in development indicated by the striped box. However, for production cost there were two factors that drove the AFN production cost to be greater than the sum of the AF and N production costs.

1. Subjective Impact – This value applied a cost penalty on the AF aircraft that now had to be produced and operated with design flexibility considerations.
2. Production Cost Modifier – Due to the diseconomy of scale indicated by the CER tool, a value of one was assumed and there were no economies of scale associated with production cost.

The same two factors that affected AFN production cost worked in a competing manner for AFN O&S cost. The same subjective impact that was applied to AFN production cost was applied to AFN O&S cost. However, according to the default inputs in the CER tool, the larger aircraft fleets realized cost savings, effectively reducing the O&S cost modifier to a value of less than one. In this case, the O&S cost savings associated with the O&S cost modifier outweighed the cost penalty of the subjective impact resulting in an the AFN O&S cost to be less than the sum of the O&S costs of a separate AF and N systems.

Several sensitivity analyses were completed to challenge the assumptions made in this study and provided further insight into if positive value exists in design flexibility for this trainer aircraft.

Sensitivity Analysis

Sensitivity analyses allowed a few of the major assumptions and parameters to be examined.

1. N, SO, and H epochs fully encompassed AF requirements
2. Probability of era occurrence
3. Subjective Impact
4. Production and O&S Cost Modifiers

The first assumption was necessary due to the limited nature of information. Subject matter experts at AFLCMC/XZE were available to provide many of the inputs into the CER tool to develop the AF cost estimate; however, the same could not be said for N, SO, and H cost estimates. In the absence of specific requirements and detailed inputs to the CER tool, N, SO, and H requirements were treated as additions to AF requirements. This meant that N, SO, and H requirements fully encompassed AF requirements. This assumption had a profound impact on the results of the study which suggested design flexibility yielded negative value. Arguably, N requirements could be very similar to AF requirements. However, SO and H requirements could be less demanding than AF requirements in terms of cost to design and implement due to lower performance requirements. A one-way sensitivity analysis was conducted via Precision

Tree to observe how decreasing the LCC of AFH's implementation cost would impact the recommended decision. The range of values captured was a 10% increase from the baseline value of $82,482M and a 25% decrease. The strategy region is shown in Figure 9: AFH Implementation Cost .

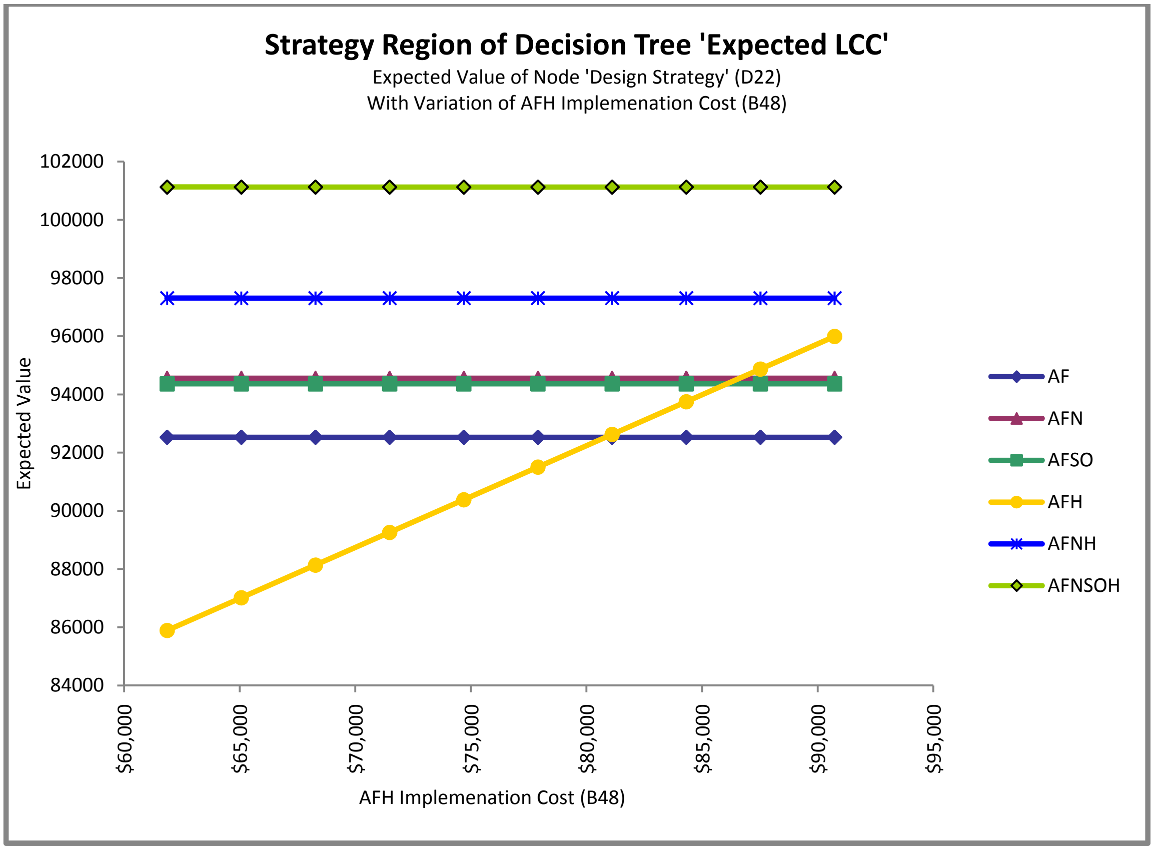

Figure 9: AFH Implementation Cost One-Way Strategy Region

At LCC values of ~$81,000M, a 1.6% decrease in the baseline AFH Implementation Cost, the expected value of choosing an AFH design strategy over the AF design strategy became more beneficial. This result suggested that with cost estimates of N, SO, and H that do not encompass AF requirements, it is easily foreseeable that a flexible design option would result in LCC savings. Another one-way analysis was similarly implemented by changing AFNSOH implementation cost. The strategy region is shown in Figure 10: AFNSOH Implementation Cost .

