Framework for Selecting a System Design Approach

by

Kelly A. Chiverton

B.S. Business Administration, Villanova University, 2007
M.A. Interdisciplinary Studies, University of Oklahoma, 2010

Submitted to the System Design and Management (SDM) program in
Partial Fulfillment of the Requirements for the Degree of

Master of Science in Engineering and Management

at the

Massachusetts Institute of Technology

February 2020

Signature redacted

Signature of Author....................................

Kelly Chiverton
Graduate Student, System Design and Management Program
November 12, 2019

Signature redacted

Certified by ....

Dr. Eric Rebentisch
Research Associate, Sociotechnical Systems Research Center
Thesis Advisor

Signature redacted

Accepted by ....

Joan Rubin
Executive Director, System Design and Management Program

THIS PAGE INTENTIONALLY LEFT BLANK

Disclaimer

The views expressed in this document are those of the author and do not reflect the official position or policies of the United States Air Force, the Department of Defense, or the United States Government.

THIS PAGE INTENTIONALLY LEFT BLANK

Framework for Selecting a System Design Approach

by

Kelly A. Chiverton

B.S. Business Administration, Villanova University, 2007
M.A. Interdisciplinary Studies, University of Oklahoma, 2010

Submitted to the System Design and Management (SDM) program in
Partial Fulfillment of the Requirements for the Degree of

Master of Science in Engineering and Management

at the

Massachusetts Institute of Technology

February 2020

Abstract

Recent discussions within the Department of Defense highlight the growing need for US military systems to rapidly respond to new missions, threats, and operational environments that the warfighter can and cannot anticipate. In an effort to respond to the government-wide emphasis of fielding Department of Defense systems smarter and faster, this thesis examines the engineering fundamentals of system design options. The thesis analyzes two umbrella categories of design strategies: static vs. flexible. It also explores subcategories of the two design approaches: optimized, robust, real options, and adapt. Relevant literature is used to define the design strategies, understand the benefits and penalties of each approach, and explore historical examples of each design's use within the Department of Defense. Based on the literature review, the thesis proposes a decision framework for selecting an optimal design approach that characterizes system tradeoffs between dynamic market needs, the rate of technology change, and a system's future operating environment against the value of the proposed design, with the goal of choosing the most cost effective and responsive system design under a given set of objectives and uncertainties. A series of interviews with Air Force Field Grade Officers are used to inform the usefulness and understandability of the decision framework. The interviews also highlight framework limitations. Ultimately, the interview responses solidify a recommendation for the Air Force to implement this framework prior to a system's development.

Thesis Supervisor: Dr. Eric Rebentisch
Title: Research Associate, Sociotechnical Systems Research Center

Acknowledgements

Thank you to my advisor, Dr. Eric Rebentisch, for his mentorship, expertise, and insightful guidance.

To my husband, Evan, and son, Declan, for their support and love.

To the many Officers who provided feedback on the framework and helped positively shape my research.

Finally, thank you to the Air Force for supporting me in this opportunity at MIT and to all the men and women serving in the United States military.

Table of Contents

List of Figures

List of Tables

List of Acronyms

ACAT	Acquisition Category
ACC	Air Combat Command
AFLCMC	Air Force Life Cycle Management Center
AFRL	Air Force Research Laboratory
AFSC	Air Force Specialty Code
AOA	Analysis of Alternatives
AOC	Air Operations Center
AWACS	Airborne Warning and Control System
COTS	Commercial-off-the-shelf
CTOL	Conventional Takeoff and Landing
CV	Carrier Variant
DACI	Driver Approver Contributors Informed
DAE	Defense Acquisition Executive
DAF	Department of the Air Force
DAU	Defense Acquisition University
DCAPE	Director of Cost Assessment and Program Evaluation
DFC	Design for Changeability
DIME	Diplomatic, Informational, Military, and Economic
DoD	Department of Defense
DoDI	Department of Defense Instruction
DoN	Department of the Navy
DTA	Decision Tree Analysis
DTRA	Defense Threat Reduction Agency
FBCE	Fully Burdened Cost of Energy
FGO	Field Grade Officer
FMS	Flight Management System
GPS	Global Positioning System
HAF	Headquarters Air Force
INCOSE	International Council on Systems Engineering
IRCCM	Infrared Counter Counter Measure
IRCM	Infrared Counter Measure
IT	Information Technology
JCIDS	Joint Capabilities Integration and Development System
JROC	Joint Requirements Oversight Council
LEO	Low Earth Orbit
MAJCOM	Major Command
MDA	Milestone Decision Authority
MDAP	Major Defense Acquisition Program
MDD	Materiel Development Decision
MIT	Massachusetts Institute of Technology
MS	Milestone
NGA	National Geospatial-Intelligence Agency
NRO	National Reconnaissance Office
NSA	National Security Agency

OUSD(A&S)	Office of the Under Secretary of Defense for Acquisition and Sustainment
PEM	Program Element Monitor
PEO	Program Executive Officer
PMESII	Political, Military, Economic, Social, Informational, and Infrastructure
PPB&E	Planning, Programming, Budgeting, and Execution
R&D	Research and Development
RACI	Responsible Accountable Consulted Informed
RCO	Rapid Capabilities Office
RO	Real Options
ROA	Real Options Analysis
SAF/AQ	Secretary of the Air Force for Acquisition
SAF/AQX	Secretary of the Air Force for Acquisition Integration
SDD	System Design and Development
SMC	Space and Missile Systems Center
SPO	System Program Office
STOVL	Short Take Off/Vertical Landing
SWOT	Strengths Weaknesses Opportunities Threats
UAV	Unmanned Aerial Vehicle
UON	Urgent Operational Need
US	United States
USB	Universal Serial Bus
USN	United States Navy

1 Introduction

1.1 Background and Motivation

During the February 2019 Air Force Association's Air Warfare Symposium, Dr. Will Roper, Assistant Secretary of the Air Force for Acquisition, Technology, and Logistics presented on the importance of "Fielding Tomorrow's Air Force Faster and Smarter" and discussed how US military systems are required to rapidly respond to new missions, threats, and changes in operational environments. While the nature of today's conflicts against terrorist organizations in the Middle East and Africa are defined by irregular warfare, the 2017 National Defense Strategy recognizes the need to keep pace with different challengers such as Russia and China who "use technology and information… to shift regional balances of power in their favor." *(Anon., 2017)* In order to establish battlespace advantage and maintain military superiority, Department of Defense (DoD) systems must "be effective in a wide range of operational contexts with the ability to respond to new or changing conditions" through adaptations and/or rapid fielding. *(Goerger, et al., 2014)* As Dr. Roper points out "it is a time of unprecedented technological advancement; the Air Force must have the fastest acquisition system to keep on winning." *(Christopherson, 2019)*

Eight years prior to Dr. Roper's Air Warfare Symposium speech, Ellen Lord, current Undersecretary of Defense for Acquisition and Sustainment, relayed a similar message at the 2011 Association of the US Army's annual conference. Ms. Lord discussed "a critical need to get smarter, faster, and cheaper with what we do." *(Erwin, 2017)* In addition to highlighting the need to field capabilities faster, she emphasized the desire to reduce costs.

The subject of controlling costs was also outlined in former Deputy Secretary of Defense Ashton Carter's September 2011 opening statement before the Senate Armed Services Committee. Carter voiced a priority to deliver better buying power to taxpayers for their defense dollars. *(Carter, 2011)* For over seven years and through three separate iterations, the Air Force encouraged Better Buying Power initiatives organized around the theme of controlling costs in major weapons systems and the insistence on starting programs with an affordability plan. *(Serbu, 2017)*

Several current efforts are aimed at encouraging cheaper, faster decision making in response to dynamic market forces and the desire to accommodate rapidly changing defense needs. The Air Force introduced Air Force Pitch Day to drastically reduce contract award timelines and increase bids from cost-effective startups. In October 2018, the Rapid Sustainment Office was stood up with the goal of quickly implementing new technologies at scale. *(Christopherson, 2019)* Finally, as highlighted in a 2017 hearing before the Committee on Armed Services, the DoD has been able to advance more quickly through rapid prototyping and more agile acquisitions, allowing early failures at a relatively low cost of time and resources. *(Office, 2017)* In addition to capitalizing on the current efforts, former Assistant Secretary of Defense for Research and Engineering, Stephen Welby, argued "in light of mounting budgetary challenges and the need to make difficult trades in the foreseeable future, one way to [address] future systems is to strengthen our commitment to systems engineering fundamentals that are the key to the success of defense programs." *(Welby, 2011)* This thesis explores the systems engineering fundamentals of early design options.

In the past 15 years, "Robust", "Flexible", and "Evolutionary" design options have been introduced as a way to more quickly respond to operational changes enterprises can and cannot anticipate. However, *(Hastings & McManus, 2004)* point out "tools for handling [these] uncertainties are immature and methods for flexible or evolutionary designs are in their infancy". Additionally, "while traditional approaches to reliability and robustness often add value, intentionally providing extra value under uncertainty, as part of the system design, is [a] current challenge." *(Hastings & McManus, 2004)* An Office of the Deputy Assistant Secretary of Defense, Systems Engineering report on affordable, adaptable, and effective systems echoes this statement, explaining, "current processes and tools have failed to keep pace with increasingly complex interactions among components and disciplines, as well as with operational demands." *(Neches & Madni, 2013)*

This thesis defines a method for the Air Force to respond to a range of conditions that result from uncertainty. The thesis proposes a decision framework for selecting an optimal design approach that characterizes system tradeoffs between dynamic market needs, the rate of technology change, and a system's future operating environment against the value of the proposed design. An MIT Professor of Engineering Systems points out, "to engineer flexibility into systems, we must be able to measure alternative possibilities so that we can compare them analytically." *(de Neufville, 2002)* The thesis argues that by comparing the various design options, the Air Force can intentionally choose the most cost effective and responsive system under a given set of objectives and uncertainties.

1.2 Research Questions

This thesis will explore the following research questions:

1. What are the different design strategies?
2. What are the tradeoffs between the design strategies?
3. What is the optimal design strategy for allowing enterprises to quickly respond to operational changes they can and cannot anticipate?

4. Is the proposed decision framework a useful tool for choosing the most cost effective and responsive system design under a given set of objectives and uncertainties?

The questions will be addressed through a literature review, the development of a decision framework, and a series of interviews with Air Force Field Grade Officers (FGOs).

1.3 Thesis Structure

The thesis is separated into the following seven sections:

Section 1 provides background and motivation for the research topic. It identifies the questions the thesis seeks to address and how the thesis is structured.

Section 2 discusses results from a literature review on the topics of system design and uncertainty. The section distinguishes between two high level system design approaches and examines four specific system design avenues. It also provides a sample of architecture principles that enable a flexible design approach.

Section 3 presents the system design framework that serves as the basis for the thesis hypothesis. Each section of the framework is discussed in detail and examples are provided to enhance an understanding of the various decision points.

Section 4 outlines the process used to collect data on interview candidates. It also examines the backgrounds and experience levels of the different participants.

Section 5 summarizes the interview responses gathered from each question. It discusses the high-level themes central to the collective group of interview candidates and ends with tactical and strategic observations captured from the interviews.

Section 6 synthesizes responses to interview findings and framework limitations. It provides a recommendation on where the framework should be integrated into the DoD acquisition lifecycle and a guide for who should answer the framework's decision steps. The section concludes with a summary of areas for future research.

2 Literature Review

In an effort to manage uncertainty, control costs, and create more responsive systems, a growing amount of research has been published on different engineering design approaches. This section outlines the array of design options discussed in literature, highlights the design approaches relevant to the thesis's decision framework, provides examples of DoD systems that implemented each design approach, and delivers an overview of uncertainty. The sources used for this review range from international conferences, to university literature, industry journals, and books.

2.1 Design Approaches

(Ferguson, et al., 2007) explain how traditional engineering design focuses on the optimization of systems with fixed design variables that are not allowed to change once a system is deployed. Therefore, system optimization seeks to identify the best point design given a fixed set of requirements for the entire lifetime of the system. *(Saleh, et al., 2009)* However, requirements for design in the 21st century have led to the emergence of systems that evolve and change based on conditions of uncertainty. To respond to this uncertainty, a newer field of design research on flexible, changeable, and reconfigurable systems has emerged. Unfortunately, these design approaches face ambiguity in terminology. *(Ferguson, et al., 2007)* Drastically different words are used interchangeably to mean the same thing, while similar terms are defined differently across sources. The following list of design approaches and sources provides an overview of more prominent options and a snapshot of the inconsistency in terminology relevant to the domain of engineering design.

Similar to the traditional method of optimized design, the concept of robust design has a strong foundation dating back to the 1960s when Genichi Taguchi pioneered the term to enhance the quality of manufactured goods. Later, the concept was applied to engineering design to describe a method for improving the consistency of a system's function across a wide range of conditions. *(de Neufville, 2004)* However, in 1978, Mandelbaum developed to the phrase "state flexibility" to describe a similar concept of a system's ability to function despite changes in the environment. Then, in 1995, Ku reverted to the term robust to describe a design resistant to change. *(Saleh, et al., 2009)*

Sometimes interchanged with the concept of robust design, but introduced more recently, is the idea of resilient design. A proceeding from the 2014 Conference on Systems Engineering Research provides a DoD perspective to engineering resilient systems and focuses on the ability of systems to adapt through reconfiguration or replacement. *(Goerger, et al., 2014)* In contrast, an Institute of Electrical and Electronics Engineers Systems Journal publication discusses resilience engineering as the ability to circumvent accidents through anticipation, survive disruptions through recovery, and grow through adaptation. *(Madni & Jackson, 2008)*

(Shultz & Fricke, 1999) introduce "Design for Changeability" (DFC) as an approach for increasing a company's responsiveness to changing markets. The core of DFC consists of four system properties: flexibility, agility, robustness, and adaptability. In this methodology, robust systems are contrasted against adaptable systems. Robustness is defined as a system's ability to deliver intended functionality under varying operating conditions without being changed. Alternatively, adaptability involves a system's capability to change itself across varying environments in order to deliver intended functionality. Flexibility is also contrasted against robustness as robustness has the quality of a rigid system, where flexibility represents the property of a system that can be changed easily and without undesired effects.

A proceeding from a 2006 International Council on Systems Engineering (INCOSE) International Symposium also addresses adaptability as the ability for a system to be changed and upgraded easily. *(Engel & Browning, 2006)* In contrast, *(Madni, 2012)* explores the idea of adaptable design by targeting platform-based engineering as a cost effective, risk-mitigated approach that allows for rapid development.

A common theme throughout recent literature is the comparison of flexible system designs against static system designs. In a conference proceeding dedicated to addressing design nomenclature, *(Ferguson, et al., 2007)* contrast flexible, reconfigurable, and changeable systems (i.e., those systems with the ability to change after system deployment) against the traditional engineering design of optimized systems with fixed design variables.

Several publications by Dr. Joseph Saleh, to include *(Saleh & Hastings, 2000), (Saleh, et al., 2003), (Saleh, 2005), (Saleh, et al., 2009),* and *(Saleh, et al., 2014)* discuss a similar shift from "rigid designs" that are optimized for a narrow set of requirements, towards flexible designs that can better accommodate changes in uncertainty.

Many of Dr. Saleh's publications also create a distinction between flexibility and robustness, acknowledging that although the two concepts refer to the ability of a system to handle change, the nature of the change and the system's reaction to the change in each case is very different. (*Saleh*, et al., 2003)

While flexibility is generally referred to as the ability to respond to change, flexibility in design solution is defined and explored in a myriad of journal publications, conference proceedings, and books by *(de Weck, et al., 2004)*, *(Ferguson, et al., 2007)*, *(Cardin, et al., 2008)*, *(de Neufville & Scholtes, 2011)*, and *(Saleh, et al., 2014)* to name a few. In fact, *(de Weck, et al., 2004)* developed a case study on communication satellites to compare the cost of the "traditional" way of designing communications satellites that optimizes the design for a specified global capacity versus a flexible approach using reconfigurable constellations that provide managers with real options.

In the classic definition, real options give the decision maker the right, but not the obligation, to exercise an action or decision at a later time. *(Mikaelian, et al., 2011)* The term was coined by Stewert Myers in 1977 and originally applied to the financial sector. However, in the last 20 years, the concept of real options has been adapted to the engineering discipline. The phrase real options "on" projects refers to managerial flexibility in making strategic decisions on project investments *(Amram & Kulatilaka, 1999)*, *(Wang & de Neufville, 2006)*, *(Miller & Clarke, 2008)*, *(Mikaelian, et al., 2011)* Alternatively, real options "in" projects denotes engineering design decisions that enable the flexibility to change a system in the future. *(Hassan, et al., 2005) (de Neufville, et al., 2005), (Wang & de Neufville, 2006), (Mikaelian, et al., 2011)*

Finally, as evident in Figure 2, Figure 1, and Figure 3, several publications categorize the prominent design approaches and visually depict them on a tradespace detailing when each approach should be used, or in some cases, how to avoid an unfavorable design approach. In Figure 1, *(Saleh, et al., 2014)* categorize the design approaches based on their relationships with the environment and the system's objectives after fielding. If the environment the system will operate in is going to change or if it is unknown, but the system's objectives after deployment are fixed, then the designer should opt for a robust design. Alternatively, if there is an expectation both the environment and the system's objectives will change after the system is deployed, the designer should proceed with a flexible design. However, if the environment is expected to remain the same during the life of the system and the system's objectives are expected to remain fixed, the designer should incorporate an optimized design. Finally, if the environment is not expected to change, but the system's objectives after fielding change, the designer built a poor design that failed to meet user needs. Poor designs should be avoided.

In Figure 2, *(Ferguson, et al., 2007)* take the concept of using an x and y axis a step further by incorporating a third axis and depicting the design approaches on a three-dimensional diagram. In addition to addressing the system's environment and objectives after deployment, *(Ferguson, et al., 2007)* look at the system's variables after deployment. If the system's variable's after fielding are fixed, the designer is directed to either an optimized or robust design. If the system's variable's after deployment are expected to change, the designer should opt for a reconfigurable system design, a concept that is synonymous to a flexible design approach. *(Ferguson, et al., 2007)* also categorize two types of unfavorable designs: limited designs and overly complex-designs. They use the cube to depict how a designer could make a mistake and opt for the two types of poor design approaches. These designs should be avoided.

Most recently, *(Lucero, 2018*) developed a unique x/y axis that incorporates a sliding scale of five design approaches based off a designer's confidence in requirements and ability to respond to requests for system changes. Instead of looking at subjective forms of measurement (e.g., "is the system's environment expected change?"), *(Lucero, 2018*) developed functions to calculate each axis. *(Lucero, 2018*) also incorporates the ability to hedge between two contrasting types of design approaches. Finally, *(Lucero, 2018*) uses the lower left portion of the tradespace to illustrate a suboptimal position of acceptance.

Common to all three charts is the use of robust and optimized design. *(Ferguson, et al., 2007)* refer to "reconfigurable design" while *(Saleh, et al., 2014)* use the term "flexible design" and *(Lucero, 2018*) breaks up the concept of flexible or reconfigurable design into two types: options and adapt. *(Lucero, 2018*) also uses the term "resilient design" as a concept interchangeable with "robust design."

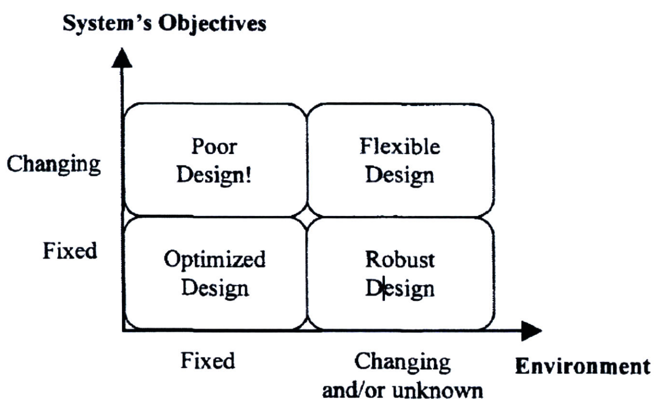


Figure 1: Designs and their Relationships (Saleh, et al., 2014)

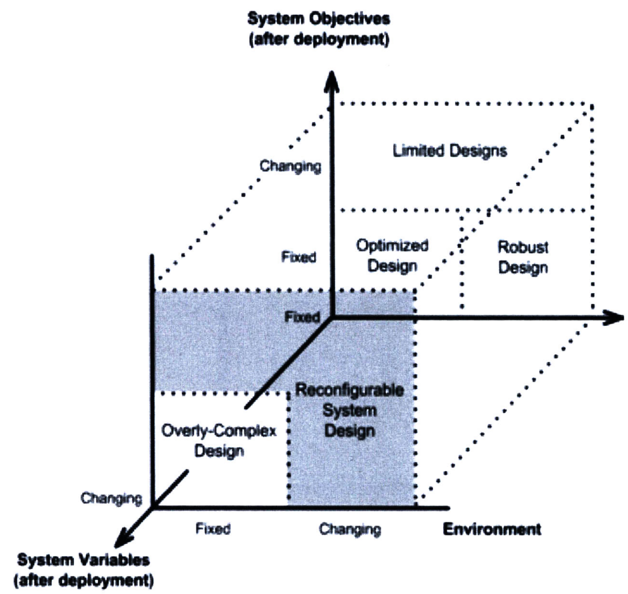


Figure 2: Designs and their Relationships (Ferguson, et al., 2007)

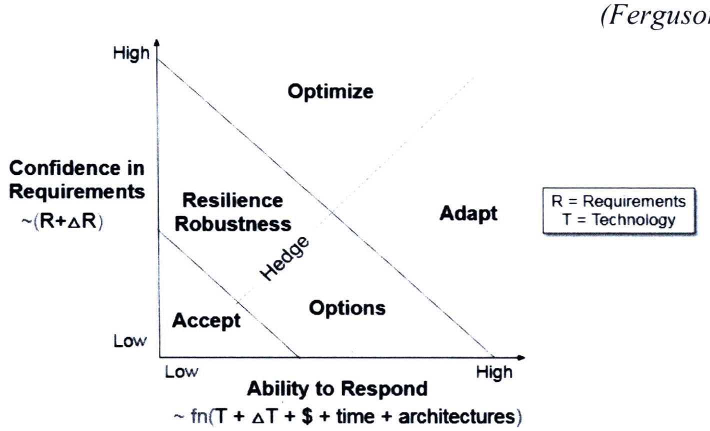


Figure 3: The Mash-up Rubric (Lucero, 2018)

Based on the above literature review of design options, this thesis synthesizes two overarching strategies decision makers can take in a system's design phase. The thesis decision framework refers to the two contrasting design categories as flexible and static. Within these categories, the thesis proposes four more specific design approaches consolidated from the ideas of *(Ferguson, et al., 2007)*, *(Saleh, et al., 2014)*, and *(Lucero, 2018)*: optimized, robust, adapt, and real options. Figure 4 represents an adaptation of the tradespace charts from *(Ferguson, et al., 2007)*, *(Saleh, et al., 2014)*, and *(Lucero, 2018)*. It depicts the attributes addressed in the remainder of the thesis.

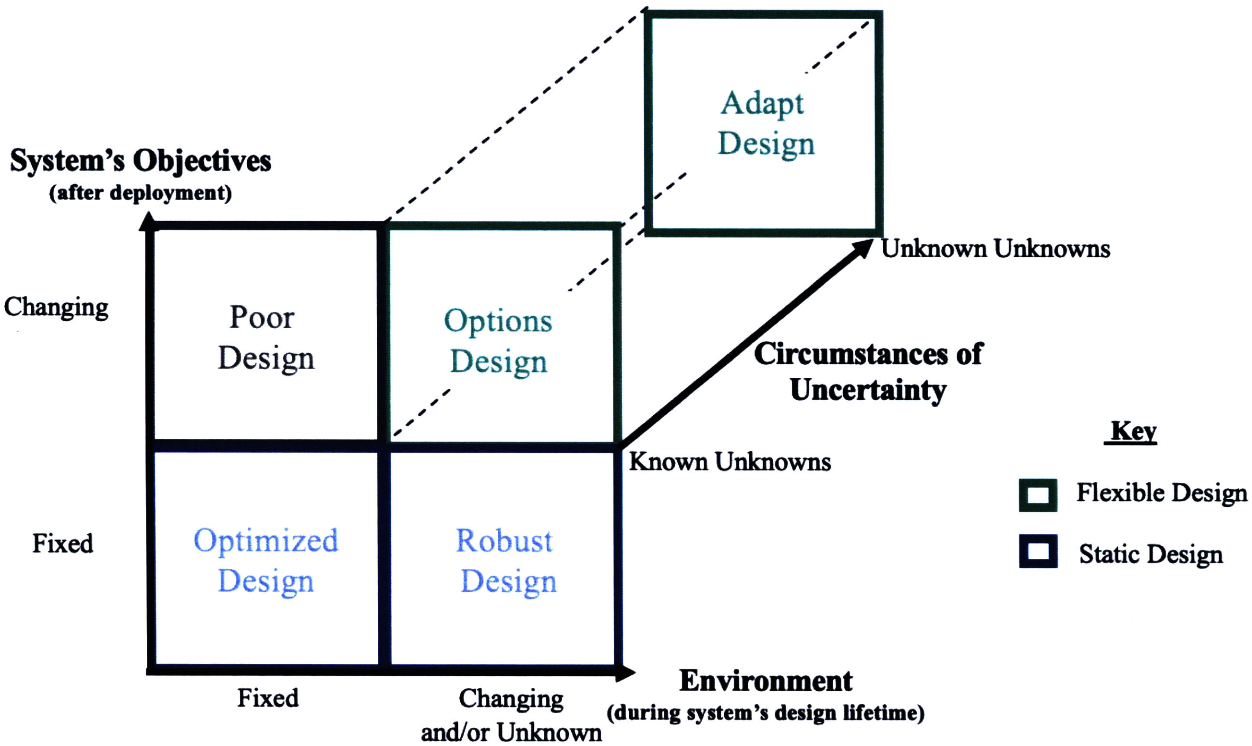


Figure 4: Designs and their Relationships Adapted for Thesis

The following sections summarize relevant literature on the approaches outlined in Figure 4. The literature review also defines the terms used to categorize the Figure 4 axis labels.

2.1.1 Static Design

To obtain an overview of static design, this section consolidates ideas from pertinent publications to define static design, discuss the optimal conditions for static design, and summarize consequences of incorrectly choosing a static design approach.

The two subcategories of a static design approach, optimized and robust, represent academically mature concepts. However, the term used to describe the umbrella category for optimized and robust designs differs greatly across publications. Literature on this topic generally fluctuates between the terms "fixed", "static", "rigid", and "non-changing". The term "static" is used for the purposes of the thesis framework, but recognize there are many acknowledged synonyms.

According to *(Ferguson, et al., 2007)*, "fixed" design variables [such as the diameter on an aircraft's windshield] are generally not allowed to change once the system has been deployed. Specifically, an enterprise is prevented from making changes to the system's state after the system is fielded.

Similar to *(Ferguson, et al., 2007)*, *(Saleh, et al., 2003)* detail a "rigid" design as one in which a system's objectives after fielding are fixed.

Both definitions are suitable for the purposes of this thesis, with the key idea that in a static design approach, it is difficult, if not impossible, to change the system after fielding. Specifically, it is prohibitively expensive and time consuming to change the system.

While *(Ferguson, et al., 2007)* and *(Saleh, et al., 2003)* define characteristics of static design, *(Fricke & Schulz, 2005)* highlight optimal circumstances for employing a static design approach, which include the following three situations[1]:

- Highly expedient, short life systems without needed product variety
- Highly precedented systems in slow changing markets with no customer need variety
- Systems developed for ultrahigh performance markets with no performance loss allowables

(Ferguson, et al., 2007) also introduce two terms related to the improper application of static design. They use "limited designs" to highlight those systems with an inability to attain optimality across multiple operating conditions. Limited designs are realized when the system's variables after deployment are fixed, but the system's objectives change after the system is fielded.

A proceeding from the INCOSE 2006 International Symposium outlines consequences of "low system flexibility." The list details negative outcomes for what *(Ferguson, et al., 2007)* refer to as limited designs.

- Extensive upgrade costs
- Significant disruptions to users
- Lost opportunities

---

[1] Fricke et al. dedicate research to understanding principles for changeability, which falls in contrast to static design. They provide a list of conditions where incorporating changeability into a system architecture may not be cost efficient. The list can also be represented as optimal circumstances for employing a static design approach.

- Unnecessary value loss for stakeholders *(Engel & Browning, 2006)*

Similarly, *(Mark, 2005)* explains how system obsolescence and retirement can be attributed to the inability of systems to meet changing mission requirements resulting from changing environments.

(Ferguson, et al., 2007) describe another undesirable scenario in which a system is designed to be reconfigurable (not static), but the environment and system objectives after deployment remain fixed. They classify systems falling within this scenario as overly complex designs. Overly complex designs typically result in an unnecessary expenditure of funds.

