An Evaluation of the Relationship Between Critical Technology Developments and Technology Maturity

by Wanda Carter Peters

B.S. in Biology, May 1983, University of Maryland, Eastern Shore
B.S. in Engineering, May 1989, Catholic University of America
M.S. in Engineering Management, January 1995, George Washington University

A Dissertation submitted to

The Faculty of
The School of Engineering and Applied Science
of The George Washington University
in partial fulfillment of the requirements
for the degree of Doctor of Philosophy

August 31, 2017

Dissertation directed by

Steven Doskey
Adjunct Professor of Engineering Management and Systems Engineering

James Moreland, Jr.
Adjunct Professor of Engineering Management and Systems Engineering

The School of Engineering and Applied Science of The George Washington University certifies that Wanda Carter Peters has passed the Final Examination for the degree of Doctor of Philosophy as of June 27, 2017. This is the final and approved form of the dissertation.

An Evaluation of the Relationship Between Critical Technology Developments and Technology Maturity

Wanda Carter Peters

Dissertation Research Committee:

Steven Doskey, Professional Lecturer of Engineering Management and Systems Engineering, Dissertation Co-Director

James Moreland, Jr., Professional Lecturer of Engineering Management and Systems Engineering, Dissertation Co-Director

Shahram Sarkani, Professor of Engineering Management and Systems Engineering; Committee Member

Thomas Mazzuchi, Professor of Engineering Management and Systems Engineering & of Decision Sciences; Committee Member

Timothy Blackburn, Professional Lecturer of Engineering Management and Systems Engineering, Committee Member

E. Lile Murphree, Professor Emeritus of Engineering Management and Systems Engineering, Committee Member

DEDICATION

This dissertation is dedicated to my husband, Fabian Peters, and my daughters, Nicole and Francesca Peters, for their love, support and encouragement throughout this journey. This dissertation is also dedicated to my parents, Raymond L. Carter, Jr. and Delores Coppedge Carter, who taught me to trust in God and to believe in myself. Their love and support are priceless.

ACKNOWLEDGEMENT

It is with gratitude and appreciation that I thank everyone who contributed to the completion of my dissertation. It is my sincere and humble thank you to my advisors, Professor Steven Doskey and Professor James Moreland, Jr. for their guidance, encouragement and support throughout my research. Their excitement about my research was uplifting, motivating and greatly appreciated. My appreciation is also extended to my entire dissertation committee for their time and advice. Additionally, I would like to express my appreciation to my Arlington Cohort, and especially Ms. Sallamar Worrell, for on-going support, camaraderie and encouragement. It has been a pleasure traveling this road with all of you.

This research would not have been possible without the financial support provided by the National Aeronautics and Space Administration's Goddard Space Flight Center Academic Investment for Mission Success (AIMS) Program. My gratitude is extended to my former supervisor, Mr. William Lee Niemeyer, for his support and encouragement that allowed me the opportunity to pursue my dream of a doctorate degree. My appreciation is extended to my supervisor, Mr. David Mitchell, for supporting my academic dream; Dr. Felicia Jones, Dr. Sherrica Holloman and Mrs. Karen Flynn for their guidance and unwavering support and to Ms. Pamela Barrett, Ms Christonya Graham, Ms. Kenya Well, and Ms. Nicole Spriggs for guiding me through the administrative paperwork.

My heartfelt appreciation and gratitude goes to my parents, Mr. Raymond Carter, Jr. and Mrs. Delores Coppedge Carter, for their continuous support and tirelessly proofreading of my dissertation. To my husband and daughters, Mr. Fabian Peters, Ms.

Nicole Peters, and Ms. Francesca Peters, without their love, patience and words of encouragement, this endeavor would have been more enduring. A special thank you to my heavenly Father, because God is my strength and inspiration!

ABSTRACT

An Evaluation of the Relationship Between Critical Technology Developments and Technology Maturity

The research presented in this dissertation investigates the relationship between critical technologies and technology maturity assessments at a key decision point in the product development life cycle. This study utilizes statistical methods for assessing technology maturity at a key decision point. A regression model is established and utilized for predicting the probability of a system achieving technology maturity. The study disclosed with a 95% confidence that there is statistical evidence that utilization of heritage technology developments, as originally designed, significantly increases the probability of achieving technology maturity at a key decision point. This finding is significance due to the potential for engineers to overestimate technology maturity when utilizing heritage designs. One challenge facing systems engineers is quantifying the impact technology developments have on technology maturity assessments, especially when transitioning from formulation to implementation. Correctly assessing the maturity of a technology is crucial for an organization's ability to manage performance, cost, and schedule. The findings from this research has the potential to reduce unacceptable or unsatisfactory technical performance and programmatic overruns through the minimization of inaccurate maturity determinations.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

AIM	Aeronomy of Ice in the Mesosphere
ANOVA	Analysis of Variance
CADRe	Cost Analysis Data Requirement
CALIPSO	Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observations
CDR	Critical Design Review
CL	Confidence Level
CYGNSS	Cyclone Global Navigation Satellite System
DoD	Department of Defense
DoE	Department of Energy
FAD	Formulation Authorization Document
GAO	Government Accountability Office
GLAST	Gamma ray Large Area Space Telescope
GOES-R	Geostationary Operational Environmental Satellite-R Series
GPM	Global Precipitation Measurement
GRAIL	Gravity Recovery and Interior Laboratory
GRACE-FO	Gravity Recovery and Climate Experiment Follow-On
IBEX	Interstellar Boundary Explorer
ICESat-2	Ice, Cloud, and Land Elevation Satellite – 2
InSight	Interior Exploration using Seismic Investigations, Geodesy and Heat Transport
IRIS	Interface Region Imaging Spectrograph
IRL	Integration Readiness Level
JWST	James Webb Space Telescope
KDP	Key Decision Point
LADEE	Lunar Atmospheric and Dust Environment Explorer
LDCM	Landsat Data Continuity Mission
LRO	Lunar Reconnaissance Orbiter
MAVEN	Mars Atmosphere and Volatile EvolutioN
MCR	Mission Concept Review
MDR	Mission Definition Review

ML	Maximum Likelihood
MMS	Magnetospheric Multiscale
MRR	Mission Readiness Review
MRL	Manufacturing Readiness Level
MSL	Mars Science Laboratory
NASA	National Aeronautics and Space Administration
NPP	NPOESS Preparatory Project
NPR	NASA Procedural Requirements
OCO	Orbiting Carbon Observatory
OCO-2	Orbiting Carbon Observatory-2
OSIRIS-Rex	Origins Spectral Interpretation Resource Identification Security Regolith Explorer
RBSP	Radiation Belt Storm Probes
PDR	Preliminary Design Review
SAC-D	Satellite de Aplicaciones Cientifico
SDO	Solar Dynamics Observatory
SDR	System Definition Review
SGSS	Space Network Ground Segment Sustainment
SIR	System Integration Review
SLS	Space Launch Systems
SMAP	Soil Moisture Active and Passive Mission
SME	Subject Matter Expert
SoS	System of Systems
SPP	Solar Probe Plus
SRL	System Readiness Level
SRR	System Readiness Review
TESS	Transiting Exoplanet Survey Satellite
TDRS Replenishment	Tracking and Data Relay Satellite Replenishment
TRA	Technology Readiness Assessment
TRL	Technology Readiness Level
US	United States
WISE	Wide-field Infrared Survey Explorer

GLOSSARY

As defined by NASA [NPR 7120.5, 2012; NASA/SP-2007-6105, 2007]

Acquisition: The process for obtaining the systems, research, services, construction, and supplies that NASA needs to fulfill its missions. Acquisition--which may include procurement contracting for products and services)--begins with an idea or proposal that aligns with the NASA Strategic Plan and fulfills an identified need and ends with the completion of the program or project or the final disposition of the product or service.

Confidence Level: A probabilistic assessment of the level of confidence of achieving a specific goal.

Critical Design Review: A review that demonstrates that the maturity of the design is appropriate to support proceeding with full-scale fabrication, assembly, integration, and test, and that the technical effort is on track to complete the flight and ground system development and mission operations in order to meet mission performance requirements within the identified cost and schedule constraints.

Decision Authority (*program and project context*)**:** The Agency's responsible individual who authorizes the transition at a KDP to the next life-cycle phase for a program/project.

Entry Criteria: Minimum accomplishments each project needs to fulfill to enter into the next life-cycle phase or level of technical maturity.

Formulation: The identification of how the program or project supports the Agency's strategic goals; the assessment of feasibility, technology, and concepts; risk assessment, team building, development of operations concepts, and acquisition strategies; establishment of high-level requirements and success criteria; the preparation of plans, budgets, and schedules essential to the success of a program or project; and the establishment of control systems to ensure performance to those plans and alignment with current Agency strategies.

Formulation Phase: The first part of the NASA management life cycle defined in NPR 7120.5 where system requirements are baselined, feasible concepts are determined, a system definition is baselined for the selected concept(s), and preparation is made for progressing to the Implementation phase.

Heritage (or legacy)**:** Refers to the original manufacturer's level of quality and reliability that is built into the parts which have been proven by (1) time in service, (2) number of units in service, (3) mean time between failure performance, and (4) number of use cycles.

Implementation: The execution of approved plans for the development and operation of the program/project, and the use of control systems to ensure performance to approved plans and continued alignment with the Agency's goals.

Implementation Phase: The part of the NASA management life cycle defined in NPR 7120.5 where the detailed design of system products is completed and the products to be deployed are fabricated, assembled, integrated, and tested and the products are deployed to their customers or users for their assigned use or mission.

Key Decision Point (or milestone)**:** The event at which the decision authority determines the readiness of a program/project to progress to the next phase of the life cycle (or to the next KDP).

NASA Life-Cycle Phases (or program life-cycle phases)**:** Consists of Formulation and Implementation phases as defined in NPR 7120.5.

Preliminary Design Review: A review that demonstrates that the preliminary design meets all system requirements with acceptable risk and within the cost and schedule constraints and establishes the basis for proceeding with detailed design. It will show that the correct design option has been selected, interfaces have been identified, and verification methods have been described.

Project: (1) A specific investment having defined goals, objectives, requirements, life-cycle cost, a beginning, and an end. A project yields new or revised products or services that directly address NASA's strategic needs. They may be performed wholly in-house; by Government, industry, academia partnerships; or through contracts with private industry. (2) A unit of work performed in programs, projects, and activities.

Risk: The combination of the probability that a program or project will experience an undesired event (some examples include a cost overrun, schedule slippage, safety mishap, health problem, malicious activities, environmental impact, or failure to achieve a needed scientific or technological breakthrough or mission success criteria) and the consequences, impact, or severity of the undesired event, were it to occur. Both the probability and consequences may have associated uncertainties.

Risk Assessment: An evaluation of a risk item that determines (1) what can go wrong, (2) how likely is it to occur, (3) what the consequences are, and (4) what are the uncertainties associated with the likelihood and consequences.

System: (1) The combination of elements that function together to produce the capability to meet a need. The elements include all hardware, software, equipment, facilities, personnel, processes, and procedures needed for this purpose. (2) The end product (which performs operational functions) and enabling products (which provide life-cycle support services to the operational end products) that make up a system.

Systems Engineering: A disciplined approach for the definition, implementation, integration, and operation of a system (product or service). The emphasis is on achieving stakeholder functional, physical, and operational performance requirements in the intended use environments over planned life within cost and schedule constraints. Systems engineering includes the engineering processes and technical management processes that consider the interface relationships across all elements of the system, other systems, or as a part of a larger system.

Technology Assessment: A systematic process that ascertains the need to develop or infuse technological advances into a system. The technology assessment process makes use of basic systems engineering principles and processes within the framework of the PBS. It is a two-step process comprised of (1) the determination of the current technological maturity in terms of technology readiness levels and (2) the determination of the difficulty associated with moving a technology from one TRL to the next through the use of the AD^2.

Technology Maturity Assessment: The process to determine a system's technological maturity via Technology Readiness Levels.

Technology Readiness Level: Provides a scale against which to measure the maturity of a technology. TRLs range from 1, Basic Technology Research, to 9, Systems Test, Launch, and Operations. Typically, a TRL of 6 (i.e., technology demonstrated in a relevant environment) is required for a technology to be integrated into a flight system or a SE process.

Chapter 1 – INTRODUCTION

Technical organizations annually invest billions of dollars in the development of engineering technologies and products. The complexity and novelty of these developmental efforts can create technical and programmatic challenges. Accurately assessing the maturity of technology developments is vital for an organization’s ability to properly manage technical performance, cost, and schedule. In many technical organizations, systems engineers are tasked with assessing the maturity of these complex systems to provide essential decision-making information. A challenge facing systems engineers is quantifying the impact critical technology developments have on technology maturity assessments. Inaccurate system maturity assessments of a technology or product development could potentially lead to reduced or unacceptable technical performance and programmatic overruns. The ability to quantify the significance of the relationships among critical technology developments and technology maturity would be beneficial to the systems engineering community. The research presented in this dissertation utilizes statistical methods for assessing technology maturity at a key decision point in the product development life cycle. A regression model is established and utilized for predicting the probability of a system achieving technology maturity. The predictive probabilistic model provides systems engineers with supplemental information for gauging a system’s ability to achieve technology maturity by a key decision point in the development life cycle.

The National Aeronautics and Space Administration (NASA) engineers have been known for designing and developing technically challenging and complex products. For approximately 40 years, NASA has utilized technology readiness levels (TRL) to assess the technology maturity of its systems and missions. In 2005, the United States Government Accountability Office (GAO) published a report entitled “NASA – Implementing a Knowledge-Based Acquisition Framework Could Lead to Better Investment Decisions and Project Outcomes” that discussed NASA’s difficulty maintaining performance, cost and schedule objectives [GAO, 2005]. According to the 2005 GAO report, “NASA’s policies do not require projects to demonstrate technologies at high levels of maturity before program start. By not establishing a minimum threshold for technology maturity, NASA increases the risk that design changes will be required later in development, when such changes are typically more costly to make” [GAO, 2005]. NASA accepted GAO’s findings and implemented a knowledge-based acquisition approach for its projects [GAO, 2005]. The purpose of the knowledge-based acquisition approach was to establish best practices for the reduction of technical risk. These best practices were designed to assist NASA in meeting technical and programmatic commitments. In 2009, GAO began tracking the technical and programmatic status of selected large-scale NASA projects at key decision points (KDP) in their life cycle. The annual GAO reports evaluated the current status of selected projects and acquisition practices. The GAO reports also provided projects’ technology maturity at preliminary design review (PDR).