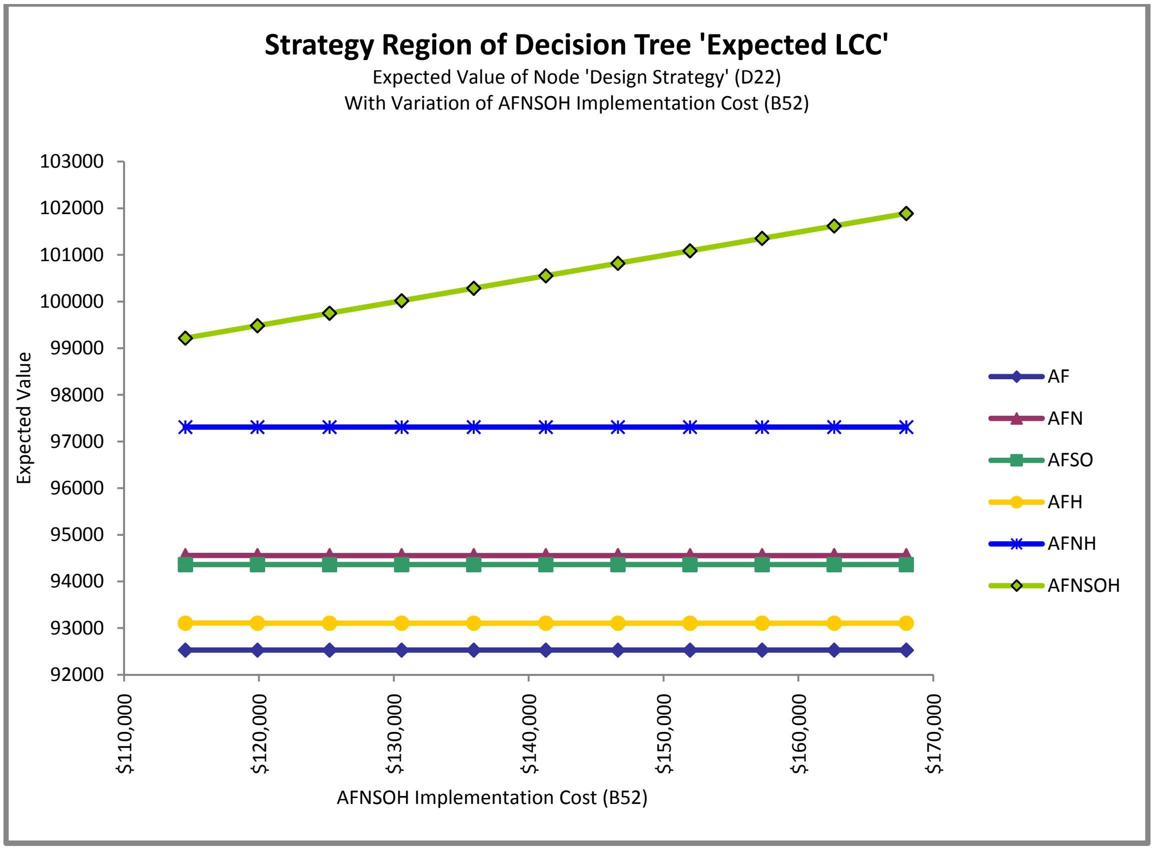

Figure 10: AFNSOH Implementation Cost One-Way Strategy Region

Despite a 25% decrease to the baseline AFNSOH Implementation Cost, the strategy region indicates that pursuing an AFNSOH design strategy is of poor value. The fact that the probability of occurrence for this era is so low is one indicator of why even a

25% decrease to the baseline value has very little impact to the expected value of the decision tree.

Another subjective parameter in this study was the distribution of probabilities among the eras. A one-way sensitivity analysis on any one of the probabilities could be completed; however, as there are eight outcomes that are collectively exhaustive, changing the probability of one outcome should affect the probability of the remainder of outcomes. The outcome probabilities in Precision Tree must be collectively exhaustive in order for a sensitivity analysis to be conducted. In order to meet this constraint, the chance probabilities were automatically normalized via the model setting option in Precision Tree. The first sensitivity analysis was conducted by observing how a change in the probability of AFN affected expected LCC. The sensitivity graph is shown in Figure 11: Normalized AFN Probability One-Way Sensitivity Graph, and the strategy region is show in Figure 12: Normalized AFN Probability One-Way Strategy Region.