The thesis decision framework seeks to direct decision makers to a static design when it provides the most responsive and cost-effective approach for DoD systems and aims to prevent decisions that lead to limited and overly complex designs.

Table 1 presents a summary of a static design approach.

Summary of Static Design
Key Takeaways
• Umbrella approach for optimized and robust designs • The system's objectives after fielding are fixed • Optimized for short life systems or those systems in a slow changing market
Pro
• Can result in a system design that offers the highest level of performance under a given set of requirements or objectives
Cons
• Technically difficult, prohibitively costly, and/or exorbitantly time consuming to make changes to the system after it is fielded • If the mission, user needs, or environment changes after system deployment, the system can be rendered obsolete before reaching the end of its design lifetime

Table 1: Static Design Approach

2.1.2 Optimized

An optimized design represents the traditional DoD engineering approach in which a need is defined and a design is created to meet the need. The concept dates back to at least 1947 when George Dantzig published work on linear optimization. Since then, the idea behind optimization has become a common paradigm used for decision-making in a variety of disciplines, including engineering design. Today, optimization focuses on various mathematical techniques for determining the best design out of a set of alternatives and a given set of constraints. Therefore, when one refers to an optimized system, there is an understanding that the system is best at what it does. An unmanned aerial vehicle optimized for endurance, for example, will have a different design than the same type of vehicle optimized for speed and aggressive maneuvering *(Saleh, et al., 2009)*.

According to a proceeding from the 2007 International Design Engineering Technical Conference, optimized designs are realized when the configuration of a system is set to achieve maximum performance under fixed operating conditions (environment). To be optimal, both the operating environment and the system objectives must be fixed (or non-changing) after deployment. In cases where the operating environment and the system objectives remain fixed, there is no need to design a system that is capable of changing configuration after deployment. *(Ferguson, et al., 2007)* Therefore, optimized systems are technically difficult, costly, and/or time consuming to change after fielding.

Although not the focus of this thesis, optimized systems should follow the traditional approach of performing a tradespace analysis that represents desired design tradeoffs and allows for the selection of an architecture design on the pareto front. Figure 5 provides an example tradespace analysis for a Low Earth Orbit (LEO) satellite constellation design that optimizes lifecycle costs and system capacity. Each asterisk corresponds to a different design option. The non-dominated designs on the pareto front represent the best achievable tradeoff between capacity and life cycle cost. *(de Weck, et al., 2004)*

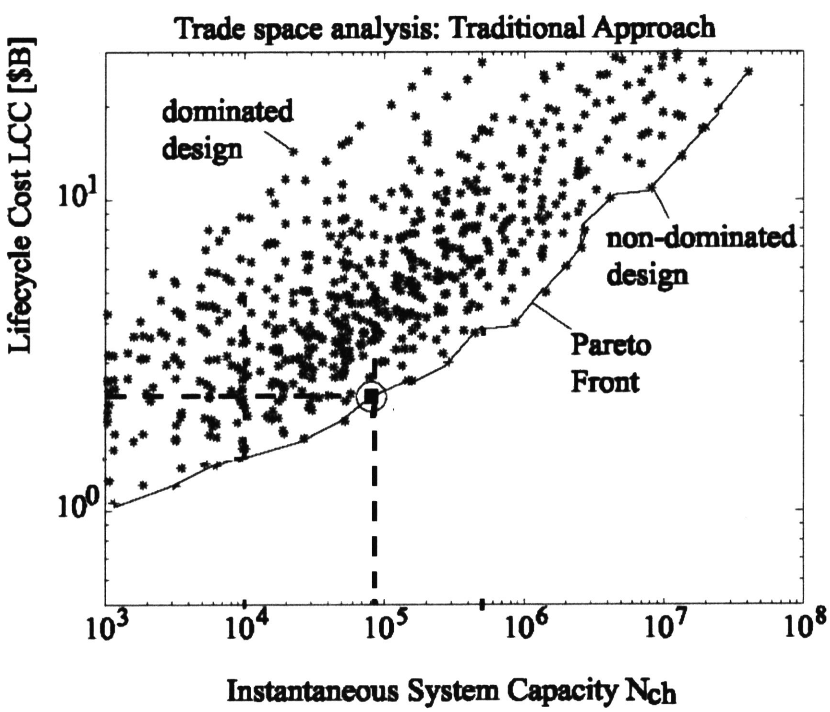


Figure 5: Tradespace of 600 LEO Constellation Architectures (de Weck, et al., 2004)

(Saleh, et al., 2014) explain, "for well-defined, static markets and fixed requirements, finding an optimal point design that minimizes cost will be the best design choice. However, today's systems are rarely characterized by such stability."

Table 2 presents a summary of an optimized design approach.

Summary of Optimized Design
Key Takeaway
• A static design approach that should be used when both the operating environment and the system's objectives are fixed after the system is fielded
Pros
• The system is developed using the best design out of a set of alternatives and constraints • Can result in a system with the highest possible level of performance and lowest development costs under fixed operating conditions
Cons
• Technically difficult, prohibitively costly, and/or exorbitantly time consuming to make changes to the system after it is fielded • If the mission, user needs, or environment changes after system deployment, the system can be rendered obsolete before reaching the end of its design lifetime

Table 2: Summary of Optimized Design

2.1.3 Robust

Robust design was pioneered by Dr. Genichi Taguchi in the 1960s and applied extensively to the manufacturing process. In 1989, Madhav S. Phadke redirected Dr. Taguchi's concept of robust design to the engineering discipline and published the book "Quality Engineering Using Robust Design." Since then, various scholars have explored the idea of robustness in engineering design.

(Saleh, et al., 2009) define robust design as the property of a system which allows it to "satisfy a fixed set of requirements, despite changes in the environment or within the system (or noise factors)." *(Ferguson, et al., 2007)* explain robust design "as a means to allow a system to satisfy a fixed set of system requirements despite stochastic changes to the operating environment, by designing the system to be insensitive to disturbances" and highlight "the expectation in robust design is that once decided upon, the design will not change as it is operated." Likewise, *(Saleh & Hastings, 2000)* explain robustness as "the property of a system which allows it to satisfy a fixed set of requirements despite changes occurring after the product has entered service, in the environment, or within the system itself, from the nominal or expected environment or system design parameters." They highlight the objective of robust design is to "maintain a target performance despite the various noise factors such as variations in the conditions of use of the system." *(Saleh & Hastings, 2000)*

Each definition of robust design, listed above, is suitable for the purpose of this thesis. The important distinction for a robust system is that it is designed for changing or unknown environments, but fixed requirements. Robust systems are not modified after fielding.

In addition to defining robust design, *(Phadke, 1989)* discusses the purpose of robust design: "to improve the quality of a product by minimizing the effect of the causes of variation without eliminating the causes" and "to economically reduce the variation of a product's function in the customer's environment." He explains that robust design is "achieved by optimizing the product and process designs to make the performance minimally sensitive to the various causes of variation."

(Phadke, 1989) also highlights several benefits of robust design and explains how the methodology improves productivity during R&D, allowing high-quality products to be fielded quickly and at low cost. In "Quality Engineering Using Robust Design," Mr. Phadke chronicles a series of AT&T systems that used robust design principles and demonstrates how robust design offers simultaneous improvements to performance and cost while enhancing an organization's ability to meet market windows.

To put the concept of robust design into context, *(Phadke, 1989)* describes how customers purchasing a car want a vehicle that will easily start in northern Canada in the winter and not overheat in southern Arizona in the summer. In this case, customers desire a car that is robust with respect to variations of use conditions. Similarly, customers prefer the car works just as well at 50,000 miles as when new. This characteristic reflects a desire for robustness against time and wear.

Although both robust and optimized approaches fall under the category of static designs, *(Saleh, et al., 2003)* provide a visual depiction of the difference between an optimized and robust solution. The illustration assumes performance is a function of only one variable, x. For a robust design, a developer is interested in identifying the flat part of the curve near the performance target because this is the area where there is a reduction in variations of performance responses caused by variations in the design variables. Alternatively, if the objective is to move the performance towards M, and considerations for a robust design are not necessary, then $x = \mu_{opt}$ is a better choice.

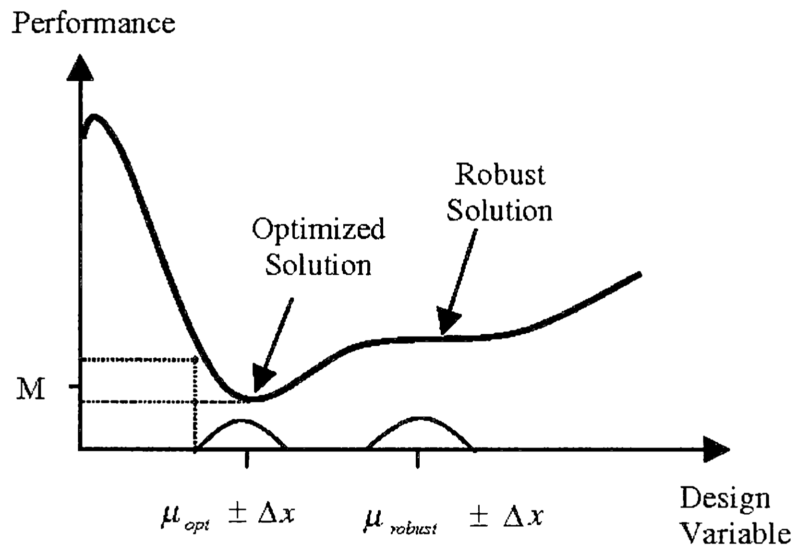


Figure 6: Optimized vs. Robust Design Solutions (Saleh, et al., 2003)

Finally, while not the focus of this thesis, *(Taguchi & Clausing, 1990)* describe how to add robustness to a product. They define robustness as the virtue of a product with a high signal-to-noise ratio and take a three-step approach to incorporating robustness into system design:

1. Define the specific robustness objective, selecting the most appropriate signal and estimating the concomitant noise.
2. Define feasible options for the critical design values, such as dimensions and electrical characteristics.
3. Select the option that provides the greatest robustness or the greatest signal-to-noise ratio.

Alternatively, *(Phadke, 1989)* outlines eight steps for creating a robust design that offer a similar approach to the above three-step process.

Table 3 presents a summary of a robust design approach.

Summary of Robust Design
Key Takeaway
• A static design approach that should be used when the system's objectives after fielding are fixed, but when the operating environment could change
Pros
• Approach that allows a system to be fielded more quickly and potentially at a lower cost than that of a flexible system • Designed to be insensitive to noise factors/environmental changes, which reduces the chance the system will be rendered obsolete before reaching the end of its design lifetime
Cons
• Technically difficult, prohibitively costly, and/or exorbitantly time consuming to make changes to the system after it is fielded • Design can result in a system performance penalty compared to the design of an optimized system

Table 3: Summary of Robust Design

2.1.4 Flexible Design

To obtain an overview of flexible design, this section consolidates ideas from relevant publications to define flexible design, discuss when flexible design is needed, highlight benefits and shortfalls of flexible design, and compare the approach against static design options.

In a 2005 internet search on the ratio of occurrence between the words optimal/optimality/ optimization, robust/robustness, and flexible/flexibility in scholarly literature *(Saleh, et al., 2009)* prove flexibility is a much less academically mature concept than optimization or robustness. Despite this, several prominent publications define flexibility in the context of engineering design. Additionally, a literature review reveals flexibility in engineering design addresses two different problems. The first focuses on flexibility in the design process and includes activities, methods, and tools designed to mitigate cost, schedule, and performance risks derived from requirement changes prior to system deployment. *(Saleh, et al., 2003)* The second issue addresses flexibility of a design itself and is concerned with changes occurring after fielding, or T_{ops}. This thesis is only concerned with flexibility of a design, graphically displayed in Figure 7.

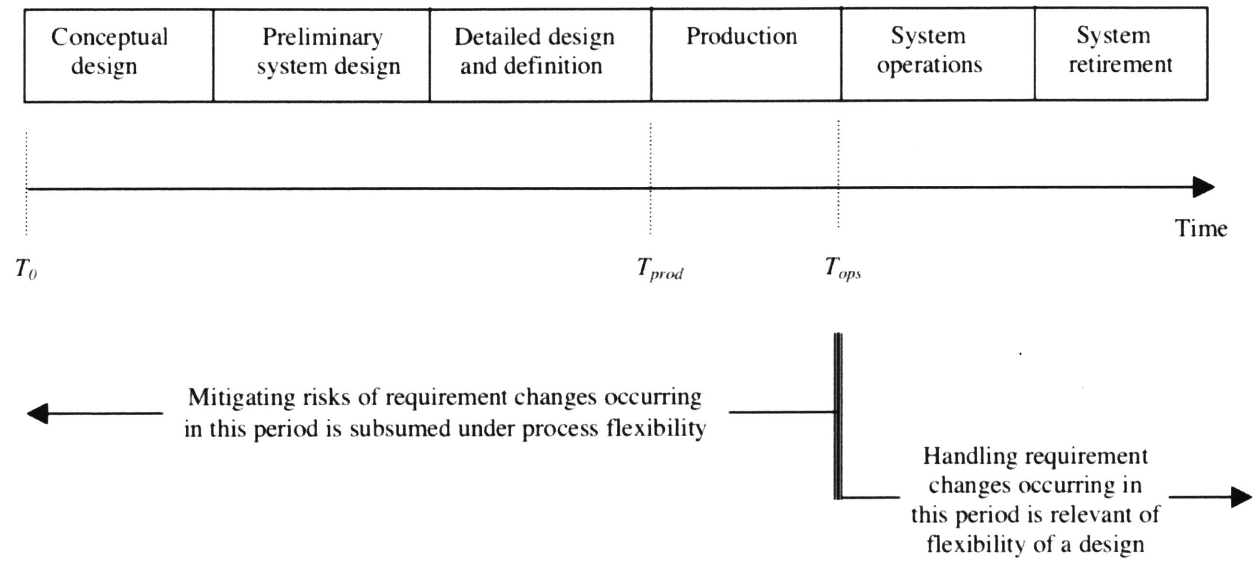


Figure 7: Time Periods Associated with Flexibility (Saleh, et al., 2003)

(Gupta & Goyal, 1990) determine flexibility is the ability to change and adapt to a range of states. *(Roser & Kazmer, 1999)* explain the notion of flexibility as the ability "to change performance while requiring minor time and cost to change the design parameters." Similarly, *(Fricke & Schulz, 2005)* highlight flexibility as a property characterizing a system's ability to be changed easily. Using the phrase "changeable systems," *(Ferguson, et al., 2007)* describe systems whose "configurations can be changed, altered, or modified after the system has been deployed." Most recently, *(Saleh, et al., 2014)* define flexible design "as the property of a system that allows it to respond to changes in its initial objectives and requirements, both in terms of capabilities and attributes, occurring after the system has been fielded (i.e., while in operation) in a timely and cost-effective way."

Each definition of flexible design, listed above, is suitable for the purpose of this thesis, but the *(Saleh, et al., 2014)* definition will be used based on the definition's level of detail.

While several publications define flexible design, *(Fricke & Schulz, 2005)* highlight optimal circumstances for employing a flexible design approach, which include the following situations:

- The system has stable core functionality, but variability in secondary functions and/or external styling
- The system has a long lifecycle with fast cycle times of implemented technologies driving major quality attributes (e.g., functionality, performance, reliability)
- The architecture and system are subject to a dynamic (i.e., rapidly growing and strongly changing) marketplace with a varying customer base and strong competition

- The architecture and system are highly interconnected with other systems sharing their operational context
- It is a complex and highly unprecedented system, with an unknown market

Additionally, *(Ferguson, et al., 2007)* discuss why enterprises need to imbed flexibility into the design of a system. They explain, "changes to system objectives and operating conditions within the operating environment can create designs that do not perform as well as originally intended."

(Saleh, et al., 2009) offer a more detailed reason for flexible design emphasizing "flexibility should be sought when the uncertainties in a system's environment are such that there is a need to evolve the system after it has been fielded in order to mitigate market/environment risks, and when the system's technology base evolves on time scales considerably shorter than the system's design lifetime, thus requiring a solution for mitigating risks associated with technology obsolescence."

(Saleh, et al., 2014) expand on the above 2009 publication and discuss why and when enterprises need to embed flexibility into the design of a system. They explain the need for flexibility comes from a mismatch between:

1.) A system's design lifetime
2.) The time constants associated with the market dynamics the system is serving, and
3.) The technology embedded in the system

Specifically, two critical changes to a system's objectives can occur after a system is fielded:

1.) Technology can change, rendering a system obsolete or competitively inferior, and/or
2.) Market needs can change, resulting in a system that no longer meets customer needs.

According to *(Saleh, et al., 2014)*, flexible design is necessary when "the expected lifetime of a system in operation is significantly greater than the time constants associated with the dynamics of its technology and its market." *(Saleh, et al., 2014)* also emphasize the case for flexibility can only be made when the cost of upgrading or adding to the system is lower than replacing the system.

In addition to understanding when and why an enterprise should use a flexible design approach, it is important to capture the benefits and costs of flexibility.

By definition, flexibility allows for timely and cost-effective changes after a system has been developed and fielded. By nature of the design approach, flexibility modifies a system's exposure to uncertainty and minimizes its risk of obsolescence. Similarly, flexibility can extend the service life and ability of a system to remain useful despite changes in the system's operational environment. *(Saleh, et al., 2003)* explain flexible systems can more easily adapt to changing environments, last longer, or outlast more rigid systems. The relationship between the ability of a system to cope with change and its life span is illustrated in Figure 8.

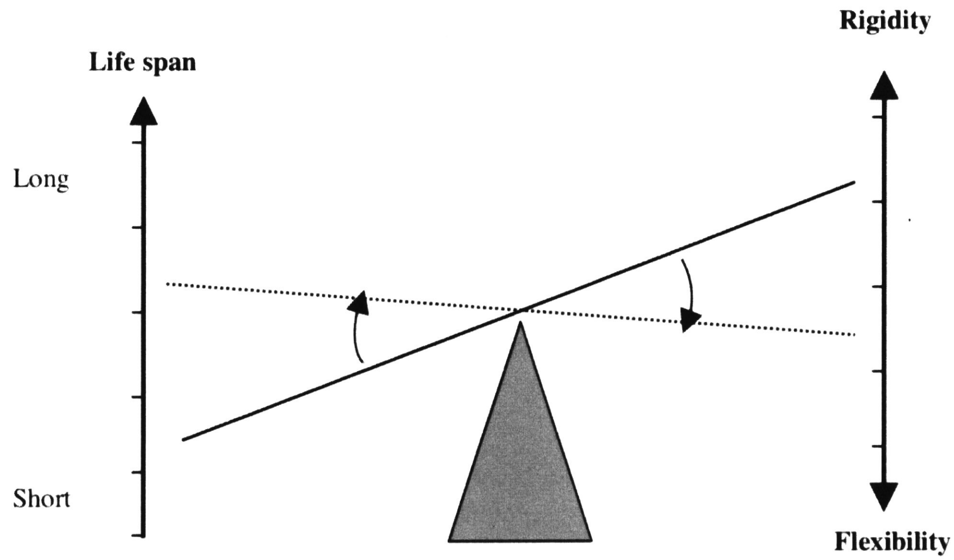


Figure 8: Relationship Between Lifespan and Flexibility (Saleh, et al., 2003)

(Saleh, et al., 2003) emphasize another advantage of flexible design, explaining "critical system requirements need not be narrowly specified prior to launch, because changes can be accommodated afterwards."

Alternatively, *(Fricke & Schulz, 2005)* highlight benefits of what they deem "changeable" systems, explaining such systems enable the ability to "stay ahead of competition in dynamic environments" and "ensure the sustainment of superior system capabilities."

(de Weck, et al., 2004) emphasize an alternative benefit of flexibility, explaining, "flexibility can reduce economic risk compared to the traditional [static] approach, even if an upfront penalty must be incurred."

In the book "Flexibility in Engineering Design," *(de Neufville & Scholtes, 2011)* argue a similar benefit to the one emphasized by *(de Weck, et al., 2004)*. They explain "both theory and case studies reveal designing a system with the flexibility to adapt to future needs and opportunities greatly increases the long-term expected value, compared to traditional [static] procedures for developing and implementing projects." The case studies in the book demonstrate increases of up to 80% in expected value. *(de Neufville & Scholtes, 2011)*

Figure 9 represents an example pulled from *(de Neufville & Scholtes, 2011)*'s "Flexibility in Engineering Design". The table shows a side by side comparison of the value of optimized versus flexible designs for a fleet of geostationary satellites.

Flexibility leads to major gains: Satellite fleet

A detailed analysis of alternative ways to deploy geostationary satellites over different regions showed that a flexible system design, which enabled system operators to reposition satellites as demand for broadcast services changed, greatly outperformed the system "optimized" for the specified "most likely" pattern of demand.[4]

As table 1.1 shows, flexible design increases overall expected value. Instead of launching the final fleet right away, systems operators initially launch a smaller fleet, reducing initial capital expenditure, and therefore the amount at risk and potential losses. The flexible design, however, allows the capture of the upside, too, when operators deploy the second module, sized and located according to actual need, thereby obtaining a maximum value if demand exceeds initial capacity.

Table 1.1
Comparison of value of "optimized" and flexible designs for a satellite fleet

	Present value, $ millions			
Design	Expected	Maximum	Minimum	Fixed cost
"Optimized"	49.9	192	−162	−393
Flexible	95.8	193	68	−275
Which better?	Flexible	Flexible	Flexible	Flexible

The design "optimized" for a single forecast performs poorly on average across the range of possible scenarios.
Source: Hassan et al. (2005)

Figure 9: Value of Optimized versus Flexible Designs
(de Neufville & Scholtes, 2011)

(de Neufville & Scholtes, 2011) also determine flexible designs provide the following two advantages:

1.) Flexibility limits losses by avoiding bad consequences when the future is unfavorable
2.) Flexibility increases possible gains by enabling systems to take advantage and benefit from new opportunities

Alternatively, *(Stigler, 1939)* observes "flexibility is not a free good" and *(Saleh, et al., 2009)* highlight the likeliness that "flexibility can only be obtained through performance and/or cost penalties." In many cases, the increased complexity required to embed flexibility into the design of a system can result in higher initial development costs, a longer development timeline, and/or performance penalties. As *(de Weck, et al., 2004)* point out, "the vast majority of space systems are designed without any consideration of flexibility… flexibility is not for free and various forms of upfront performance, mass, reliability and cost penalties must often be accepted in order to embed flexibility in a complex, technical system."

In Figure 10, *(Fricke & Schulz, 2005)* describe the relationship between the sources of cost imposed on a flexible system architecture.

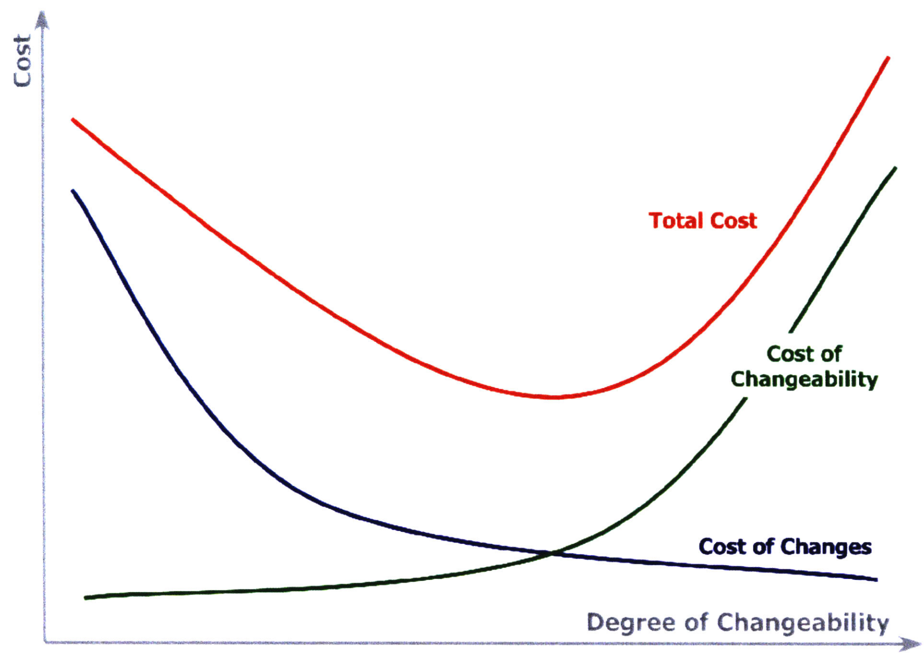


Figure 10: Relationship Between Costs and Degree of Changeability (Fricke & Schulz, 2005)

The diagram highlights the optimal point where the cost of changes and cost of flexibility are the same, resulting in lowest total system costs. From this point, as the degree of flexibility increases, the cost of imbedding flexibility into the system exponentially rises, resulting in an overly complex and unnecessarily costly system. Likewise, if the degree of flexibility in a system is too small, the cost to make changes to the system is very high, resulting in an overly expensive, limited system.

Several publications discuss the difference between flexible designs and the two static design approaches used in this thesis: optimized and robust. Figure 11 and Figure 12 highlight the performance tradeoffs between an optimized and flexible design approach. In Figure 11, *(Saleh, et al., 2009)* visually depict optimization over a single period and the resulting large performance gap should requirements change in a second period. The Period 2 portion of the diagram highlights what *(Ferguson, et al., 2007)* refer to as limited designs.

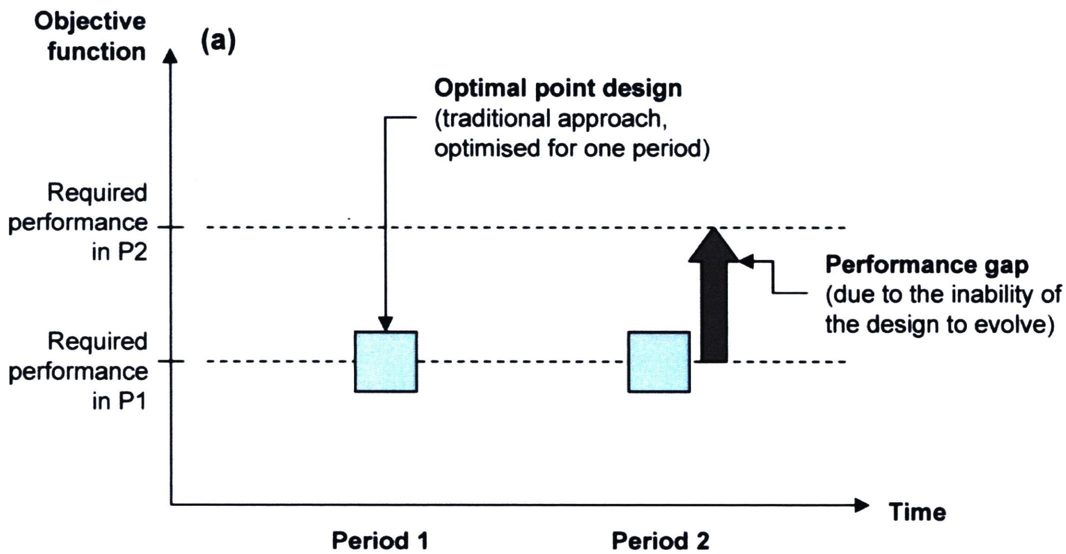


Figure 11: Optimized Design (Saleh, et al., 2009)

Alternatively, Figure 12 depicts a flexible system's design evolution. Although the initial system may experience a performance gap with respect to the optimal point design, there is a comparatively smaller performance gap in Period 2 when the requirements change.

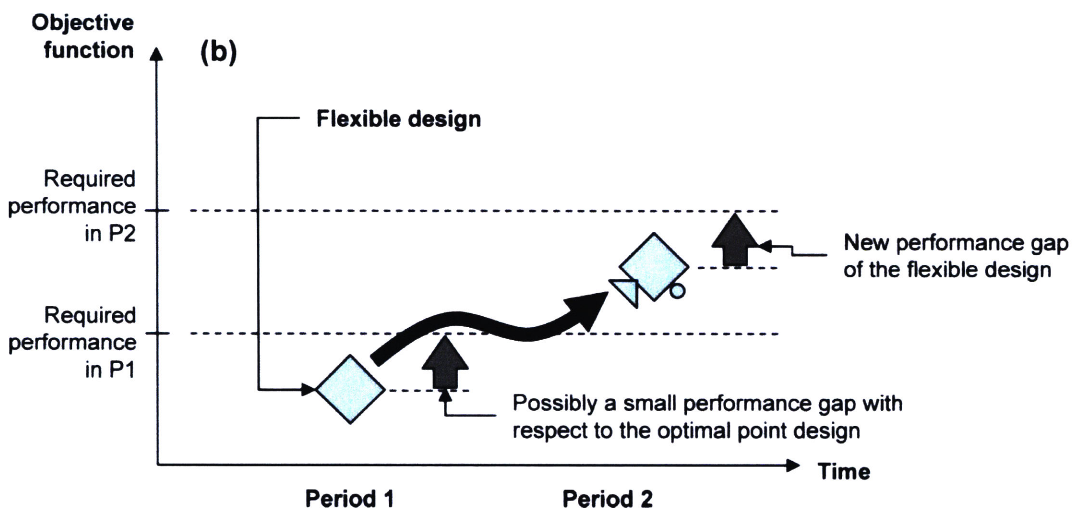


Figure 12: Flexible Design (Saleh, et al., 2009)

Whereas *(Saleh, et al., 2009)* discuss the difference between optimized and flexible designs, *(Saleh, et al., 2003)* comment on the distinction between robust and flexible designs. They explain, "although both concepts refer to the ability of a system to handle change, the nature of the change and the system's reaction to the change are very different in each type of design". Specifically, flexible designs are capable of "satisfying changing requirements after a system has been fielded", whereas robustness involves "satisfying a fixed set of requirements despite changes in the system's environment or within the system itself." *(Saleh, et al., 2003)*

To capture the difference between flexible and robust designs, *(Saleh, et al., 2003)* provide the hypothetical example of designing a spacecraft. The challenge of maintaining on-board functionality after launch and despite changes in spacecraft characteristics due to radiation impacts, malfunctions, aging, etc. is indicative of the need for robustness of design. Alternatively, the challenge of creating new functionalities on-board for changes in requirements occurring after launch, as new environments are explored and new data becomes available, is indicative of the need for flexibility of design.