1.1 Problem Statement

According to the 2015 released GAO report, twenty-three percent of the selected large-scale NASA projects did not meet technology maturity criteria, placing cost and schedule for those missions in jeopardy [GAO, 2015]. The remaining seventy-seven percent of the selected NASA projects met the technology maturity criteria. As indicated in the 2009 GAO report, “When complex development programs proceed without understanding whether technologies can work as intended, they end up facing unanticipated technical problems that have costly, reverberating effects on other aspects of the program” [GAO, 2009].

1.2 Purpose of Research

The purpose of this study is to investigate technology maturity assessments at a KDP through the evaluation of acquisition attributes and development types. This study investigates the significance and strength of the relationships between technology maturity and factors used to assess acquisition product development. The GAO acquisition factors consist of complexity of heritage technology, new technology developments, and technical challenges at the key decision points of PDR. This study utilizes data from NASA missions to evaluate achieving technology maturity by a KDP and to establish a predictive model framework that provides the probability of achieving technology maturity by a given KDP.

1.3 Relevance and Importance

For any system or technology development, challenges are typically experienced in three major areas: technical performance, cost and schedule. A well planned and managed technology program can significantly minimize the uncertainty and risk associated with these areas of concern [Mankins, 2009]. Therefore, having an accurate assessment of system and technology maturity is necessary. Numerous technology readiness studies in the literature recommended future research in the areas of system readiness and maturity assessments. Several of these studies were related to technology maturity assessments of space systems using TRL. The literature revealed aerospace missions and defense weapon acquisitions depended heavily on TRL assessments for system engineering decision-making. Moreover, the literature review disclosed gaps in the body of knowledge regarding the accuracy of readiness and maturity assessments. According to Cornford [2004], “One of the most significant sources of risk in any spacecraft development program is the accurate assessment of technological maturity” [Cornford and Sarsfield, 2004]. The literature discussed the utilization of TRL methods and tools developed to assess technology readiness. However, these methods and tools rely on inputs from subject matter experts (SME), making them susceptible to SME’s subjectivity. Additionally, some of the studies discussed the limitations of TRL and System Readiness Levels (SRL) methodologies, which further emphasized the necessity to quantify the uncertainty associated with technology and system maturity assessments. It was also noted that the literature lacked information concerning confidence intervals associated with technology maturity assessments. This apparent missing body of information raises questions about the amount of confidence a systems engineer should place on the accuracy of any given system maturity determinations and a comprehensive understanding of the relationship between critical technologies and technology maturity.

1.4 Research Questions

The accurate assessment of technology maturity is extremely important for managing a system development. It is a generally accepted supposition in the aerospace community that the risk of cost overruns and schedule delays is reduced when technical maturity is achieved early in the life cycle of the flight project. It is also a generally accepted best practice to utilize heritage technology designs instead of new technology developments for reducing the risk of cost and schedule growth [GAO, 2005]. Heritage, also known as legacy, refers to “the original manufacturer’s level of quality and reliability that is built into parts and which has been proven by (1) time in service, (2) number of units in service, (3) mean time between failure performance, and (4) number of use cycles” [NASA/SP-2007-6105, 2007]. As stated in the NASA Systems Engineering Handbook [2007], modification of a heritage system using the original design in a different form, fit or function should be considered a technology development [NASA/SP-2007-6105, 2007]. As a result, some of the questions confronting system engineers and project managers are:

1. How accurate are technology maturity assessments?
2. Is a heritage design that is modified in form, fit, or function considered heritage or new?
3. Is a heritage design that is modified due to obsolescence still considered heritage?
4. Are there correlations among technology maturity and acquisition factors?
5. Do acquisition factors influence the assessment of technology maturity?
6. Is the technology development truly mature?
7. What is the level of confidence associated with a technology maturity assessment?

In an effort to gain a more comprehensive understanding with regards to the influence of development types on technology maturity assessments, the research question explored for this investigation is as follows: “What is the relationship between a critical technology development and technology maturity at a key decision point in the product development life cycle?”

1.5 Significance

In the early 2000s, NASA experienced several challenges pertaining to meeting technical performance, cost and schedule requirements for their flight missions. In response to these challenges, NASA revised its program/project management policy and developed an agency-wide systems engineering policy [GAO, 2005]. NASA implemented a knowledge-based acquisition process for flight and ground systems. The knowledge-based process was implemented to improve the technical and programmatic performance of NASA acquisitions, allowing for informed decision-making by managers and systems engineers.

For decades, NASA has utilized the TRL methodology for assessing the readiness or maturity of technologies and products at the system level, subsystem level and component level. TRL is generally used for evaluating flight systems at the component or subsystem levels. The accepted rule of thumb for assigning a TRL at the system level is “the TRL of a system cannot be higher than the lowest TRL of its constituents” [Leete, 2015]. In order to determine the TRL of the system, a thorough evaluation of the system’s subsystems and components should be performed. Furthermore, TRL definitions do not have standardized interpretations, which potentially could lead to subjective, inconsistent, and inaccurate TRL assessments [Seablom, 2012]. Using TRL solely for the assessment of technology maturity has its limitations, especially at the system level.

In 2015, the NASA Agency’s annual budget was approximately 18.5 billion dollars. Inaccurate technology maturity assessments could have an adverse financial impact, resulting in the expenditure of multi-million dollars due to technical problems and cost overruns. Having an efficient and effective way to gauge the accuracy of technology maturity assessments could minimize potential losses. With institutionalization of TRL as a viable method for evaluating technology and system maturity, the accuracy of assessments should be investigated. Thus, results from this study have the potential to quantify the accuracy of technology maturity determinations. The focus of this study is to investigate the relationship between critical technology developments and system-level technology maturity assessments and to provide a framework for a probability predictive model related to achieving technology maturity.

1.6 Scope and Limitations

This research focuses on technology maturity assessments of NASA missions, using data from GAO annual assessment reports and the NASA Cost Analysis Data Requirement (CADRe) system. This investigation seeks to provide a better understanding of technology maturity and critical technology developments. The following characteristics and constraints were applied to this research.

- The primary source of information is the GAO annual reports;
- GAO technology maturity assessments are reported as “Yes” or “No” responses;
- Technology maturity assessments reflected the state of the mission at PDR;
- The overall TRL assessments for the NASA missions from the CADRe systems are no greater than the lowest TRL assessment for the associated instruments payload.

1.7 Contribution to the Body of Knowledge

The information, data, and analysis contained in this study provides a better understanding the relationships among critical technologies and technology maturity assessments, adding to the body of knowledge needed for system definition, design, and development. Insight gained from this research could potentially provide valuable information to the systems engineering community, contributing to the effective management of technical and programmatic performance. The primary stakeholders are the system engineers responsible for technology readiness and maturity assessments, as well as the organizations responsible for the design, manufacture, integration and test, and deployment of engineering products and technologies. The results from this research will be extremely beneficial to NASA. The research results, especially the predictive model framework for achieving technology maturity at a KDP in the product development life cycle, has the ability to be of great interest to the Department of Defense (DoD), the Department of Energy (DoE), the aerospace industry, and engineering development organizations.

1.8 Organization of the Document

This dissertation is organized into six chapters. Chapter 1 introduces technology maturity and frames the problem associated with inaccurate technology assessments. It describes the impact of inaccurate technology maturity assessments on technical and programmatic performance. This chapter also discusses the relevance and significance of this problem and identifies gaps in the body of knowledge that will be filled with the results of this research.

Chapter 2 provides background information concerning previous and current research and studies in the area of technology readiness and maturity assessments. It discusses the establishment and utilization of TRL, TRL methodologies, TRL tools, and SRL for the evaluation of technology maturity. Additionally, the chapter provides the conceptual framework for this research. It also outlines information in the literature that supports the need for quantifying the accuracy of technology maturity determinations through quantitative statistical methods and details.

Chapter 3 provides the research methodology used to investigate the relationships among technology developments types, acquisition attributes, and technology maturity assessments. The chapters presents research questions and hypotheses and outlines the statistical approaches used for this research, which include binary logistic regression analysis and Adjusted Wald Technique. Binary logistic regression analysis was used to evaluate acquisition attributes of 33 NASA missions obtained from the GAO reports. Adjusted Wald Technique was used for establishment of confidence intervals for technology maturity assessments. The Mann-Whitney test and the Kruskal-Wallis test were used to statistically evaluate TRL assessment of the 33 NASA missions obtained from the CADRe system.

Chapter 4 describes the source of the data and the acquisition attributes data set used in the analysis. It describes two sample sets of 33 NASA missions and the data collection philosophy. The chapter focuses on the evaluation of technology maturity and the significance of its relationship to the other acquisition attributes and details how acquisition attributes influenced the establishment of confidence intervals. It also describes the approach used for conducting the sensitivity study of technology maturities and critical technologies.

Chapter 5 presents the statistical results from the binary logistic regression analysis, the Adjusted Wald Technique, the Mann-Whitney test, and Kruskal-Wallis test. The research findings in this chapter are organized by the research questions and hypotheses.

Chapter 6 summarizes the findings and presents conclusions of the research. It discusses the implications of the finding to the stakeholders, especially systems engineering community. This chapter also discusses the limitations of the findings and provides recommendations for future research.

Chapter 2 – LITERATURE REVIEW

In researching technology maturity assessments, many of the scholarly literature discussed various methodologies, concepts and tools for determining technical readiness. Additionally, several discussions in the literature depicted how technical readiness impacted cost and schedule performance. TRL, SRL, Integration Readiness Levels (IRL), Manufacturing Readiness Levels (MRL), TRL calculators, and TRL worksheets were some of the more commonly cited methodologies and tools referenced in the literature for assessing system and technology maturity. The most recent studies published on technology or system maturity focused primarily on SRL models or using TRL to predict cost and schedule impacts. Nevertheless, the methodology referenced most by the engineering community in the literature for assessing system and technology maturity was TRL.

2.1 Technology Readiness Levels

The application of TRL for the determination of technology maturity is utilized extensively by the engineering community for technical acquisitions and developments. In 1974, Stan Sadin, a NASA researcher, introduced the concept of TRL for improving the assessment of technology maturity [Mankins, 2009; Leete, 2015]. In 1995, John C. Mankins, from the NASA Office of Space Access and Technology, published a white paper expanding the original seven TRL definitions proposed by Sadin to nine more specific TRL definitions [Mankins, 1995]. The nine TRL definitions provided a more precise description of the developmental stage a technology, system, subsystem, or component must achieve or demonstrate for the purpose of assigning a maturity level

[Sauser, 2006; Azizian et al., 2011; McConkie, 2012]. According Mankins, “Technology Readiness Levels (TRLs) are a systematic metric/measurement system that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology” [Mankins, 1995]. The nine NASA TRL definitions, as specified by Mankins, are listed in Table 2.1.

Table 2.1: NASA Technology Readiness Levels Definitions

TRL	Definition
9	Actual system “flight proven” through successful mission operations
8	Actual system completed and “flight qualified” through test and demonstration (ground or space)
7	System prototype demonstration in a space environment
6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
5	Component and/or breadboard validation in relevant environment
4	Component and/or breadboard validation in laboratory environment
3	Analytical and experimental critical function and/or characteristic proof-of-concept
2	Technology concept and/or application formulated
1	Basic principles observed and reported

In 1999, GAO recommended that the Department of Defense (DoD) adopt the NASA TRL methodology for assessing technology maturity due to challenges associated with “holding design reviews and making production decisions without demonstrating the level of technology maturity” [GAO, 1999, Sauser, 2006; Sauser, 2008]. In 2000, DoD adopted and implemented a modified version of the NASA TRL methodology for evaluating the maturity and stability of technologies and systems [DoD, 2003; DoE, 2009; Azizian et al., 2011]. In 2006, as a result of continued DoD weapons system technology developments’ cost and schedule growth, the United States (US) Congress passed legislation that required DoD to certify that technologies have demonstrated TRL-

6 (in a relevant environment) prior to beginning the design phases or DoD must provide justification for a waiver to proceed without this demonstration [DoE, 2009].

During the same time period, NASA was experiencing challenges with meeting technical, cost, and schedule commitments. When GAO reported these challenges, NASA implemented a knowledge-based acquisition approach [GAO, 2005]. The reduction of technical risk was the primary focus of the knowledge-based approach. NASA established a best practice that utilized the TRL methodology. NASA’s technology maturity evaluation criteria consisted of a component or system demonstrating a TRL-6 or higher prior to being incorporated in the product developmental phase of the space flight project [GAO, 2009]. The 2015 GAO report stated:

> “*… a technology readiness level (TRL) of 6, demonstrating a technology as a fully integrated prototype in a relevant environment that simulates the harsh conditions of space, is the level of technology maturity that can minimize risks for space systems entering product development. Demonstrating that both critical and heritage technologies will work as intended in a relevant environment serves as a fundamental element of a sound business case, and projects falling short of this standard before preliminary design review, the point at which the TRL is assessed, often experience subsequent technical problems, which can increase the risk of cost growth and schedule delays*” [GAO, 2015]

In 2007, GAO also recommended that the Department of Energy (DoE) adopt a TRL methodology similar to NASA and DoD to address the cost growth and schedule delays associated with their technology developments. DoE tailored the TRL process and implemented the modified methodology in 2009 [DoE, 2009]. In response to the application of the TRL methodology by multiple US government agencies, non-governmental technology organizations began assessing technology maturity of their technology and systems developments through the implementation of technology readiness methodologies. This implementation resulted in the TRL concept being widely used by the systems engineering community as a decision-making tool in the electronics, automobile, aeronautics, aerospace, defense, academia and oil industries [Philbin, 2013; Loxley, 2014].