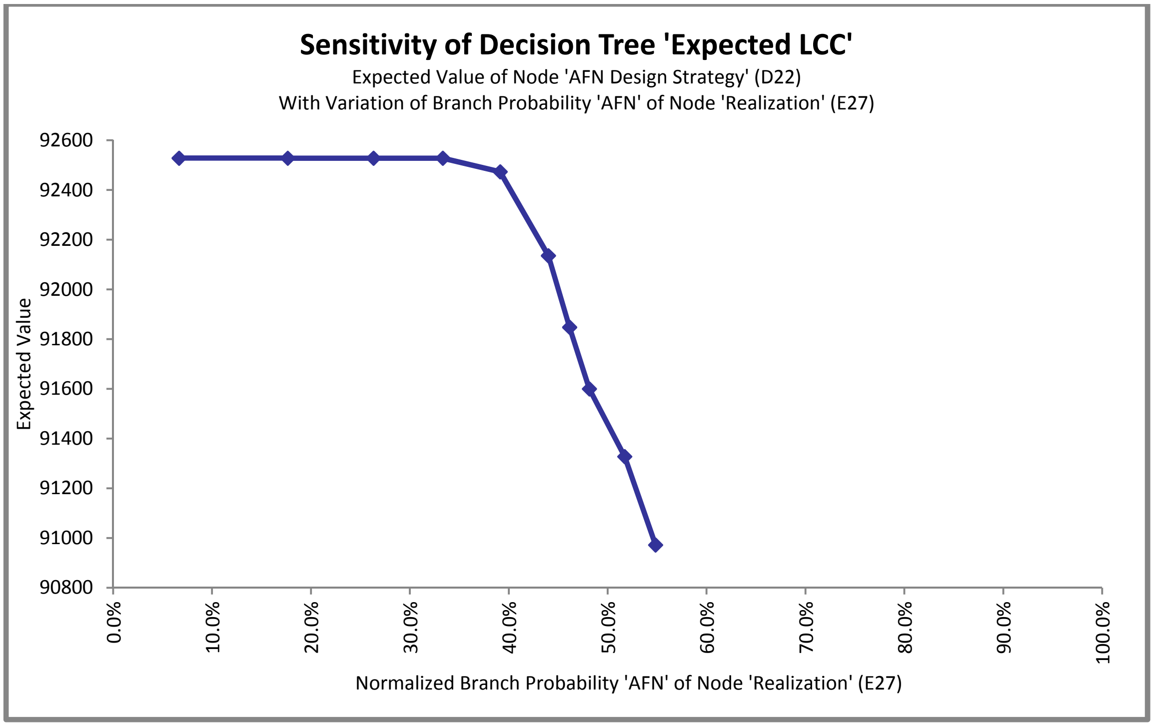

Figure 11: Normalized AFN Probability One-Way Sensitivity Graph

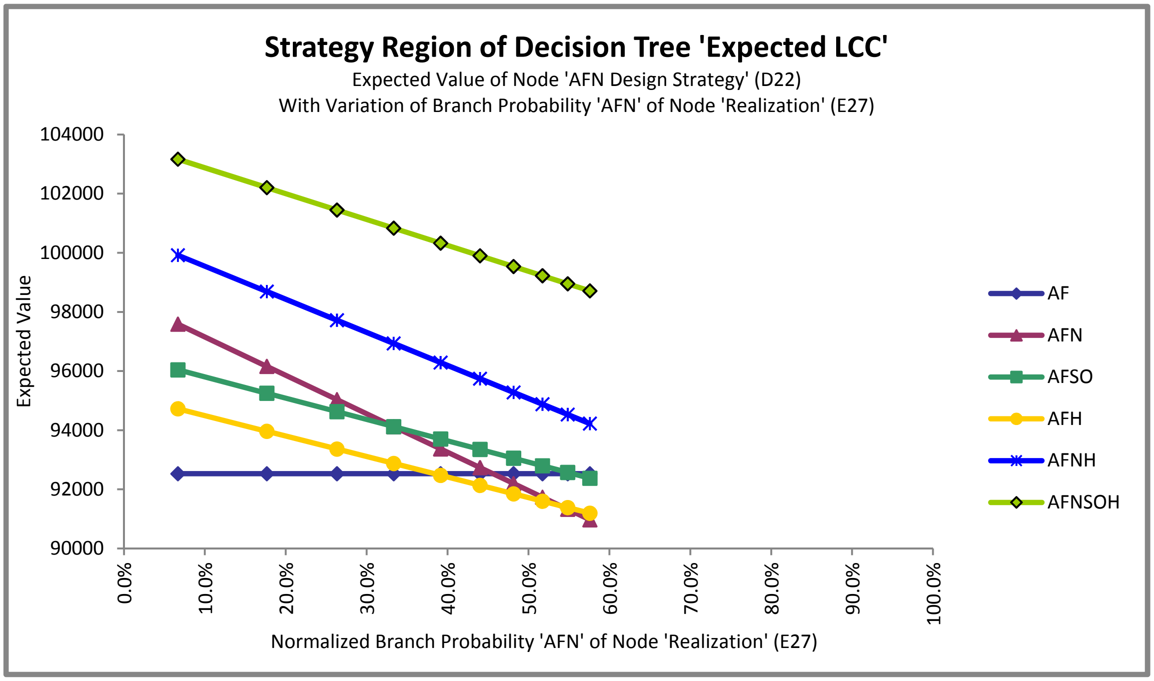

Figure 12: Normalized AFN Probability One-Way Strategy Region

The sensitivity graph states that the expected value of the decision tree decreases as the probability of AFN increases. The strategy region recommends the AF design strategy for lower probabilities of AFN and recommends an AFH design strategy and eventually an AFN design strategy as the normalized probability for AFN continue to increase. This result is likely driven by the first major assumption observed, the fact that N, SO, and H fully encompass AF requirements.

A two-way analysis was conducted to explore the tradespace of changing the probability of AFN and the production cost modifier which was held at a constant value of one during the baseline analysis to avoid diseconomies of scale. The strategy region for the two-way analysis is shown in Figure 13: Production Cost Modifier & Normalized Probability Two-Way Strategy Region.