Finally, while not the focus of this thesis, *(de Neufville & Scholtes, 2011)* provide guidance on how managers can implement flexibility into a system using a four phased approach. Additionally, *(Saleh, et al., 2009)* highlight the importance of understanding that flexibility in design "implies a system has been designed with certain characteristics, for example, additional design parameters, design margins, or a particular modular or platform-based architecture that allow the system to be easily modified should the requirements change after the system has been fielded." They also emphasize that "the requirements changes can be known or unknown upfront." *(Saleh, et al., 2009)*

Table 4 presents a summary of a flexible design approach.

Summary of Flexible Design
Key Takeaways
• Umbrella approach for real options and adapt designs • Allows for modifications to the system after development • The system's objectives and environment can change after fielding • Optimized for systems with long lifecycles, systems operating in dynamic markets, and system's with varying customer needs (i.e., systems exposed to uncertainty)
Pros
• Enables timely, cost-effective changes to the system after fielding • Approach mitigates the risk of technology obsolescence and the risk of designing a system that no longer meets user needs during the design lifetime of the system • Can extend the service life of a system and allow the system to last longer than a static counterpart
Cons
• The added complexity of designing for flexibility can result in higher upfront development costs, a longer upfront development schedule, and/or initial system performance penalties

Table 4: Summary of Flexible Design

2.1.5 Real Options

The idea behind real options was developed by Stewert Myers in the 1970s in the context of strategic decision making within the financial sector. *(Mikaelian, et al., 2011)* explain "the goal of Real Options Analysis (ROA) is to value decisions under uncertainty by taking into account the options available to the decision maker in the future." In the classic definition, a real option is defined as "the right, but not the obligation, to take an action at a future time." *(Mikaelian, et al., 2011)*

More recently, the concept of real options moved to the engineering realm in order to value and design flexibility in uncertain environments. In the context of ROA, literature provides methods to calculate the financial value of engineering flexibility into the design of a system. More applicable to this thesis is the idea of embedding flexibility into a project. A distinction has been set between real options "on" projects and real options "in" projects. The former involves the management domain and references a decision maker's ability to make strategic decisions on project investments. The latter term refers to "engineering design decisions that enable the flexibility to change the system in the future." *(Mikaelian, et al., 2011)*

This thesis focuses on real options "in" projects; the act of actively designing systems that enable flexibility in future operational settings.

In order to represent the future flexibility of a design, several different types of real options have been documented. The following list and associated definitions are applicable types of real options for this thesis:

- Defer: wait to proceed or invest in subsequent development
- Abandon: leave the project
- Switch: move between different inputs and/or outputs
- Expand: increase capacity or capability
- Contract: downsize the level of operations *(Mikaelian, et al., 2011)* and *(Kalligeros & de Weck, 2004)*

(de Neufville, et al., 2005) walk through an example of designing real options into a parking garage with multiple levels. The case discusses uncertainty around demand for the garage, as the location of the structure is proposed in a region where the population is expected to grow by an unpredictable amount. Developers face a dilemma of designing a parking garage too large for the eventual size of the population, resulting in costs that cannot be recovered. Alternatively, if developers design a small parking garage, there could be missed opportunities for revenue if the population increase results in demand that cannot be met by the size of the garage. As a solution, *(de Neufville, et al., 2005)* propose using real options in the design of the structure by

strengthening the buildings footings and columns. The design involves greater upfront costs, materials, and resources, but provides the option to build a smaller parking garage now and expand to additional levels, if future demand necessitates such expansion. Through this case study, *(de Neufville, et al., 2005)* demonstrate the benefits of real options:

- The expected value of a project increases
- The maximum possible loss of a project is reduced
- The maximum possible gain of a project is increased
- Initial capital costs are reduced

Similarly, *(de Weck, et al., 2004)* evaluated real options in satellite communication systems. The case study involved using additional positioning rockets and fuel in order to achieve a flexible design that could adjust capacity according to speed. Through the study, they determined their use of flexible options could increase the value of satellite communications systems by at least 25%.

In addition to the benefits, *(Mikaelian, et al., 2011)* highlight the major limitation of a real options approach, explaining "real options are most appropriate for managing uncertainties that are anticipated to be resolved in the future, and are not well suited for managing unknown unknowns." The developer must have some level of understanding in where the uncertainty will come from in order to build in the appropriate real option.

While not the focus of this thesis, *(Mikaelian, et al., 2011)* discuss how real options can be embedded into the design of a system using a "mechanism". The term, mechanism "is defined as an action, decision, or entity that enables a real option." The mechanism, or source of flexibility, enables the future real options to take place. For example, "designing a modular payload bay for a UAV is a mechanism that enables the real option to switch the type of payload." (Mikaelian, et al., 2011) Likewise, *(Wang & de Neufville, 2006)* propose a screening and simulation model for how to identify real options "in" engineering systems.

Table 5 presents a summary of a real options design approach.

Summary of Real Options Design
Key Takeaways
• A flexible design approach that should be used when the system is subjected to anticipated uncertainties (known unknowns) • Allows for modifications to the system after development
Pros
• Enables timely, cost-effective changes to the system after fielding • Reduces the maximum possible loss of a system • Increases the maximum possible gain of a system • Approach mitigates the risk of technology obsolescence and the risk of designing a system that no longer meets user needs during the design lifetime of the system • Can extend the service life of a system and allow the system to last longer than a static counterpart
Cons
• There can be upfront cost, schedule, and/or performance penalties for imbedding an option, even if it never exercised

Table 5: Summary of Real Options Design

2.1.6 Adapt

While the idea of real options in projects is relatively new, the concept is well defined and recognized with similar understanding across various publications and sources. Unfortunately, a literature review on an adapt design approach yields different results; publications that reference adaptable design offer few clarifying details to differentiate adaptability from the umbrella category of flexible systems.

According to *(Ferguson, et al., 2007)*, "adaptability has been defined as characterizing a system's ability to adapt itself to deliver intended functionality under varying conditions through the design variables changing their physical values." *(Crawley, et al., 2004)* define adaptability as "the ability of a system to change internally to fit changes in its environment, usually by self-modification to the system itself." *(Fricke & Schulz, 2005)* describe adaptability as a system's ability to adapt itself towards changing environments and under varying operating conditions, through changing themselves. Finally, *(Engel & Browning, 2006)* look to *Webster* and define adaptability as "the ability of the system design to be changed to fit altered circumstances, where circumstances include both the context of a system's use and its stakeholders' desires."

(Madni, 2012) takes the above definitions a step further and explains, "system engineering methods…need to be transformed to enable rapid, cost-effective development of both anticipated and unanticipated changes in the operational environment." He points to "adaptable platform-

based engineering" as a specific adaptable design method capable of responding to unanticipated changes, or what *(Hastings & McManus, 2004)* deem unknown unknowns.

(Madni, 2012)'s understanding of adaptable designs provides a helpful compliment to real options. In a real options approach, the enterprise has a deliberate understanding of the uncertainty (e.g., future budget uncertainty, future capacity uncertainty, uncertainty with regards to how long the avionics technology will remain relevant, etc.). Real options represent a design paradigm that reduce risks for known unknowns.

Alternatively, in the context of this thesis, adapt designs will be used to imply a faster and more cost-effective method for managing unknown unknowns or emergent uncertainties that an enterprise may not be able to anticipate at the time of development.

Design approaches that enable new variants, platform-based engineering that employs a common structure from which derivative products can be more rapidly developed, or large-scale block upgrades represent various ways to employ an adapt design approach.

(Madni, 2012) provides the example of Lockheed Martin's C-130, which was developed in the 1950s using a common platform-based engineering approach, modular software and avionics subsystems, and with the intention of developing a series of block upgrades or major aircraft and avionics revisions. Originally designed as a troop, medevac, and cargo transport aircraft, *(Madni, 2012)* explains, "today's C-130s fill roles as diverse as Search and Rescue to Gunship applications, all leveraging a common airframe." Additionally, "a variety of software and weapons suites can be added to the airframe" with varying cost and schedule impacts. Lockheed Martin's website touts the C-130 as having "17 different mission capabilities and 11 production variants" many of which were not anticipated during the aircraft's initial development in the 1950's. *(Stinn, 2019)*

Table 6 presents a summary of an adapt design approach.

Summary of Adapt Design
Key Takeaways
• A flexible design approach that should be used when the system is subjected to anticipated and unanticipated uncertainties (unknown unknowns) • Allows for modifications to the system after development
Pros
• Enables timely, cost-effective changes to the system after fielding • Approach mitigates the risk of technology obsolescence and the risk of designing a system that no longer meets user needs during the design lifetime of the system • Can extend the service life of a system and allow the system to last longer than a static counterpart
Cons
• The added complexity of an adapt design can result in higher upfront development costs, a longer upfront development schedule, and/or initial system performance penalties

Table 6: Summary of Adapt Design

2.2 Architecture Principles that Enable Real Options Designs

There are many architecture principles that enable flexibility. This thesis does not address each method in detail, but attempts to provide a small sample of principles to better enhance the reader's understanding of how to implement flexibility. This section provides a brief overview of three architecture concepts that enable real options designs: modularity, integrability, and scalability.

According to *(Fricke & Schulz, 2005)*, modularity "aims at building a system architecture that clusters the system's functions into various modules while minimizing the coupling among the modules (loose coupling) and maximizing the cohesion within the modules (strong cohesion)." According to *(Fricke & Schulz, 2005)*, "modularity is strongly supported by making modules as independent as possible from other modules, because this reduces the number of interfaces and makes a clustering of modules much easier."

(Fricke & Schulz, 2005) highlight six types of modularity distinguished in literature. The six examples are graphically displayed in Figure 13. Component sharing modularity uses the same components within several architectures. Component swapping varies the same platform by adding different components. Fabricate to fit uses standardized components that are scalable. Mix modularity uses standardized components that are not scalable. Bus modularity varies the same platform by adding different components using a standardized interface. Finally, sectional modularity uses various components with standardized interfaces, but no platform. *(Fricke & Schulz, 2005).*

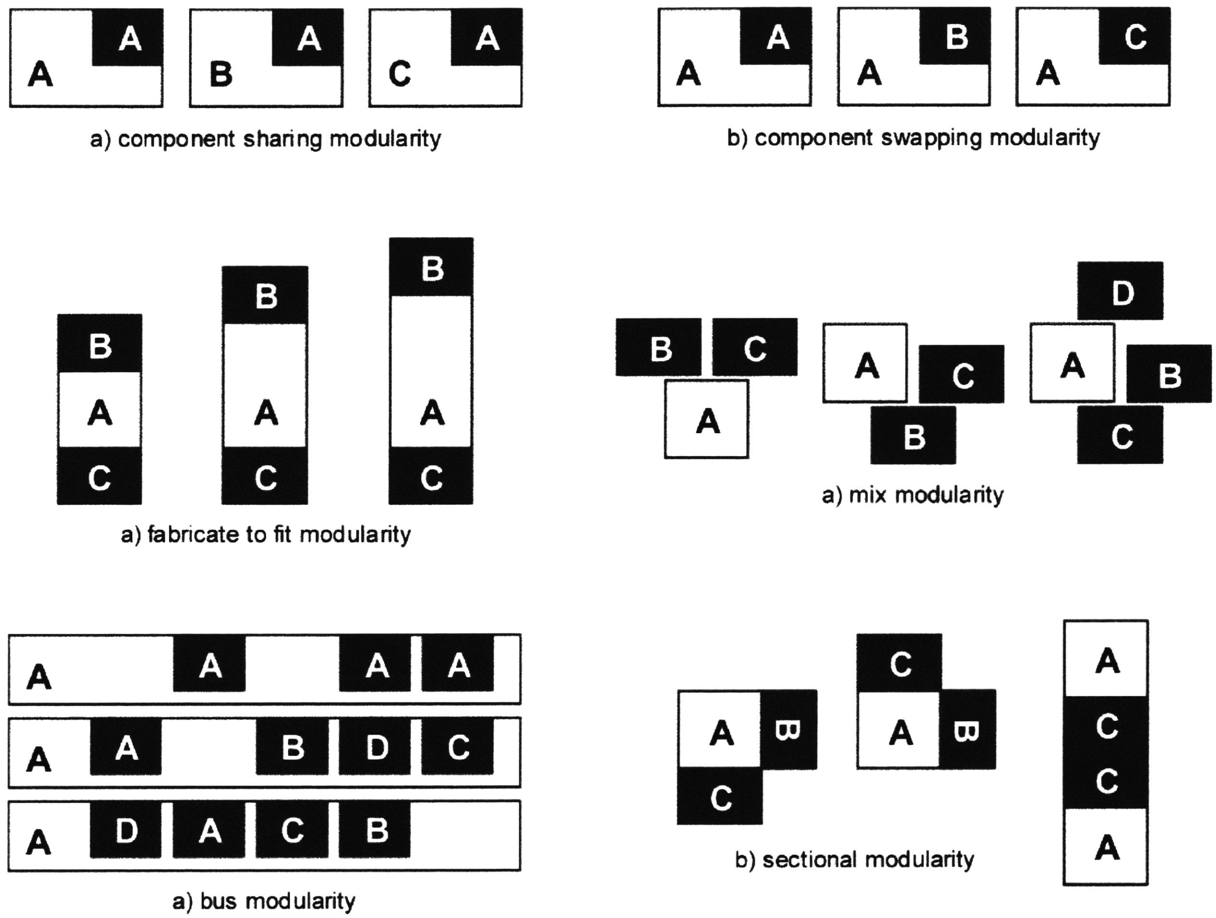


Figure 13: Six Types of Modularity (Fricke & Schulz, 2005)

(Fricke & Schulz, 2005) also describe the principle of integrability. They explain how integrability is "characterized by compatibility and interoperability applying generic open, or common/consistent interfaces." *(Crawley, et al., 2016)* describe a Lego block as an example of a design with open variants because of the large number of shapes that can be constructed by combining many different Lego blocks. Likewise, *(Fricke & Schulz, 2005)* provide the example of universal serial bus (USB) ports, which provide integrability to external devices. This architecture principle supports a real options design approach because it provides the user with a switch option. In the case of a laptop USB port, users can switch between charging a cell phone, backing up pictures to an external thumb drive, or playing a DVD. Figure 14 shows a graphical depiction of the principle of integrability and highlights the difference between closed interfaces, or those interfaces that are not interchangeable, and open interfaces that allow for interchangeable components.

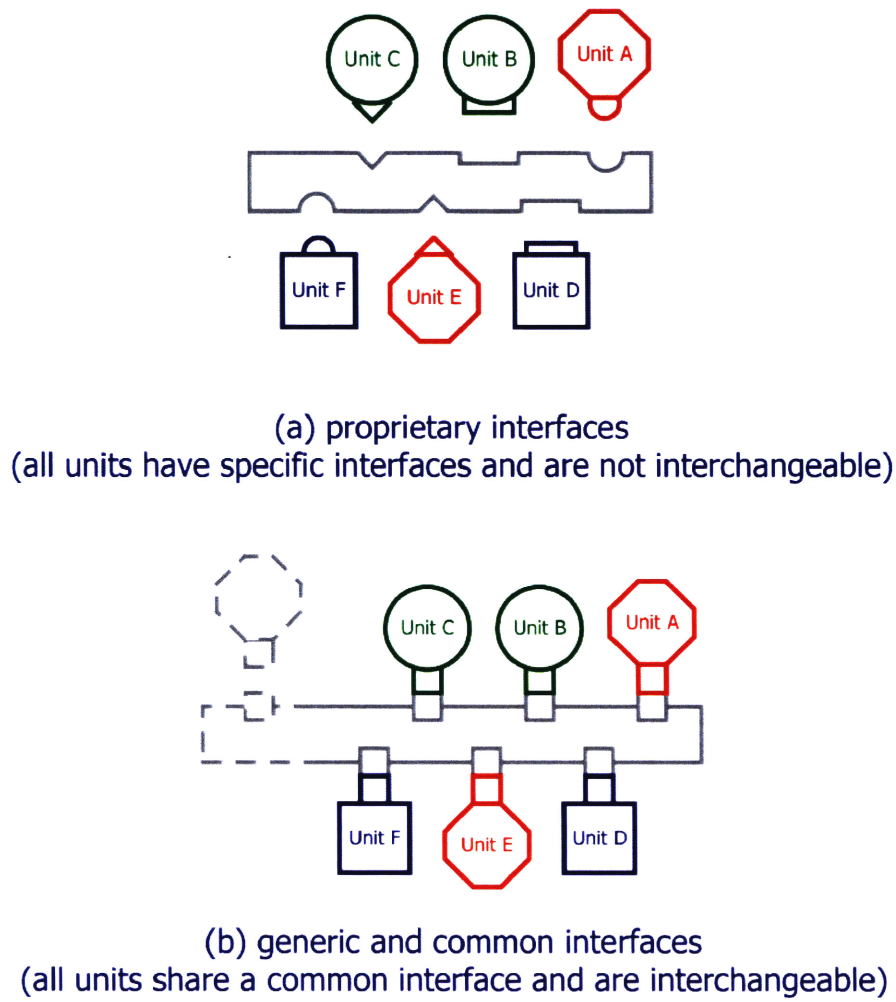


Figure 14: Principle of Integrability (Fricke & Schulz, 2005)

The third and final architecture principle highlighted in this section is the principle of scalability. According to *(Fricke & Schulz, 2005)*, scalability is "characterized by units independent from scale or self-similar/fractals." This principle allows architectures to scale up or down. One way this can be accomplished is when the basic system architecture provides the capability for an unrestricted increase or decrease of total unit size within the system. In this case, a single element of the architecture is downsized or upsized. *(Fricke & Schulz, 2005)* This method is visually depicted in part (a) of Figure 15. A second way to scale an architecture up or down is by linking together identical elements of the architecture to provide scaled performance or functionality. *(Fricke & Schulz, 2005)* This method is visually depicted in part (b) of Figure 15. To better understand the principle of scalability, *(Fricke & Schulz, 2005)* provide an example of the Ariane 4, a European Space Agency expendable launch vehicle that used additional boosters to send heavier payloads into orbit. They explain how the Ariane 4 employed the principle of scalability to customize each rocket to customer demand. This architecture principle supports a real options design approach because it provides the user with an expand option to use additional boosters if the expendable launch vehicle's payload increases.

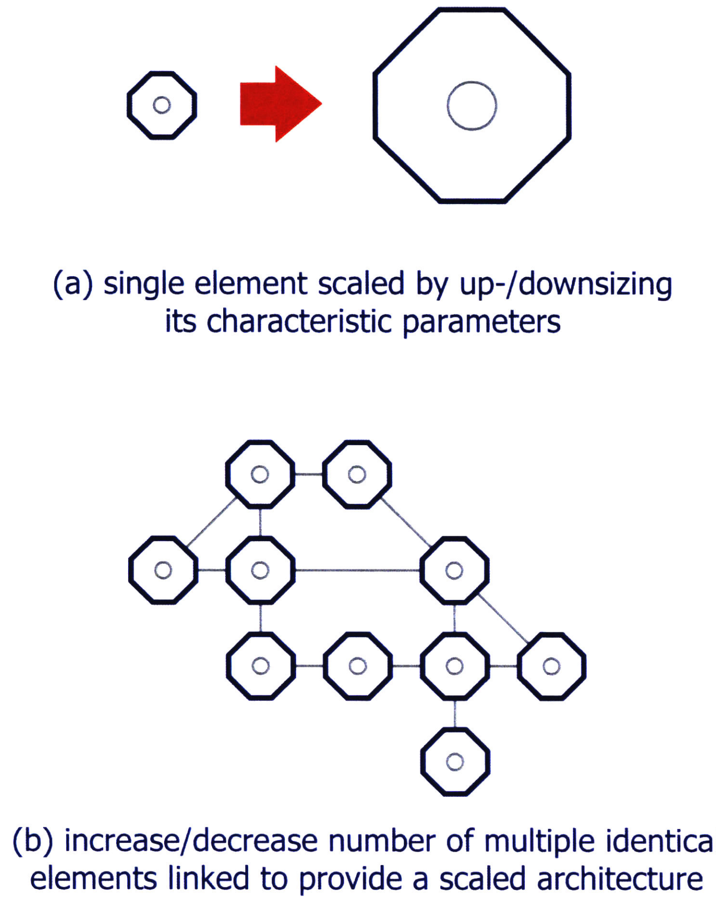


Figure 15: Principle of Scalability (Fricke & Schulz, 2005)

2.3 Architecture Approaches that Enable Adapt Designs

This section delivers an overview of one architecture concept that enables adapt designs: product platforms. As stated previously, this thesis does not provide an all-inclusive representation of architecture principles that enable flexibility, but instead references a sample to provide the reader a basic understanding of how to employ the two flexible design approaches explored in this thesis.

According to *(Madni, 2012)*, platform-based engineering employs a common structure through which derivative products can be rapidly developed. He highlights the two major characteristics of platform architecture:

1. The platforms are reusable, configurable, and extensible system implementation infrastructures that include both physical platforms (e.g., aircraft) and information platforms.
2. The platforms encompass domain-specific components and services that reflect the commonalities of systems in the domain and variables across the domain, along with the interface conventions that ensure they can plug-and-play with the domain infrastructure and common components. *(Madni, 2012)*

Similarly, *(Simpson, 2003)* defines a product platform as a "set of common parameters, features, and/or components that remain constant from product to product, within a given product family."

Just as *(Madni, 2012)* highlights two characteristics of platform architecture, *(Saleh, et al., 2009)* also summarize two basic approaches to platform-based engineering:

1. Choosing representative design parameters that can be scaled to produce variants.
2. Developing a modular product architecture that can be easily modified through the exchange of modules.

Based on the summary by *(Saleh, et al., 2009)*, it is clear several of the architecture characteristics that enable real options design (e.g., modularity, scalability) play a role in platform architecture and adapt designs. However, *(Crawley, et al., 2016)* identify the primary difference with platform architecture by explaining how "it must deal with the uncertainty of future applications" where future use cases and performance characteristics may not be known.

The diagrams in Figure 16 showcase blueprints for civilian and military variants of a helicopter manufactured by Sikorsky Aircraft. The drawings demonstrate the basic frame design and components that represent commonality across the five variants. They also highlight unique modular conventions such as the addition of torpedoes, auxiliary fuel tanks, and the external stores support system. Finally, the blueprints demonstrate how product platforms focus on architecture designs that allow for the creation of variants to optimize costs and reduce development time. *(Ferguson, et al., 2007)* As *(Saleh, et al., 2009)* explain, platform engineering brings about an ease of change to generate product derivatives that address different customer needs and requirements while allowing for cost reductions and economies of scope.

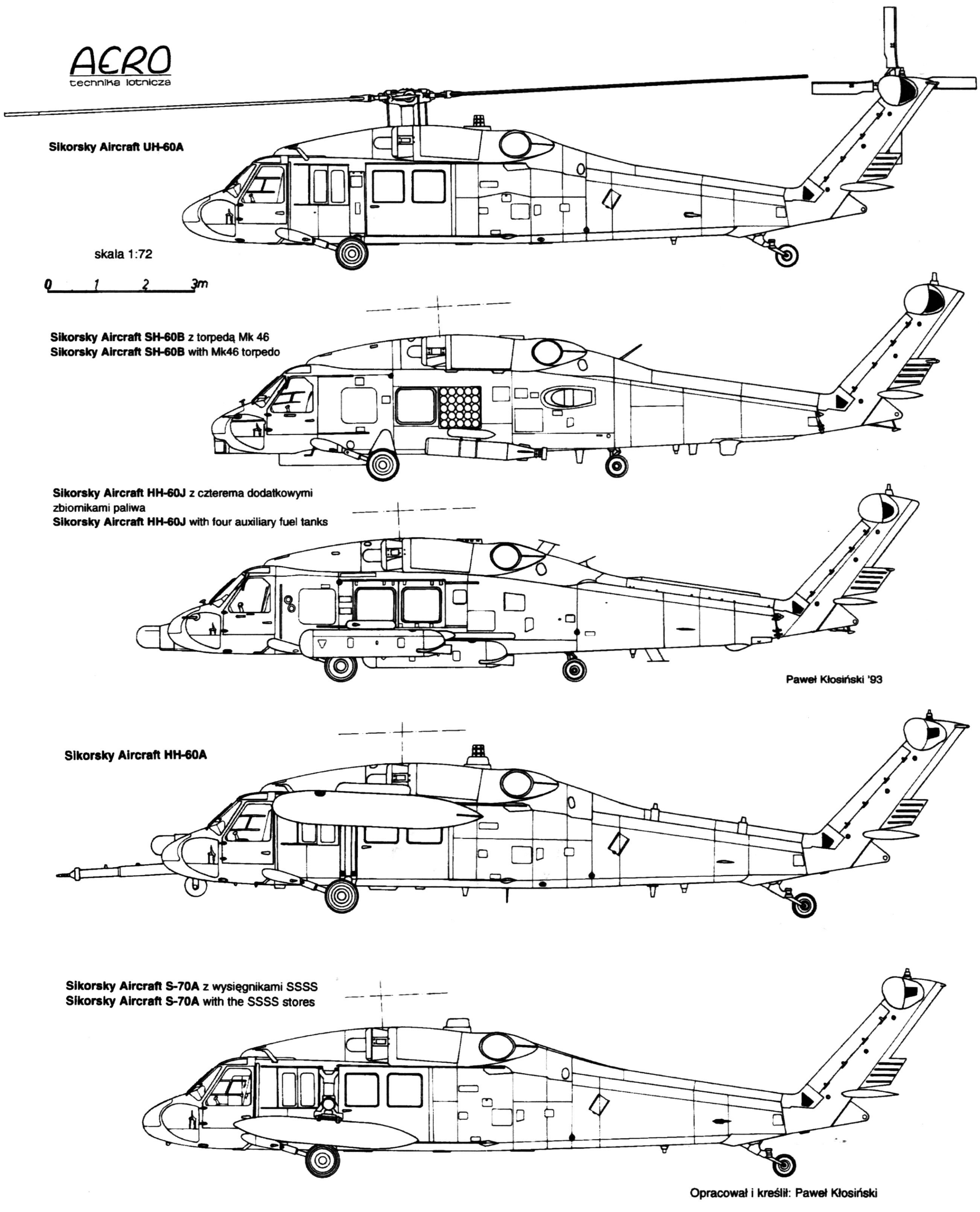


Figure 16: Sikorsky Aircraft Platform Variants (Klosinski, 1993)

2.4 DoD Examples of the Design Approaches

This section consolidates examples from relevant publications to provide a representation of DoD systems that fit the categories of optimized, robust, real options, adapt, limited, and overly complex designs.

The Coriolis satellite built by Spectrum Astro represents an example of an Air Force system that falls into the category of optimized design. The system was built as an experimental satellite for two specific purposes:

1. To demonstrate the viability of using polarimetry to measure ocean surface wind speed and direction from space
2. To demonstrate predictions of geomagnetic disturbances through the continuous observation of Coronal Mass Ejections *(Wade, 2019)*

The system had a three-year meteorological science mission, an objective based on the likelihood of demonstrating the above two requirements. *(Wade, 2019)* The power, command, data handling, and capabilities (e.g., WindSat Polarimetric Microwave Radiometer) were optimized for the mission of the satellite and were unable to be altered after fielding and launch. Spectrum Astro was selected to provide the satellite in March of 1999. As prime contractor, Spectrum Astro had end-to-end system responsibility, including spacecraft design, development, integration, and test. The company shipped the Coriolis to the National Research Laboratory in August of 2001, a mere two years after being selected for the prime contractor role. Then, in December 2002, the Coriolis was moved to the launch pad. *(Krebs, 2019)* and *(Wade, 2019)* Based on the Air Force's operating objectives, the level of certainty in the operating environment, and the intended design life, the Coriolis was optimized for a specific function that it met with satisfaction.