While the TRL concept has been extensively used by the technology development community, it is essential for systems engineers to understand the limitations of TRL. The TRL concept, as it was originally applied, was for the assessment of a single technology development. The TRL assessment of a single technology development has evolved, due to increases in the complexity of technology and system developments, into maturity assessments of multiple technologies in a system of systems (SoS) configuration. TRL definition interpretation is not applied in a standardized or formal manner by the various technical organizations. The TRL definitions allow the latitude for broad interpretation of maturity level achievement, which contributes to the possibility of subjective assessments even when using best engineering judgment or past experience [Cornford and Sarsfield, 2004; Tan, 2011]. According to Magnaye [2009], the utilization of TRL for assessing maturity is being applied beyond its original design and TRL definitions do not provide guidance for addressing uncertainty as the technology development increases in maturation [Magnaye, 2009]. Traditionally, TRL focuses on only specific elements of a technology or system. It does not include challenges that relate to system-to-system integration [Cornford and Sarsfield, 2004].

Additionally, the TRL scale is ordinal. Due to the ordinal nature of the scale, there are limitations to the mathematical operations that can be performed on TRL numerical values [Conrow, 2011; McConkie, 2013]. As stated by Conrow [2011], TRL scale does not estimate risk and is weakly correlated to risk [Conrow, 2011]. According to Conrow [2011], the TRL scale is to some extent related to risk probability with regard to hardware; however, the TRL scale is unrelated to consequence portion of risk [Conrow, 2011]. Thus, the TRL methodology does not integrate well with cost and risk models [Cornford and Sarsfield, 2004] and it does not give a complete picture of the risk associated with the integration of a technology into a system [Azizian et al., 2010]. According to Mankins [2002], TRL functions as a guide for current and desired levels of technology maturity. Additional methodologies are required for evaluating readiness and maturity to allow the identification of "technology-derived" uncertainty in system developments [Mankins, 2002].

2.2 Technology Assessments

There are several studies cited in the literature that assess the readiness and maturity of a technology. Technology maturity assessments have been used by DoE systems engineers to assess the "time to operational readiness" of technology-based programs through the establishment of a technical maturity model [Kenley, 1999]. A study conducted by Conrow [2011] applied an analytical hierarchy process methodology that transformed ordinal TRL scale values into cardinal TRL scale coefficients for performing mathematical operations [Conrow, 2011]. Azizian [2011] investigated the relationships between technology readiness assessment and acquisition factors of productivity, cost, schedule and customer satisfaction [Azizian et al., 2011].

The evaluation of technology maturity and its relationship or impact on cost and schedule have been the subject of multiple studies [El-Khoury, 2012; Katz, 2015]. Katz [2015] discussed the research of design maturity, based on technology readiness level, impact on cost and schedule changes, recommending future work related to the investigation of potential benefits of design readiness assessment and technical readiness assessment with respect to design maturity [Katz, 2015]. There also have been additional studies that examined technology readiness and its impact on risk and life-cycle schedules [Dubos, 2008, 2011; Conrow, 2011]. Dubos [2008] discussed evaluation of the risk of schedule slippage of 28 NASA programs through the utilization of TRL and schedule growth data obtained from GAO reports [Dubos, 2008]. Dubos further investigated TRL and time-to-delivery schedule data to develop a probabilistic model for predicting the risk of schedule growth [Dubos, 2011]. Conrow [2011] challenged the assertion that there is a significant correlation between TRL and schedule slippage [Conrow, 2011].

TRL approaches have been investigated and modeled in numerous ways to evaluate technology readiness and technology maturity. Moreover, it is generally acknowledged by the engineering community that TRL assessments have the potential to be subjective based on an individual’s interpretation of the TRL definition. As stated in the NASA Systems Engineering Handbook [2007]:

> “*When the bottom-up process is operating, a problem for the systems engineer is that the designers tend to become fond of the designs they*

> *create, so they lose their objectivity; the systems engineer often must stay an "outsider" so that there is more objectivity. This is particularly true in the assessment of the technological maturity of the subsystems and components required for implementation. There is a tendency on the part of technology developers and project management to overestimate the maturity and applicability of a technology that is required to implement a design. This is especially true of "heritage" equipment"* [NASA/SP-2007-6105, 2007].

The possibility of subjective interpretation of TRL definitions leads to questions about the accuracy of assessments related to system and technology maturity. These questions concerning the overestimation of maturity assessments highlight a gap in the body of knowledge and remain an area of interest for the systems engineering community.

2.3 Technology Readiness Level Assessment Tools and Methods

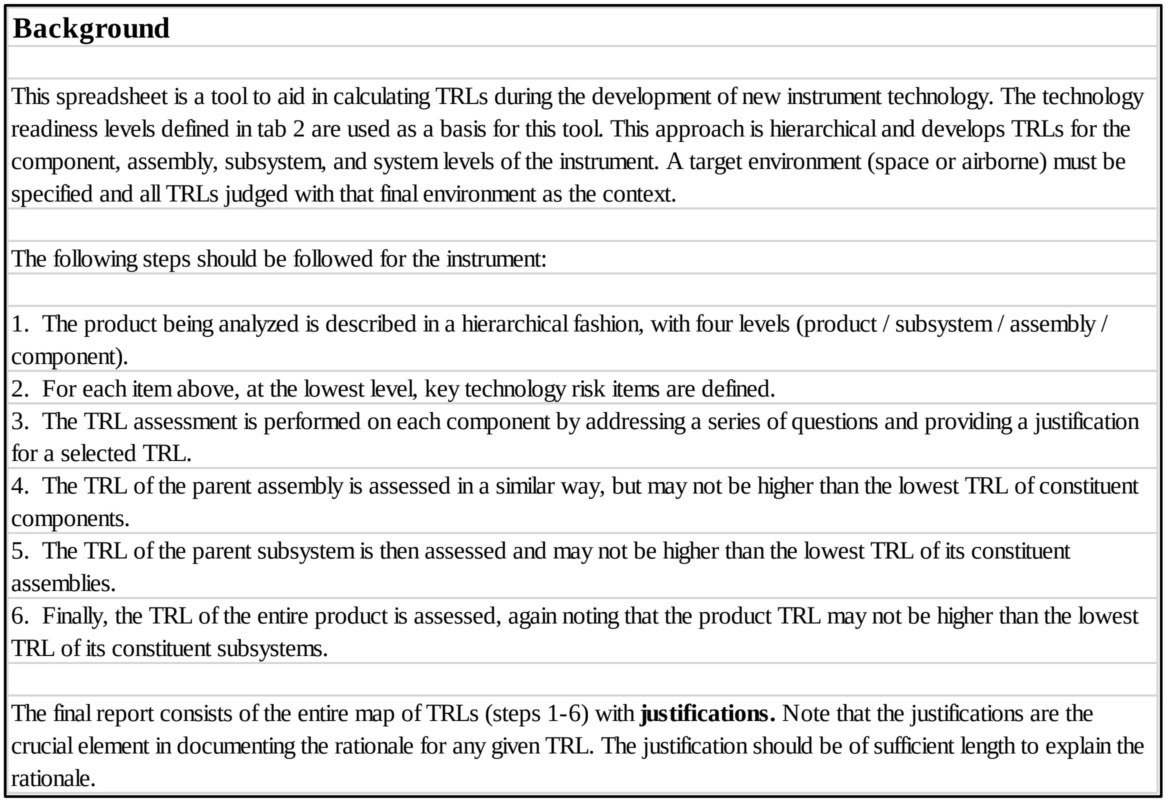
There have been several methods and tools developed for assessing TRL. DoD has a statutory requirement that mandates the technology readiness assessment of all major acquisitions. The Technology Readiness Assessment (TRA), also known as the TRA Desktop, is the DoD formal process for evaluating the maturity of critical hardware and software technologies [DoD, 2011]. The TRA process consist of an independent readiness assessment of the critical technologies by a panel of subject matter experts. TRA is considered a tool for evaluating program risk and the adequacy of technology maturity planning [DoD, 2001]. With the employment of subject matter experts in the interpretation of a critical technology's compliance in achieving a specific TRL definition, the TRA process has a level of subjectivity.

The TRL Calculator was developed by Nolte [2005] as a tool for assessing TRL values for a given technology [Nolte, 2005]. The TRL Calculator proposes questions for various categories that requires the user to select the best response, to supply the percentage for completion value, and to provide the relative importance of the question through entering a percentage for weighing TRL values. The same set of questions must be answered by the user each time it is used for computing the TRL of technologies under development, which provides for a level of process repeatability [Nolte, 2005]. However, the TRL Calculator still is susceptible to the subjectivity of the user.

In an effort to establish a more objective method for assessing TRL, Sarfaraz [2012] introduced another approach for assessing technology readiness involved using the DoD Architecture Framework model in combination with the TRL calculator tool [Sarfaraz, 2012]. This approach was designed to provide a structured process for capturing system architecture data for making informed technology maturity and technology development decisions. However, this method also relies on the opinions of subject matter experts.

At NASA, the technology maturity assessments process primarily occur during the formulation phase of the NASA mission life cycle. The TRL assessment process is outlined in the NASA Systems Engineering Handbook. The process is written in general terms and is not implemented in a standardized manner by the various NASA centers. NASA centers have utilized various approaches from convening a group of subject matter experts, chief engineers, and chief technologists, employing their experience and expertise, to utilizing a TRL worksheet or one of the previously mentioned assessment tools for assessing the TRL of components and subsystems for their missions. Figures

2.1, 2.2, 2.3, and 2.4 depicts one example of an excel worksheet used by NASA to assess technology maturity.



Background

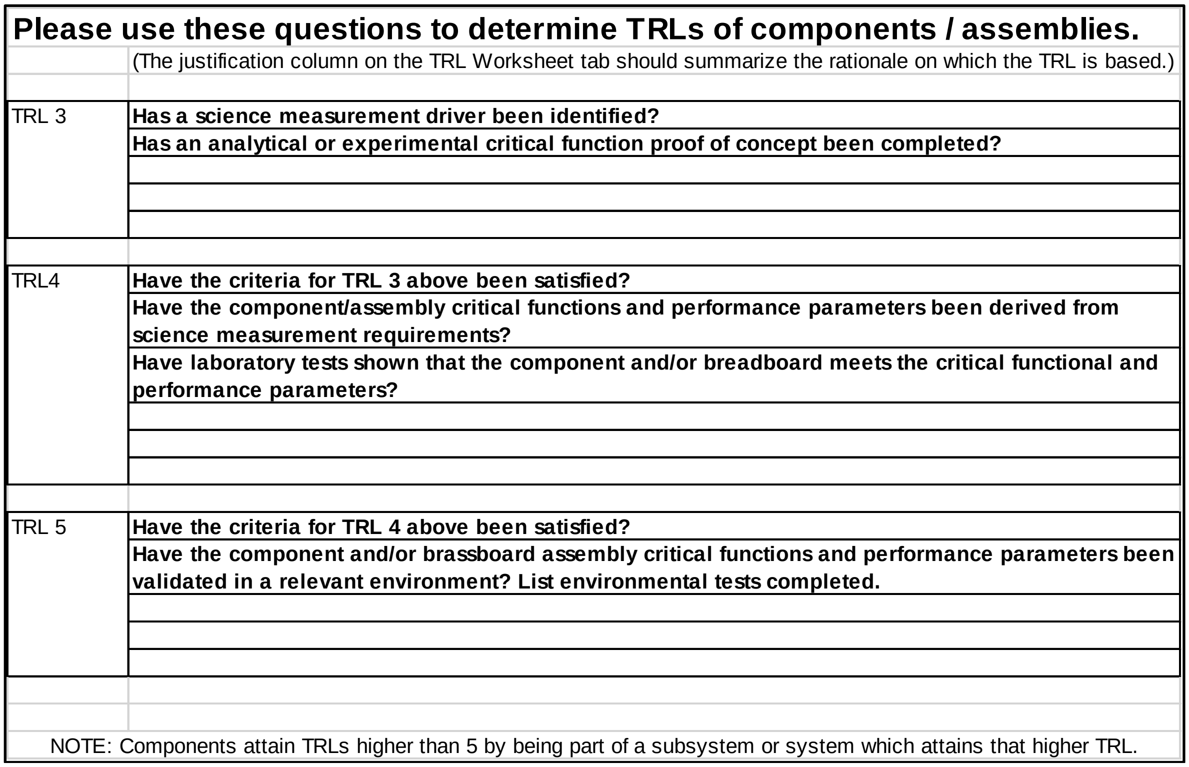
This spreadsheet is a tool to aid in calculating TRLs during the development of new instrument technology. The technology readiness levels defined in tab 2 are used as a basis for this tool. This approach is hierarchical and develops TRLs for the component, assembly, subsystem, and system levels of the instrument. A target environment (space or airborne) must be specified and all TRLs judged with that final environment as the context.

The following steps should be followed for the instrument:

1. The product being analyzed is described in a hierarchical fashion, with four levels (product / subsystem / assembly / component).
2. For each item above, at the lowest level, key technology risk items are defined.
3. The TRL assessment is performed on each component by addressing a series of questions and providing a justification for a selected TRL.
4. The TRL of the parent assembly is assessed in a similar way, but may not be higher than the lowest TRL of constituent components.
5. The TRL of the parent subsystem is then assessed and may not be higher than the lowest TRL of its constituent assemblies.
6. Finally, the TRL of the entire product is assessed, again noting that the product TRL may not be higher than the lowest TRL of its constituent subsystems.

The final report consists of the entire map of TRLs (steps 1-6) with **justifications.** Note that the justifications are the crucial element in documenting the rationale for any given TRL. The justification should be of sufficient length to explain the rationale.