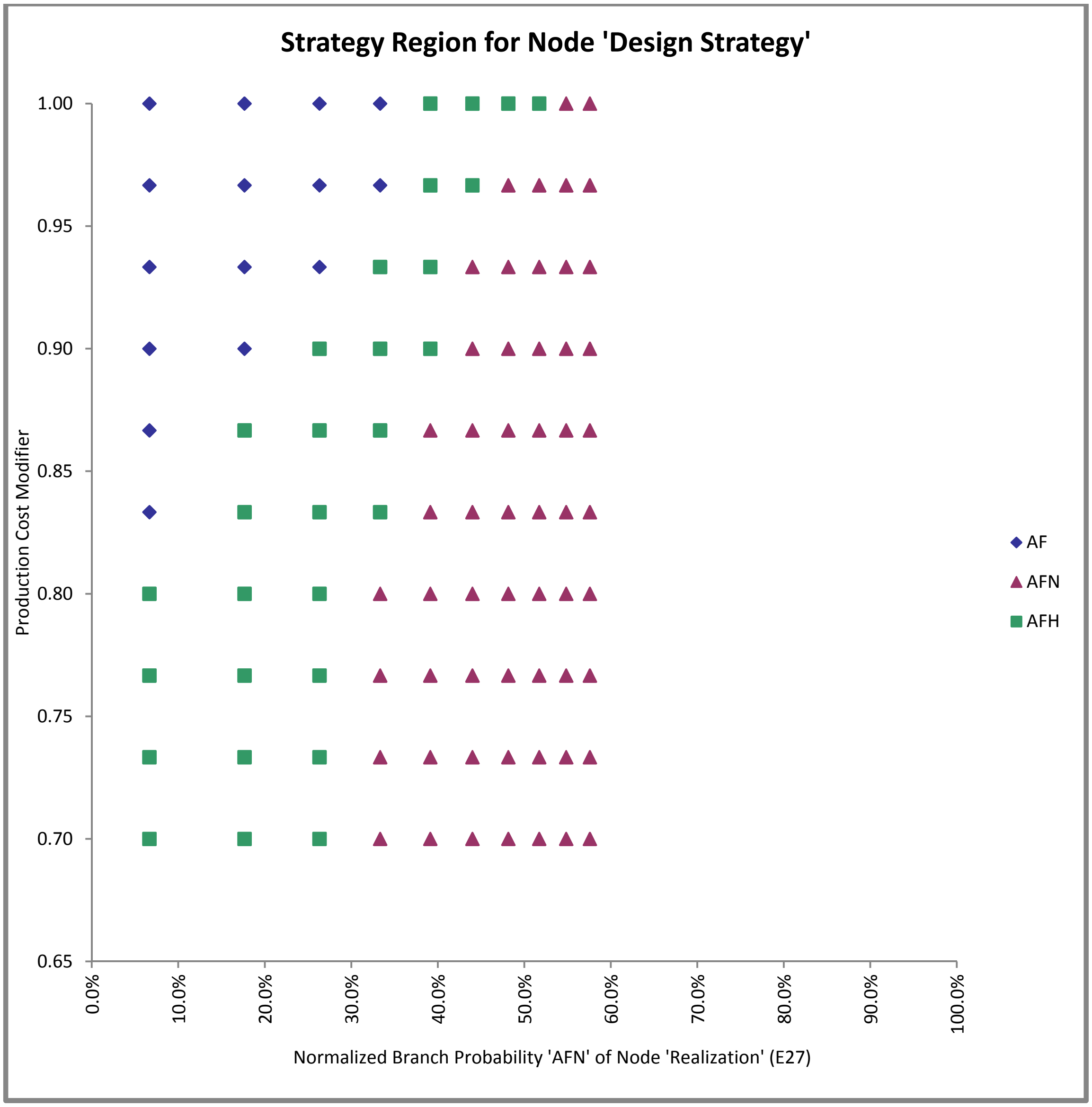

Figure 13: Production Cost Modifier & Normalized Probability Two-Way Strategy Region

As AFN probability increased and the production cost modifier decreased, it became more advantageous to choose the AFN design strategy over the AFH or AF design strategy. This same trend was also apparent in the two-way analysis sensitivity graph shown in Figure 14: Production Cost Modifier & Normalized Probability Two-Way Sensitivity Graph.