The Chrysler Defense M1 Abrams tank is an example of an Army system that falls into the category of robust design. The vehicle was designed in the 1970s as a Cold War reaction to the new generation of Soviet tanks and the US's failed MBT-70 program. With mounting Cold War pressure, Congress directed the Army to field the M1 under strict cost and time limitations. *(Gao, 2019)* Although the vehicle was intended for use in the moderate climate of central Europe, it ended up being driven extensively in Iraq during Operation Desert Storm. In a discussion with *The Washington Post,* Lt. Gen. Claude Christianson, a senior logistics officer, described how Abrams were being driven up to 4,000 miles a year, five times the number of miles at home training bases. *(Ricks, 2004)* The robust design of the M1 Abrams allowed for successful adaptation to a drastically different climate and prevented the Army from fielding a new tank or modifying the current tank to operate in the desert warfare environment of the Middle East.

The Sikorsky medium lift UH-60 Black Hawk helicopter is an example of an Army system that falls into the category of adapt design. The helicopter was developed in the 1970s in response to a rotary-winged aircraft program called Utility Tactical Transport Aircraft System. Decision makers required the helicopter to perform a variety of missions to include troop transport, air cavalry, and medical evacuation. They also dictated reliability and maintainability standards, as well as an all-weather, day/night capability. To meet these requirements, the UH-60 was developed under a platform architecture design (see Figure 16). *(Saleh, et al., 2003)* emphasize, "the intrinsic ability of the UH-60 baseline architecture to accommodate changes following new customer requirements – in a timely and cost-effective way in order to achieve a different configuration vehicle – made it possible to develop different derivatives." Today, the helicopter has over 35 derivatives that perform a series of expanded mission roles and capabilities beyond what was envisioned in the 1970s. *(Saleh, et al., 2003)*

The Boeing B-52 Stratofortress provides an example of an Air Force system that falls into the category of real options design. When the initial specifications for the bomber were issued in 1945, the system was designed to carry nuclear weapons, fly at high altitudes, and serve a Cold War-era deterrence mission. A few years later, the bomber's mission changed. The flexible design of the aircraft prevented the platform from becoming obsolete. Instead, the belly of the aircraft was reconfigured to carry air-launched cruise missiles for lower-altitude missions. This weapons load reconfiguration represents an example of a switch option. Additionally, many of the aircraft's systems could be decomposed into subsystems with well-defined interfaces. These subsystems could then be upgraded when new technology entered the market. As *(Saleh, et al., 2003)* explain, B-52 upgrades since the early 1980's include several new and improved systems such as:

- Offensive avionics
- Environmental control
- Auto-pilot
- Enhanced electronic countermeasures
- Engines

Each of the above enhancements represent examples of expand options that are primarily a result of the modular and integrable design of the aircraft's subsystems. For example, the aircraft's Pratt & Whitney engines were designed to hang low off of the platform as opposed to other aircraft with engines embedded within the wing. This flexible design feature permitted several relatively inexpensive and fast engine replacements throughout the life of the B-52. As a result of the B-52's highly flexible design, the bomber assumed conventional roles in Vietnam, the Gulf War, and Operation Enduring Freedom, drastically different environments from which the initial system requirements were derived. In fact, based on the bomber's flexible design, current engineering analysis shows the B-52 life span can be extended beyond the year 2045. *(Saleh, et al., 2003)*

The Convair B-58 Hustler is an example of an Air Force system that falls into the category of what *(Ferguson, et al., 2007)* describe as limited design. This bomber's system design was optimized to fly at supersonic speeds and high altitudes to avoid Soviet fighters. Shortly after fielding, intercontinental ballistic missiles entered the service. Unfortunately, the bomber's optimization led to an inflexible wing and airframe design that prevented the bomber from accommodating different weapons and performing missions other than the one it was initially designed for. With the B-58's primary mission removed and an inability to adapt to new roles in new environments, the B-58 was consigned to storage after only ten years in service. *(Saleh, et al., 2003)*

The Lockheed Martin F-35 Joint Strike Fighter is an example of a system that falls into the category of what *(Ferguson, et al., 2007)* describe as an overly complex design. The F-35 is a supersonic, multi-role, 5th generation stealth fighter. The aircraft has three variants derived from a common design: Conventional Takeoff and Landing (CTOL), Short Take Off/Vertical Landing (STOVL), and Carrier Variant (CV). In the early stages of development, Lockheed Martin targeted 70% commonality across the three variants. *(Boas, 2008)* As *(Boas, 2008)* points out, Lockheed Martin's main goal for the F-35's System Design and Development phase was to create an "affordable program through the development of a highly common tri-variant aircraft family and common manufacturing line. The expected benefits of commonality were a drastic reduction in development, manufacturing, and lifecycle operating costs." Specifically, Lockheed Martin attempted to build a flexible platform that could adapt to three different customer needs. However, several issues during the development of the F-35 forced Lockheed Martin to revert to optimized designs. *(Boas, 2008)* estimates the initial F-35s were delivered with 27.8% commonality in the CV variant, 29.9% commonality in the STOVL variant, and 39.2% commonality in the CTOL variant. *(Boas, 2008)*

(Boas, 2008) walks through the first of many design changes within the F-35 program. He describes how the original F-35 design heritage set the CTOL variant as the baseline, aimed to add STOVL capability after the CTOL was designed, and then planned to scale the CTOL for carrier operations. *(Boas, 2008)* explains "as the initial CTOL design matured, it became apparent the STOVL variant would be 3,000 pounds overweight." After this realization, the entire program came to a halt and restarted with a focus on the STOVL weight problems. Optimization of the airframe components for STOVL requirements became paramount to the program's success, as these components represented a significant amount of weight. Penalties that had been introduced for the sake of commonality could no longer be accepted. For example, the original, one-piece wing that enabled a high degree of commonality, proved too heavy and was modified for the STOVL version. Common weapons bay requirements were also changed

and optimized for the STOVL variant, which resulted in second and third order changes to the STOVL's bomb and missile capacity, bay doors, and actuator mechanisms. After this program re-plan, a decision was made to follow STOVL development with a second "optimized" CTOL design that would leverage the detailed STOVL design and prior CTOL development. Overall, the re-plan included a System Design and Development (SDD) cost increase of $5 billion, an 18-month SDD schedule extension, and the delay of the first CTOL flight by one year. *(Boas, 2008)*

2.5 Uncertainty

(Hastings & McManus, 2004) explain, "The Department of Defense's current environment of rapidly changing technologies, threats, needs, and budgets, has made it necessary to better understand classes of uncertainties and their effects on complex airspace systems." Over the past decade, there has been a growing amount of research published on the subject of uncertainty and on designs to reduce uncertainty. This section summarizes concepts from relevant literature to address uncertainty as uncertainty plays a significant role in determining an optimal system design approach.

2.5.1 Uncertainty Defined

Although uncertainty is used differently throughout a variety of fields, the following definitions provide insight into the meaning of uncertainty applied to engineering.

A conference proceeding from the 2004 MIT Engineering Systems Symposium defines uncertainty as a thing that is not known, or known only imprecisely and further identifies classes of uncertainties to include "known unknowns" and "unknown unknowns." Known unknowns are characterized by circumstances that are known with outcomes that are not known. Future budgets, adversaries, and the performance of new technology are examples of uncertainties that may fit into the category of known unknowns. Alternatively, unknown unknowns are "gotchas" that are not foreseen. An asteroid striking a vehicle is an example of an event that fits into the category of unknown unknowns. *(Hastings & McManus, 2004)*

Earl et al., outline a taxonomy for uncertainty similar to the one proposed by Hastings and McManus. They introduce the terms, "known uncertainties" and "unknown uncertainties." Known uncertainties are based on variability in past cases where the uncertainties are known, but their effects on behavior are not known. Unknown uncertainties occur as surprises when there is no expectation of such an event. The occurrence of 9/11 and its impact on the aerospace industry is provided as an example of an unknown uncertainty. *(Clarkson & Eckert, 2005)*

A proceeding from the 2007 International Conference on Engineering Design characterizes uncertainty as "an amorphous concept that is used to express both the probability that certain assumptions made during design are incorrect as well as the presence of entirely unknown facts that might have a bearing on the future state of a product or system and its success in the marketplace." *(de Weck, et al., 2007)*

All of the above definitions are relevant to this thesis.

2.5.2 Sources of Uncertainty

Although some sources of uncertainty are concealed, there are several identifiable sources of uncertainty that decision makers should attempt to understand at the start of a program's design effort. Understanding sources of uncertainty can help guide designers investigate project risks.

A proceeding from the 2007 International Conference on Engineering Design characterizes sources of uncertainty and their contexts in Figure 17. In addition to classifying uncertainty by context, uncertainty is categorized as either endogenous, arising from within the system boundary, or exogenous, uncertainties outside an enterprise's direct control. *(de Weck, et al., 2007)*

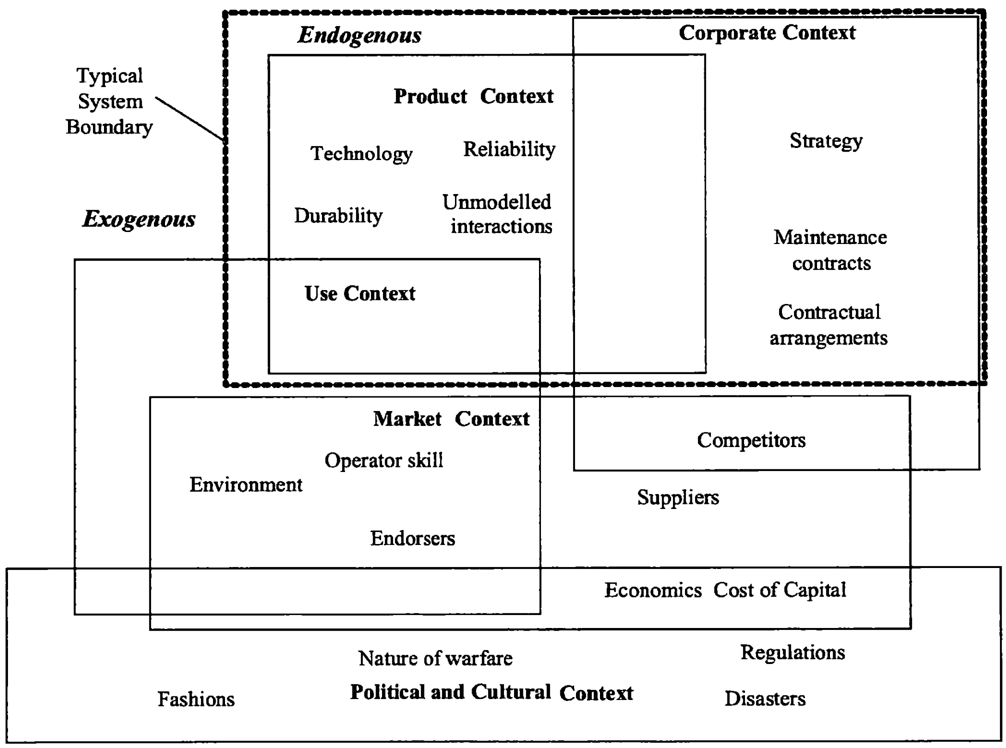


Figure 17: Sources of Uncertainty by Context (de Weck, et al., 2007)

In Figure 18, categorizes sources of uncertainty into different layers, but captures many of the same sources of uncertainty identified by *(de Weck, et al., 2007).* According to *(Lessard & Miller, 2000),* enterprises have greatest influence over the uncertainties near the inner layer and progressively lower influence over uncertainties in the outer layers.

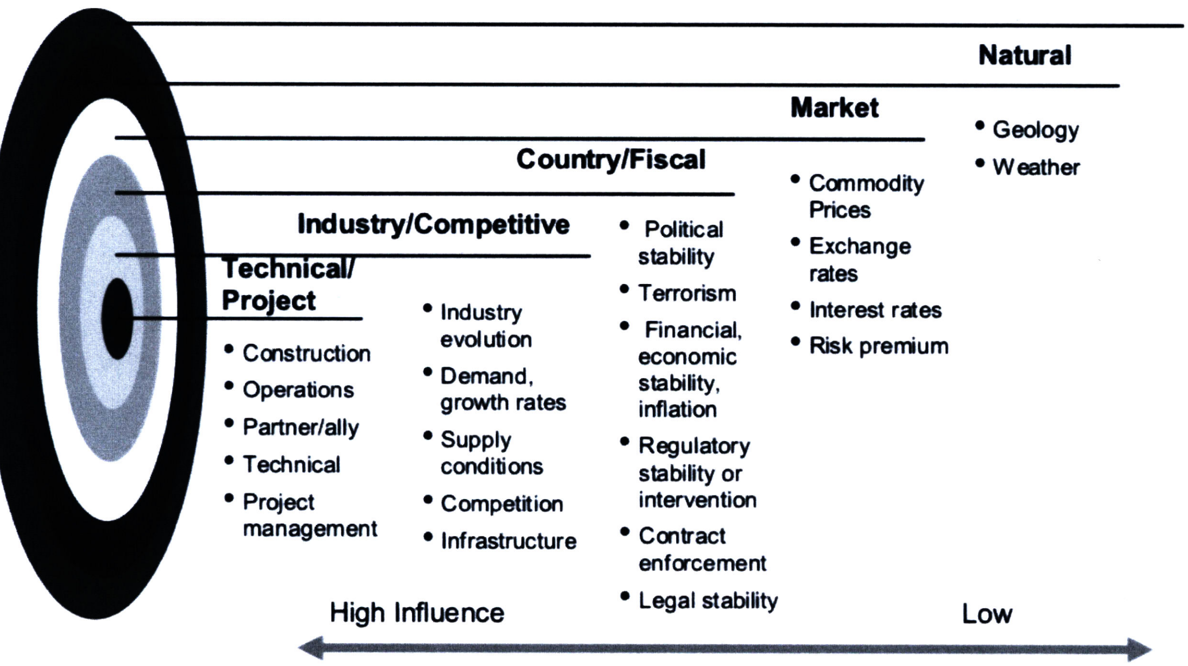


Figure 18: Sources of Uncertainty by Layer (Lessard & Miller, 2000)

Many of the sources of uncertainty outlined by *(Lessard & Miller, 2000)* and *(de Weck, et al., 2007)* relate to the challenges that contribute to highly complex, rapidly evolving environments highlighted by *(Saleh, et al., 2014)* and *(Shultz & Fricke, 1999)* in section 2.1.4 of this thesis. Where *(Saleh, et al., 2014)* focus on the rate of change of technology and the idea of a dynamic marketplace, *(Shultz & Fricke, 1999)*, describe variety of environment, technological evolution, and a dynamic marketplace.

In applying uncertainty analysis to satellite systems, *(Hastings & Walton, 2004)* define similar types of uncertainties deemed important to assess. They discuss "obsolescence uncertainty" as "uncertainty of performing to evolving expectations in a given lifetime" and "development technology uncertainty" as "uncertainty of technology to provide performance benefits." These sources of uncertainty are similar to the concepts of technological evolution and rate of change of technology. Akin to the concept of dynamic marketplace, *(Hastings & Walton, 2004)* define "market uncertainty" as "uncertainty in meeting demands of an unknown market." Finally, *(Hastings & Walton, 2004)* discuss "political uncertainty" as "uncertainty of funding instability."

2.5.3 Risks from Uncertainty

(Hastings & McManus, 2004) point out that there are consequences of uncertainties to a program or system and use the term "risk" to highlight the negative effects of uncertainty. Figure 19 lists general types of risks associated with an enterprise's inability to effectively plan for uncertainty.

The thesis decision framework seeks to reduce the risks associated with program deviations, market shifts, and need shifts.

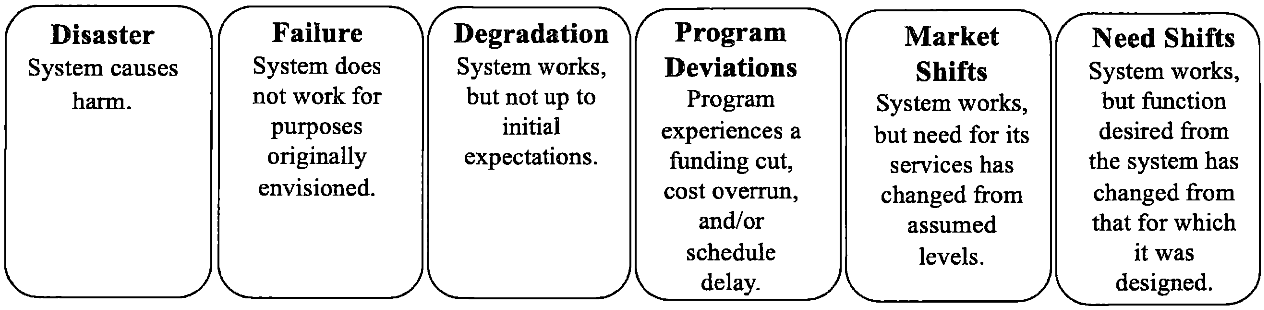


Figure 19: Types of Risks adapted from (Hastings & McManus, 2004)

(de Weck, et al., 2007) highlight how "uncertainty can negatively and positively impact the proper functioning and market success [of] any new or modified product. It can also impact how easy or difficult it is to incorporate changes in future generations of existing products and systems." Later, *(de Weck, et al., 2007)* explain "by ignoring uncertainty and relying only on past averages or best guesses, systems become inflexible. Once the true nature of demand reveals itself, necessary changes become slow and prohibitively expensive to make."

Given the motivation for this thesis is to construct a design framework that allows decision makers to more quickly and inexpensively respond to operational changes, incorporating uncertainty into the framework is vital.

2.5.4 Managing Uncertainty

(Hastings & McManus, 2004) list a series of uncertainty mitigation strategies used in consideration for aerospace systems to include:

- Margins: Designing systems to be more capable, to withstand worse environments and to last longer than necessary.
- Redundancy: Including multiple copies of systems or subsystems to assure that at least one works.
- Design Choices: Choosing design strategies, technologies, and or subsystems that are not vulnerable to a known risk.
- Verification and Testing: Testing after production to drive out known variation, bound known unknowns, and surface unknown unknowns.
- Serviceability/Upgradeability: Systems or subsystems that can be modified to improve or change function.
- Modularity, Open Architectures, and Standard Interfaces: Functions grouped into modules and connected by standard interfaces in such a way that they can plug-and-play.

- ➢ Tradespace Exploration: Analyzing or simulating many possible solutions under many possible conditions.
- ➢ Portfolios and Real Options: Program strategy of carrying various design options forward and trimming options in a rational way as more information becomes available and/or market conditions change.

A fundamental question is which of these strategies best applies in a given situation? Additionally, *(de Neufville, 2004)* discusses how "uncertainty can be actively managed and exploited [and can] provide opportunities." This thesis defines a method to manage and exploit areas of uncertainty by incorporating several of the above strategies into a decision framework that can be used to choose the most cost effective and responsive system design in a given situation.

2.6 Results of Literature Review

The literature review in this thesis summarizes relevant research conducted on static design approaches, flexible design approaches, and uncertainty. Table 7 synthesizes the key points of the design approaches. The table should be treated as a general guide.

Design Approach		When to Use the Design Approach					
		Environment		System's Objectives after Fielding		Circumstances of Uncertainty	
		Fixed	Changing/ Unknown	Fixed	Changing	Anticipated Changes	Unanticipated Changes
Static	Optimized	X		X			
	Robust		X	X		X	
Flexible	Real Options		X		X	X	
	Adapt		X		X		X
Design Approach		Primary Benefits of the Design Approach					
		Timely System Changes	Cost-Effective System Changes	Enables a Longer Service Life	Mitigates Risk of Technology Obsolescence/ Market Shift/ Needs Shift	Lower Upfront Development Costs/Shorter Upfront Development Schedule	Higher Initial Performance Levels
Static	Optimized					X	X
	Robust				X	X	X
Flexible	Real Options	X	X	X	X		
	Adapt	X	X	X	X		
Design Approach		Example Engineering Methods/Architecture Principles that Enable the Design Approach					
		Non-Dominated Designs on Pareto Front of Tradespace	Signal to Noise Ratio Comparison	Platform-Based Engineering	Modularity	Scalability	Integrability
Static	Optimized	X					
	Robust		X				
Flexible	Real Options				X	X	X
	Adapt			X			

Table 7: Summary of Design Approaches

Evident from the literature review, most research on engineering design is spread across different publications and sources. Few documents provide a consolidated overview of static and flexible designs, as presented in section 2.1. Additionally, with the exception of Figures 1-3, current research fails to offer a model or framework for choosing the most cost effective and responsive system design under a given set of objectives and uncertainties. An Office of the Deputy Assistant Secretary of Defense, Systems Engineering report explains, "looking towards the future, it is becoming increasingly apparent that, for defense systems, engineering design and development processes need to…support both rapid fielding activities and traditional acquisitions." *(Neches & Madni, 2013)* Similarly, *(Madni, 2012)* states, "there is a pressing need for models with the requisite semantics to represent different types of designs and to enable more detailed analysis of design properties."

Based on data obtained from the literature review, this thesis outlines and tests a decision framework for different types of engineering designs that respond to the above two needs.

3 System Design Framework

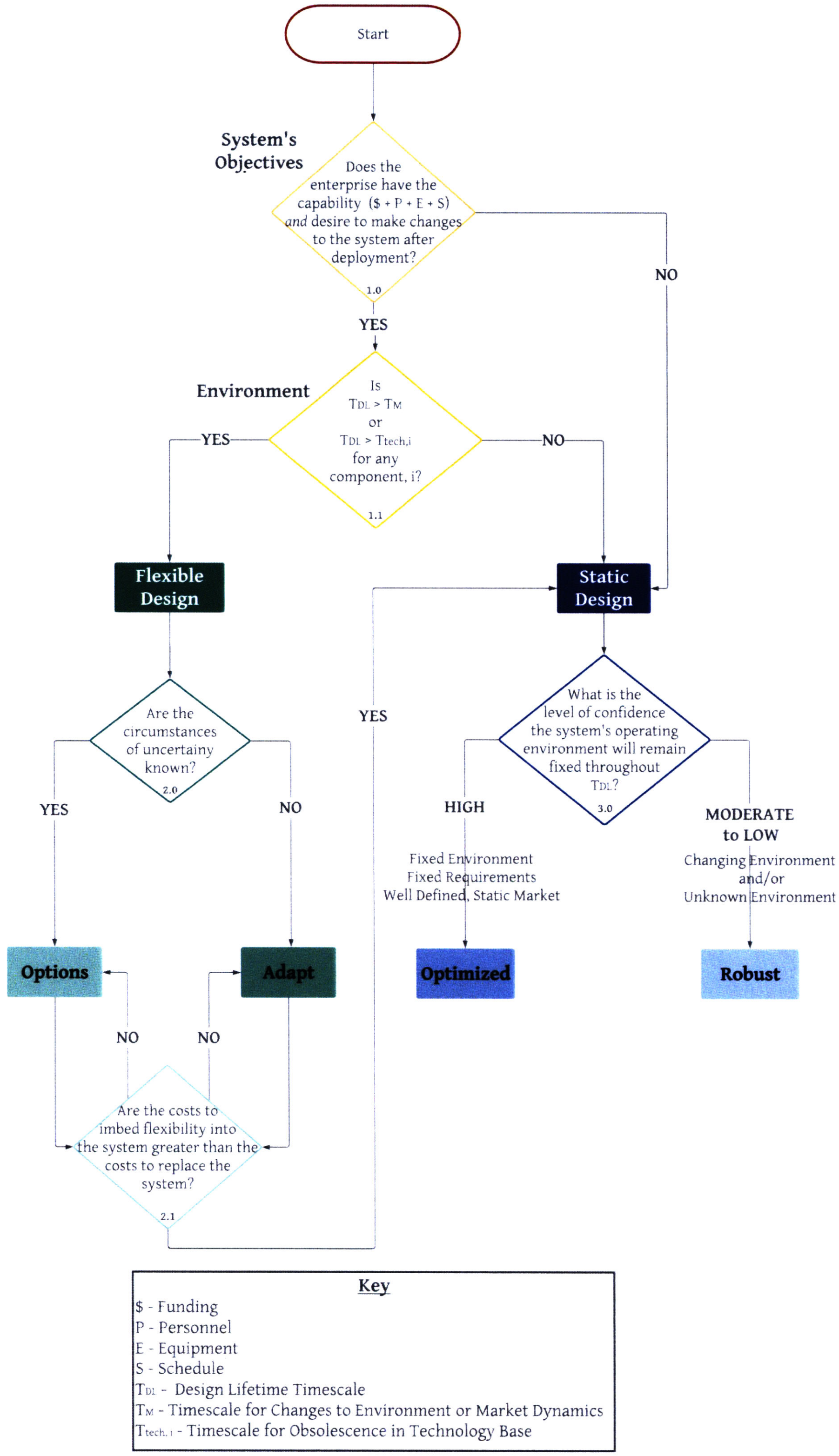


Figure 20: System Design Framework[2]

3.1 Framework Orientation

The above decision framework was developed out of the literature review material presented in Section 2 of this thesis. The framework is based off an understanding of the different design strategies and tradeoffs between those strategies. The goal of the framework is to direct a user to the most cost effective and responsive system design under a given set of objectives and uncertainties.

The framework is arranged through a vertical hierarchy of questions. Different sections of the diagram are characterized by contrasting colors. Yellow represents introductory questions that directly correlate to the tradespace depictions developed by *(Saleh, et al., 2014)* and *(Ferguson, et al., 2007)* in Figure 1 and Figure 2, respectively. Green illustrates a flexible design and the corresponding flexible design approaches explored in this thesis: options and adapt. Blue portrays a static design and the associated static design approaches explored in this thesis: optimized and robust. The rectangle labeled "Flexible Design" and the rectangle labeled "Static Design" exist on the same horizontal plane to represent the two umbrella categories of design approaches investigated in this thesis. The rectangles individually labeled "Options", "Adapt", "Optimized", and "Robust" are also depicted on a single horizontal plane. No one approach has greater importance over another approach. Selecting the optimal approach is based on tradeoffs between a particular system's future market needs, rate of technology change, and future operating environment paired with the value of the proposed design.

Users step through the decision tree, starting with 1.0, the yellow diamond marked "System's Objectives." By definition, a static design prohibits changes to the system's objectives after fielding, whereas a flexible design allows for relatively inexpensive and timely modifications to the system, if system objectives change after deployment. The question in 1.0 is twofold. If the answer to either or both parts of the question is "no", users proceed to the diamond labeled 3.0. If the answer to both parts of the question is "yes", users proceed to the diamond labeled 1.1.

The first half of the question in 1.0 asks if the enterprise has the capability to make changes to the system after it is deployed. This is determined by the availability of funding, the number of skilled personnel, the type/availability of equipment, and the enterprise's schedule availability. To answer this question, the enterprise must assess the ability and likelihood of getting these resources in the future, when modifications to the system will need to be made.

The second half of the question points to the enterprise's desire to make changes. It is possible the enterprise will have the capability to make changes to the system after deployment, but not the need. For example, a program office in the Space and Missile Systems Center (SMC) could be well equipped from a funding, personnel, equipment, and schedule perspective to modify a

[2] $T_{DL} > T_M$ and $T_{DL} > T_{tech,\,i}$, for any component, i are adapted from *(Saleh, et al., 2002)*.

satellite demonstrator after development. However, if the satellite demonstrator has a 2-year design lifetime and is sent into orbit for the sole purpose of collecting a specific mission set of data, there should be no additional need to change the system after the data is gathered.

If the answer to either part or both parts of the question in 1.0 is "no", users are directed to a subsequent question in a blue diamond marked 3.0. Answering 3.0 will determine the most cost effective and responsive static design approach for the system.

The question in 3.0 asks about the level of confidence in understanding the system's operating environment throughout the system's design lifetime, T_{DL}. In order to answer this question, a user must characterize two key decision variables: 1.) the system's intended design lifetime, and 2.) the potential environment(s) the system could operate in during its lifetime. The system's intended design lifetime represents the length of time in which the system is expected to operate before performance and/or capability degradation. Regular maintenance and sustainment efforts should be factored into calculating this figure. Additionally, the variable should be characterized in months or years, as applicable.

Predicting the system's operating environment(s) during its design lifetime requires market research. Depending on the nature of the system, research could involve discussions with intelligence officials, end users, or political and military advisors. Using forecasted elements of the Diplomatic, Informational, Military, and Economic (DIME) model and associated Political, Military, Economic, Social, Informational, and Infrastructure (PMESII) effects is another useful tool for understanding the system's potential operating environment(s).

If the enterprise has high confidence the system's operating environment will remain fixed during the lifetime of the system, the enterprise is directed to an optimized design. If the operating environment is expected to change, or if the enterprise has moderate to low confidence in understanding the system's operating environment(s), the enterprise is directed to a robust design.