Figure 2.1: Screenshot of a NASA TRL Worksheet Instruction Page

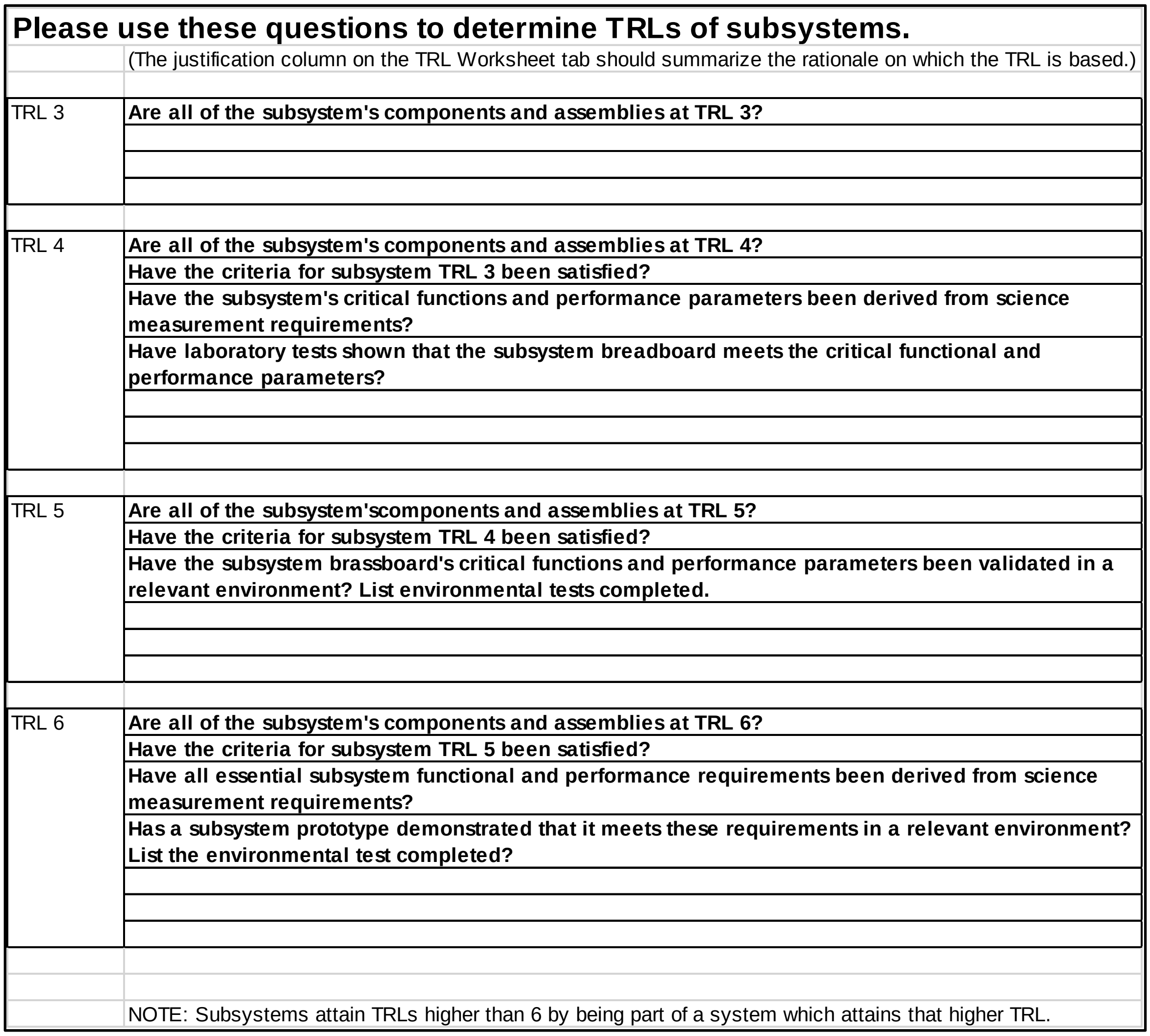


Please use these questions to determine TRLs of components / assemblies.

	(The justification column on the TRL Worksheet tab should summarize the rationale on which the TRL is based.)
TRL 3	**Has a science measurement driver been identified?**
	Has an analytical or experimental critical function proof of concept been completed?
TRL4	**Have the criteria for TRL 3 above been satisfied?**
	Have the component/assembly critical functions and performance parameters been derived from science measurement requirements?
	Have laboratory tests shown that the component and/or breadboard meets the critical functional and performance parameters?
TRL 5	**Have the criteria for TRL 4 above been satisfied?**
	Have the component and/or brassboard assembly critical functions and performance parameters been validated in a relevant environment? List environmental tests completed.

NOTE: Components attain TRLs higher than 5 by being part of a subsystem or system which attains that higher TRL.

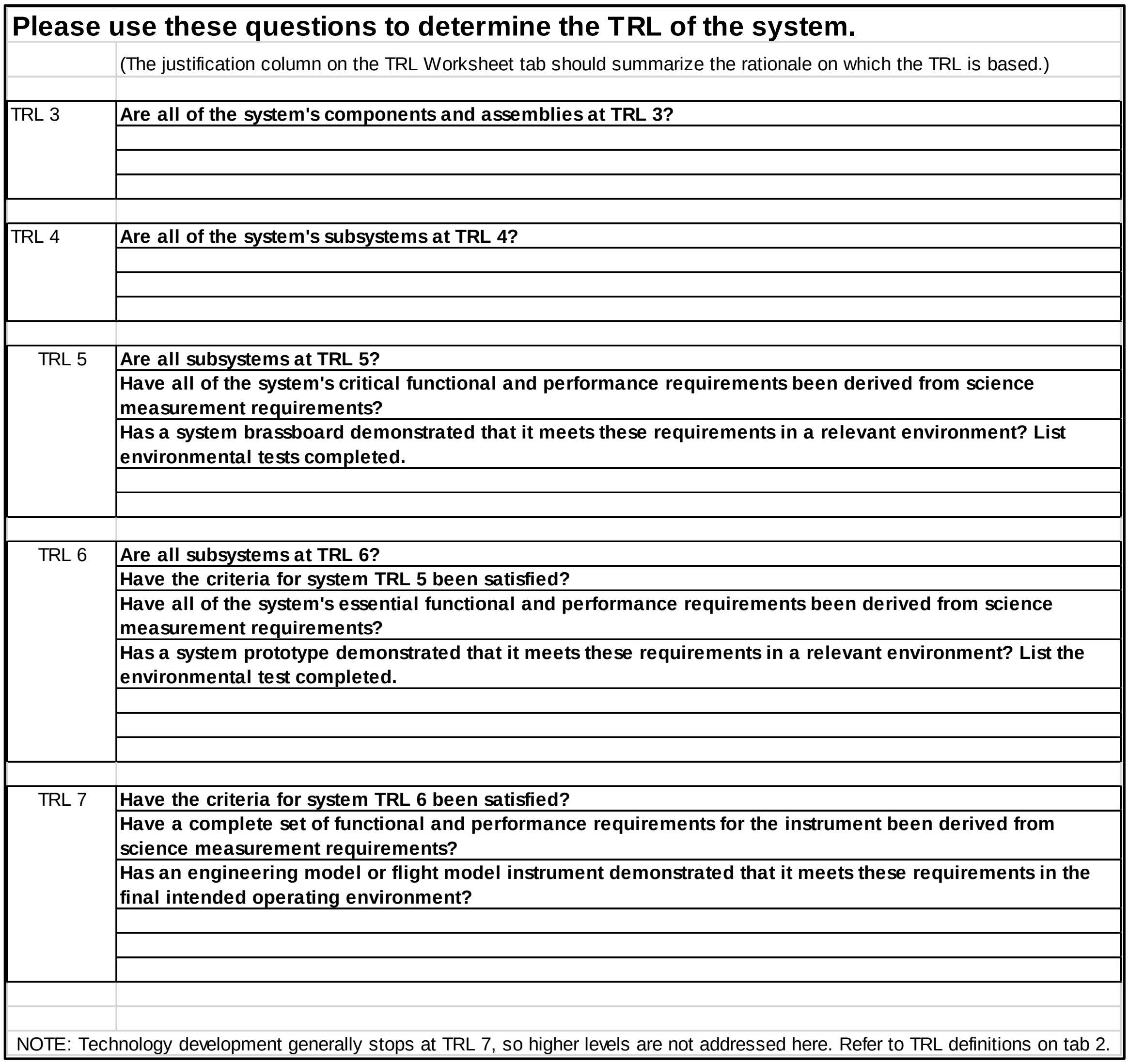
Figure 2.2: Screenshot of NASA Worksheet – Questions for Assessing TRLs of Components and Assemblies



Please use these questions to determine TRLs of subsystems.

	(The justification column on the TRL Worksheet tab should summarize the rationale on which the TRL is based.)
TRL 3	**Are all of the subsystem's components and assemblies at TRL 3?**
TRL 4	**Are all of the subsystem's components and assemblies at TRL 4?**
	Have the criteria for subsystem TRL 3 been satisfied?
	Have the subsystem's critical functions and performance parameters been derived from science measurement requirements?
	Have laboratory tests shown that the subsystem breadboard meets the critical functional and performance parameters?
TRL 5	**Are all of the subsystem'scomponents and assemblies at TRL 5?**
	Have the criteria for subsystem TRL 4 been satisfied?
	Have the subsystem brassboard's critical functions and performance parameters been validated in a relevant environment? List environmental tests completed.
TRL 6	**Are all of the subsystem's components and assemblies at TRL 6?**
	Have the criteria for subsystem TRL 5 been satisfied?
	Have all essential subsystem functional and performance requirements been derived from science measurement requirements?
	Has a subsystem prototype demonstrated that it meets these requirements in a relevant environment? List the environmental test completed?
	NOTE: Subsystems attain TRLs higher than 6 by being part of a system which attains that higher TRL.

Figure 2.3: **Screenshot of NASA Worksheet – Questions for Assessing TRLs of Subsystems**



Please use these questions to determine the TRL of the system.	
	(The justification column on the TRL Worksheet tab should summarize the rationale on which the TRL is based.)
TRL 3	**Are all of the system's components and assemblies at TRL 3?**
TRL 4	**Are all of the system's subsystems at TRL 4?**
TRL 5	**Are all subsystems at TRL 5?**
	Have all of the system's critical functional and performance requirements been derived from science measurement requirements?
	Has a system brassboard demonstrated that it meets these requirements in a relevant environment? List environmental tests completed.
TRL 6	**Are all subsystems at TRL 6?**
	Have the criteria for system TRL 5 been satisfied?
	Have all of the system's essential functional and performance requirements been derived from science measurement requirements?
	Has a system prototype demonstrated that it meets these requirements in a relevant environment? List the environmental test completed.
TRL 7	**Have the criteria for system TRL 6 been satisfied?**
	Have a complete set of functional and performance requirements for the instrument been derived from science measurement requirements?
	Has an engineering model or flight model instrument demonstrated that it meets these requirements in the final intended operating environment?
NOTE: Technology development generally stops at TRL 7, so higher levels are not addressed here. Refer to TRL definitions on tab 2.	

Figure 2.4: Screenshot of NASA Worksheet – Questions for Assessing TRLs of Subsystems

2.4 System Readiness Level

In 2006, Sauser [2006] proposed a concept for addressing maturity assessments at the operational system level called SRL [Sauser, 2006]. According to Sauser [2006], the SRL model assesses the maturity of a system as a function of TRL and IRL [Sauser, 2006]. The model uses the TRL and IRL values of the individual components of a system and normalizes the values to compute the SRL index. The TRL value represent the technology readiness level of each individual technology or subsystem. The IRL value represents the maturity level of the integration link between individual technologies or subsystems. The SRL index identifies the system readiness at that specific state of system development [Sauser, 2006]. The SRL concept is comprised of five levels. Each level has a system readiness definition that correlates to the DoD system phases of development. The SRL levels are defined in Table 2.2.

Table 2.2: SRL Definitions [Sauser, 2006]

SRL	DoD Phase	Definition
5	Operations & Support	Execute a support program that meets operational support performance requirements and sustains the system in the most cost-effective manor over its total life cycle.
4	Production & Development	Achieve operational capability that satisfies mission needs.
3	System Development & Demonstration	Develop a system or increment of capability; reduce integration and manufacturing risk; ensure operational supportability; reduce logistics footprint; implement human systems integration; design for producibility; ensure affordability and protection of critical program information; and demonstrate system integration, interoperability, safety, and utility.
2	Technology Development	Reduce technology risks and determine appropriate set of technologies to integrate into a full system.
1	Concept Refinement	Refine initial concept. Develop system/technology development strategy

A study was conducted by Tan [2011] to further mature the application of SRL through the development of a probabilistic approach for assessing system readiness using SRL [Tan, 2011]. Tan [2011] discussed a multi-objective optimization model for SRL for the identification of development alternatives to enhance system maturity of complex systems [Tan, 2011]. The probabilistic approach uses a Monte Carlo simulation to produce SRL confidence interval estimations, which is based on the assumption that TRL/IRL assessments conform to probability distributions [Tan, 2011]. Tan [2011] stated that the study has its limitation and requires additional research, recommending future work related to the expansion of the model for decision making capabilities and developing a cost estimation model that would provide resource data for upgrading technology readiness and integration readiness levels

According to Kujawski [2012], there is a need for further quantitative scrutiny of SRL methodology relating to the mathematical handling of TRL and IRL to calculate the SRL [Kujawski, 2012]. In response to questions raised by Kujawski [2010] and others in reference to how the SRL model performs its calculations, several studies were conducted to quantify mathematical operations or to propose alternative mathematical methods for computing SRL indexes [Chang, 2012; McConkie, 2013; London, 2014]. McConkie [2013] discussed the need to quantify metrics used for measuring readiness of systems by introducing mathematical operations that better defined system SRL, recommending future work in the evaluation of the various combinations of TRL and IRL values for determining SRL [McConkie, 2013]. Additionally, in 2013, Jimenez [2013] discussed the use of TRL and IRL in the assessment of systems, which presented the perspective of integration readiness being a sub-attribute of technology readiness [Jimenez, 2013]. Jimenez [2013] recommended future work to address the gap in knowledge concerning integration readiness and its relationship to technology readiness [Jimenez, 2013].

2.5 Readiness versus Maturity

Technology readiness assessments and technology maturity assessments have been the subject of numerous studies throughout the last two decades. In several of the studies, the terms “readiness” and “maturity” are used interchangeably. The utilization of readiness and maturity assessments for predicting, validating or controlling developmental cost was discussed in some of the studies [Shishko, 2004; Robinson, 2009; Terrile, 2015]. According to Tetlay [2009], system “maturity” and system “readiness” are two distinct entities, whereby a system must first achieve maturity prior to the system being ready for use [Tetlay, 2009]. Dr. Mandelbaum, Institute of Defense Analysis, agreed with this assessment, stating that “Technology readiness is a measure of the maturity of that technology for use in a specific application” [Azizian et. al., 2011]. McConkie [2013] added that although maturity and readiness are similar and sometimes used interchangeably, there is a slight and distinct difference between system maturity and system readiness [McConkie, 2013]. The focus of this investigation is technology maturity assessments.