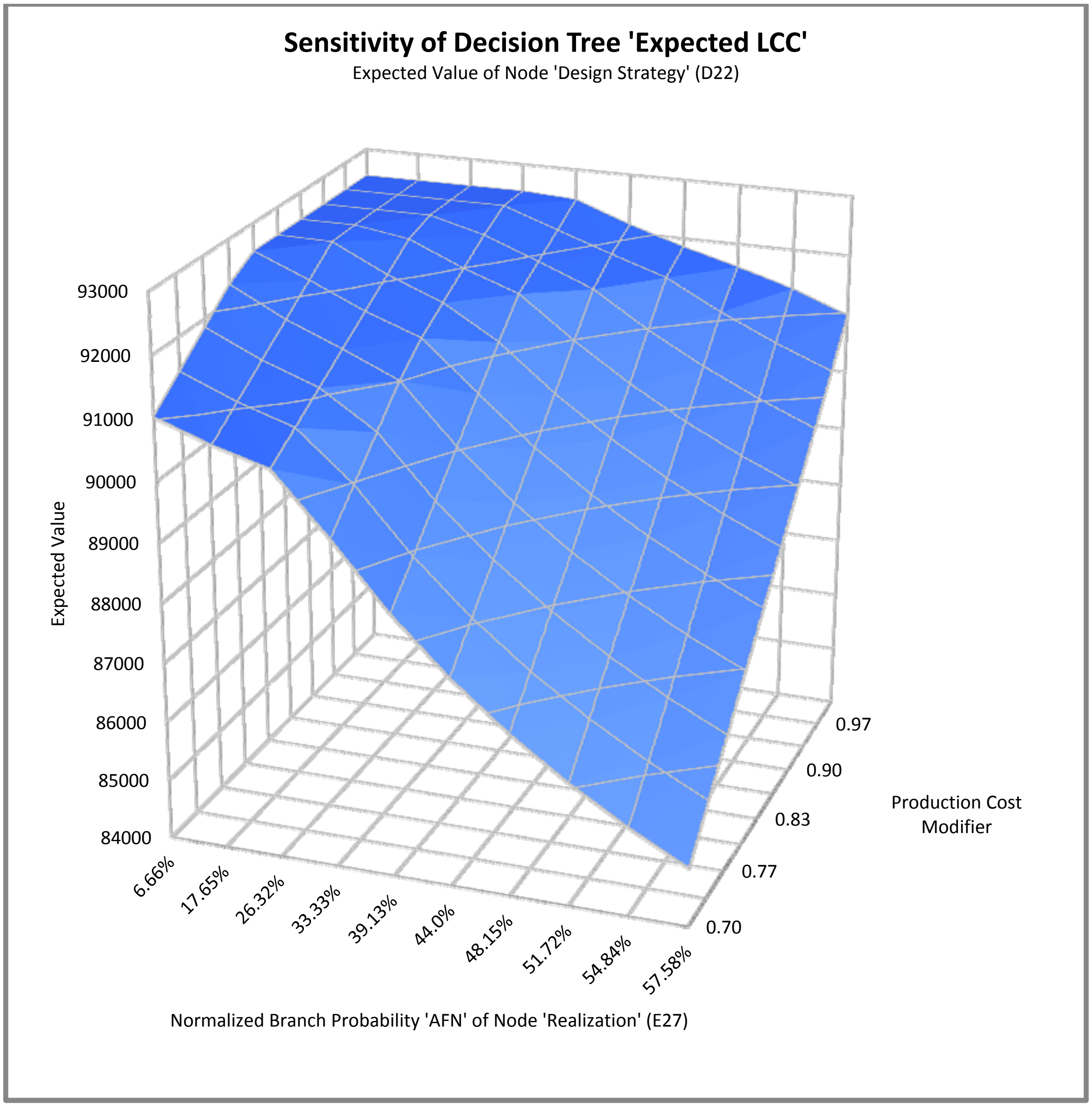

Figure 14: Production Cost Modifier & Normalized Probability Two-Way Sensitivity Graph

Due to the normalization of probabilities across the eight outcomes, the probabilities shown on the x-axis in Figures 11 - 14 were the raw values of the sensitivity analysis. Table 12: Raw vs Normalized Probabilities shows the normalized values of probability for a better understanding of how the actual probability of AFN occurring affected expected LCC.

Table 12: Raw vs Normalized Probabilities

AFN Probabilities (30% baseline)	
Raw Value	**Normalized Value**
10%	12.50%
20%	22.22%
30%	30.00%
40%	36.36%
50%	41.67%
60%	46.15%
70%	50.00%
80%	53.33%
90%	56.25%

In the sensitivity analysis, Precision Tree incremented the AFN probability by a specified value, normalized all the probabilities within that design strategy, and output the result. As the probability of occurrence increased, the expected LCC difference for each respective era approached negative values. This indicated cost savings. According to both sensitivity analyses, a production cost modifier combined with a high probability of era occurrence would suggest LCC savings.

The final parameter observed with sensitivity analysis was the subjective impact that design flexibility imparted on the AF baseline. The strategy region is shown in Figure 15: N Subjective Impact One-Way Strategy Region.

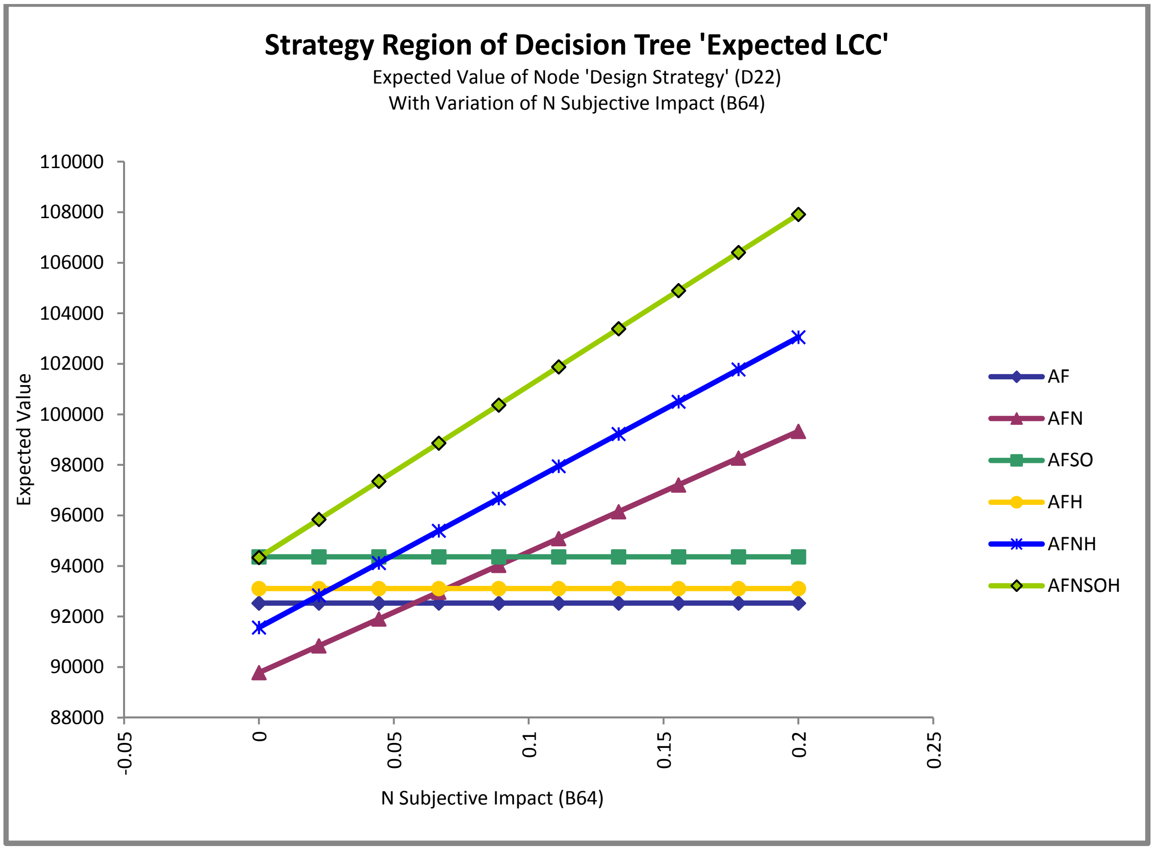

Figure 15: N Subjective Impact One-Way Strategy Region

It's reasonable to see that as the subjective impact imparts a smaller penalty on flexible design, the decision to choose the AFN design strategy over the AF becomes more favorable. However, with all other inputs held equal, even with a 0% impact, an AFN design strategy does not become the ideal decision. Another two-way sensitivity analysis was conducted to determine how changing N subjective impact and AFN implementation cost would affect the ideal design strategy. The strategy region for this analysis is shown in Figure 16: N Subjective Impact & AFN Implementation Cost Two-Way Strategy Region.