In the following example, AF/A5R and SAF/AQX provide Air Combat Command (ACC) with an Urgent Operational Need (UON) to acquire (i.e., develop) a sensor that supports an expected six-month mission targeting insurgent operations in Afghanistan. Based primarily on the nature of materials used to satisfy the design of the sensor, the system has a design lifetime of eight months. ACC expects to field the sensor in five months. After conducting market research, the enterprise determines that during the next 13 months, it is very unlikely US operations will shift to a new environment. The enterprise has high confidence the environment for the sensor will remain fixed during its design lifetime. As a result, the enterprise is directed to an optimized design approach. In a well-defined, static market, an optimized design should offer the highest level of performance, lowest development costs, and shortest development timeframe compared to the other three design approaches.

In a modified example, the same sensor referenced above is expected to have a design lifetime of seven years, based primarily on the nature of materials used to satisfy the design of the sensor. ACC expects to field the sensor in five months. After conducting market research, the enterprise determines that during the next four years, it is very likely US operations will shift to a new environment in Africa where the sensor could provide valuable mission support capabilities. The enterprise has moderate to low confidence US operations will remain fixed in Afghanistan during the sensor's design lifetime. As a result, the enterprise is directed to a robust design approach. Proceeding with a robust design could result in an initial performance penalty and/or higher development costs over that of an optimized design. However, a robust design will allow the system to maintain a target performance despite various noise factors, minimize the risk of market or needs shift, and ultimately mitigate the threat of obsolescence should the system's environment change.

If the answer to both parts of the question in 1.0 is "yes", users are directed to a subsequent question in a yellow diamond marked 1.1. The question captures uncertainty related to different time scales or clockspeeds[3] involved in the system's operating environment. The question in 1.1 is twofold. If the answer to both parts of the question is "no", users proceed to the diamond labeled 3.0. If the answer to either or both parts of the question is "yes", users proceed to the diamond labeled 2.0.

In order to answer this question, a user must characterize three key decision variables: 1.) the system's intended design lifetime, T_{DL}, 2.) the timescale associated with changes to the system's operating environment or market dynamics, T_M, and 3.) the timescale associated with obsolescence for any component of the system, $T_{tech,\,i}$. All three figures should be characterized consistently using either months or years.

The first segment of the question in 1.1 asks if T_{DL} is greater than T_M. At a basic level, the question is examining if the environment is expected to change during the design lifetime of the system or if user needs are expected to change during the design lifetime of the system. The second segment of the question asks if T_{DL} is greater than $T_{tech,\,i}$. This segment queries if the embedded technology in the system will need to be updated in order to prevent obsolescence. It is important to note that although T_M and $T_{tech,\,i}$ are characterized as two different measurements, it is difficult to represent each term orthogonally. As *(Allen, 2001)* explains, "a shift or advance in technology can very often stimulate existing markets or open completely new ones. Similarly, market changes can stimulate technology change."

[3] The term "clockspeed" was characterized by Charles H. Fine in 1996 to characterize the rate of change of an industry.

The following example highlights how a user should proceed after answering each question. A highly advanced UAV is being developed with an expected design lifetime of four years. The enterprise determines market dynamics should change every five years and the technology embedded in the UAV will likely become obsolete four and a half years after fielding. These conditions would direct the enterprise to design a static system. Alternatively, if the enterprise determines market dynamics are expected to change every two years and the technology embedded in the UAV will become obsolete in six months, the enterprise would initially be directed to design a flexible system.

Unfortunately, the difficulty with the question in diamond 1.1 is estimating T_M and $T_{tech,\,i}$ using theoretical deduction rather than empirical observation. Methods for estimating T_M and $T_{tech,\,i}$ are discussed below.

As *(Saleh, et al., 2002)* explain, "market dynamics is a typical example of a macro descriptor that makes sense intuitively, but is difficult to formally capture and measure." Market dynamics are primarily driven by Porter's Five Forces (Figure 21). Different industries have varying dynamics. Some industries, such as information technology (IT), rapidly undergo dramatic changes. Other industries undergo little change and remain stable despite changes occurring elsewhere in the business environment. *(Saleh, et al., 2002)* Additionally, *(Fricke & Schulz, 2005)* suggest market dynamic might be indicated by "the number of competitors, strength of competition, or degree of uncertainty of customer needs."

(Allen, 2001) also discusses market change and the way in which customers' and society's needs vary in different ways and at different rates. He introduces the formula $(\frac{dM}{dt})$ to signify the rate of change of a market. The formula could provide insight into the similar relationship between T_M and T_{DL}. Unfortunately, neither *(Allen, 2001)* nor *(Saleh, et al., 2002)* provide a procedure for estimating the parameters. Additionally, *(Saleh, et al., 2002)* states, "it is doubtful whether such parameter[s] can be quantified."

A detailed literature reveals there is no well-defined calculation for determining if the market dynamics of a system will change during the system's lifetime. Therefore, it is suggested T_M be quantified through one of two methods:

Method one involves using the historical rate of change in the environment or market dynamics of a comparable system that has already been fielded.

In the following example, an enterprise is developing the computer network and associated IT systems to support a new Air Operations Center (AOC) for the Indo-Asia-Pacific region. In order to understand how often user needs are expected to change and whether changes to the operating environment may dictate changes to the systems, the enterprise reaches out to the current users and associated acquisition program offices responsible for developing and sustaining the 613th AOC assigned to Headquarters, Pacific Air Forces, Joint Base Pearl Harbor-Hickam, Hawaii. The enterprise learns user needs and market dynamics associated with the systems and subsystems supporting the 613th AOC change every four months to five years. Based on this response, and the intended 15-year design lifetime of the new AOC, the enterprise responds "yes" to this segment of the question in 1.1.

Although method one proves helpful for systems with a historical precedent, the DoD frequently develops new systems for which there is no like reference. In these cases, method one would not serve as a useful means to quantify T_M. If an enterprise does not have a historical, relevant, system in which to perform a market dynamics comparison, it is suggested the enterprise following method two.

Method two involves conducting market research and customer interviews to analyze the market using the Porter's Five Forces framework. The results of this analysis can be used to develop an estimate for the timescale associated with changes to the system's environment or market dynamics.

The Porter's Five Forces framework is depicted below in Figure 21.

Figure 21: Porter's Five Forces (Mind Tools, 2019)

Depending on the nature of the system, research associated with "competitive rivalry" should not be exclusive to domestic and international competitors, but should also include adversaries. If the enterprise is developing a weapon's system, for example, primary research should focus on the number of adversaries and the capabilities of those adversaries. Secondary research could be conducted on the differences between competitors (e.g., Boeing, Lockheed Martin, and Raytheon). However, if developing a pay system for DoD employees, understanding adversary systems would be less important than researching the competitive IT market related to financial management systems.

In addition to forecasting T_M, the second segment of the question in diamond 1.1 requires users to determine the timescale for obsolescence in the technology base of the system. A literature review on the topic reveals a useful formula for answering this segment of the question. The below formula, adapted from *(Saleh, et al., 2002)*, captures time to obsolescence and the "H Vector" of a design. The formula is also explained in detail using text from *(Saleh, et al., 2002)*.

$$H = \left[\frac{T_{obs_1}}{T_{DL}}, \frac{T_{obs_2}}{T_{DL}}, \ldots, \frac{T_{obs_n}}{T_{DL}} \right]$$

> "Where T_{obs} represents Time to Obsolescence, we define the H vector of a system with a design lifetime of T_{DL} as follows:
>
> H characterizes the exposure of the design to problems of component obsolescence, starting from the time the system is fielded. A system is unaffected by obsolescence problems if $H_i \approx \theta(1)$, i.e., is of the order of 1, for all i. In other words, all components have similar Time to Obsolescence to the system's design lifetime. When this is not the case, H allows program managers to identify problem components that are likely to become obsolete early in the system's operational life, that is, for which $H_i << 1$, and to take actions in order to mitigate the risk of early component obsolescence." *(Saleh, et al., 2002)*

(Saleh, et al., 2002) also provide the following micro-level example of applying the above formula to a subsystem on the Boeing 777.

> "In the case of the Boeing 777 and the Intel 80486 in its Flight Management System (FMS), it is well known that Intel introduces major product improvements on the market every sixteen to twenty-four months. The price of the current product is reduced when the new product is introduced; then, as the market assimilates the

new product, the older product is typically phased out in three to four years. Assuming the 777 will remain in service for thirty years, then:

$$H_{\mu p} \approx \frac{3}{30} = 0.1$$

It is therefore clear that the processor will become obsolete during the aircraft's operational lifetime (assuming all else remaining constant, the processor will be lagging ten generations behind the technology leading edge by the time the aircraft is consigned to storage). Upgrade opportunities that offer improved or new functionality will therefore become available. The aircraft's FMS should be designed in a way to accommodate changes in a timely and cost-effective way, that is, flexibility should be embedded in the design of the FMS." *(Saleh, et al., 2002)*

To validate the decision framework, the above formula will be applied to macro-level components and/or subsystems of DoD systems.

In the following hypothetical example, an enterprise is evaluating $T_{tech,\,i}$ for the design of a new AIM-9X Block IV Sidewinder Missile. The enterprise expects the missile to have a T_{DL} of 15 years. The enterprise breaks out each major component of the AIM-9X as shown in Figure 22.

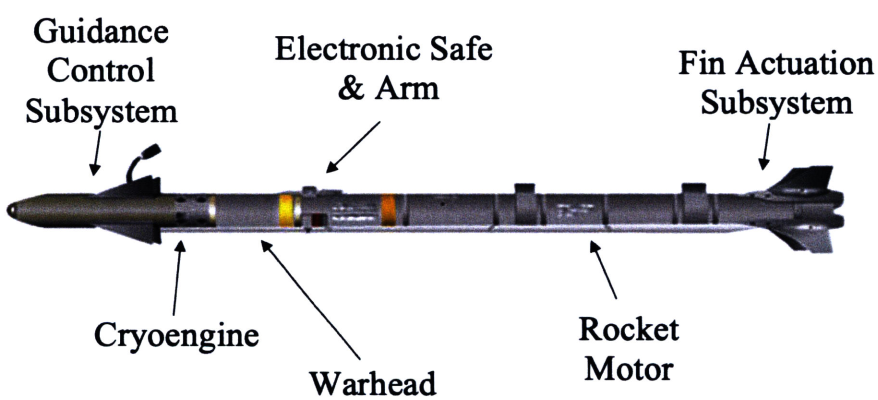


Figure 22: AIM-9X Subsystems adapted from (Global Data, 2019)

Through detailed research, the program office determined rocket motors are stable pieces of technology. The current state-of-the-art rocket motor being used for the Block IV could last 16 years before a major improvement is introduced to the market. Setting up the equation for this component, as shown in, Figure 23 reveals $H_{rm} \approx \frac{16}{15} = 1.07$. It is clear the rocket motor should not become obsolete during the missile's operational design lifetime. There is no need to imbed flexibility into the design of the rocket motor. The enterprise then examines the warhead. The Block IV aims to use a new insensitive munitions warhead. The warhead could last 17 years before a major improvement is introduced to the market. Setting up the equation for this component, as shown in Figure 23, reveals $H_w \approx \frac{17}{15} = 1.13$. It is unlikely the warhead will become obsolete during the missile's operational design lifetime. As such, there is also no need to embed flexibility into the design of the warhead. The enterprise then explores the guidance control unit. Despite the fact that the Block IV will incorporate an advanced Imaging Infrared seeker, the enterprise determines major adversaries make improvements to their Infrared Counter Measure (IRCM) systems every seven to eight years. Setting up the equation for this component, as shown in Figure 23, reveals $H_{gc} \approx \frac{7}{15} = 0.47$. It is clear the guidance control unit could become obsolete during the missile's operational design lifetime. More advanced adversary IRCM capabilities would limit the usefulness and accuracy of the Block IV's seeker and Infrared Counter Counter Measure (IRCCM) technology. Therefore, the enterprise may want to embed flexibility into the electronics component of the guidance control unit and allow the IRCCM technology to be reprogrammable, for example. Regardless, the enterprise would proceed through the remaining components of the AIM-9X in a similar manner and respond "yes" to this segment of the question.

Rocket Motor *Warhead* *Guidance Control Unit*

$$\boldsymbol{H} = \left[\frac{16}{15}, \frac{17}{15}, \ldots, \frac{7}{15} \right]$$

Figure 23: Hypothetical H Vector of AIM-9X

The next question in the framework is located in a green diamond labeled 2.0. This question refers to whether the enterprise understands where the uncertainty will come from. If the enterprise has a deliberate understanding of the uncertainty, the answer is "yes" and the user is directed to an options approach. An options approach reduces risks for known unknowns.

Alternatively, if the enterprise recognizes uncertainty exists (e.g., based on the long timeframe associated with T_{DL}), but cannot anticipate the circumstances surrounding the uncertainty, the answer is "no" and the user is directed to an adapt approach. An adapt approach reduces risks for unknown unknowns.

In the following example, an enterprise is developing a mobility vehicle with the capacity to seat 12 personnel and nine cubic feet of equipment. Through conversations with the lead Major Command (MAJCOM) and warfighters, the enterprise recognizes user needs may change throughout the mission. Specifically, there is an indication the vehicle will require less personnel capacity and more equipment space. In this example, the enterprise obtains a deliberate understanding of the uncertainty and can build in the option to easily remove seats in order to reduce personnel seating capacity and increase equipment capacity.

The final step in the flexible design path of the decision framework requires answering a question in a green diamond marked 2.1. The question directs the user to calculate whether the lifecycle cost of embedding flexibility into the system is greater than replacing the system. Highlighted in the literature review, there can be additional complexity for designing flexibility into a system. The additional complexity may result in cost penalties during the initial development of the system. Therefore, it is possible an enterprise can build a static system and replace that static system before it becomes obsolete for a lower total ownership cost than the cost of one flexible system. When responding to this question, it is important to note that there are additional tangential impacts to consider such as the cost of retraining the end user on a second optimized system or the risk of a schedule slip to the second optimized system. These additional costs need to be factored into answering the question.

In a typical DoD program office, answering the question in 2.1 would require the assistance of a cost analyst or cost estimation team. Depending on the enterprise's resources, a prime contractor may also assist in pricing out the contrasting design options. While the DoD has extensive experience estimating the lifecycle cost of static systems, less emphasis and training has been placed on evaluating the cost of flexible systems. However, over the last two decades, several scholars have developed methods for valuing flexibility. In addition to traditional approaches using Net Present Value or Discounted Cashflows, *(Casanova, et al., 2016)* introduce a binomial lattice pricing model that places a numerical value on design options. *(Saleh, et al., 2003)* suggest a different tool for capturing the value of flexibility. They use a concept coined Decision Tree Analysis (DTA) and demonstrate application of the tool to both nonprofit and commercial on-orbit systems. Finally, *(Kalligeros & de Weck, 2004)* take a third approach. They use standard options valuation theory and optimization techniques to value the design of an Exploration Headquarters for British Petroleum in Aberdeen, Scotland.

4 Research Method and Approach

4.1 Methodology

In order to inform the usefulness and understandability of the system design framework outlined in Figure 20, I conducted interviews with ten Air Force FGOs. Candidates were selected as participants in the research based on their experiences in the DoD. A typical Air Force FGO has a minimum of ten-years time-in-service; some FGOs have accumulated over 20 years of service in the military. Many engineer and acquisition coded FGOs have worked with over five distinct systems at varying decision-making levels. By targeting this segment of officers, I was able to obtain feedback from individuals who have demonstrated an understanding on many different types of systems that will be discussed further in section 4.2.

All participants received a two-page thesis primer (Appendix B) approximately one week prior to the interview. Interview candidates also signed a consent to participate form that indicated the voluntary nature of the interview, lack of compensation for participation, and the fact that the interview would not be recorded. Finally, interview participants were notified their names would not be identified in the thesis.

Nine of the ten interviews were conducted in person. The remaining two interviews took place over the phone. All interviews were conducted individually and each interview lasted approximately one hour.

Each interview began with four demographic questions and progressed through the aid of a PowerPoint presentation[4] (Appendix C). Following the demographic questions, each participant received the same introduction and definition of the following terms: static design, optimized design, robust design, flexible design, options design, and adapt design. After each participant confirmed an understanding of the terms, the session proceeded with a serial walkthrough of the framework's decision steps. Feedback was gathered at each step and specific questions were asked both during the walkthrough and at the conclusion of the walkthrough. The voice track of the presentation and associated examples reflected similar language to the material in section 3.1 of this thesis.

Figure 24 displays the questions asked during each interview.

[4] The final System Design Framework in Figure 20 is different from the original framework used for each interview. Specific differences include the number scheme, the layout, the statements in Figure 20's diamonds labeled 1.1 and 3.0, and the language used for T_M and *Ttech, i* in the key. Modifications to the final System Design Framework shown in Figure 20 were made based on feedback from the ten interviews.

Before Presentation:

- How many years of experience do you have in a program management role in the Air Force?
- How many years of experience do you have in an engineering role in the Air Force?
- Do you have any Air Force experience in other roles?
- Can you describe the different levels of experience in which you have worked (e.g., Program Office Level, SAF/AQ, etc.)?

During Presentation:

Diamond 1.0

- Do you have suggestions for more appropriately assessing "capability"?
- In your experience in the Air Force, who would answer this question?

Diamond 3.0

- In your experience in the Air Force, is the design lifetime of a system something discussed prior to development?

Diamond 1.1

- Do you have any suggestions for how to better assess market dynamics?

Diamond 2.1

- Based on your experience in the Air Force, who would calculate the cost for each type of system?

After Presentation:

- Can you point out any portions of the framework that are confusing or incorrect?
- Do you have recommendations for making the framework more understandable?
- Do you know of offices in the Air Force where people make these kinds of decisions?
- In your opinion, who should be worrying about this topic? The Chief Engineer at the program office level? The Program Manager at the program office level? SAF/AQ?
- Does the framework appear to be a useful tool for an Air Force program office responsible for designing, developing, and fielding a system? Why or why not?
- Are there certain Air Force program offices where the framework would be more or less applicable?
- Where do you think is the best place to teach this framework?
- Can you think of a program you have worked on where this framework would be applicable? If so, walk me through the framework at a very high level so we can talk through how this would be applied and identify any potential weaknesses in the framework.

Figure 24: Interview Questions

4.2 Profile of Interview Participants

The ten candidates I interviewed had a collective 70 years of DoD experience in program management roles and 83 years of DoD experience in engineering roles. The interview participants held air force specialty codes (AFSCs) of either 63A (Acquisition Manager) or 62E (Developmental Engineer) for the majority of their time in the Air Force. Several FGOs had career broadening tours. These interview candidates brought experience from Missile Operations (13N), Air Battle Management (13B), Officer Training School (81T), Financial Management (63F), and Cyberspace Operations (17D).

Many of the interview participants had Air Force assignments in other DoD agencies to include the Defense Threat Reduction Agency (DTRA), the National Geospatial-Intelligence Agency (NGA), the National Reconnaissance Office (NRO), the National Security Agency (NSA), and the United States Navy (USN).

In addition to working in System Program Offices (SPOs) at the Air Force Life Cycle Management Center (AFLCMC), Air Force Research Lab (AFRL), and SMC, five interview participants held Program Element Monitor (PEM) positions with SAF/AQ, four candidates worked at either the squadron or wing level for test engineering, four participants served in positions at the Program Executive Office (PEO) level, one interview candidate worked at Kessel Run, and one candidate served in a legislative liaison role.

Finally, the following list demonstrates a subset of the programs the interview candidates developed and sustained: aircraft hardware; aircraft software; air operations center information technology; battle management systems; command, control, & communication technology; Global Positioning System (GPS) user equipment; intelligence sensors; intelligence satellites; meteorological satellites; nuclear power plants; radars; small launch vehicles; and UAVs.

5 Summary of Results

5.1 Interview Responses

This section summarizes the interview responses from the ten participants. It does not restate each individual response to the 13 questions, but accurately captures the primary feedback provided by the collective group of candidates. Participants are not referred to by name in order to maintain anonymity.

After reviewing the content in diamond 1.0, participants were asked to provide additional suggestions for assessing an enterprise's capability to make changes to a system after deployment. Initially, most interview candidates confirmed the current suggestion of funding, personnel, equipment, and schedule is sufficient. A few participants discussed other variables to include political power, knowledge, and authority/scope. Through further exploration of the topic, we determined political power would be subsumed by funding and the desire to make changes to the system. In examining "people", we resolved that the enterprise must consider more than the number of personnel. "People" encompasses the ability to obtain the correct number of employees *with* the requisite skillsets to design, develop, and appropriately modify the system. Finally, we agreed authority/scope would coincide with leadership's desire to make changes to the system after deployment and get appropriately inserted into the necessary congressional justification documents (e.g., R-Docs). At the conclusion of discussions, each interview candidate confirmed satisfaction with the original variables.

Several interview participants attempted to find weaknesses in this decision step and prompted discussion of the following questions that will be addressed in section 6.1:

- What if the enterprise does not have the correct number of people, the right equipment, or enough funding, but the desire to make modifications is so strong they are willing to take a risk and build a flexible system?
- What if an enterprise answers "no" to the questions in diamond 1.0 and proceeds to a static system, but during sustainment of the static system, they discover significant modifications need to be made to keep the system relevant and current with emergent technology?

After focusing on the first half of the question in diamond 1.0, interview candidates were asked to identify the decision-making body in the Air Force that would assess whether the enterprise has the desire to make changes to the system after deployment. Responses consistently pointed to a collaboration between the end users/warfighters, the lead command, and the requirements sponsor for the system (e.g., the MAJCOM). Several participants also suggested collaboration would need to include SAF/AQ and the program office. Ultimately, participants concluded the decision-making body will vary based on the nature/type of system and its dollar value. A comprehensive answer to this question is addressed further in section 6.1.

As the interview progressed to an overview of diamond 3.0, participants were asked if "design lifetime" of a system is something discussed and identified prior to development. This is a crucial question because two sections of the framework depend on the identification and accuracy of a system's intended design lifetime. Every candidate with SPO-level development experience confirmed a system's design lifetime is addressed before development. In many experiences, this timeframe is initially informed by the requirements sponsor/end user, developed by the engineering staff, and levied on the contractor.

Several interview participants identified a weakness in using this variable in the decision framework. They highlighted that design lifetime is not always accurate and frequently underestimated. Specifically, the Air Force operates many satellite systems (e.g., Block IIA, IIR, and IIR-M satellites in the GPS constellation) and major weapons systems (e.g., A-10, F-16, F-15) for a much longer period of time than originally intended. In many cases, the Air Force struggles to provide an accurate design lifetime because of the difficulty in predicting the future. Sometimes schedule delays prevent the on-time fielding of a follow-on system, requiring the operational system to remain in sustainment longer than expected. Other times, Congress acts to keep systems in service to avert factory shut-downs within their districts. A response to this observation is explored further in section 5.2.

Following a discussion of diamond 3.0, the interview shifted to diamond 1.1. Interview participants were asked to provide suggestions for better assessing market dynamics. Each participant confirmed the two methods in the framework appear sound. Approximately half the interview candidates were aware of the Porter's Five Forces framework prior to the interview; the other half learned the framework during the interview and found it useful. Many participants provided insights to supplement and enhance the framework. These comments are summarized below:

- Several participants suggested modifying Porter's Five Forces to more appropriately fit the types of systems created by the DoD. They highlighted how the category "competitive rivalry" could be applicable to IT, business enterprise systems, and computer environments. Historically, competitive forces and rivalries play an important role in how the Air Force leverages commercial technology. However, suggestions were made to tailor this category to "adversary rivalry" for other types of systems (e.g., weapon's systems) where adversary capabilities are more important than domestic or international competition. This feedback was accepted and captured in section 3.1.
- In line with the previous point, one interview candidate highlighted how all five categories of Porter's Five Forces may not always be relevant for estimating the

timescale for market dynamics. This FGO provided an example of working at the RCO, where a significant portion of the portfolio focuses on building capabilities that do not already exist. As a result, market research is used extensively to shape the design strategy of RCO-developed systems. While market research teams spend considerable time understanding supplier power, adversary capabilities, and threats of substitution, buyer power remains an irrelevant area of research because the RCO rarely purchases off-the-shelf capabilities, supplies, and/or materials.

- Several participants brainstormed other analytic planning tools, such as the strengths weaknesses opportunities threats (SWOT) analysis. Each candidate concluded Porter's Five Forces was most appropriate for the context of determining market dynamics.
- Many interview candidates highlighted the importance of looking beyond the domestic landscape when conducting market research in line with the Porter's Five Forces framework. Depending on the nature of the system and technology being used, exploring the progress of international governments and commercial entities can be a valuable source for improving the accuracy of the market dynamics estimate. However, looking at internal market research should not be underestimated. Market research teams should be adequately trained to scour domestic labs and gather data on the science and technology developed within the US's government community.
- One participant emphasized the DoD's limited existence of inbound marketing practices. The military tends to rely on a formal needs procedure for processing requirements through the Joint Requirements Oversight Council (JROC), but stops short of conducting extensive market research. Increased education and training in the area of market research may be necessary to ensure the DoD is capable of carrying out this decision-making step.
- Several interview candidates stressed the difficulty in predicting the future market dynamics of a system. It was concluded that in the absence of concrete information, the enterprise will have to make an estimate based on reasonable judgement.

The next interview question took place after explaining diamond 2.1. The question asked candidates to look at their experiences across the Air Force and determine who would calculate the cost estimates required to compare the flexible system against the series of static systems. Most responses pointed to a collaboration between the SPO-level cost analysts and subject matter experts (e.g., engineering staff). Depending on the arrangement of the program office, the information could also be validated at a higher level (e.g., SAF/AQ or SAF/FM) or through the prime contractor's independent estimate.

All participants agreed there are additional tangential impacts to consider when building the cost estimates. Risk (e.g., schedule slips), training costs, and logistics costs were the primary areas discussed as supplementary inputs necessary to shape this decision. This feedback is captured in section 3.1.

Finally, a few participants noted the degree of resources required to appropriately respond to this question. For a start-up program office not yet staffed for development or for a well-established SPO managing a portfolio of multiple systems, developing these cost estimates may prove cumbersome and take several weeks or months to carry out. This is a clear limitation of the framework, discussed further in section 5.3.

After walking through the framework, diamond by diamond, interview candidates were asked a series of general questions.

The first general question solicited feedback on portions of the framework that are confusing or incorrect. Interview candidates were also asked to provide recommendations for making the framework more understandable.

In terms of identifying mistakes in the framework, the first interview candidate pointed out an incorrect use of the logic tree for decision 1.1. The error was fixed immediately after identification and confirmed as valid by the remaining participants.

Several participants noted inconsistences for measuring the variables in decision 1.1. The original framework indicated the enterprise needed to determine the rate of change in market dynamics and rate of change in technology and compare those figures to the design lifetime. Users were asked to equate rate of change in time against time, two unequal units. This inconsistency was fixed in section 3.1.

Many of the candidates spent considerable time analyzing the sequential relationship between the question in 1.0 and the question in 1.1 in order to determine whether the two decision points were placed in the correct order. Each candidate concluded the order is valid.

When asked to identify confusing portions of the framework, approximately half the participants self-identified as understanding the framework before I walked them through each step. The other half acknowledged many terms, variables, and decision points were initially confusing, but understandable after the in-depth walkthrough presentation I delivered. As one Officer explained, "there is no way you can hand this to someone and say 'go', but the framework is very straightforward with the appropriate level of instruction" *(Officer, 2019)*. This comment highlights a recurring theme of training that will be further explored in a subsequent interview question and in section 5.2.

Another area some participants noted as confusing involves the characterization of flexible design. After walking through the AIM-9X example, also detailed in section 3.1, several interview candidates discussed how a flexible approach does not mean every component in the system is flexible, but only that some components contain flexible design attributes while other subsystems contain static design features. This is a valid point, that should be incorporated into training.

Finally, many interview participants provided feedback for making the framework more understandable. Below is a summary of those suggestions:

- The loop back from diamond 2.1 back to static design could use an interim step that involves calculating the value of the different options from a long-term perspective. This feedback was incorporated by expanding the definition of "cost" in diamond 2.1.
- Many participants asked where the framework fits into the acquisition cycle/process and emphasized the importance of identifying when the enterprise needs to use this tool. Most interview candidates noted the framework was clearer after the realization that it is a pre-milestone (MS)-A exercise. However, these same participants continued to stress the importance of figuring out the specific acquisition document or engineering task that dictates the requirement to start walking through the framework. This topic is discussed further in section 6.1.
- In line with the previous suggestion, most interview participants expressed the importance of identifying the entity responsible for answering each decision point in the framework. Many FGO's suggested complementing the ACAT decision authority chart found in Enclosure 1 of DoD Instruction (DoDI) 5000.02. One candidate proposed using a stakeholder classification model such as DACI (Driver Approver Contributor Informed) or RACI (Responsible Accountable Consulted Informed) to categorize the role for each level in the enterprise at each decision step. This topic is discussed further in section 6.1.
- A few interview participants noted the visual imbalance of the original framework layout and suggested moving the static design box onto a parallel plane with the flexible design box in order to prevent users from assuming the framework placed emphasis on the static design options. This feedback was incorporated in section 3.1.
- An interview participant with experience in sustainment suggested official documentation dictating the outcome of the design framework that stays with the life of the program. This could negate the problem in which a sustainment office is directed to modify a static system, without fully recognizing the system is static and without a proper understanding of the high cost and technical difficulty of modify static systems.