2.6 Technology Maturity and NASA Flight Systems

NASA is known for designing and building unique, one-of-a-kind products. Systems engineers are responsible for the selection of the best design solution that meets system requirements, technology performance, cost, schedule, risk, and any other relevant limitation. Technology developments are part of that best design solution space. Technology developments are also essential and important parts of the system acquisition process.

From a NASA project’s perspective, the term “technology development” has historically been synonymous with the development of a “new” technology. Often overlooked is the utilization of heritage systems that are modified to operate in a different manner than it was originally designed. When the heritage design is modified or used in a different way than previously operated, the design should be treated as a technology development. The maturity of this modified heritage technology development should be assessed based on the manner in which it will operate in the current design, not based solely on its previous usage.

NASA requires periodic assessments of the system's or technology's maturity as part of the technology development process. According to the NASA Systems Engineering Handbook [2007], technology maturity assessment is defined as "the process to determine a system's technological maturity via TRLs" [NASA/SP-2007-6105, 2007]. The NASA Procedural Requirements (NPR) 7120.5E, NASA Space Flight Program and Project Management Requirements, requires the assessment of technologies at specific KDPs over the life cycle of the NASA flight system. A best practice for technologies, as stated in the NPR 7120.5E, is the achievement of TRL-6 by PDR [NPR 7120.5, 2012]. A technology's achievement of TRL-6 is the generally accepted as the threshold for technology infusion. Figure 2.5 depicts the NASA life cycle and key decision points throughout the life cycle [GAO, 2014].

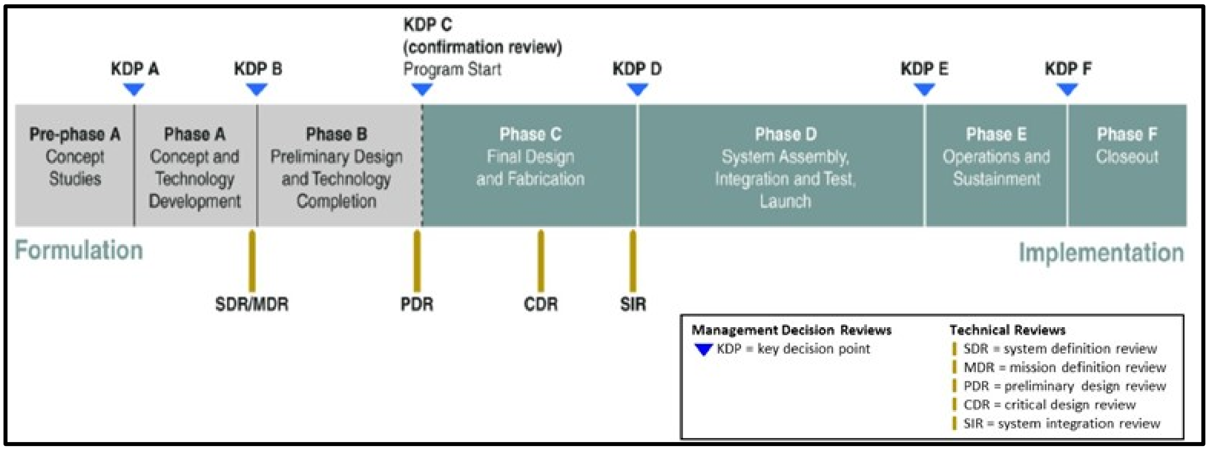


Figure 2.5: NASA Life Cycle for Flight Systems [GAO, 2014]

As stated in the 2005 GAO report, "Technology readiness levels (TRL), a concept developed by NASA, can be used to gauge the maturity of individual technologies. The higher the TRL, the more the technology has been proven and the lower the risk of performance problems and cost and schedule overruns" [GAO, 2005]. This statement was based on a GAO assessment of 54 DoD systems that showed a significant increase in cost for programs with immature technologies versus programs with mature technologies [GAO, 2005].

According to the 2005 GAO report, developers prefer a maturity level of TRL-7 prior to entering product development for minimizing risk. As previously stated, NASA's policy is the demonstration of a maturity level of TRL-6 prior to entering the implementation stage of the life cycle. Both practices acknowledge the introduction of an immature technology into the product development phase increases the level of risk. By having technologies achieve a specified level of maturity, it places the development in a better position to succeed. Thus, being able to accurately assessment a technology's maturity level is crucial. Figure 2.6 depicts GAO's interpretation of the relationship between risk level and technology readiness for technology development.

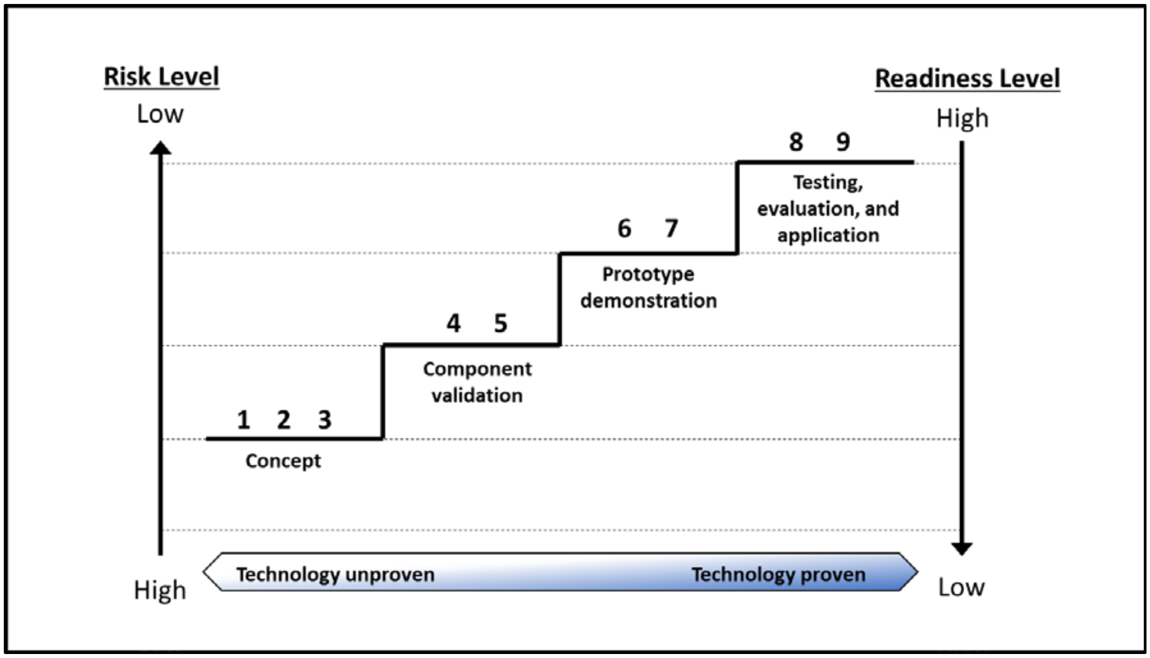


Figure 2.6: Technology Readiness Levels and Risk [GAO, 2005]

Since 2009, GAO has released eight annual reports that detailed the assessment of multiple NASA projects. The GAO reports described the state of key acquisition attributes at KDP in the project’s life cycle. The acquisition attributes selected for evaluation by GAO are: technology maturity; design stability; complexity of heritage technology; new technology; technical challenges; external partner and/or contractor performance; funding performance; and schedule performance. Among these attributes, complexity of heritage technology developments and new technology developments were identified by GAO as the critical technology developments used to assess technology maturity of the mission at PDR. It is recommended to watch these attributes closely for achieving a successful acquisition. If not monitored closely, challenges associated with these attributes have the potential to result in problems with cost, schedule and technical performance.

2.7 Key Decision Point Recommended Practice

A best practice recommended by GAO is the utilization of heritage technologies for reducing the risk associated with acquisition cost and schedule growth [GAO, 2009]. This recommended practice leveraged the application of heritage designs to attain technology maturity by PDR, reducing the uncertainty associated with new critical technology developments. PDR is the accepted KDP for transitioning a development from the formulation phase to the implementation phase in the life cycle. For NASA projects, the minimum technology readiness level threshold for transitioning a system or subsystem to the implementation phase is a demonstration of at least TRL-6 by PDR. Achieving technology maturity of meeting or exceeding TRL-6 by PDR is the recommended best practice of GAO. As stated in the NASA Systems Engineering Handbook, the purpose of a PDR is as follows:

> *“The PDR demonstrates that the preliminary design meets all system requirements with acceptable risk and within the cost and schedule constraints and establishes the basis for proceeding with detailed design. It will show that the correct design options have been selected, interfaces have been identified, approximately 10 percent of engineering drawings have been created, and verification methods have been described. PDR occurs near the completion of the preliminary design phase (Phase B) as the last review in the Formulation phase*” [NASA/SP-2007-6105, 2007].

2.8 Conceptual Framework

A critical element in the development of engineering systems is technology maturity. The lack of technology maturity at KDP increases the potential for future problems. The 2010 GAO report stated that problems occurred when the heritage technology designs were not sufficiently matured to meet form, fit, and function requirements by PDR [GAO, 2010]. The report further disclosed:

> *“Commitments were made to deliver capability without knowing whether the technologies needed could really work as intended. Time and costs were consistently underestimated, and problems that surfaced early cascaded throughout development and magnified the risks facing the program. NASA acknowledges in its Systems Engineering Handbook that modification of heritage systems is a frequently overlooked area in technology development and that there is a tendency on the part of project management to overestimate the maturity and applicability of heritage technology”* [GAO, 2010].

Thus, this research focuses on investigating a methodology for evaluating the relationship and influence critical technologies have on technology maturity assessments for NASA missions. This investigation seeks to provide a more comprehensive understanding of technology maturity at the system level and how maturity assessments are impacted by the development types. The findings from this research have the potential of adding to the body of knowledge by enhancing functionality and aspects of system definition, design, and development. The insight gained from this research will provide beneficial and valuable information to the systems engineering community.

A visual representation of the conceptual framework for this research is depicted in Figure 2.7. The framework depicts the theoretical relationships among technology maturity and other attributes that are used to assess the state and healthiness of product development acquisition. Publicly accessible information reported by GAO regarding the assessment of NASA large-scaled projects provided the rationale for this conceptual framework [GAO, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016]. This research investigates the relationships among the various acquisition attributes to ascertain any correlations to technology maturity. For this study, technology maturity is identified as the dependent attribute. The remaining attributes are identified as independent variables.

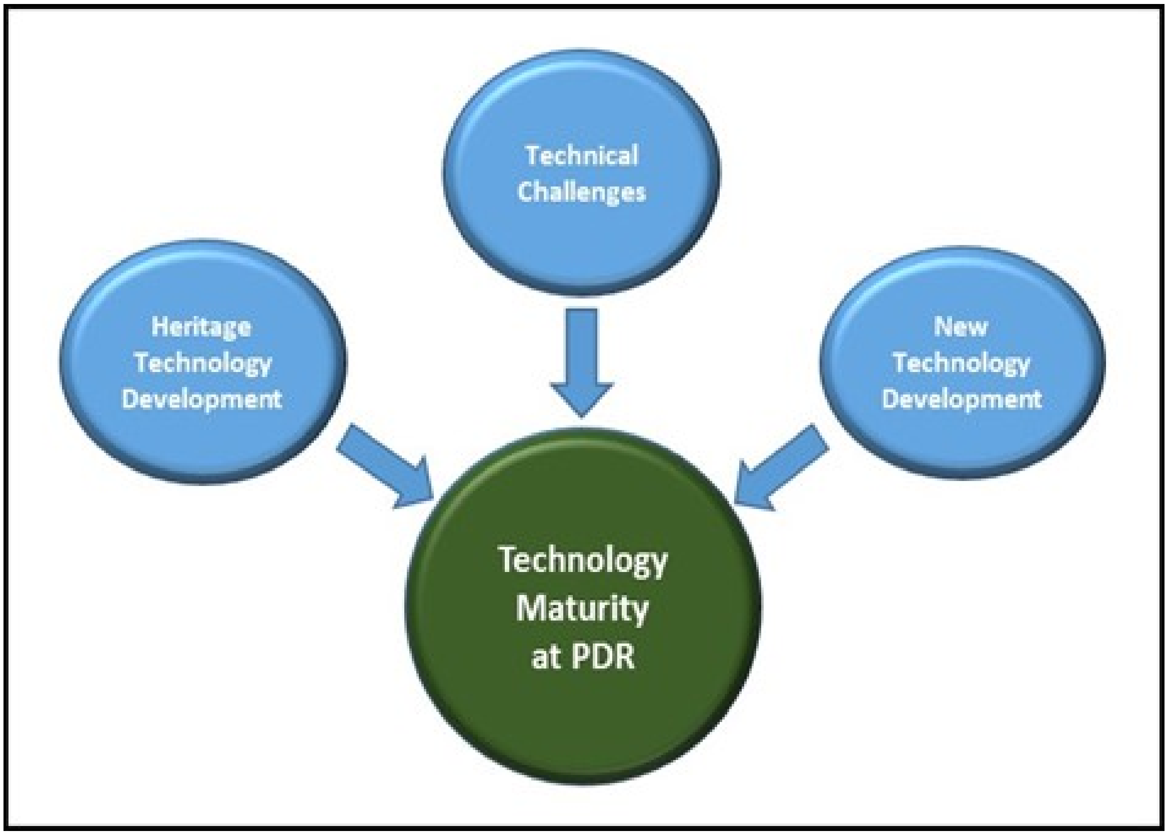


Figure 2.7: Technology Maturity Assessment Conceptual Framework

Chapter 3 – RESEARCH METHODOLOGY

This research concentrated on investigating technology maturity assessments by evaluating the relationships among acquisition attributes and establishing a predictive probability model for application as a validation gauge. Within the aerospace community, access to technology maturity data can be difficult to obtain due to the competition sensitive, proprietary and classified nature of the data. The annual GAO reports for the assessment of large NASA missions were the primary data source for technology maturity assessments and other acquisition attributes information related to multiple NASA missions. The information is self-reported by NASA, analyzed by GAO and presented as binary discrete data at KDP [GAO, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016]. In the GAO reports, technology maturity assessments are provided at PDR, reflecting the overall status of the spacecraft (system) for a sample set of 33 NASA missions. TRL data for a second sample set of 33 NASA missions were also obtained from the NASA CADRe system.