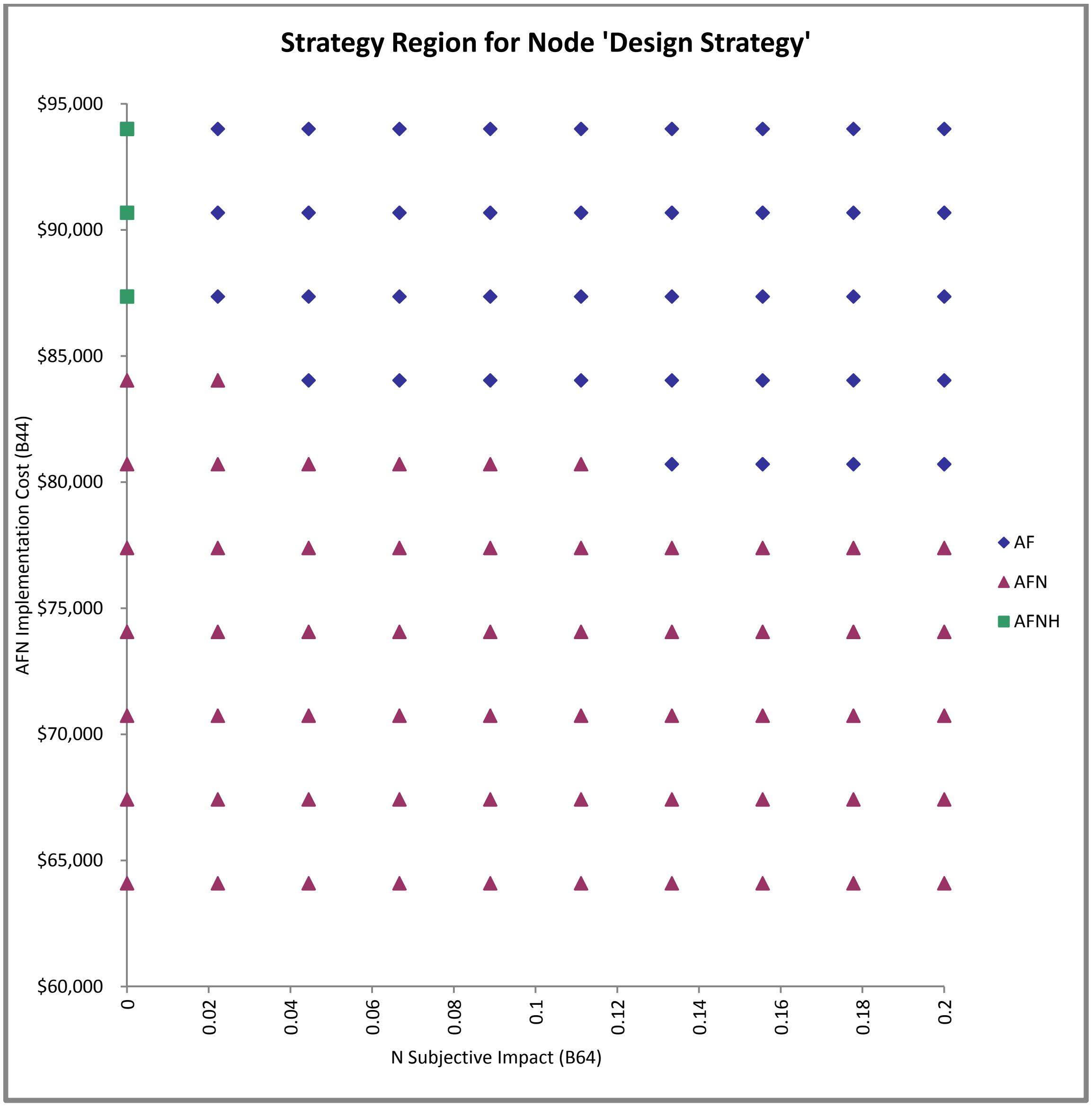

Figure 16: N Subjective Impact & AFN Implementation Cost Two-Way Strategy Region

When both the N subjective impact and AFN Implementation Cost were varied, a ~5.5% decrease in the baseline AFN Implementation Cost triggered the strategy region for this analysis to recommend an AFN design strategy over the AF design strategy. As Implementation Cost further decreased, subjective impact was given the freedom to adopt a higher value.

Results

The analysis suggests that designing for flexibility can be more cost effective than developing two separate systems. However, based upon this method, the value of design flexibility is largely dependent on the likelihood that an era will occur, the subjective impact the design will have on the production and O&S costs of the baseline design, and economies of scale associated with larger fleet sizes. Given the baseline parameters, the AFN era is the only scenario where the expected LCC differences of an AF baseline with design flexibility would be favorable over two separate airframes. The output value of the study is of less important than the methodology demonstrated. Beyond the expected LCC differences calculated, a methodology was demonstrated to quantitatively measure the value of design flexibility.

V. Conclusions and Recommendations

Chapter Overview

This chapter summarizes the research completed in this study, revisits the investigative questions, and provides recommendations for future action and research.

Conclusions of Research

This research concluded that a methodology could be developed that quantitatively measured design flexibility and the expected impact to LCC based upon era realization. The quantitative measurement was accomplished by using LCC as a proxy metric. Realistically, value consists of many factors including LCC. Making a decision based off LCC alone would be foolish if certain design strategies failed to meet the key performance parameters of the baseline system.