After providing the above feedback, interview candidates were asked to identify offices in the Air Force where people already make the types of decisions present in the framework. The majority of interview participants alluded to the fact that many SPOs touch on similar decisions. One Officer discussed his experience with Air Force software systems, describing the design decisions the engineering team evaluates with regards to modularity and open architecture. Another Officer expressed how the RCO focuses on several of the framework concepts, without using the same terminology. Finally, a third FGO with experience in the NRO mentioned a comparable decision cycle conducted during early system design that focuses on available materials, sensors, and technology. However, all interview candidates agreed current decision-making processes are not carried out through a series of methodical tradeoffs between value, user needs, and the future operating environment.

Overall, it was greatly acknowledged that program offices do not make a concentrated effort to address all of the decisions present in the framework. As a result, acquisition programs fail to develop systems that represents the most cost effective and responsive design given an understanding of each system's future market needs, rate of technology change, and potential operating environments. As one FGO explained, "most program offices should be making these decisions, but in the absence of a well-defined framework, their design choices are executed in the dark." *(Officer, 2019)*.

Following the discussion on what offices make the decisions present in the system design framework, interview candidates were asked who should be worrying about this topic. Responses to this question varied. Most participants pointed to the MAJCOM, because they own the mission. Other participants emphasized the importance of SAF/AQ or a higher headquarters level in conjunction with the MAJCOM as the former creates acquisition policy and the latter defines the requirements that will shape the decisions in the framework.

Several FGOs commented that everyone in the chain needs to worry about this topic. As one Officer highlighted, the program office executes the design, so they need to make sure the decisions are feasible from an engineering, logistics, program management, and resources perspective. In many cases, the MAJCOM obtains the funding and defines the requirements. They play a large role in shaping the decisions along the framework's path. Finally, SAF/AQ coordinates with the JROC and entities that leverage the requirements. These two offices need to be aligned with the rest of the chain because they make decisions that affect the framework and also help to communicate the system's overall vision to Congress, OSD, and higher headquarters. Involving the end user is also critical to ensure the chosen design approach meets user needs.

In a similar response, another FGO suggested the framework initially be addressed from the top down. First, OUSD(A&S) should generate policy that formally introduces the framework and guides the Air Force or DoD to implement it in the current acquisition process. In conjunction with this step, the Defense Acquisition University (DAU) should stand up training to educate the acquisition and engineering force on how to properly address each step throughout the decision framework. Finally, the end user, program office, MAJCOM, and SAF/AQ should collectively work to address the framework. Depending on the question, different entities throughout the chain will have decision making roles, while others will merely be informed of the decisions. Regardless, all stakeholders should be involved.

Although the collective group of candidates did not come to the same consensus for answering this interview question, each participant introduced well-thought out points backed by sound rationale. It is evident a robust response to this question could be explored by policy makers within the Air Force or DoD.

After contemplating who should worry about the system design framework, interview candidates were asked whether the framework appears to be a useful tool for an Air Force program office responsible for designing, developing, and fielding a system.

All interview participants unanimously agreed the framework is useful, but many candidates followed their response with a caveat. Below is a list of those caveats:

- As long as the framework is addressed at the correct time within the acquisition cycle.
- Providing the decisions are well-documented and transferred to each follow-on office (e.g., from the development SPO to the sustainment SPO). Each organization will have to understand the results and live with them.
- Only if the necessary number and mix of resources with the appropriate levels of training are imbedded in the offices making each framework decision. Significant upfront effort is required to gather the right level of information to make well-informed decisions and also to competently answer the questions in each decision step.
- Given decision makers understand sacrifices may need to occur in the short-term in order to achieve long-term cost savings. This is particularly true if the framework directs the enterprise to a flexible design approach that carries cost, schedule, or performance penalties during the system's initial development effort.

In addition to providing caveats, several interview candidates supported their response with the following clarifying comments:

- One FGO explained, "The framework establishes a deliberate thought process to make decisions and recognizes the need for change. As the world evolves to using more software-centric systems, addressing change and actively weighing the value of flexibility is important. As we move to a highly adaptive world, we need more frameworks to determine where to put the layers of abstractions and recognize where to imbed the option for needed changes." *(Officer, 2019)*.
- A different Officer stated, "I think the framework is a useful tool to help a program office understand what they are doing and to defend why they are doing it. The framework will help programs advocate to higher levels of leadership." *(Officer, 2019)*.
- A third interview candidate offered, "It seems like a useful tool to get folks to start thinking about design approaches other than an optimized design. Current DAU

education tends to direct the Air Force towards optimization. The framework is also a helpful way for the program office to convey, in a meaningful manner, why they chose a certain approach. It will allow the Air Force to recognize any penalties, but also show the potential upsides of a design strategy. The Air Force struggles with outbound marketing and the framework could help in this area." *(Officer, 2019)*.

- Finally, a candidate with an extensive background working Air Force sustainment programs acknowledged the importance of the framework by explaining how the Air Force has historically failed to deliberately identify whether a system is built to be static or flexible. As a result, inherently static systems are developed without the community's understanding that the systems are prohibitively expensive and time consuming to modify. Instead, efforts from the users, requirements community, and lead command will dictate changes to the systems in order to maintain each system's relevancy. In turn, the Air Force acquisition community will waste considerable time, money, and resources attempting modifications that do not meet the user's desired end state. Sometimes, a decision is finally made to build a new system. Other times, the Air Force is reluctant to allocate additional money to a new system after such a significant amount of resources were expended trying to modify the current system, leaving users with an antiquated system that fails to fully meet warfighter needs. If implemented correctly, the framework should eliminate this problem.

At the conclusion of the discussion on usefulness, interview candidates were asked to identify Air Force program offices where the framework would be more or less applicable. Most participants affirmed the framework appears robust enough for use across most systems and their associated program offices. Individuals with experience outside the Air Force (e.g., NRO, NGA, etc.) determined the framework could also be used in other DoD agencies.

Several Officers stated that innovative, flexible program offices such as Big Safari, Kessel Run, or the RCO are perfect test beds for the model. Another FGO suggested that although new starts represent the optimal place for walking through the decision steps, sustainment offices attempting system modernization could also benefit from the framework. A third interview candidate with experience working space systems held the opinion that SMC is a forward leaning organization and would likely be open to adopting the new process.

Although most Officers had trouble selecting a system or program office where the framework would not work, one FGO remembered experience purchasing gliders for the Air Force Academy and suggested programs performing pure commercial-off-the-shelf (COTS) purchases, such as the academy gliders, would have no need for the framework.

After discussing the System Design Framework's applicability, interview candidates were asked to reflect on the best way to teach the model. Every FGO recommended DAU. Most suggested teaching the framework in the initial ACQ 101 course and also advocated refresher instruction as part of the capstones (e.g., PM 352b) for both Program Management and System Engineering Level's 1, 2, and 3. They highlighted the importance of teaching the model upfront and early to newly commissioned acquisition officers, but also emphasized the value of continued education and reinforced training throughout an officer's career. For example, most Materiel leaders complete Level 3 capstone classes. Incorporating refresher framework training in the Level 3 capstone would ensure officers in leadership roles are well positioned to enforce the model and correctly mentor the rest of the acquisition workforce on how to execute the framework.

One Officer commented that on top of DAU, several organizations (e.g., SMC and LCMC) have an Acquisition Center of Excellence that could prove to be helpful secondary centers for training the workforce. Kessel Run also imbeds DAU professors that are currently trying to revamp the acquisition curriculum. An FGO offered that Kessel Run professors would likely latch onto the framework as a valuable new educational tool.

Finally, many Officers stressed the benefits of both top-down and bottom-up training. OUSD(A&S) could address the framework from a policy and requirements standpoint. They represent a necessary higher leadership level for introducing the framework to the workforce and helping it gain traction across the DoD. From a bottom-up standpoint, positioning posters of the framework throughout SPOs and ensuring the model is used as a best practice within program offices is another helpful approach.

For the last interview question, participants were asked to conduct a high level walk through of the framework using a system they worked on during their time in the Air Force. The goal of this question was to identify weaknesses in the framework. It was noted that a proper walkthrough of the framework requires significantly more resources and time than allocated during the interview. As a result, some of the response may contain inaccuracies. The following summarizes responses from three Officers:

Response A:
System – Lockheed Martin F-35 Lightening II Joint Strike Fighter Program
Background – The F-35 program is a joint DoD program intent on fielding a common family of fifth generation, multi-role fighter aircraft. As of 2016, the F-35 served as the DoD's largest cooperative acquisition program, with eight international partners participating with the United States for development, production, sustainment, and follow-on development. The program is considered an ACAT I Major Defense Acquisition Program (MDAP). The Defense Acquisition Executive (DAE) serves as the Milestone Decision Authority for the Joint Strike Fighter program. The Service Acquisition Executive Authority alternates between the Department of the Air Force (DAF) and the Department of the Navy (DoN). *(Winter, 2016)*.

The following responses were provided as the interview candidate walked through the system design framework. The Joint Strike Fighter has already been fielded, so most of these answers were conducted in hindsight. The walkthrough is visually depicted in Figure 26.

1.0 – The candidate started in diamond 1.0 and recognized the enterprise has the capability and desire to make changes to the system after deployment. The DoD made an enormous resource investment in the F-35; given the high-level, international importance of this program, the DoD will ensure the necessary funding, personnel, equipment, and schedule are available to support potential future modifications. In line with historical precedence set by other fighter aircraft development programs, the DoD has the desire to make changes to the F-35 system in order to ensure it remains capable against adversaries.

Based on this answer, the interview candidate was directed to diamond 1.1 of the framework.

1.1 – In terms of T_M, the interview candidate recognized T_{DL} is expected to be greater than T_M. The enterprise's response to this segment of the question could be formulated using method one, which involves researching the historical rate of change in the environment or market dynamics of a comparable system that has already been fielded. In the case of the F-35, the enterprise could look to the F-16, A-10, F-22, F/A-18, and AV-8B.

The interview candidate also recognized T_{DL} is expected to be greater than $T_{tech,\,i}$. Due to the extensive number of subsystems present in the F-35, the interview candidate did not conduct the exercise of breaking out the T_{obs} for each subsystem and comparing each figure to the system's T_{DL}. However, the FGO highlighted that specific subsystems such as the avionics and navigation software, sensors, distributed aperture system, and electro optical targeting system will likely become obsolete during the lifetime of the aircraft and therefore require flexible system designs. The candidate also noted that based on the complexity of the platform, it may be beneficial to conduct one iteration of the design framework walkthrough against the airframe/hardware and a second iteration of the design framework walkthrough against the electronic subsystems.

Based on the answer to diamond 1.1, the interview candidate was directed to diamond 2.0.

2.0 – The candidate explained the circumstances of uncertainty are known for many of the subsystems. For example, based on the rate of change in optics and processing power, some of the sensors become obsolete every 18 months to two years. As a result, building in the option to upgrade the processing power would be beneficial. However, it was also recognized that based on the extensive number of roles the platform is expected to fulfill, the length of time the system will remain operational, and the future uncertainty around adversary capabilities and environments, some circumstances of uncertainty for the F-35 system are not known. The interview candidate acknowledged the system was built using a platform approach across the three different variants. This could be helpful for future unknown unknowns as well.

2.1 – The candidate could not provide a response to this question without additional resources. An assumption was made that the cost of imbedding flexibility into the system is smaller than the cost of replacing the system.

Based on this response, the interview candidate was directed to an options and adapt design. The candidate agreed with this conclusion, explaining how the attributes of each design approach would allow the DoD to more easily respond to new missions and threats, some of which the F-35 program office can anticipate, and some of which the F-35 program likely cannot anticipate. Given the F-35 is already fielded, the interview participant offered the knowledge that many F-35 subsystems were built with architecture characteristics supporting a real options design approach. However, without the guidance of the System Design Framework, it is possible instances of overly-complex designs and/or limited designs exist.

Response B:
System – Replacement Surveillance Radar for the Boeing E-3 Sentry Airborne Warning and Control System (AWACS)
Background – The E-3 Sentry AWACS is an all-weather surveillance, command, control, and communications aircraft developed in the 1970s. The aircraft is based off the Boeing 707, which is no longer in production. The E-10 MC2A was originally intended to replace the E-3 Sentry, but the program was canceled by the DoD in 2007 based on competing budget priorities. As a result, the United States began a series of incremental improvements to increase the performance standards of the E-3 Sentry aircraft. One improvement includes replacing the surveillance radar. *(Air Combat Command, 2015)*.

The following responses were provided as the interview candidate walked through the system design framework. The walkthrough is visually depicted in Figure 27.

1.0 – The candidate started in diamond 1.0 and recognized the DoD may have the capability to make changes to the system after deployment, but the enterprise does not have the desire to make changes to the system after it is fielded. This answer is based on the fact that the radar is intended to be one of the last upgrades on a platform that will eventually be replaced by a new system.

Based on the answer to diamond 1.0, the interview candidate was directed to diamond 3.0.

3.0 – The interview participant concluded the level of confidence in which the radar's operating environment will remain fixed throughout T_{DL} is moderate to low. The radar is a final service life extension for the platform, which is estimated to remain operational through 2035. Today, the E-

3 Sentry is primarily used for operations supporting efforts in the Middle East. However, in the next 15-20 years, operations could shift to alternate environments, against different adversaries and different surveillance collection requirements.

Based on the answer to diamond 3.0, the interview candidate was directed to a robust design. The participant agreed this conclusion made sense given the end-of-life assumptions of the system's E-3 Sentry platform. However, the candidate noted there could be a desire to use the surveillance radar on other platforms or for alternative purposes. More extensive market research would need to be conducted to solidify the future use cases for the radar. If there are expectations of using the radar for additional purposes other than the E-3 Sentry, there could be a desire to embed flexibility into the system, a logical approach given the system's extensive design lifetime.

Response C:
System – Northrop Grumman Minotaur VI Rocket
Background – The Minotaur VI falls under the Air Force Orbital/Suborbital Program-3 contract, which provides space launch services for a series of rocket launchers. The purpose of the Minotaur VI is to launch government-sponsored payloads into space. The space launch vehicle is an evolutionary version of the Minotaur IV and provides a combination of government motors and commercial boosters. The Minotaur family of launch vehicles are managed by SMC. *(Luchi, 2018).*

The following responses were provided as the interview candidate walked through the system design framework. The Minotaur VI has already been designed, so most of the candidate's answers were conducted in hindsight. The walkthrough is visually depicted in Figure 28.

1.0 – The candidate started in diamond 1.0 and recognized the DoD has the capability to make changes to the system after deployment. The Officer described the program office's cost reimbursable funding approach, which accounts for the funding portion of capability. The FGO also explained how the personnel, equipment, and schedule allocated to the program allow for changes to the system after its initial fielding. In terms of desire, the FGO discussed the enterprise's request for a cost-effective space launch solution and the need to send varying sized payloads into different orbits (e.g., LEO). As a result, the enterprise does desire to make changes to the system after it is initially designed/fielded.

Based on the answer to diamond 1.0, the interview candidate was directed to diamond 1.1.

1.1 – In terms of T_M, the interview candidate recognized T_{DL} is expected to be greater than T_M. The candidate initially struggled to answer this question because each rocket is developed for a specific mission/purpose/payload and is usually launched within six to eight months after fielding. User needs do not change during this timeframe. However, the participant then recognized T_{DL} refers to design lifetime and acknowledged user needs will consistently change during the ~ten+ year design lifetime of the rocket; each government launch mission is unique.

The interview candidate assumed T_{DL} is not expected to be greater than $T_{tech,\ i}$. for any component of the system. Specifically, the rocket motors, attitude control system, spacecraft separation systems, fairings, and interfaces are not expected to become obsolete during the design lifetime of the system.

Based on the answer to diamond 1.1, the interview candidate was directed to a flexible design.

2.0 – The candidate explained the circumstances of uncertainty are known. There is uncertainty around the trajectory of the rocket launcher. The trajectory is based on whether a payload is intended for LEO or High Earth Orbit (HEO) missions. There is also uncertainty surrounding payload dimensions/weight specifications as each payload will have a unique size. Additionally, the number of payloads could vary based on user needs. Finally, uncertainty exists around each launch site, although this factor has a negligible impact on the design of the system.

2.1 – The candidate could not provide a concrete response to this question without additional resources. An assumption was made that the cost of imbedding flexibility into the system is smaller than the cost of redesigning a new system.

Based on this response, the interview candidate was directed to an options design.

In reality, the program office did go with a flexible options design approach. For example, the vehicle was designed with switch options using the architecture principles of integrability. To accommodate different sized payloads, the Minotaur VI uses a standard 92-inch diameter spacecraft fairing, but the vehicle can be developed with an optional 110-inch diameter spacecraft fairing. Both fairings can be assembled and integrated independently from the launch vehicle stages and each fairing has the same standard interface of 38.81 inches (see Figure 25). The Minotaur VI was also designed with an expand option of using a hydrazine upper stage for multiple orbit altitude capabilities. Additionally, the system includes the option for launching more than one payload using a Multiple Payload Adapter Fitting. Finally, the Minotaur VI uses the architecture principle of scalability with an optional upper stage that provides up to 200 kg of increased performance. *(Luchi, 2018)*.

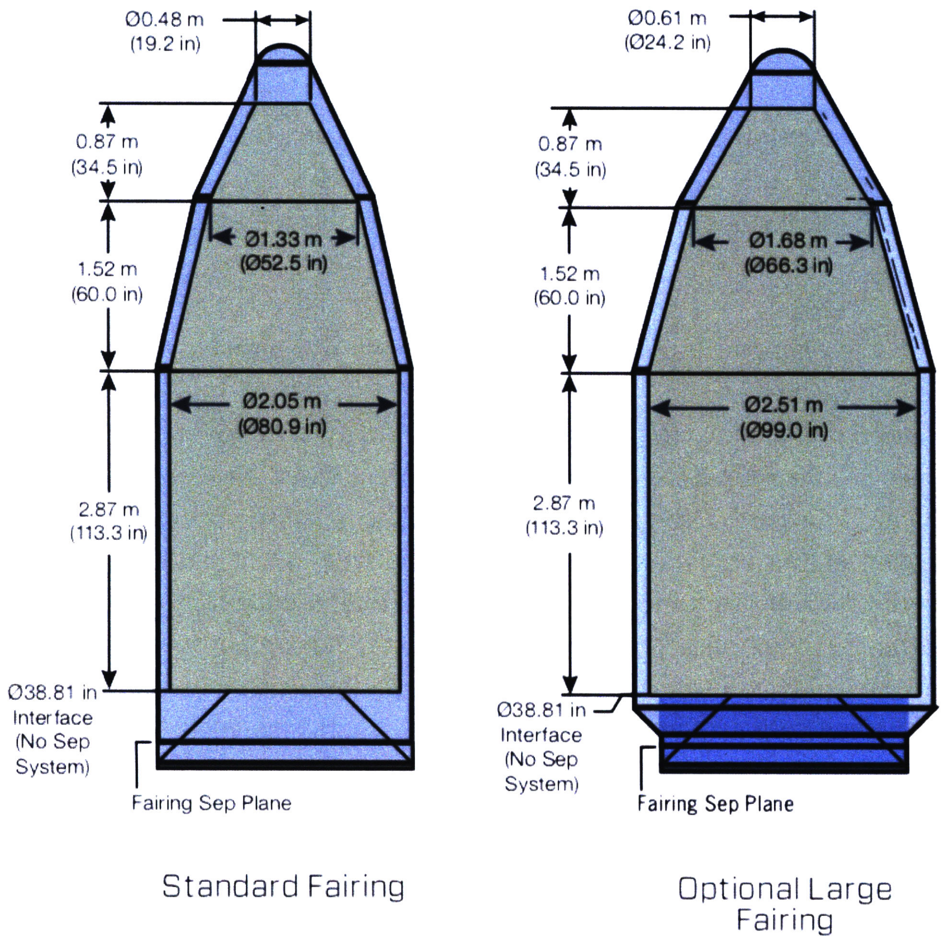


Figure 25: Minotaur VI Fairing Designs

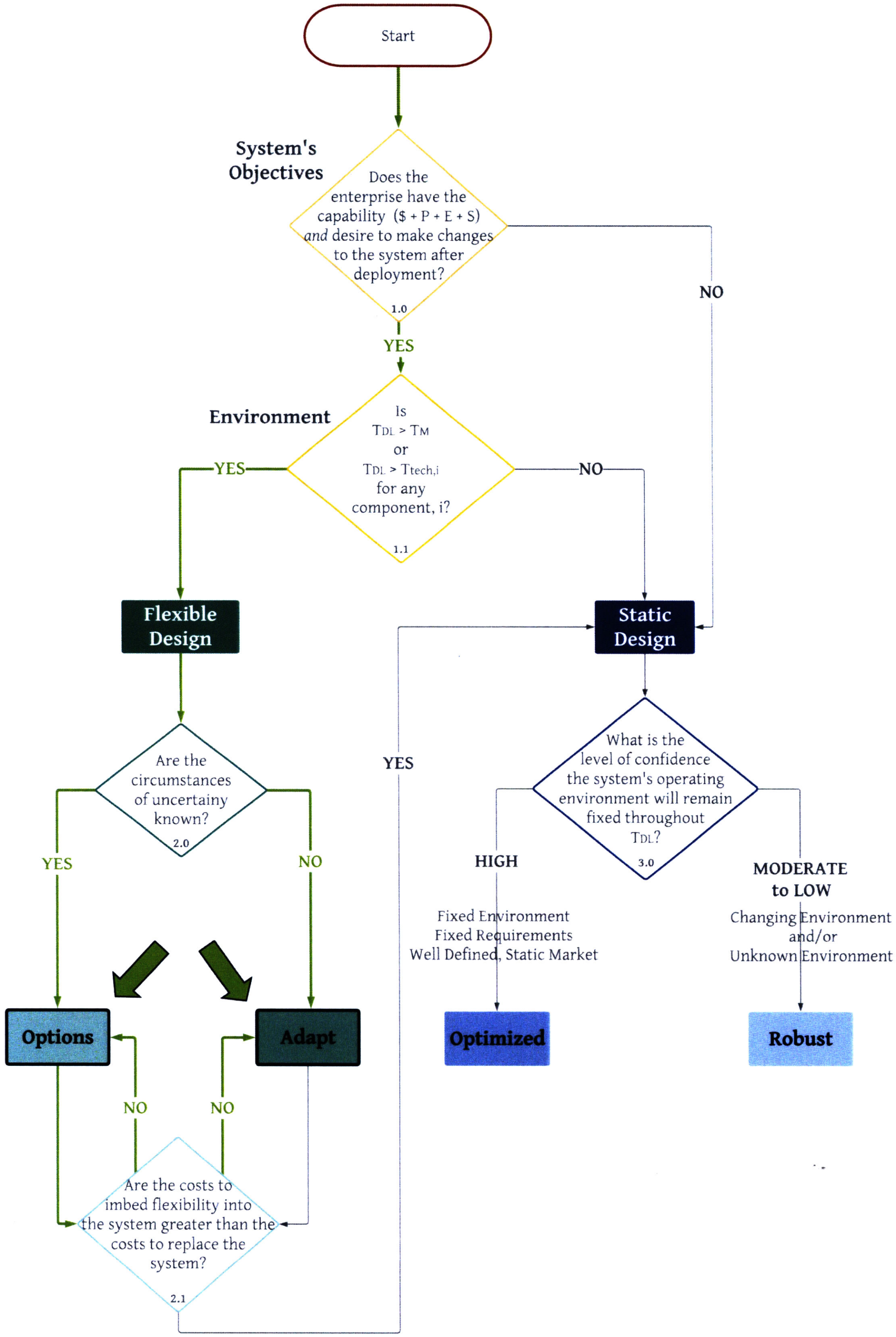


Figure 26: Interview Generated System Design Framework for F-35

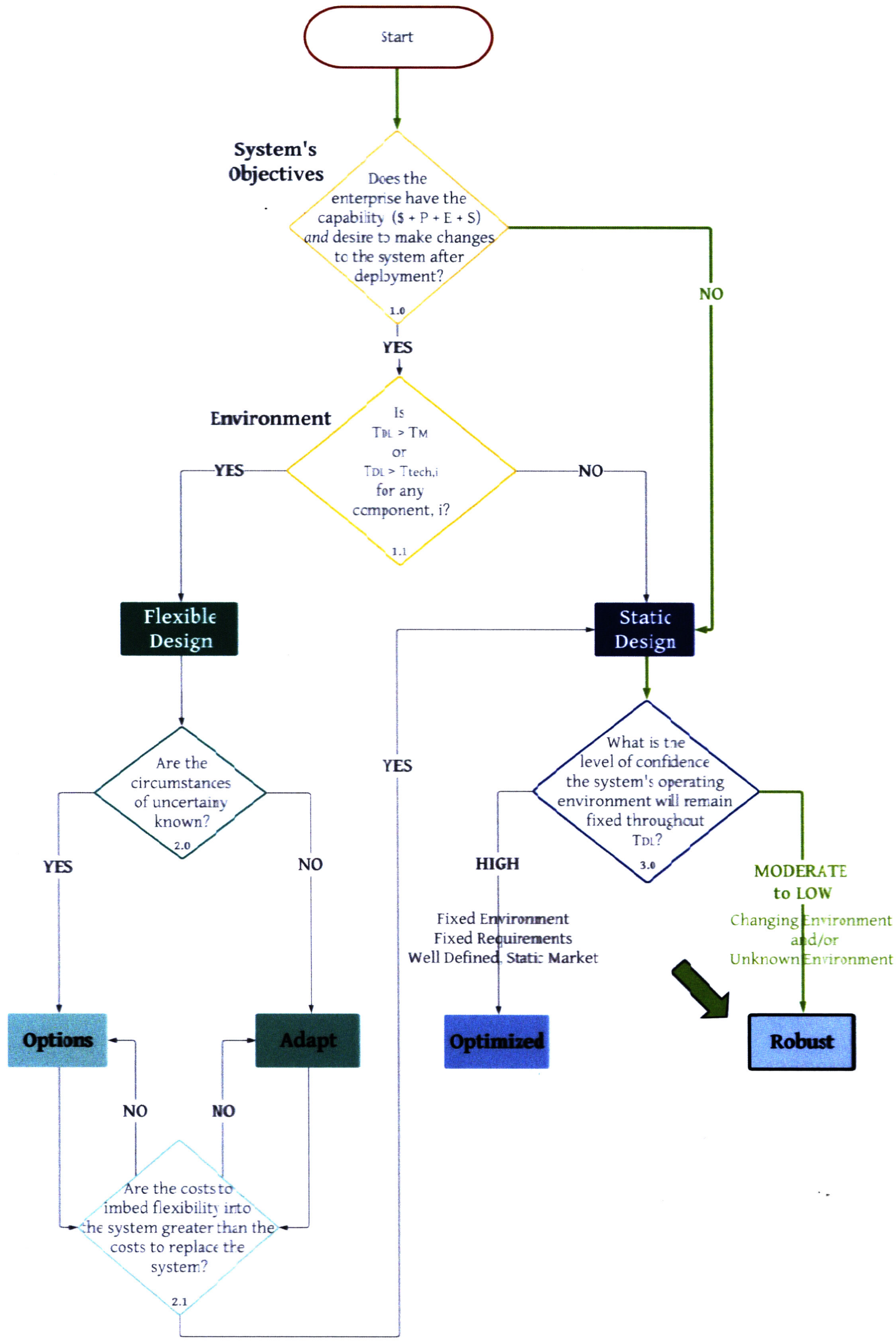


Figure 27: Interview Generated System Design Framework for E-3 Replacement Surveillance Radar

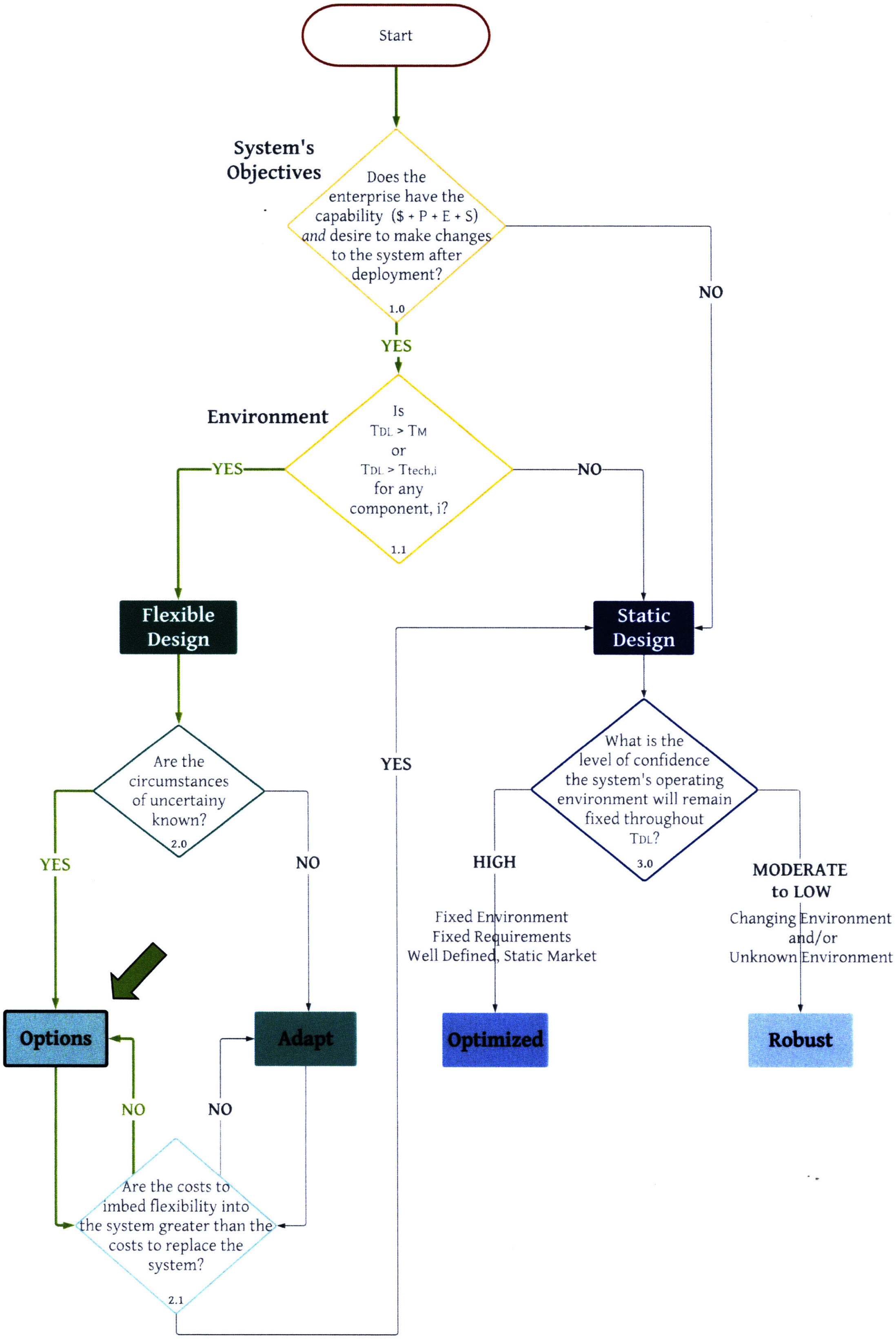


Figure 28: Interview Generated System Design Framework for Minotaur VI

5.2 Tactical Observations

This section provides an overview of observations drawn from the interview responses. The first two observations result from the F-35 system design framework walkthrough. The remaining reflections come from the collective group of interview candidates.