As stated in Chapter 2, the rule of thumb for system level technology maturity assessments is that the overall maturity of the system cannot be any higher than the lowest component or subsystem TRL value comprising the system. In the GAO reports, NASA projects are analyzed to monitor the health and well-being of the project development. Information is provided concerning whether or not a project achieved technology maturity at the specified KDP. Successful achievement of technology maturity for NASA projects is described as the projects meet and/or exceed the TRL-6 threshold [GAO, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016]. Technology maturity is not achieved when the system does not meet the TRL-6 threshold. In addition to information about the maturity of the project, the report also noted whether or not the project was experiencing any challenges, problems or issues in the identified areas regarding the acquisition attributes. The GAO reports were the sole source of acquisition attribute binary data analyzed in this research. Table 3.1 provides descriptions for each attributes.

Table 3.1: Acquisition Attributes Descriptions

Attribute	Description
Technology Maturity	Meeting or exceeding TRL-6 by the specified KDP
Complexity of Heritage Technology Development	Heritage technology development form, fit, or function issues
Critical New Technology Development Challenges	New technology development issues
Design Stability	90% drawings release at KDP
Technical Challenges	Technical issues that are not technology development related
External Partner and/or Contractor Performance	Meets contractual/agreed commitments for good performance
Funding Performance	Maintaining cost commitments constitutes good performance
Schedule Performance	Meeting schedule commitments constitutes good performance

3.1 Research Question and Hypotheses

The need for a more comprehensive understanding of the accuracy associated with technology maturity assessments was determined based on a thorough analysis of the literature. This study seeks to answer the question: What is the relationship between a critical technology development and technology maturity at a key decision point in the product development life cycle for NASA missions? This research question concerning the impact critical technologies have on technology maturity assessments at PDR, led to the additional sub-questions, such as:

- Which acquisition attributes influence technology maturity?

- What is the significance of the relationships between the various acquisition attributes and the technology maturity assessments at PDR?
- What impact does an attribute with a significant relationship to technology maturity have on the confidence interval of a maturity assessment at PDR?
- Are confidence interval influenced by development type?

This investigation proposed the establishment of a probability predictive tool to gauge the accuracy of technology maturity assessments. In order to establish a predictive probability model and gain additional insight regarding the influence critical technologies have on maturity assessments, the relationships between technology maturity and acquisition attributes must be investigated. As a result of the systems engineering community’s demand for a more comprehensive understanding of technology maturity and the current body of knowledge on this topic in the literature, the following null hypotheses were developed for this study:

$H1_0$: Heritage technology developments significantly increase a project’s ability to achieve technology maturity by PDR.

$H2_0$: At PDR, the relationships between critical technologies attributes and technology maturity are significant.

3.2 Statistical Methods for GAO Binary Data

The research methodology for this study consisted of utilizing statistical methods for analyzing discrete data. Discrete data is quantitative and can only take on distinct values. As previously stated, the GAO data for the acquisition attributes of NASA projects are reported as binary responses. Binary responses conveys whether an event did or did not occur. Statistical means are employed to assess relationships among acquisition attributes and to provide a framework for predicting the probability of achieving technology maturity at KDP.

Sample set averages are calculated using Adjusted Wald Method. Binary logistic regression analysis is used to evaluate the significance and strengths of the relationships among technology maturity and the other acquisition attributes for GAO 33 NASA projects sample population. The binary logistic regression analysis produces a regression model, which estimates the probability that an event will occur. Upon quantifying the significance of the relationships among acquisition attributes and the generation of sample set averages as a function of technology development type, a sensitivity analysis is conducted on the technology maturity assessments as a function of acquisition attributes and development type.

3.2.1 Correlation and Regression Analysis

Correlation analysis assesses the strength between two variables and regression analysis provides a mathematical equation for predicting or estimating the values of a dependent variable based on the known values of independent variable [Greenfield, 1998]. Logistic regression is an accepted statistical mathematical modeling approach that describes the relationships between a dichotomous dependent variable and multiple independent variables [Kleinbaum and Klein, 2010]. Correlation and regression analysis methods are used to evaluate the significance and strength of relationships between technology maturity and the other acquisition attributes used by GAO to assess NASA projects.

Binary logistic regression is a statistical analysis method where binary responses describe a set of discrete and/or continuous descriptive variables. Since the sample set contained binary discrete data, binary logistic regression was selected as the statistical method for analyzing the research data. The binary logistic regression also provides information on the probability or odds of a response. The regression analysis generates a predictive log model, which estimates the probability that an event will occur based on the impact independent variables have on the dependent variable. For a regression analysis with a binary response, the expected value of the binary response is symbolized by π, which represents the probability of a success binary response (Yes or 1). Equation 3.1 represents the logistic regression predictive model:

$$\pi = \frac{exp(\beta_0 + \beta_1 x_1 + \ldots. + \beta_k x_k)}{(1 + exp(\beta_0 + \beta_1 x_1 + \ldots. + \beta_k x_k))} \qquad \textbf{3.1}$$

where,
β = regression coefficient
x = independent variables
k = total number of independent variables

The statistical software utilized to perform the binary logistic regression analysis was Minitab® 17. Minitab® is a recognized software tool for performing statistical data analysis. Minitab® allows for the processing of binary data as specified by the end user. For this study, the data extracted from the GAO reports on the 33 NASA projects were captured as “Yes” or “No” binary responses. The binary responses described the status of the specific acquisition attributes at PDR. The binary logistic regression analysis was used to evaluate the significance of attributes’ relationship and to develop a regression equation for predicting the probability of achieving the technology maturity threshold at the KDP.

The Minitab® regression analysis function is used to gain insight concerning the observation responses, p-values, regression coefficients, odds ratio (OR), and goodness-of-fit tests associated with the evaluation of the acquisition attributes for the GAO 33 NASA projects. Observation responses provides the number of “Yes” responses and the number of “No” responses for the sample data set. The p-values is typically used to measure the adequacy of regression model. The p-value provides information concerning the significance and strength of the binary logistic regression analysis results. It is used to test for statistical evidence that the independent variables have an effect on the dependent variable’s response. Interpretation of the p-value is as follows a number between 0 and 1 and interpreted in the following way:

- The p-value is a number between 0 and 1
- For p-value ≤ 0.05, there is strong evidence against the null hypothesis
- For p-value > 0.05, there is weak evidence against the null hypothesis
- For p-value $\cong 0.05$, the evidence is marginal and could or could not be significant

The regression analysis produces a p-value for each acquisition attribute. The p-value of each acquisition attribute was appraised to determine if an acquisition attribute (the independent variable) had a significant relationship with technology maturity (the dependent variable). Any p-value of an independent variable with a response less than or equal to 0.050 constituted a significant relationship between technology maturity (the dependent variable) and that particular acquisition attribute (the independent variable). If the p-value of the independent variable is greater than 0.050, than there is not a significant relationship between the dependent and independent variables. High p-values represent very weak relationships between the independent variable and the dependent variable.

The regression coefficients are interpreted as the rate of change in the conditional mean of the dependent variable. The odds ratio can be used to measure or quantify the effect an independent variable has on the outcome of an event or response. The odds ratio represents the probability an outcome will occur given the presence of a particular event compared to the absence of a particular event. In other word, the probability that technology maturity will be achieved given the "Yes" response of an acquisition attribute compared to the "No" response of that same acquisition attribute. The goodness-of-fit test measures how well the binary data corresponds to the fitted regression model. Minitab® is also used to generate the regression model equation for evaluating the probability of a specific event or response. The combination of this information is used to analyze the NASA projects data, assessing the significance and strength of any relationship between the dependent and independent variables.

3.2.2 Adjusted Wald Method

The Adjusted Wald Method, which is a recognized statistical tool for accommodating small data sets, is a known method for calculating sample averages and a 95% confidence interval using binary data. According to Sauro [2005], "It appears that the best method for practitioners to compute 95% confidence intervals for small sample completion rates is to add two successes and two failures to the observed completion rate, then compute the confidence interval using the Wald method (the "Adjusted Wald Method"). This simple approach provides the best coverage, is fairly easy to compute, and agrees with other analyses in the statistics literature" [Sauro, 2005].

Sauro [2005] described the study conducted to evaluate the accuracy of statistical methods used to calculate confidence intervals. In his study, Monte Carlo simulations were used to evaluate the Wald method, the Adjusted Wald method, the Score method and the Exact method. The method identified by the Monte Carlo simulation for providing the coverage closet to 95% was the Adjusted Wald method [Sauro, 2005]. Thus, Adjusted Wald method is recommended for calculating confidence intervals for small sample completion rates [Sauro, 2005].

According to Agresti [1998], the simplistic idea behind the Adjusted Wald method is to adjust the observed proportion of the task success to account for the small sample sizes that are used in usability tests [Agresti and Coull, 1998]. The transition from the Wald method to the Adjusted Wald method involved the addition of two successes to the proportion of the trails that were successes and the addition of four (two successes and two failures) to the total number of trails. The Adjusted Wald method changes the interval estimation of a proportion from a highly liberal estimator to slightly conservative estimator and is slightly more conservative than the score method [Agresti and Coull, 1998]. The formula used by the Adjusted Wald method for calculating the confidence interval is shown in Equation 3.2 [Agresti and Coull].

$$p_{adj} \pm z \times \sqrt{\frac{\left(p_{adj} \times \left(1 - p_{adj}\right)\right)}{n_{adj}}} \qquad \textbf{3.2}$$

Equation 3.3 represents the adjusted sample proportion, p_{adj}:

$$p_{adj} = \frac{\left(p + \frac{z^2}{2}\right)}{(n + z^2)} \qquad \textbf{3.3}$$

Equation 3.4 represents the adjusted total number of trails, n_{adj}:

$$n_{adj} = (n + z^2) \qquad \textbf{3.4}$$

where, n = total number of trails
p = sample proportion of trials that were successes
z = z-value corresponding to the chosen CL

The sample size for this research consisted of 33 NASA projects. Due to the small sample size, the confidence intervals associated with the technology maturity assessments were calculated using the Adjusted Wald technique. The Adjusted Wald technique has the benefit of being an easy method for calculating sample averages and confidence interval using binary data. The Adjusted Wald technique is designed to calculate the "margin of error" value that are used to determine the upper and lower limits of the confidence interval.

As previously stated, the data exacted from the GAO reports for populating the sample set were in the form of discrete binary responses. Implementation of the Adjusted Wald method consisted of converting the binary responses of "Yes" and "No" to numerical responses of 1 and 0, respectively, for calculating the confidence interval. The step by step Adjusted Wald method for computing a 95% confidence interval is described below. When computing the 95% CL, $z = 1.96$, which is converted to $z \cong 2$ when rounded up.

1. Find the average (sample proportion) by adding the number of successes ("1" responses) and divide by the total number of trails (all "1" and "0" responses).
2. Adjust the sample proportion to improve the accuracy of the calculation due to a small sample size, by:
    a. Adding 2 to the number of successes ("1" responses)

    b. Adding 4 to the total number of trails (total of all “1” and “0” responses).
    c. Divide the adjusted number of successes by the adjusted number of trails, which results in the adjusted sample proportion.
3. Compute the standard error by:
    a. Multiplying the adjusted sample proportion by (1 – the adjusted sample proportion).
    b. Divide the result in Step 3a by the adjusted number of trails (value from Step 2b).
    c. Take the square root of the value in Step 3b, which is the standard error.
4. Compute the “margin of error” by multiplying the standard error (result from Step 3c) by 2.
5. Compute the confidence interval:
    a. Add the margin of error to the sample proportion from Step 1 (not the adjusted sample proportion), which results in the upper limit of the confidence interval
    b. Subtract the margin of error from the sample proportion (not the adjusted sample proportion), which results in the lower limit of the confidence interval.

The range from upper limit to the lower limit is the computed confidence interval. For the sensitivity analysis, the average percentage of NASA missions achieving technology maturity by PDR were computed as a function of development type.

Technology maturity assessments were then evaluated to examine any sensitivities due to attribute influence.

3.3 Comparison of TRL Sample Sets

To validate the analysis of the binary data, TRL data were acquired from the NASA CADRe system for instruments from 33 NASA missions. The TRL data of 94 instruments from the NASA missions in the CADRe system were used to establish mission level TRL values and to evaluate technology development type characteristics. The GAO reported NASA missions binary responses were converted to TRL values for comparison purposes.

The statistical methodologies used for analyzing and comparing the two sample sets of 33 NASA missions consisted of the Mann-Whitney test and Kruskal-Wallis test. The Mann-Whitney test compares the mean of two sample sets that came from the same population. It is widely used statistical method for nonparametric data as an alternate test to the parametric *t*-test. The Kruskal-Wallis test is a recognized rank-based statistical test that is more suited for analyzing nonparametric data (ordinal data) [Shah and Madden, 2004]. The Kruskal-Wallis test is used when the Analysis of Variance (ANOVA) normality assumption may not apply to the sample data. The statistical software utilized to analyze the two sample sets was Minitab® 17. As previously stated, Minitab® is a recognized software tool for performing statistical data analysis.

3.4 Data Collection

The GAO reports on the assessment of major NASA projects are the primary source of data for this investigation. The eight GAO reports described the technical, cost, and schedule performance of various NASA projects. GAO analyzed acquisition attributes to assess technical and programmatic conditions for the identification and tracking of performance trends. These performance trends are reported by GAO to the United States (U.S.) Congress for assessing the health and well-being of NASA projects. The U.S. Congress utilizes this information for fiscal oversight purposes.

The GAO assessments are conducted on an annual basis. The reports provided a narrative for the overall status of technology maturity and design stability from 2009 through 2016 for the selected NASA projects. GAO began tracking the achievement of technology maturity at PDR in 2010. Figure 3.1 displays the major NASA missions reviewed by GAO over the last eight years.