Probability of occurrence, the subjective impact of design flexibility, and cost modifiers associated with economies of scale were large drivers of expected LCC. If this method were implemented again, these factors should be well understood in the context of the relevant study.

Given the assumptions of the study, this method has demonstrated that when expected LCC is used as a value of design flexibility, a quantifiable return on investment can be measured.

Investigative Questions Answered

1. How can design flexibility, as a proxy measure for design flexibility, be quantifiably measured in the early stages of development of a system?

The method developed in this study was driven by the limitations of the provided CER tool. Expected LCC has been demonstrated as a proxy measurement for design flexibility in previous work and the results of this analysis support that claim [Ryan, Jacques and Colombi 2013].

2. Can we measure the impact to expected LCC stemming from design changes to accommodate flexibility given uncertain future requirements?

There a numerous factors that can affect the impact to expected LCC when measuring design flexibility. The assumptions made in this study were to aid in the absence of detailed information and to help scope the many possibilities in which new requirements could be levied on a system. Following the general methodology listed in Table 13: General Methodology to estimate Impact to Expected LCC, it was possible to estimate the impact to expected LCC stemming from design changes to accommodate flexibility given uncertain future requirements.

Table 13: General Methodology to estimate Impact to Expected LCC

Step	Cross-Reference
Establish appropriate epoch variables using available cost estimation method	Table 4: Epoch Variables
Assign range of values to epoch variables to capture uncertainty and model LCC	Table 5: Epoch Cost Averages
Assign probability of occurrence associated with each era	Table 3: Era Summary
Establish design strategy and era tradespace	Figure 5: AF Design Strategy Figure 6: AFN Design Strategy
Calculate expected LCC of each design strategy	Table 10: Design Strategy and Era Realization Summary
Note optimal design strategy	N/A
Conduct sensitivity analysis on assumptions and observe changes to optimal design strategy	Figure 14: Production Cost Modifier & Normalized Probability Two-Way Sensitivity Graph

The methodology used in this study is only relevant given the timeline assumptions outlined in Figure 2: Era Timeline Assumption.

3. Can a general method be developed that can be applied to other domains beyond airframes?

With similar resources, the methodology in Table 13: General Methodology to estimate Impact to Expected LCC, could arguably be applied to other domains. Depending on the information available, similar assumptions would have to be established. A CER tool specific for the applied domain will be required to substitute the aircraft CER tool used in this study.

Significance of Research

The ability to measure design flexibility can potentially save the DOD a considerable amount of money over the course of a system’s life cycle. With a general method to capture the expected LCC differences by choosing a system with design flexibility versus procuring two separate systems, decision-makers will have a better idea of the value of pursuing a flexible design option.

Recommendations for Action

To improve the accuracy of the result of this study, gathering unique requirements for the epochs would be necessary instead of assuming they fully encompassed AF requirements. LCC was the only measure of value in this study. Realistically, if design flexibility negatively affected an epoch's aircraft on a large enough scale, key performance parameters could be at risk. Future work could identify certain performance characteristics and their associated penalties due to the separate epoch variables. Once established, breakpoints in the design flexibility implemented can be identified where, despite LCC savings, key performance parameters would no longer be met. At this point it would no longer be in the best interest of the decision-maker to pursue a given design strategy.

A uniform distribution was assumed when the average cost of an epoch was calculated across a range of aircraft weight and avionics weight. A distribution based off actual or parametric data would help improve the output of this method.

The cost modifiers associated with economies of scale were calculated by observing changes to cost as modeled by the CER tool. Further research could be done by examining existing literature on economies of scale and applying real world values to this method which would further improve the outputs of the study.

Another area of subjectivity to be addressed is the subjective impacts associated with each era's requirements. Like the cost modifiers, further research into how parameters such as aircraft weight impacts production and O&S cost would greatly improve the estimates of this study.

Recommendations for Future Research

Taking the methodology proposed in this study and directly applying it to a different domain using an appropriate CER tool would be valuable to see if similar results could be replicated. Research that replicates this methodology across multiple domains would lend greater credence to the methodology proposed in this paper.

Developing a specific CER tool that has accommodations for quantifying design flexibility is another area of future research. Currently, the methodology takes a CER tool that inherently does not account for design flexibility, makes several assumptions, and outputs expected LCC differences. If a CER tool could be created that accounts for the assumptions of this study such as concurrent production, equal service life, equal disposal times, and same base year dollars, the estimate for design flexibility has the potential to be much more accurate.

Summary

Given the baseline values for era probability of occurrences, subjective impacts, and cost modifiers, the expected LCC differences were not as substantial as originally anticipated. Sensitivity analyses revealed how varying the subjective parameters impacted expected LCC differences. Although this research could not point out specific break points due to the notional nature of many of the inputs, it has identified certain regions where design flexibility may no longer be of value to decision makers. Ultimately, this study’s goal is to take another small step towards the DOD valuable resources on future acquisitions when the opportunity exists to design flexibility into a baseline system.

References

AFLCMC/XZE. "Cost Reference." AFLCMC/XZE, July 2013.

Blanchard, Benjamin S, and Wolter J Fabrycky. *Systems Engineering and Analysis.* Upper Saddle River, NJ: Pearson Prentice Hall, 2006.

Brown, Own. *System Lifecycle Cost Under Uncertainty as a Design Metric Encompassing the Value of Architectural Flexibility.* Arlington, VA: DARPA, 2008.

"Defense Acquisition University." *DAU.* 2013. https://dag.dau.mil/Pages/Default.aspx [accessed October 2013].

Defense Acquisition University. *Defense Acquisitions Guidebook.* Fort Belvoir: Defense Acquisition University, 2013.

Department of Defense. "JCIDS Manual." January 19, 2012.

Fitzgerald, Matthew E., Adam M. Ross, and H. Donna Rhodes. "A Method Using Epoch-Era Analysis to Identify Valuable Changeability in System Design." *Conference on Systems Engineering Research.* Los Angels, CA, 2011.