During the system design framework walkthrough of the F-35, the interview candidate concluded it would be prohibitively time consuming for a single entity to break out the expected time to obsolescence for each component of the aircraft, as required in decision step 1.1. Instead, efficiencies would be gained if the framework was individually implemented against larger F-35 subsystems. This assessment is valid for many complex DoD systems.

In response to this observation, it was determined an enterprise can enforce the framework on each distinct development group within an ACAT I program office. In the F-35 case, there was a group working the aircraft's avionics, another unit designing the airframe, and a third entity focused on engine acquisitions and integration. Each faction could have applied the framework to the component of the aircraft they were tasked to design.

An alternate suggestion is to apply the framework to the different layers of acquisitions. One group can focus on hardware, another on the control systems interfacing with the hardware, and a third on software. The decision on how to apply the framework to a complex system should vary based on the enterprise's organizational structure and the system itself; however, it is clear the framework will be more manageable applied individually to components of ACAT I systems.

The second observation derived from the F-35 system design walkthrough relates to the results. The interview candidate concluded the F-35 should use both types of flexible design approaches: options and adapt. This appears to be a logical and acceptable conclusion based on the reasoning provided by the candidate. The result is also reflective of the reality of the F-35's design. However, if the framework walkthrough was individually applied to smaller subsystems or components of the aircraft, it is less likely the framework would direct a user to two types of design approaches, once again making the architectural design effort more manageable.

A third observation, evident from the literature review and collection of interview responses, highlights an important point: flexible systems can contain static design components. Specifically, an enterprise directed to a flexible design approach should recognize only some components of the system will be designed using architecture principles that allow for cost effective and timely modifications after system deployment. Alternatively, an enterprise directed to a static system design must understand all components of the system will be static.

A final tactical-level observation relates to comments from interview participants regarding a common Air Force issue in which schedule delays prevent the on-time fielding of a follow-on system. As a result, operational systems are forced to remain in sustainment longer than expected. This problem was discussed extensively during the last interview question with a candidate that conducted a high-level system design framework walkthrough on a meteorological satellite. The candidate noted the satellite system was tightly coupled with associated ground stations. The satellite was designed with flexible software components, but the ground stations were designed under a static approach. A problem arose when the satellite's follow-on program encountered significant schedule delays. The delays forced the operational satellite to remain in orbit for over ten years, but the system was only designed with a three-year lifetime. Fortunately, the program office was able to overcome some of the satellite's hardware failures and accommodate life extensions to the system through advancements in the satellite's software, which allowed for modifications while the system was in orbit. Unfortunately, significant issues were encountered by the office trying to extend the design life of the static ground stations that began to fail. Without the ability to modify the systems, the Air Force's only option was to scour the market for obsolete replacement parts.

The system design framework could reduce the likelihood Air Force systems will encounter the above problem. The framework forces an enterprise to make deliberate, well-informed decisions. In the case of future ground station designs, a framework user could look to the above situation and reach a new conclusion that there *is* a desire to modify ground stations after fielding. In decision step 1.1, they would discover the time to obsolescence for various components can exceed the design lifetime of the system, requiring flexible design options. With regards to the replacement meteorological satellite, the program office would conduct market research in decision step 1.1 and discover the historical situation in which a similar satellite was forced to remain operational significantly longer than the original design lifetime. This could prompt the office to implement additional options into the design of the new satellite, such as greater fuel capacity, which was a problem factor excluded from design decisions of the original satellite.

5.3 Strategic Takeaways

In addition to tactical observations, a series of strategic-level themes and limitations emerged from the interview responses. Most importantly, feedback from the ten interviews indicates the proposed decision framework can be a useful tool for choosing the most cost effective and responsive system design under a given set of objectives and uncertainties. In addition to receiving verbal confirmation of the framework's usefulness from all ten candidates, each participant who walked through the framework with a sample system effortlessly achieved a logical outcome.

Several common themes resonated throughout the interviews. Without adequate attention, these themes represent framework limitations. First, well-developed training is necessary to ensure DoD personnel can competently apply the framework to a system. The training should encompass a detailed explanation of how to respond to each decision step within the framework and real-life examples that enhance the framework's understandability. Additional education should focus on the mechanics of successful market research, understanding Porter's Five Forces, proper cost estimation techniques for flexible systems, methods for estimating a system's time to obsolescence, and the strengths and weaknesses of each design decision. Within the Air Force, these additional areas of training should be tailored to specific AFSCs (e.g., 62E Officers should obtain training on methods for estimating a system's time to obsolescence, but not cost estimation techniques for flexible systems).

Second, DoD headquarters must allocate the necessary number of resources, types of resources, and schedule to each program office tasked to use the framework. The exact plus-up of personnel and pre-MS-A schedule allocation will vary based on the complexity of the system. However, it is clear several areas of the framework are resource intensive. Sections 1.1, 2.1, and 3.0 require subject matter experts (e.g., engineers, intelligence officials, policy makers, cost estimators, etc.) to derive well-formulated, accurate responses. Without the necessary resources, there is a risk the enterprise will make inadequate assumptions, proceed down the wrong path, and choose a system design that does not represent the most cost effective and responsive option under true objectives and uncertainties.

Finally, in addition to higher headquarters support in the form of resource allocation and training, the framework requires formal policy. Policy should standardize when to exercise the framework, where to document the framework's decisions and final outcomes, and who represents the framework's decision-making authority. Without formal policy, the framework could fall under the category of "best practice" and get forgotten as military personnel transition to new roles or retire. Standardization suggestions are offered in section 6.1.

6 Discussion and Synthesis

6.1 Response to Interview Findings

This section responds to two significant framework limitations identified in the series of ten interviews. All other suggested limitations were addressed at the time of acknowledgement and remedied or negated in sections 3 through 5 of this thesis.

Most interview candidates concluded the proposed System Design Framework is incomplete for two reasons:

1. It lacks a well-defined, logical placement in the DoD acquisition cycle
2. It does not provide an understanding of who makes the decisions at each step

Responding to these limitations necessitates additional research and discussions with subject matter experts that could not be accomplished during each interview. Based on a post-interview review of the DoDI 5000.02, various DoD handbooks, and relevant DAU material, it is clear the System Design Framework is best suited for the Analysis of Alternatives (AoA).

As stated in the DoDI 5000.02, "The AoA assesses potential materiel solutions that could satisfy validated capability requirement(s) documented in the Initial Capabilities Document, and supports a decision on the most cost-effective solution to meeting the validated capability requirement(s). In developing feasible alternatives, the AoA will identify a wide range of solutions that have a reasonable likelihood of providing the needed capability." *(USD(AT&L), 2017)*.

The System Design Framework aligns with the intent of the AoA in that it provides a framework to evaluate different architecture approaches that could satisfy a validated capability requirement. Not only does the System Design Framework support a decision on the most cost-effective solution to meet the validated capability, but it also supports a decision on the most responsive solution. Finally, the document is written early enough in the DoD acquisition cycle that elements of the decision can be incorporated into other required DoD process documents (e.g., the Systems Engineering Plan).

DAU provides a detailed explanation of the AoA and the document's placement in the DoD acquisition lifecycle, explaining, "The AoA focuses on identification and analysis of alternatives, measures of effectiveness, cost, schedule, concepts of operation, and overall risk. The AoA addresses trade space to minimize risk and also assesses critical technology elements associated with each proposed materiel solution. This includes technology maturity, integration risk, manufacturing feasibility, and, where necessary, technology maturation and demonstration needs. The AoA normally occurs during the Materiel Solution Analysis phase of the Acquisition process, is a key input to the Capability Development Document, and supports the materiel solution decision at Milestone A." *(Defense Acquisition University, 2018).*

Figure 29 provides a high-level overview of the DoD acquisition process. As evident in the chart, the AoA is developed prior to MS-A. This placement aligns with the interview candidates' recommendations. According to policy, "The final AoA written report will be provided to the Director of Cost Assessment and Program Evaluation (DCAPE) not later than 60 calendar days prior to the Milestone A review (or the next decision point or milestone as designated by the Milestone Decision Authority (MDA)). Not later than 15 business days prior to the Milestone A review, DCAPE evaluates the AoA and provides a memorandum to the MDA, with copies to the DoD Component head or other organization or principal staff assistant assessing whether the analysis was completed consistent with DCAPE study guidance and the DCAPE-approved study plan."[5] *(USD(AT&L), 2017).*

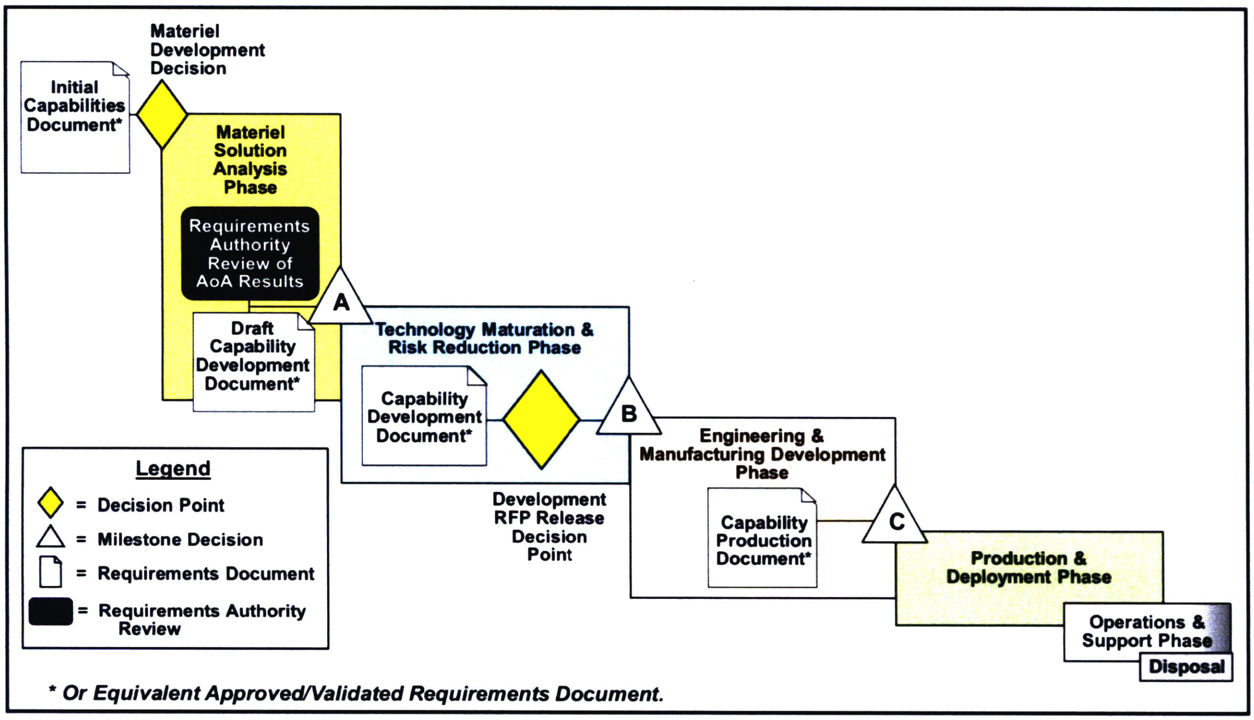


Figure 29: Generic DoD Acquisition Process (Defense Acquisition University, 2018)

Upon review of the AoA template and assessment criteria, it is clear the System Design Framework seamlessly fits into the AoA process. The AoA Study Plan and final report require minimal modifications in order to incorporate analysis of the System Design Framework.

---

[5] For ACAT I and IA programs, DCAPE prepares study guidance for MDA review and approval at the Materiel Development Decision (MDD). For ACAT II and III programs, component AoA procedures apply. Following the MDD, the organization responsible for conducting the AoA develops the AoA Plan, coordinates it with the MDA, and submits it to DCAPE for approval prior to the start of the AoA.

Figure 30 provides a sample template for an AoA, as adapted from the Analysis of Alternatives Handbook. The template can be tailored based on the system, but the basic contents remain the same for all DoD programs. At a minimum, the System Design Framework should be added into the following sections of the AoA:

- 1.6 – Description of Alternatives
- 3 – Cost Analysis
- 5 – Alternative Comparison and Cost Capability Analysis
- Appendix D – Detailed Description of the AoA Methodologies.

In line with current guidance, section 1.6 should incorporate a high-level overview of the design approaches and tradeoffs. Section 3 should include the life cycle cost results for the recommended system design approach. Section 5 should encompass a walkthrough of the System Design Framework with the associated responses and justifications for each decision step. Finally, Appendix D should incorporate a pictorial representation of the model itself, similar to Figure 26, Figure 27, and Figure 28.

To capture the above recommendations, HAF/A5 should issue an updated Analysis of Alternatives Handbook. No changes are required to the DoDI 5000.02 or other associated policy documents.

Although minimal changes are required to incorporate the System Design Framework into the AoA, the AoA's evaluation process can remain as-is. According to Enclosure 9 of the DoDI 5000.02, DCAPE's evaluation of the AoA assesses the extent to which the document:

1. Examines sufficient feasible alternatives
2. Considers tradeoffs among cost, schedule, sustainment, and required capabilities for each alternative considered
3. Achieves the affordability goals established at the MDD
4. Uses sound methodology
5. Discusses key assumptions and variables and sensitivity to changes
6. Bases conclusions or recommendations, if any, on the results of the analysis
7. Considers the fully burdened cost of energy (FBCE), in cases where FBCE is a significant discriminator among alternatives *(USD(AT&L), 2017)*.

In addition to DCAPE's assessment, the final AoA is reviewed by the requirements validation authority prior to the MS-A decision. At a minimum, the requirements validation authority:

1. Assesses how well the recommended alternative satisfies validated requirements in the most cost-effective manner for the warfighter

2. Identifies any opportunities to adjust or align capability requirements for better synergy across the joint force capabilities
3. In accordance with the responsibilities identified in title 10 of U.S. Code Title 10, U.S.C. (Reference (g) (h)), offers alternative recommendations to best meet the validated capability requirements *(USD(AT&L), 2017)*.

Similar to the DCAPE assessment, the requirements validation authority criteria do not require modification in order to incorporate the System Design Framework into the AoA.

Contents

Figure 30: Sample AoA Outline (Office of Aerospace Studies , 2016)

With the first limitation addressed, the following paragraph details who should respond to each decision step in the System Design Framework.

Ultimately, the program office team writing the AoA will complete the System Design Framework walkthrough. At a minimum, the team should consist of a program manager, engineer, designer, and cost estimator. The size of the team will vary based on the size of the program. The program manager should seek input to the responses from a variety of outside sources. As recommended by the interview candidates, these sources include the end users/warfighters, the lead command, the requirements sponsor, and SAF/AQ. The program office may have to reach out to industry, historians, the intelligence community, and other useful experts in order to answer the questions in diamonds 1.1 and 3.0. If a response to 1.0 is not explicit after a collaboration with the end user, lead command, requirements sponsor, and SAF/AQ, the program office should refer to the designated MDA. Enclosure 1, Table 1 of the DoDI 5000.02 provides decision authority guidance based exclusively on a program's ACAT level. Table 8 provides a truncated version of the relevant portions of the DoDI 5000.02 Milestone Decision Authority table for use by the AoA team. It should also be noted that based on policy, both DCAPE and the requirements validation authority will review the decisions in the AoA prior to MS-A. DCAPE will provide evaluation results in a memorandum to the MDA and DoD Component head.

ACAT	Decision Authority
ACAT I	ACAT ID: DAE or as delegated ACAT IC: Head of the DoD Component or, if delegated, the CAE
ACAT IA	ACAT IAM: DAE or as delegated ACAT IAC: Head of the DoD Component or, if delegated, the CAE
ACAT II	CAE or the individual designated by the CAE
ACAT III	Designated by the CAE

Table 8: System Design Framework 1.0 Decision Authority adapted from (USD(AT&L), 2017)

6.2 Future Research

This thesis set to explore four research questions:

1. What are the different design strategies?
2. What are the tradeoffs between the design strategies?
3. What is the optimal design strategy for allowing enterprises to quickly respond to operational changes they can and cannot anticipate?

4. Is the proposed decision framework a useful tool for choosing the most cost effective and responsive system design under a given set of objectives and uncertainties?

The thesis answered the research questions, identified weaknesses in the proposed framework, and offered solutions to increase the usefulness of the tool. However, future research in this area could further improve the government's desire to field DoD systems smarter and faster.

Future research should be dedicated to understanding the competing paradigms of flexible and static designs. Evident from the literature review, flexible systems can exhibit an initial cost, schedule, or performance penalty compared to static systems. Additional research is needed to explore the dynamics that drive the performance penalties for flexible systems and methods designers can take to minimize performance penalties when opting for a flexible design approach. Similarly, while flexible systems allow for relatively easy modifications to a system after deployment, the initial complexity of building in flexibility can result in higher upfront development costs. As *(Ferguson, et al., 2007)* suggest, studying the relationship between the cost of flexibility and the value of flexibility can help the DoD establish a more strategic position in the growing marketplace of flexible systems.

In addition to exploring the tradeoffs between flexibility and rigidity, the DoD should look to compliment the System Design Framework with equivalent improvements to the Defense Acquisition System depicted in Figure 31. The System Design Framework addresses system engineering fundamentals. A corollary approach can be implemented that creates efficiencies related to the DoD's management, requirements, and funding methods.

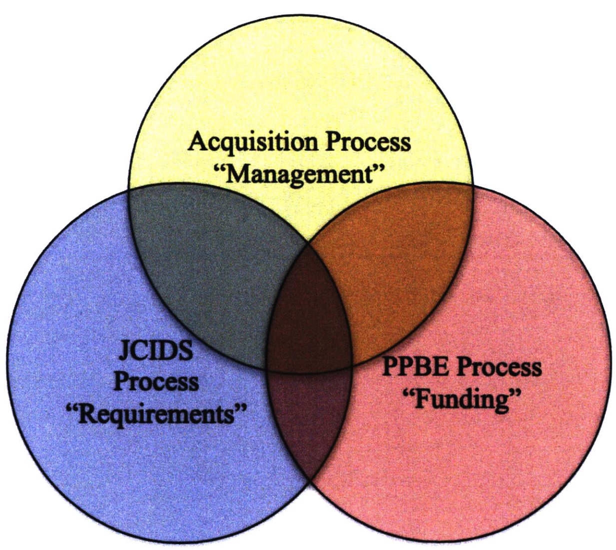


Figure 31: Defense Acquisition System adapted from (AcqNotes, 2019)

On the management side, research should focus on optimizing or revising the defense acquisition lifecycle process (see Appendix D). The process involves a series of stage gates (e.g., MS-A, MS-B, etc.) that prioritize documentation and approval over rapid capability delivery. By nature of the requirements for each stage, proceeding to the next gate can take several years. This bureaucratic process hinders improvements made to speed up system development timelines from the engineering side and requires reform focused on lean product management processes.

The Joint Capabilities Integration and Development System (JCIDS) is the DoD's process for defining the acquisition requirements and associated performance criteria that generate the capabilities required by warfighters. Research should be dedicated to exploring the time and warfighter satisfaction tradeoffs between prioritizing user feedback over tracing, implementing, and validating requirements. Additionally, the current JCIDS requires the enterprise to define all requirements upfront. This hinders the ability for systems to be designed and iterated upon and can result in wasted time and resources. Specifically, when all of the requirements are defined upfront and incorporated into the design and development of a system, it is more difficult for the enterprise to respond to warfighter feedback. In some cases, the upfront requirements approach leads to the delivery of capability that does not provide value to the end user, which is neither smart nor cost effective.

Finally, the Planning, Programming, Budget, and Execution (PPB&E) process should be studied in order to identify greater efficiencies in the areas of financial management and resource allocation. A potentially smarter and revolutionary approach Kessel Run is exploring involves funding according to value creation. Instead of issuing a 5-year budget, acquisition programs would receive small injects of funding to support an initial capability delivery. If the capability proves valuable to the warfighter, the program would receive additional funding for the next capability delivery. Otherwise, the funding would be reallocated to a more effective program. This level of effort model could also optimize the PPB&E process's ability to respond to change and uncertainty.

THIS PAGE INTENTIONALLY LEFT BLANK

7 Works Cited

AcqNotes, 2019. *Acquisition Process.* [Online] Available at: http://acqnotes.com/acqnote/acquisitions/acquisition-process-overview [Accessed 16 October 2019].

Air Combat Command, P. A. O., 2015. *E-3 Sentry AWACS Fact Sheet.* [Online] Available at: https://www.af.mil/About-Us/Fact-Sheets/Display/Article/104504/e-3-sentry-awacs/ [Accessed 7 October 2019].

Allen, T. J., 2001. *Organizing for Product Development,* Cambridge: MIT.

Amram, M. & Kulatilaka, N., 1999. *Real Options: Managing Strategic Investment in an Uncertain World.* 1 ed. Boston: Harvard Business School Press.

Anon., 2017. *National Security Strategy of the United States of America,* Washington DC: White House.

Boas, R., 2008. *Commonality in Complex Product Families: Implications of Divergence and Lifecycle Offsets,* Cambridge: MIT.

Cardin, M.-A., de Neufville, R. & Dahlgren, J., 2008. *Extracting Value from Uncertainty: Proposed Methodology for Engineering Systems Design,* Cambridge: Massachusetts Institute of Technology.

Carter, A. B., 2011. *Opening Statement Before Senate Armed Services Committee.* Washington DC, US Congress.

Casanova, C., Sarkani, S. & Mazzuchi, T., 2016. System Architecture to the Indentificatio and Valuation of Design Option Flexibilities Under Uncertainty. *The International Journal of the Constructed Environment,* 7(2), pp. 37-53.

Christopherson, A., 2019. *US Air Force News.* [Online] Available at: https://www.af.mil/News/Article-Display/Article/1771387/faster-smarter-speed-is-key-in-acquisition-reform/[Accessed 19 June 2019].

Clarkson, J. & Eckert, C., 2005. *Design Process Improvement - A Review of Current Practice.* London: Springer.

Crawley, E., Cameron, B. & Selva, D., 2016. *System Architecture: Strategy and Product Development for Complex Systems.* Hoboken: Pearson Higher Education, Inc.

Crawley, E. et al., 2004. *The Influence of Architecture in Engineering Systems.* Cambridge, MIT ESD.

de Neufville, R., 2002. *Architecting/Designing Engineering Systems Using Real Options.* Cambridge, ESD International Symposium.

de Neufville, R., 2004. *Uncertainty Management for Engineering Systems Planning and Design.* Cambridge, Engineering Systems Symposium.

de Neufville, R. & Scholtes, S., 2011. *Flexibility in Engineering Design.* 1 ed. Cambridge: MIT Press.

de Neufville, R., Wang, T. & Scholtes, S., 2005. Valuing Real Options by Spreadsheet: Parking Garage Example. *ASCE Journal of Infrastructure Systems.*

de Weck, O., de Neufville, R. & Chaize, M., 2004. Staged Deployment of Communications Satellite Constellations in Low Earth Orbit. *Journal of Aerospace Computing, Information, and Communication,* Volume 1, pp. 119-136.

de Weck, O., Eckert, C. & Clarkson, J., 2007. *A Classification of Uncertainty for Early Product and System Design.* Paris, International Conference on Engineering Design.

Defense Acquisition University, 2018. *Acquipedia: Analysis of Alternatives.* [Online] Available at: https://www.dau.edu/acquipedia/pages/articledetails.aspx#!13[Accessed 11 October 2019].

Engel, A. & Browning, T. R., 2006. *Designing Systems for Adaptability by Means of Architecture Options.* Los Angeles, INCOSE.

Erwin, S., 2017. *Pentagon Procurement Chief Ellen Lord: 'Lots of Needs, Opportunity in Space'.* [Online] Available at: https://spacenews.com/pentagon-procurement-chief-ellen-lord-lots-of-needs-opportunity-in-space/ [Accessed 19 June 2019].

Ferguson, S., Siddiqi, A., Lewis, K. & de Weck, O. L., 2007. *Flexible and Reconfigurable Systems: Nomenclature and Review.* Las Vegas, ASME 2007 International Design Engineering Technical Conference & Computers and Information in Engineering Conference.

Fricke, E. & Schulz, A. P., 2005. Design for Changeability (DfC): Principles to Enable Changes to Systems Throughout their Entire Lifecycle. *Wiley Interscience,* 8(4), pp. 342-359.

Gao, C., 2019. *Meet the M1 Abrams: The Tank Making the 'Rounds' at the Salute to America Bash.* [Online] Available at: https://nationalinterest.org/blog/buzz/meet-m1-abrams-tank-making-rounds-salute-america-bash-65866 [Accessed 8 July 2019].

Global Data, 2019. *AIM-9X Sidewinder Air-to-Air Missile.* [Online] Available at: https://www.airforce-technology.com/projects/aim-9x-sidewinder-air-to-air-missile/[Accessed 20 August 2019].

Goerger, S. R., Madni, A. M. & Eslinger, O. J., 2014. *Engineered Resilient Systems: A DoD Perspective.* Los Angeles, Conference on Systems Engineering Research.

Gupta, Y. P. & Goyal, S., 1990. Flexibility of Manufacturing Systems: Concepts and Measurements. *European Journal of Operational Research,* 43(2), pp. 119-135.

Hassan, R., de Neufville, R. & McKinnon, D., 2005. *Value-at-Risk Analysis for Real Options in Complex Engineered Systems.* Waikoloa, IEEE International Conference.

Hastings, D. E. & Walton, M. A., 2004. Applications of Uncertainty ANalysis to Architecture Selection of Satellite Systems. *Journal of Spaecraft and Rockets,* 41(1), pp. 75-84.

Hastings, D. & McManus, H., 2004. *A Framework for Understanding Uncertainty and its Mitigation and Exploitation in Complex Systems.* s.l., MIT Engineering Systems Symposium.