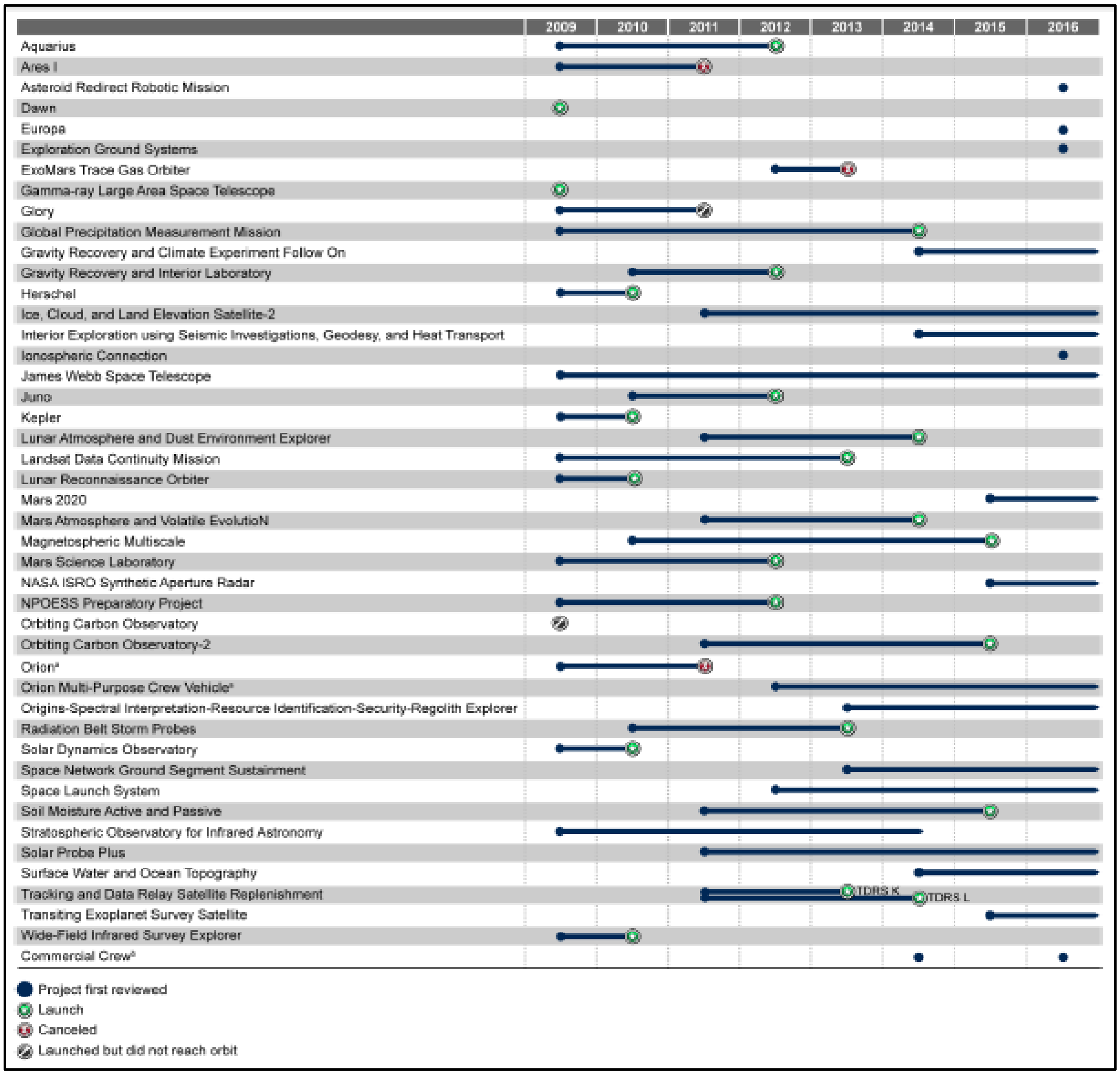


Figure 3.1: Major NASA Projects Reviewed in GAO's Annual Assessment Reports [GAO, 2016]

Since 2009, GAO has reviewed 45 NASA projects. The projects were assessed during formulation and implementation phases of the life cycle. The 45 NASA projects were reviewed at various stages in the acquisition process and after multiple KDPs. Figure 3.2 depicts a chart from the 2016 GAO report that displayed the percentage and number of assessed NASA projects that achieved technology maturity by PDR.

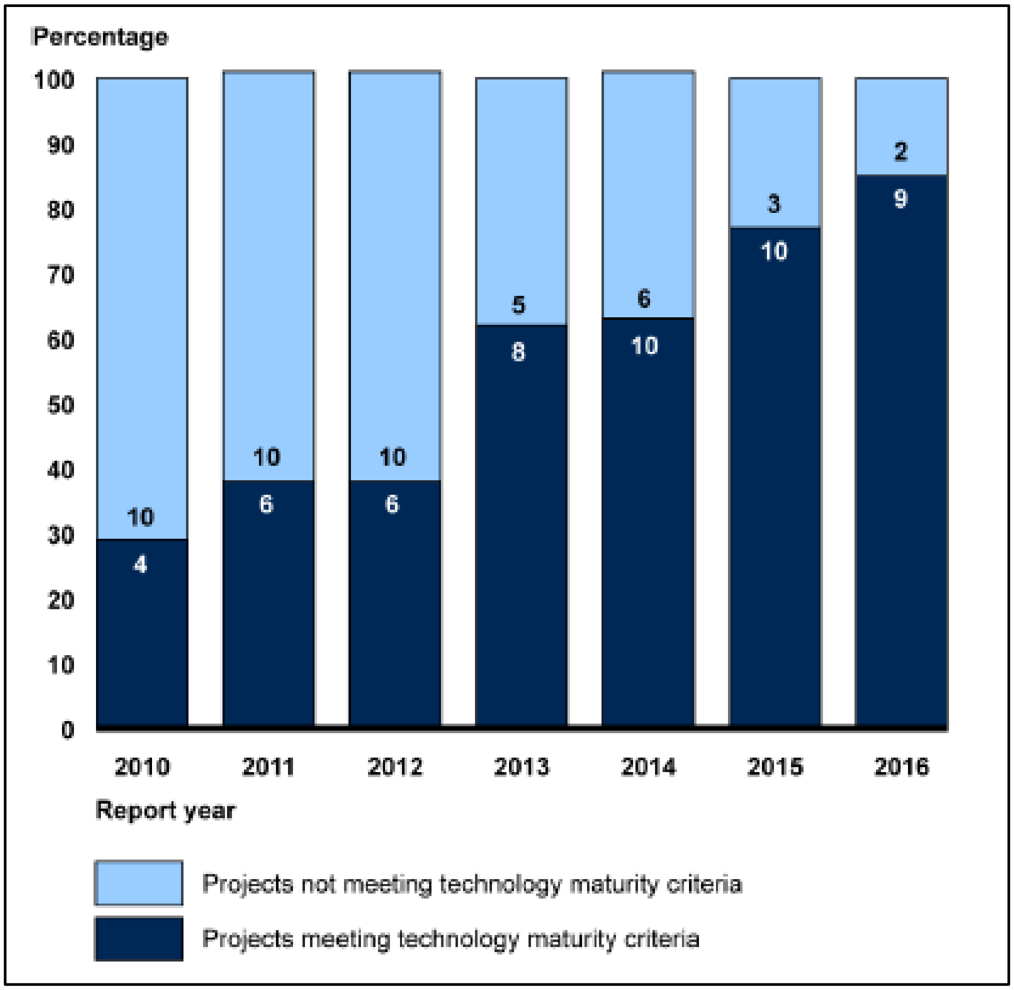


Figure 3.2: NASA's Major Projects Attaining Technology Maturity by PDR [GAO, 2016]

One of GAO's recommended best practices for controlling cost and schedule growth was to increase the utilization of heritage technologies and to minimize the use of new critical technology developments in the design of the flight system. As part of the GAO's analysis, the number of new critical technology developments was tracked. Figure 3.3 shows the average number of new critical technologies in developments. Figure 3.4 displays the number of NASA projects as a function of the associated number of critical technologies.

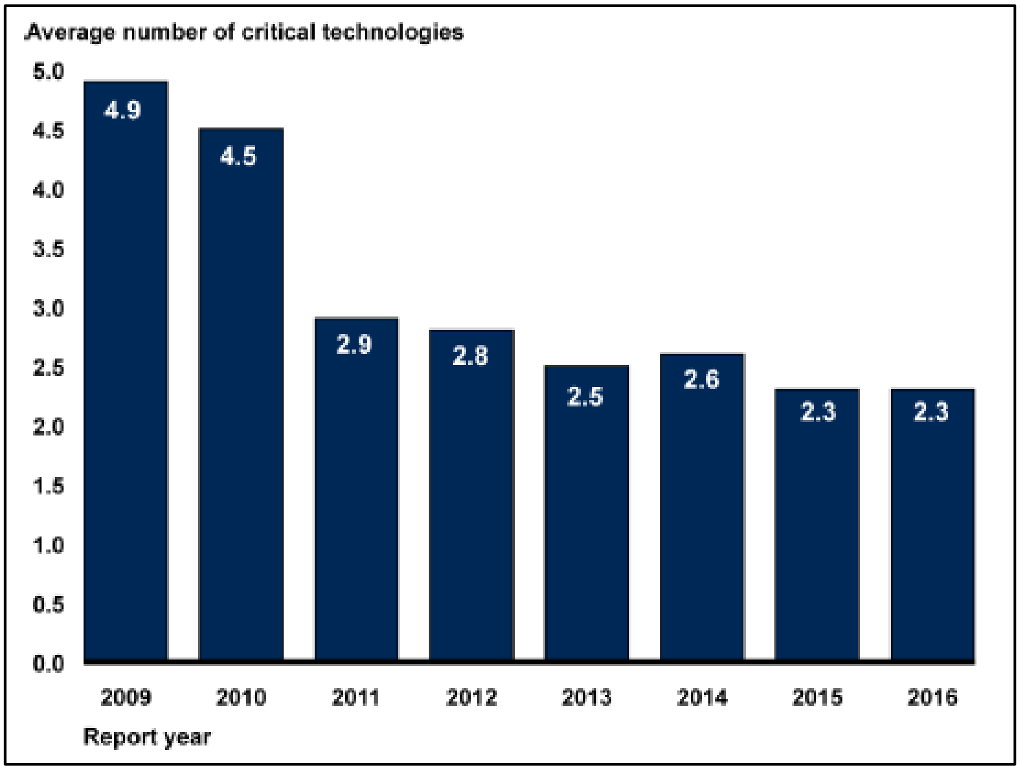


Figure 3.3: Critical Technologies of Assessed Major NASA Projects in Development [GAO, 2016]

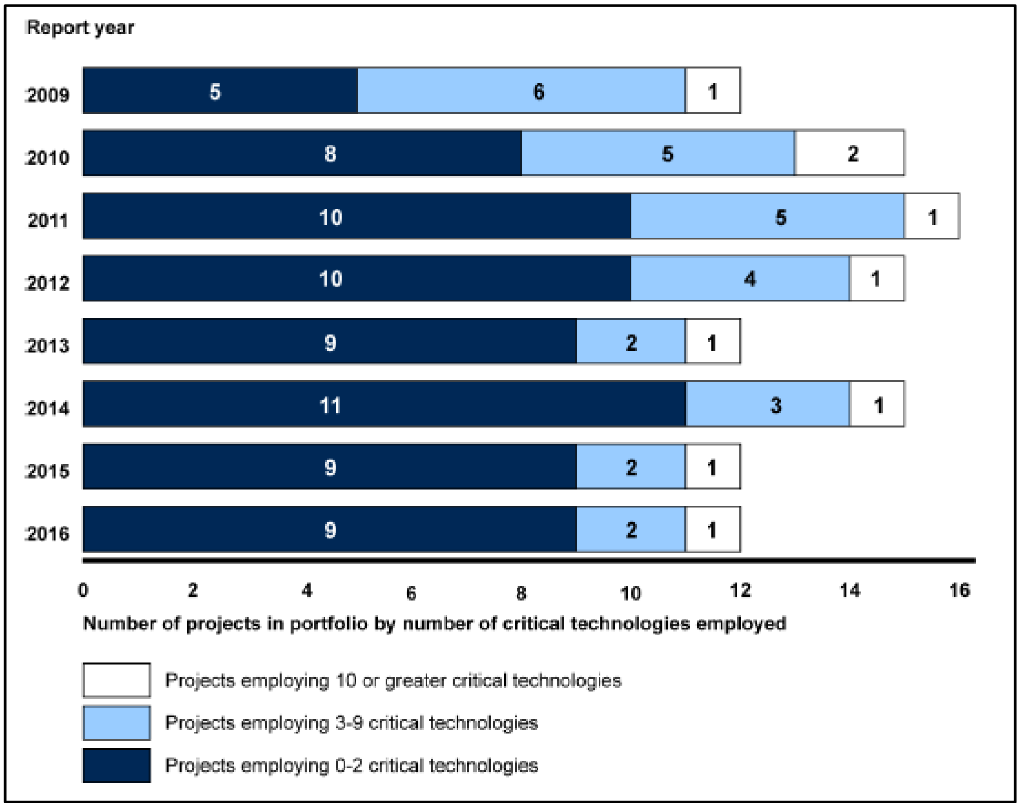
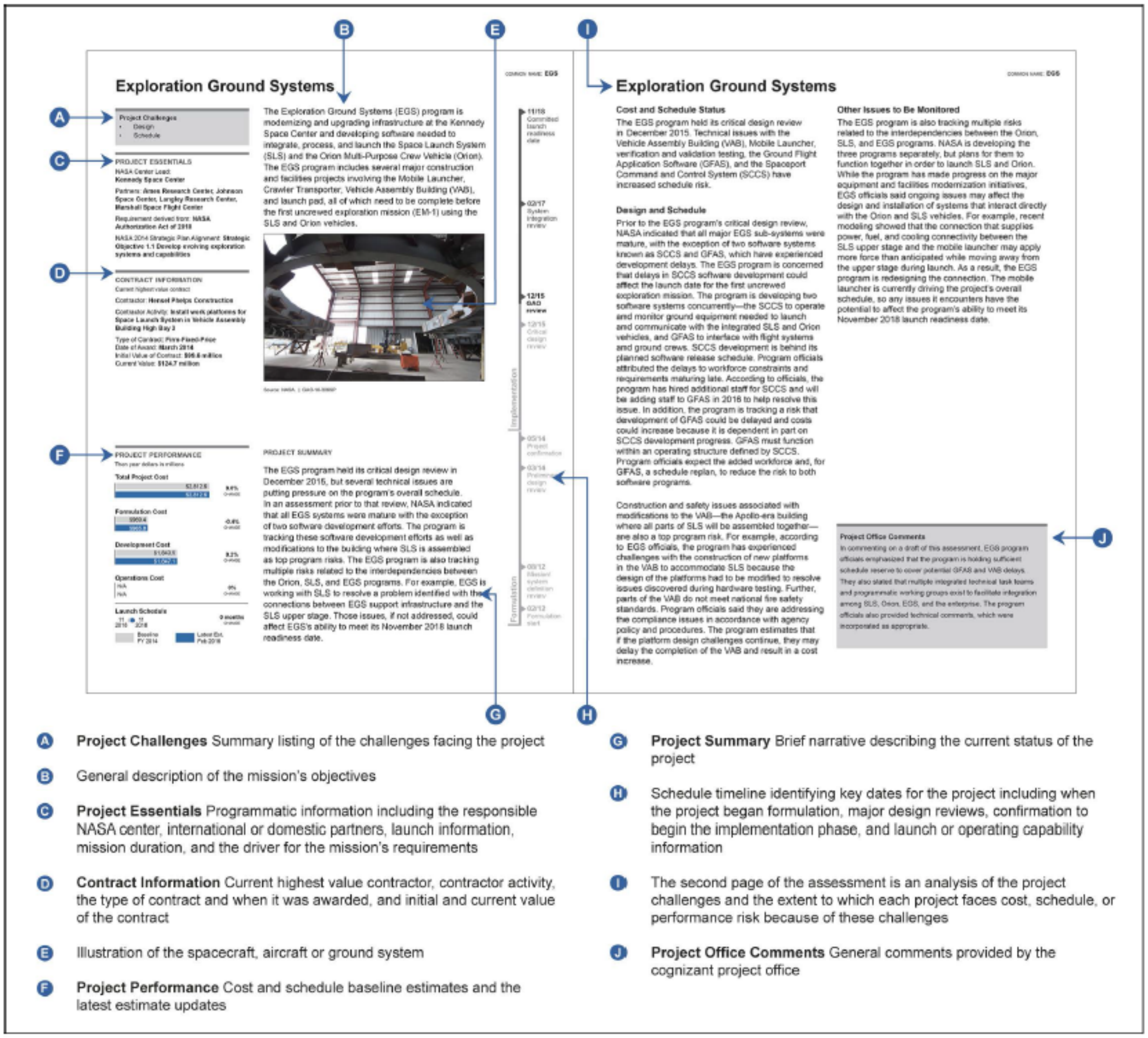