Palisade Corporation. "@RISK Users Guide." *Palisade.* September 2013. https://www.palisade.com/downloads/manuals/62/EN/RISK6_EN.pdf [accessed January 2014].

Ross, A, D Hastings, J Warmkessel, and N Diller. "Multi-Attribute Tradespace Exploration as a Front-End for Effective Space System Design." *AIAA Journal of Spacecraft and Rockets*, 2004.

Ross, Adam Michael. *Managing Unarticulated Value: Changeability in Multi-Attribute Tradespace Exploration.* PhD Thesis, Cambridge, MA: Massachusetts Institute of Technology, 2006.

Ross, Adam Michael. *Multi-Attribute Tradespace Exploration with Concurrent Design as a Value-Centric Framework for Space System Architecture and Design.* PhD Thesis, Cambridge, MA: Massachusetts Institute of Technology, 2003.

Ryan, E, D Jacques, J Ritschel, and J. Colombi. "A Cost-Based Decision Tool for Valuing DoD System Design Options." *Conference on Systems Engineering Research.* Atlanta, GA, 2013. 1180-1189.

Ryan, Erin. "A Macro-Stochastic Model for Improving the Accuracy of Department of Defense Life Cycle Cost Estimates." *Journal of Cost Analysis and Parametrics* [Air Force Institute of Technology], 2013: 43-74.

Ryan, Erin T, David R Jacques, and John M Colombi. "An Ontological Framework for Clarifying Flexibility-Related Terminology via Literature Survey." *Systems Engineering,* 2013: 99-110.

Ryan, Maj Erin. *Ph.D. Specialty Exam.* PhD Exam, Wright Patterson AFB, OH: Air Force Institute of Technology, 2010.

Saleh, J, Mark, G, and N Jordan. *Flexibility: A Multi-disciplinary Lit Review & a Research Agenda for Designing Flexible Engr Systems.* Journal of Engr Design, 2009.

Sanchez, Ron. "Modularity, Flexibility, and Knowledge Management in Product and Organization Design." *Strategic Management Journal*, 1996: 63-76.

Shmueli, Galit. *Predictive vs. Explanatory Modeling in IS Research.* College Park, MD: University of Maryland, 2007.

Simpson, Timothy W., and Brayan S. D'Souza. *Assessing Variable Levels of Platform Commonality Within a Product Family Using a Multiobjective Genetic Algorithm.* SAGE Publications, 2008.

United States Air Force. *EC-130H Compass Call.* May 27, 2005. http://www.af.mil/AboutUs/FactSheets/Display/tabid/224/Article/104550/ec-130h-compass-call.aspx [accessed February 2014].

—. *T-1A Jayhawk.* September 14, 2005. http://www.af.mil/AboutUs/FactSheets/Display/tabid/224/Article/104542/t-1a-jayhawk.aspx [accessed Febraury 2014].

—. *T-38 Talon Fact Sheet.* January 2014. http://www.af.mil/AboutUs/FactSheets/Display/tabid/224/Article/104569/t-38-talon.aspx [accessed 2014].

United States Navy. *C-12 Huron.* October 2012. http://www.navair.navy.mil/index.cfm?fuseaction=home.display&key=8BED05D0-71F0-48D2-A855-1039521AD208 [accessed February 2014].

—. *T-45A Goshawk Training Aircraft.* February 18, 2009. http://www.navy.mil/navydata/fact_display.asp?cid=1100&tid=2000&ct=1 [accessed September 2, 2013].

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)* 27-03-2013	**2. REPORT TYPE** Master's Thesis	**3. DATES COVERED** *(From - To)* Sept 2012 - March 2014

4. TITLE AND SUBTITLE

Exploring a Method to Quantitatively Measure Design Flexibility Early in the Defense Acquisition Life Cycle

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Kim, Joseph S., Captain, USAF

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Air Force Institute of Technology
Graduate School of Engineering and Management (AFIT/EN)
2950 Hobson Way
Wright-Patterson AFB OH 45433-7765

8. PERFORMING ORGANIZATION REPORT NUMBER

AFIT-ENV-14-M-32

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Chief, Future Systems Concepts Branch, Ms. Alicia R. Hartong (GS-14)
Air Force Life Cycle Management Center
1970 Monohan Way, Bldg 11A
WPAFB, OH 45433-7765
alicia.hartong@wpafb.af.mil

10. SPONSOR/MONITOR'S ACRONYM(S)

AFLCMC/XZE

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Distribution Statement A. Approved for Public Release; Distribution Unlimited.

13. SUPPLEMENTARY NOTES

This material is declared a work of the U.S. Government and is not subject to copyright protection in the United States.

14. ABSTRACT

The purpose of this research was to demonstrate a methodology using an Epoch-Era Analysis to quantify and estimate the value of design flexibility early in the Department of Defense's (DOD) acquisition life cycle. This method was implemented using a possible replacement to the Air Force's fighter-trainer aircraft as a baseline and a set of future requirements that would change the baseline. An existing Cost Estimating Relationship tool was utilized in conjunction with a decision tree modeling approach to accommodate uncertain future needs. Sensitivity analysis was performed to identify model parameters with dominant effects on the recommended design strategies. The results indicated that this methodology can quantitatively measure design flexibility using existing tools when key assumptions are made. The methodology exists as a proof of concept within the domain of aircraft to quantitatively measure design flexibility early in the acquisition life cycle. Further research is required to characterize the assumptions of this study and to test this methodology in other domains to validate its broader applicability.

15. SUBJECT TERMS

Design Flexibility, Epoch-Era Analysis, Decision Tree, Sensitivity Analysis

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Dr. David R. Jacques, AFIT/ENV
U	U	U	UU	77	**19b. TELEPHONE NUMBER** *(Include area code)* (937) 255-3636 x3329 david.jacques@afit.edu

Reset

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18