Kalligeros, K. & de Weck, O., 2004. *Flexible Design of Commercial Systems Under Market Uncertainty: Framework and Application.* Albany, American Institute of Aeronautics and Astronautics.

Klosinski, P., 1993. *Aero Technika Lotnicza Drawing Database.* [Online] Available at: https://drawingdatabase.com/wp-content/uploads/2014/04/04.jpg [Accessed 7 October 2019].

Krebs, G. D., 2019. *Coriolis (P98-2).* [Online] Available at: https://space.skyrocket.de/doc_sdat/coriolis.htm [Accessed 15 07 2019].

Lessard, D. R. & Miller, R., 2000. *The Strategic Management of Large Engineering Projects Shaping Institutions, Risks, and Governanc.* Cambridge: Massachusetts Institute of Technology.

Lucero, S., 2018. *The Mash-up Rubric: Strategies for Integrating Emerging Technologies to Address Dynamic Requirements.* Washington DC, INCOSE International Symposium.

Luchi, T., 2018. *Northrop Grumman Minotaur VI Space Launch Vehicle.* [Online] Available at: https://www.northropgrumman.com/Capabilities/Minotaur/Documents/MinotaurVI_Factsheet.pdf [Accessed 2 October 2019].

Madni, A. M., 2012. Adaptable platform-based engineering: Key enablers nad outlook for the future. *Journal of Systems Engineering,* 15(1), pp. 95-107.

Madni, A. M. & Jackson, S., 2008. Towards a Conceptual Framework for Resilience Engineering. *IEEE Systems Journal,* 1(132), pp. 1-12.

Mark, G., 2005. *Incorporating Flexibility into System Design: A Novel Framework and Illustrated Developments,* Cambridge: Department of Aeronautics and Astronautics, Massachusetts Institute of Technology.

Mikaelian, T., Nightingale, D. J., Rhodes, D. H. & Hastings, D. E., 2011. Real Options in Enterprise Architecture: A Holistic Mapping of Mechanisms and Types of Uncertainty Management. *IEEE Transactions on Engineering Management,* 58(3), pp. 457-470.

Miller, B. & Clarke, J.-P., 2008. Strategic Guidance in the Development of New Aircraft Programs: A Practical Real Options Approach. *IEEE Transactions on Engineering Management,* 55(4), pp. 566-578.

Mind Tools, 2019. *Porter's Five Forces.* [Online] Available at: https://www.mindtools.com/media/Diagrams/Porters-Five-Forces-Fig-1.pdf [Accessed 19 August 2019].

Neches, R. & Madni, A. M., 2013. Towards Affordably Adaptable and Effective Systems. *Systems Engineering,* 16(2), pp. 224-234.

Office of Aerospace Studies , 2016. *Analysis of Alternative Handbook,* Kirtland AFB: HAF/A5R-OAS.

Officer, A. F., 2019. *In-Person* [Interview] (22 August 2019).

Officer, A. F., 2019. *In-Person* [Interview] (21 August 2019).

Officer, A. F., 2019. *Phone* [Interview] (11 September 2019).

Officer, A. F., 2019. *Phone* [Interview] (2 September 2019).

Office, U. G. P., 2017. *Hearing Before the Committee on Armed Services.* [Online] Available at: https://www.govinfo.gov/content/pkg/CHRG-115shrg30987/html/CHRG-115shrg30987.htm [Accessed 19 June 2019].

Phadke, M., 1989. *Quality Engineering Using Robust Design.* 1 ed. Englewood Cliffs: AT&T Bell Laboratories.

Ricks, T., 2004. *General Reported Shortages in Iraq.* [Online] Available at: http://www.washingtonpost.com/wp-dyn/articles/A40321-2004Oct17.html [Accessed 8 July 2019].

Roser, C. & Kazmer, D., 1999. *Risk Effect Minimization Using Flexible Product and Process Design.* Las Vegas, ASME Design for Manufacturing Conference.

Saleh, J. H., 2005. Perspectives in Design: The Deacon's Masterpiece and the Hundred-Year Aircraft, Spacecraft, and Other Complex Engineering Systems. *Journal of Mechanical Design,* Volume 127, pp. 845-850.

Saleh, J. & Hastings, D., 2000. *On Flexibility in Design: Analyzing Flexibility of Space Systems.* Long Beach, American Institute of Aeronautics & Astronautics.

Saleh, J. H. & Brathwaite, J., 2009. Value-centric Framework and Pareto Optimality for Design and Acquisition of Communication Satellites. *International Journal of Satellite Communications,* Volume 27, pp. 330-348.

Saleh, J. H. & Hastings, D. E., 2000. *On Flexibility in Design: Analyzing Flexibility of Space Systems.* Long Beach, CA, American Institute of Aeronautics & Astronautics, pp. 1-8.

Saleh, J. H., Hastings, D. E. & Newman, D. J., 2003. Flexibility in System Design and Implications for Aerospace Systems. *Acta Astronautica,* Volume 53, pp. 927-944.

Saleh, J. H. et al., 2014. *On Flexibility in System Design.* Cleveland, INCOSE International Symposium.

Saleh, J. H., Mark, G. & Jordan, N. C., 2009. Flexibility: a Multi-disciplinary Literature Review and a Research Agenda for designing Flexible Engineering Systems. *Journal of Engineering Design,* 20(3), pp. 307-323.

Saleh, J., Lamassoure, E., Hastings, D. & Newman, D., 2003. Flexibility and the Value of On-Orbit Servicing: New Customer-Centric Perspective. *Journal of Spacecraft and Rockets,* 40(2), pp. 279-291.

Saleh, J., Marais, K., Hastings, D. & Newman, D., 2002. *The Case for Flexibility in System Design.* Cambridge, MIT.

Serbu, J., 2017. *The legacy of Better Buying Power: DoD's Gambit to Reform Acquisition 'from within'.* [Online] Available at: https://federalnewsnetwork.com/defense/2017/02/bbpndaa-special-report-part-1/[Accessed 19 June 2019].

Shultz, A. & Fricke, E., 1999. *Incorporating Flexibility, Agility, Robustness, and Adaptability within the Design of Integrated Systems - Key to Success?.* St. Louis, IEEE.

Simpson, T., 2003. *Product Platform Design and Customization: Status and Compromise.* Chicago, ASME Design Engineering Technical Conferences and COmputers and Information Engineering Conference.

Stigler, G., 1939. Production and Distribution in the Short Run. *The Journal of Political Economy,* 47(3), pp. 305-327.

Stinn, S., 2019. *C-130J Super Hercules One Aircraft, Many Capabilities.* [Online] Available at: https://www.lockheedmartin.com/en-us/products/c130.html [Accessed 15 07 2019].

Taguchi, G. & Clausing, D., 1990. Robust Quality. *Harvard Business Review,* 1(January-February), pp. 1-27.

USD(AT&L), 2017. *DoDI 5000.02,* District of Columbia: Department of Defense.
Wade, M., 2019. *Coriolis.* [Online] Available at: http://www.astronautix.com/c/coriolis.html [Accessed 15 07 2019].

Wang, T. & de Neufville, R., 2006. *Identification of Real Options "in" Projects.* Orlando, 16th International Engineering Symposium.

Welby, S. P., 2011. *Systems Engineering Challenges in DoD.* Dayton, Ohio, USAF Systems Engineering Conference.

Winter, M., 2016. *Selected Acquisition Report (SAR): F-35 Lightning II Joint Strike Fighter Program (F-35),* Arlington, VA: Department of Defense.

8 Appendix A: COUHES Research Exemption

From <COUHES_CONNECT@MIT EDU>
Subject. Exempt Evaluation: Determination. E-1573, Chiverton
Date. August 15, 2019 at 21.36 05 EDT
To <kchiv@mit.edu>, <deweck@mit edu>
Reply-To: <kc-help@mit edu>

The proposed research activities outlined in Exempt ID E-1573 Framework for Selecting a System Design Approach **have been determined to be exempt**
No further actions in COUHES Connect are required

As the Principal Investigator or Faculty Sponsor, you must adhere to the policies within the Investigator Responsibilities for Exempt Research and ensure that all members of the research team comply with these policies

Your study may proceed as long as all research procedures correspond with responses within the Exempt Evaluation If the scope or procedures of the research undergo significant alterations, you must submit a new Exempt Evaluation

Any deviation or violation of the Investigator Responsibilities for Exempt Research or alterations from the study as described in the Exempt Evaluation must be reported to the COUHES office for further review

----

E-1573, Framework for Selecting a System Design Approach

Principal Investigator: Chiverton, Kelly Ann
Faculty Sponsor: de Weck, Olivier L
Start Date. AUG-01-2019
End Date: DEC-31-2019

Determination(s)· Exempt

Exempt Category 3 - Benign Behavioral Intervention

Research involving benign behavioral interventions where the study activities are limited to adults only and disclosure of the subjects' responses outside the research could not reasonably place the subjects at risk for criminal or civil liability or be damaging to the subjects' financial standing, employability, educational advancement, or reputation Research does not involve deception or participants prospectively agree to the deception 45 CFR 46 104(d)(3)

Exempt Category 2 - Educational Testing, Surveys, Interviews or Observation

Research involving surveys, interviews, educational tests or observation of public behavior with adults or children and disclosur! e of the subjects' responses outside the research could not reasonably place the subjects at risk for criminal or civil liability or be damaging to the subjects' financial standing, employability, educational advancement, or reputation Research activities with children must be limited to educational tests or observation of public behavior and cannot include direct intervention by the investigator 45 CFR 46 104(d)(2)

If you have questions, please contact COUHES directly

email couhes@mit edu | phone 617-253-6787 | website couhes mit edu | online COUHES Connect

This is an automated notification Please do not reply directly to this email

Massachusetts Institute of Technology
COUHES - Committee on the Use of Humans as Experimental Subjects
77 Massachusetts Avenue Building E25-143b, Cambridge, MA 02139

9 Appendix B: Interview Primer

Summary: Research is being conducted under the MIT Sloan School of Management and School of Engineering related to the System Design and Management (SDM) program. This research feeds thesis activity for a Master of Science in Engineering and Management.

Scope: This research analyzes two umbrella categories of design strategies: static vs. flexible. It also explores subcategories of the above design approaches: optimized, robust, real options, and adapt. Based on an understanding of the different design strategies and the tradeoffs between the strategies, a decision framework is developed (see page 2) that attempts to direct a user to the most cost effective and responsive system design under a given set of objectives and uncertainties. This research will inform the usefulness and understandability of the decision framework.

Background: This thesis examines relevant literature on design strategies in order to define the designs, understand the benefits and penalties of the approaches, and explore examples of each design used in a Department of Defense (DoD) system. The thesis proposes a decision framework for selecting an optimal design approach that characterizes system tradeoffs between dynamic market needs, the rate of technology change, and a system's future operating environment against the value of the proposed design, with the goal of choosing the most cost effective and responsive system design under a given set of objectives and uncertainties.

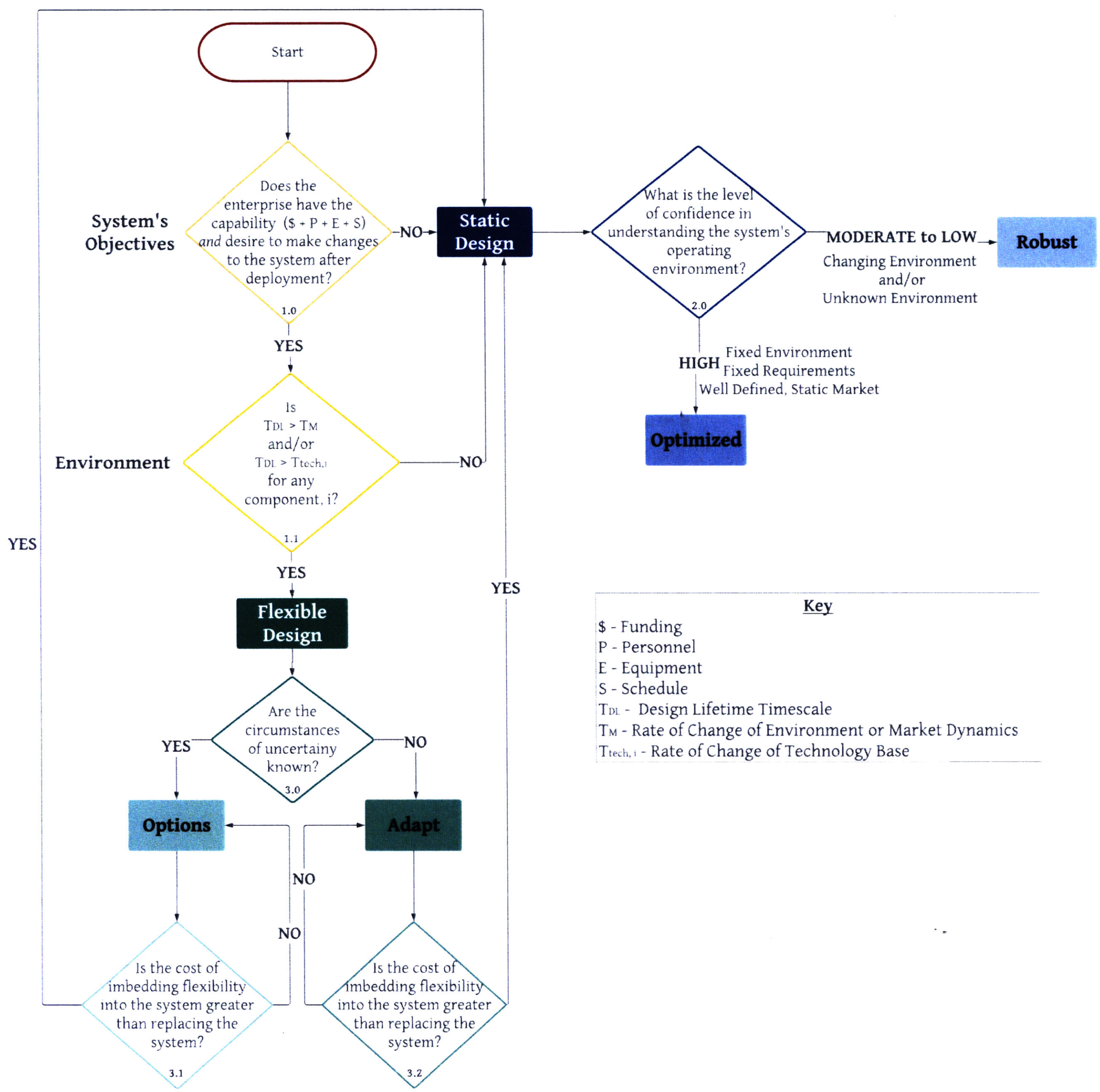
Rationale for Framework:
- Government-wide emphasis on fielding DoD systems smarter and faster
- Growing need for US military systems to rapidly respond to new missions, threats, and changes in operational environments that enterprises can and cannot anticipate
- Desire to strengthen the DoD's commitment to systems engineering fundamentals

Research Questions:
- What are the different design strategies?
- What are the tradeoffs between the design strategies?
- What is the optimal design strategy for allowing enterprises to quickly respond to operational changes they can and cannot anticipate?
- Is the proposed decision framework a useful tool for choosing the most cost effective and responsive system design under a given set of objectives and uncertainties?

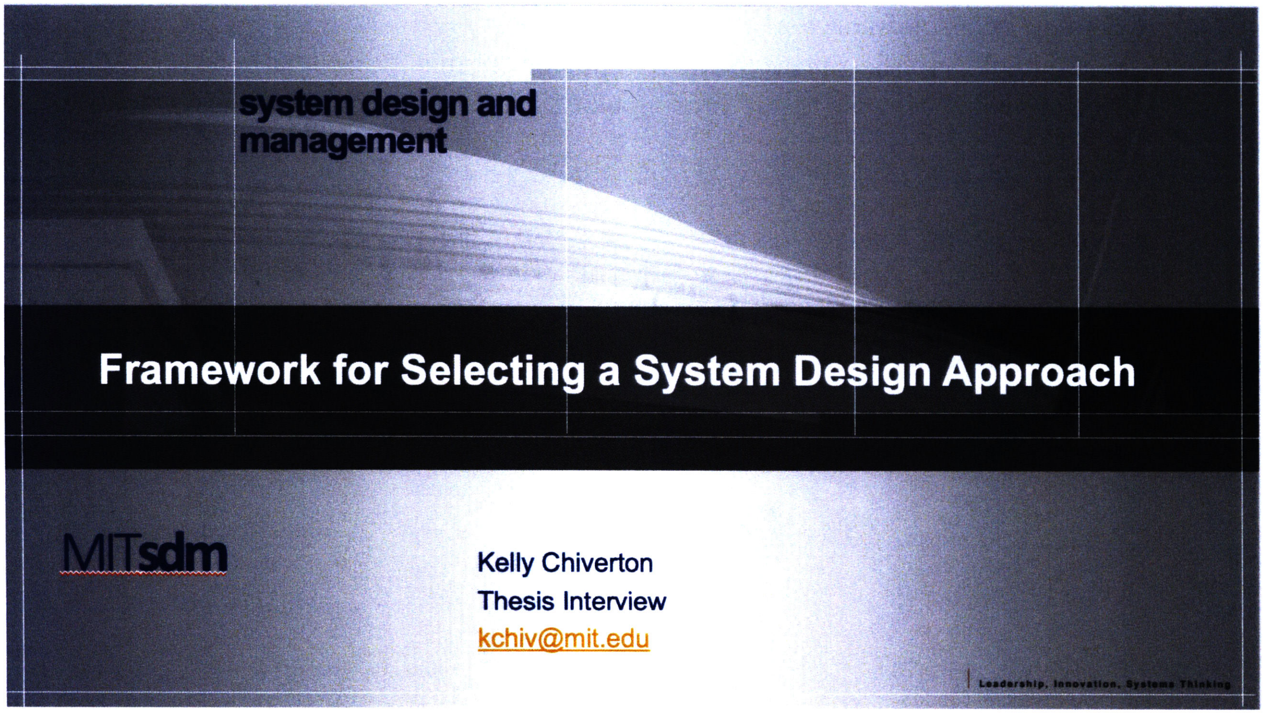
Discussion Topics:
- Are there sections of the framework that appear confusing? Do you have recommendations for making the framework more understandable?
- Based on your experience in the industry, do any portions of the framework look wrong to you?
- In your opinion, who should be worrying about this topic? (e.g., the Chief Engineering at the program office level, the Program Manager at the program office level, SAF/AQ, etc.)
- Does the framework appear to be a useful tool for an Air Force program office responsible for designing, developing, and fielding a system? Why or why not?

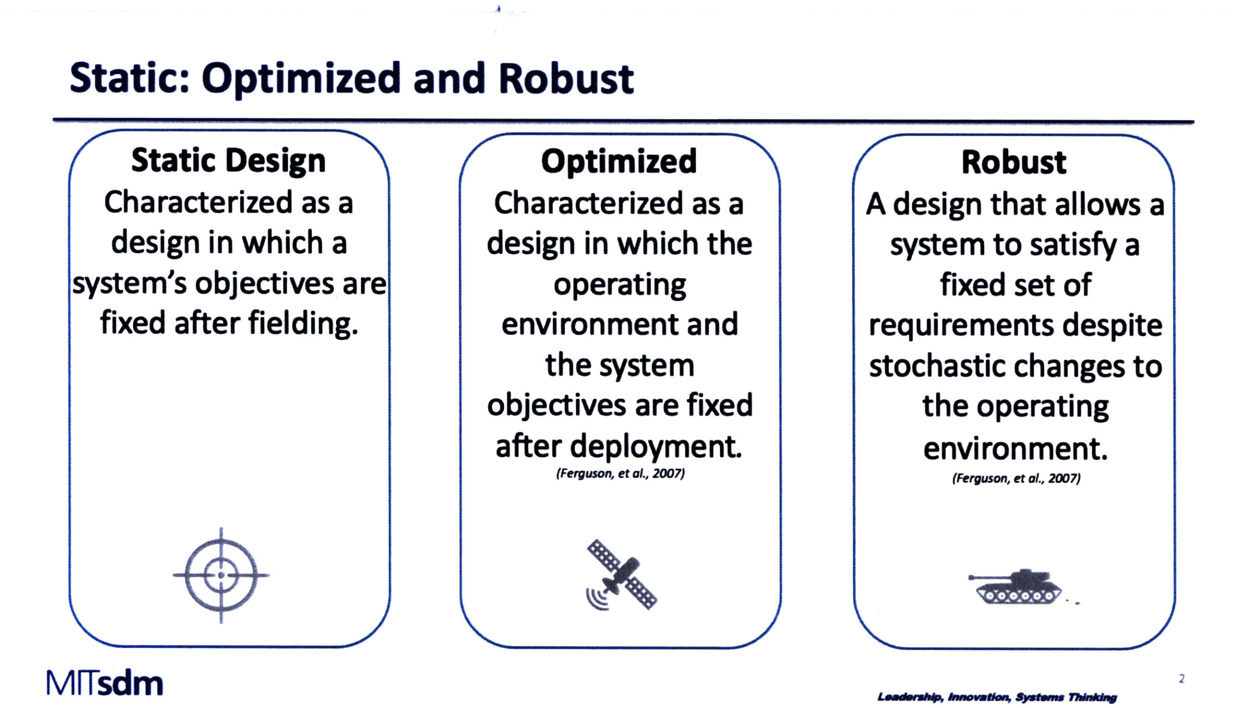
- Are there certain Air Force program offices where the framework would be more/less applicable?
- Do you have suggestions for more appropriately assessing (i.e., measuring) the various constructs in the decision framework?
- Where do you think is the best place to teach or implement this framework?
- Can you suggest enhancements to the format, layout, and/or organization of the framework?

System Design Framework:



10 Appendix C: Interview Presentation





Flexible: Options and Adapt

Flexible Design
The property of a system that allows it to respond to changes in its initial objectives and requirements, occurring after the system has been fielded, in a timely and cost-effective way.
(Saleh, et al., 2014)

Options
Characterized as engineering design decisions that enable the flexibility to change a system in the future and reduce risks for known unknowns.

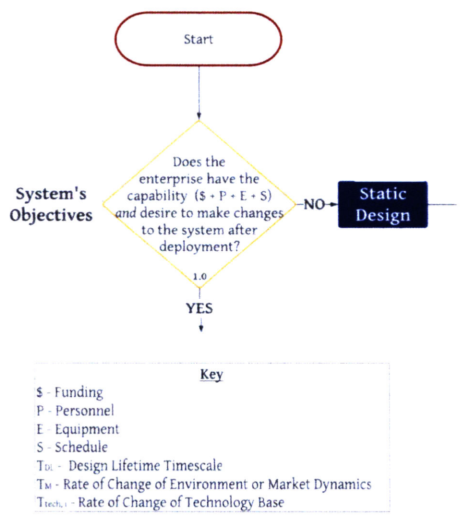
Adapt
Characterized as a system's ability to respond to unanticipated or emergent changes in the environment and/or operating conditions.

MITsdm

Leadership, Innovation, Systems Thinking 3

Design Framework Walkthrough: 1.0

- Capability is a factor of funding, personnel, equipment, and schedule.
- Desire for change would be answered by the enterprise's leadership (e.g., PEO, SAF/AQ, etc.).

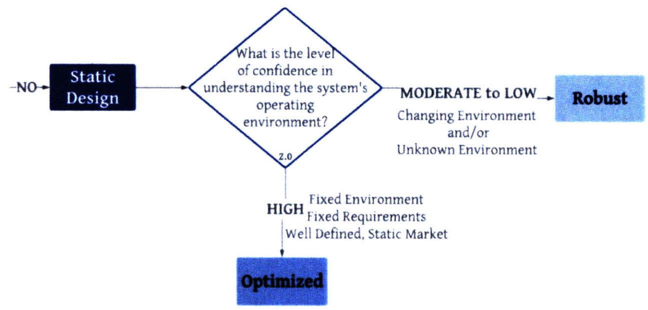


MITsdm

Leadership, Innovation, Systems Thinking 4

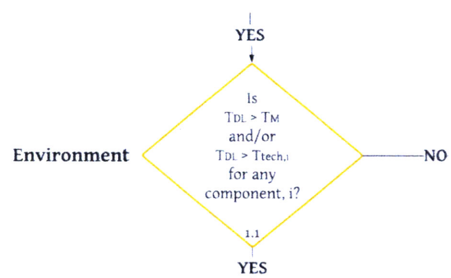
Design Framework Walkthrough: 2.0

- Key decision variables: design lifetime & operating environment
- In a well defined, static market an optimized design approach should offer the highest level of performance, lowest development costs, and shortest development timeframe.
- If the operating environment is expected to change, the enterprise can minimize risks of market shift or needs shift using a robust design approach.
  - May carry a cost or performance penalty.
  - Allows the system to maintain a target performance despite different noise factors.
  - Can mitigate the threat of obsolescence if the system's environment changes.



Design Framework Walkthrough: 1.1

- Key decision variables:
  - design lifetime
  - market dynamics
  - rate of change in technology
- Key questions:
  - Is the environment expected to change?
  - Are user needs expected to change?
  - Will the embedded technology need to be updated in order to prevent obsolescence?
- Difficult to estimate T_M and $T_{tech,\,i}$ using theoretical deduction.



Key

- $ - Funding
- P - Personnel
- E - Equipment
- S - Schedule
- T_{DL} - Design Lifetime Timescale
- T_M - Rate of Change of Environment or Market Dynamics
- $T_{tech,i}$ - Rate of Change of Technology Base

Design Framework Walkthrough: 1.1 Market Dynamics

For this thesis, it is suggested T_M be quantified through one of two methods:

1. Using the historical rate of change in the environment or market dynamics of a comparable system that has already been fielded.
2. Conducting market research and customer interviews to analyze the market using the Porter's Five Forces framework and using the results to develop an estimate for the rate of change in the system's environment or market dynamics.

Porter's Five Forces

MITsdm

Leadership, Innovation, Systems Thinking 7

Design Framework Walkthrough: 1.1 Rate of Change in Technology

- Rate of change in technology will be calculated using a formula adapted from *(Saleh, et al., 2002)* that captures time to obsolescence and the "H Vector" of a design.

$$H = \left[\frac{T_{obs_1}}{T_{DL}}, \frac{T_{obs_2}}{T_{DL}}, \ldots, \frac{T_{obs_n}}{T_{DL}} \right]$$

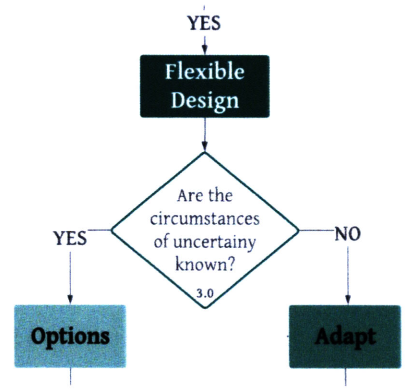
- A system is unaffected by obsolescence problems if $H_i \approx$ on the order of 1, for all i.
- The formula will be applied to macro-level components and/or subsystems of DoD systems.

MITsdm

Leadership, Innovation, Systems Thinking 8

Design Framework Walkthrough: 3.0

- If the enterprise has a deliberate understanding of the uncertainty the answer is "YES".
  - A real options approach reduces risks for known unknowns.
- If the enterprise recognizes uncertainty exists but is unable to come up with the circumstances surrounding the uncertainty, the answer is "NO".
  - An adapt approach reduces risks for unknown unknowns.



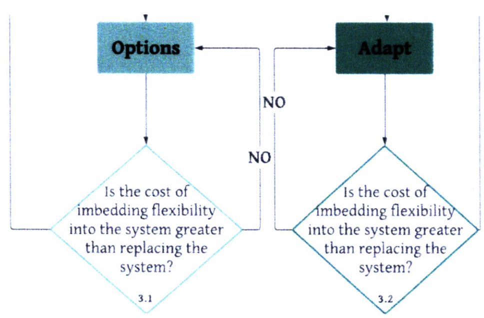
MITsdm

Leadership, Innovation, Systems Thinking

9

Design Framework Walkthrough: 3.1 and 3.2

- This step should be conducted by the cost estimation team (or equivalent entity).



MITsdm

Leadership, Innovation, Systems Thinking

10

References

- Ferguson, S., Siddiqi, A., Lewis, K. & de Weck, O. L., 2007. *Flexible and Reconfigurable Systems: Nomenclature and Review.* Las Vegas, ASME 2007 International Design Engineering Technical Conference & Computers and Information in Engineering Conference.
- Lucero, S., 2018. *The Mash-up Rubric: Strategies for Integrating Emerging Technologies to Address Dynamic Requirements.* Washington DC, INCOSE International Symposium.
- Saleh, J. et al., 2014. *On Flexibility in System Design.* Cleveland, INCOSE International Symposium.
- Saleh, J., Marais, K., Hastings, D. & Newman, D., 2002. *The Case for Flexibility in System Design.* Cambridge, MIT.

MITsdm

Leadership, Innovation, Systems Thinking

11

11 Appendix D: Defense Acquisition Lifecycle Chart