Figure 3.4: Major Projects by Number of Critical Technologies [GAO, 2016]

For this research, the process of gathering sample data required careful examination of the GAO reports' narratives. In some cases, the assessment took place shortly after the PDR. In other cases, the assessment took place after both PDR and CDR. Figure 3.5 illustrated a sample assessment layout for a NASA project. The illustration provides descriptions of the provided information in the assessment.



COMMON NAME: EGS

Exploration Ground Systems

Project Challenges
- Design
- Schedule

PROJECT ESSENTIALS

NASA Center Lead: **Kennedy Space Center**

Partners: **Ames Research Center, Johnson Space Center, Langley Research Center, Marshall Space Flight Center**

Requirement derived from: **NASA Authorization Act of 2010**

NASA 2014 Strategic Plan Alignment: **Strategic Objective 1.1 Develop evolving exploration systems and capabilities**

CONTRACT INFORMATION

Current highest value contract

Contractor: **Hensel Phelps Construction**

Contractor Activity: **Install work platforms for Space Launch System in Vehicle Assembly Building High Bay 3**

Type of Contract: **Firm-Fixed-Price**
Date of Award: **March 2014**
Initial Value of Contract: **$98.6 million**
Current Value: **$124.7 million**

The Exploration Ground Systems (EGS) program is modernizing and upgrading infrastructure at the Kennedy Space Center and developing software needed to integrate, process, and launch the Space Launch System (SLS) and the Orion Multi-Purpose Crew Vehicle (Orion). The EGS program includes several major construction and facilities projects involving the Mobile Launcher, Crawler Transporter, Vehicle Assembly Building (VAB), and launch pad, all of which need to be complete before the first uncrewed exploration mission (EM-1) using the SLS and Orion vehicles.

Source: NASA. | GAO-16-304SP

PROJECT PERFORMANCE

Then year dollars in millions

Total Project Cost

Formulation Cost

Development Cost

Operations Cost

Launch Schedule

PROJECT SUMMARY

The EGS program held its critical design review in December 2015, but several technical issues are putting pressure on the program's overall schedule. In an assessment prior to that review, NASA indicated that all EGS systems were mature with the exception of two software development efforts. The program is tracking these software development efforts as well as modifications to the building where SLS is assembled as top program risks. The EGS program is also tracking multiple risks related to the interdependencies between the Orion, SLS, and EGS programs. For example, EGS is working with SLS to resolve a problem identified with the connections between EGS support infrastructure and the SLS upper stage. Those issues, if not addressed, could affect EGS's ability to meet its November 2018 launch readiness date.

COMMON NAME: EGS

Exploration Ground Systems

Cost and Schedule Status

The EGS program held its critical design review in December 2015. Technical issues with the Vehicle Assembly Building (VAB), Mobile Launcher, verification and validation testing, the Ground Flight Application Software (GFAS), and the Spaceport Command and Control System (SCCS) have increased schedule risk.

Design and Schedule

Prior to the EGS program's critical design review, NASA indicated that all major EGS sub-systems were mature, with the exception of two software systems known as SCCS and GFAS, which have experienced development delays. The EGS program is concerned that delays in SCCS software development could affect the launch date for the first uncrewed exploration mission. The program is developing two software systems concurrently—the SCCS to operate and monitor ground equipment needed to launch and communicate with the integrated SLS and Orion vehicles, and GFAS to interface with flight systems and ground crews. SCCS development is behind its planned software release schedule. Program officials attributed the delays to workforce constraints and requirements maturing late. According to officials, the program has hired additional staff for SCCS and will be adding staff to GFAS in 2016 to help resolve this issue. In addition, the program is tracking a risk that development of GFAS could be delayed and costs could increase because it is dependent in part on SCCS development progress. GFAS must function within an operating structure defined by SCCS. Program officials expect the added workforce and, for GFAS, a schedule replan, to reduce the risk to both software programs.

Construction and safety issues associated with modifications to the VAB—the Apollo-era building where all parts of SLS will be assembled together—are also a top program risk. For example, according to EGS officials, the program has experienced challenges with the construction of new platforms in the VAB to accommodate SLS because the design of the platforms had to be modified to resolve issues discovered during hardware testing. Further, parts of the VAB do not meet national fire safety standards. Program officials said they are addressing the compliance issues in accordance with agency policy and procedures. The program estimates that if the platform design challenges continue, they may delay the completion of the VAB and result in a cost increase.

Other Issues to Be Monitored

The EGS program is also tracking multiple risks related to the interdependencies between the Orion, SLS, and EGS programs. NASA is developing the three programs separately, but plans for them to function together in order to launch SLS and Orion. While the program has made progress on the major equipment and facilities modernization initiatives, EGS officials said ongoing issues may affect the design and installation of systems that interact directly with the Orion and SLS vehicles. For example, recent modeling showed that the connection that supplies power, fuel, and cooling connectivity between the SLS upper stage and the mobile launcher may apply more force than anticipated while moving away from the upper stage during launch. As a result, the EGS program is redesigning the connection. The mobile launcher is currently driving the project's overall schedule, so any issues it encounters have the potential to affect the program's ability to meet its November 2018 launch readiness date.

Project Office Comments

In commenting on a draft of this assessment, EGS program officials emphasized that the program is holding sufficient schedule reserve to cover potential GFAS and VAB delays. They also stated that multiple integrated technical task teams and programmatic working groups exist to facilitate integration among SLS, Orion, EGS, and the enterprise. The program officials also provided technical comments, which were incorporated as appropriate.

- A **Project Challenges** Summary listing of the challenges facing the project
- B General description of the mission's objectives
- C **Project Essentials** Programmatic information including the responsible NASA center, international or domestic partners, launch information, mission duration, and the driver for the mission's requirements
- D **Contract Information** Current highest value contractor, contractor activity, the type of contract and when it was awarded, and initial and current value of the contract
- E Illustration of the spacecraft, aircraft or ground system
- F **Project Performance** Cost and schedule baseline estimates and the latest estimate updates
- G **Project Summary** Brief narrative describing the current status of the project
- H Schedule timeline identifying key dates for the project including when the project began formulation, major design reviews, confirmation to begin the implementation phase, and launch or operating capability information
- I The second page of the assessment is an analysis of the project challenges and the extent to which each project faces cost, schedule, or performance risk because of these challenges
- J **Project Office Comments** General comments provided by the cognizant project office

Figure 3.5: Sample Illustration of NASA Project Assessment Summary [GAO, 2016]

Binary information was extracted from the assessment summary for each NASA project used in this research. The narrative at the beginning of the GAO reports provided supplementary information to these assessment summaries. Care was taken to extract data that was representative of only the PDR time period. The data represented a “snap shot” of PDR to minimize or eliminate the introduction of bias data that could potentially skew analysis results.

For example, when an assessment summary stated that a project had technical challenge, the challenge was examined to determine if it was due to a technology development problem or a general technical problem such as excessive mass. If the challenges were a technology development problem, then they were recorded as either a complexity of heritage technology development challenge or a new technology development challenge based on the type of technology development. However, if the challenge was due to an excess mass problem, then it was recorded as a technical challenge. Hence, the data was examined very closely to eliminate and/or minimize biases.

The GAO reports discussed whether or not an attribute experienced challenges or issues at PDR. The GAO report was also evaluated for identification of critical technology development types. All critical technologies based primarily on a heritage design were designated as heritage. Heritage technologies changed due to obsolescence were designated as modified heritage. The critical technologies requiring new developments were designated as new development types. Combinations of heritage and new developments were designated as heritage/new. The following logic was used to convert the binary responses collected from the GAO reports to TRL values.

- Not achieving technology maturity at PDR = TRL-5
- Achieving technology maturity by PDR and having modified or new technology = TRL-6

- Achieving technology maturity by PDR and only using heritage technologies = TRL-7

For purposes of statistical validation, TRL data was obtained from the NASA CADRe system. Information was gathered from 33 NASA missions at PDR. The 33 missions included TRL data for 94 instruments. The rule of thumb, as previously stated, is the overall maturity of the system is no greater than the lowest TRL value of a component or subsystem comprising the system. A TRL value was assigned to each of the NASA missions based on the lowest TRL value of the associated instruments for that specific mission. The 94 instruments were also categorized by development type using the same logic used for the GAO data designations.

Chapter 4 – DATA ANALYSIS

For this study, the published GAO reports were reviewed to obtain data at PDR in the life cycle. The gathered information provided details on the status of the acquisition attributes at PDR. The binary data set, used for this analysis, was comprised of only acquisition attributes data at PDR snap shot, pertaining to the status of technology maturity, complexity of heritage technology, new technology, and technical challenges. Only the NASA projects that completed PDR were included in the binary data set.

The GAO reports provided narratives and summaries that described whether or not an attribute exhibited challenges or issues at PDR. When the report stated that an attribute did not have a challenge or issue at PDR, the response for that attribute was recorded as "YES". If the report noted that an attribute had a problem or challenge at PDR, the response for that attribute was recorded as "NO". Table 4.1 details the number on NASA projects assessed each year by GAO and how many of the projects reached technology maturity by PDR.

Table 4.1: GAO Assessed NASA Projects

GAO Assessment Year	Projects Achieving Maturity	Projects Not Achieving Maturity	Total Projects Assessed	Average for Achieving Maturity	Average for Not Achieving Maturity
2009	4	9	13	31%	69%
2010	4	10	14	29%	71%
2011	6	10	16	38%	63%
2012	6	10	16	38%	63%
2013	8	5	13	62%	38%
2014	10	6	16	63%	38%
2015	10	3	13	77%	23%
2016	9	2	11	82%	18%

Binary data was collected for 33 NASA projects obtained from the GAO annual assessment reports. The raw data was maintained in an excel spreadsheet. Table 4.2

contains the technology development type and the acquisition attribute data collected from the GAO reports that is representative of the attribute's status at PDR.

Table 4.2: Snap Shot of Attribute Data at Preliminary Design Review

NASA Mission	Technology Design Type	Technology Maturity	No Complexity of Heritage Technology Challenges	No New Technology Development Challenges	No Technical Challenges or Issues
Aquarius	Modified Heritage	Yes	Yes	Yes	Yes
Dawn	Heritage/New	Yes	Yes	Yes	Yes
GLAST	Heritage/New	Yes	Yes	No	Yes
Glory	New	No	No	Yes	Yes
GPM	Modified Heritage	Yes	Yes	Yes	No
GRAIL	Heritage	Yes	No	Yes	Yes
GRACE-FO	Modified Heritage	Yes	Yes	Yes	Yes
Herschel	New	No	Yes	No	Yes
ICESat-2	Heritage/New	Yes	Yes	Yes	Yes
ICON	Modified Heritage	Yes	Yes	Yes	Yes
InSight	Heritage/New	Yes	Yes	Yes	Yes
Juno	Heritage/New	Yes	Yes	Yes	Yes
JWST	Heritage/New	Yes	Yes	Yes	No
Kepler	Heritage	Yes	No	Yes	Yes
LADEE	Heritage/New	No	No	Yes	No
LDCM	New	Yes	Yes	Yes	Yes
LRO	Heritage/New	Yes	No	Yes	Yes
MAVEN	Heritage/New	Yes	Yes	Yes	No
MMS	New	Yes	No	Yes	Yes
MSL	New	No	No	No	No
NPP	New	No	No	No	No
OCO	Heritage/New	Yes	Yes	Yes	Yes
OCO-2	Heritage	Yes	Yes	Yes	No
OSIRIS-Rex	New	Yes	Yes	No	Yes
RBSP	Heritage/New	Yes	Yes	Yes	No
SDO	Modified Heritage	Yes	No	Yes	Yes
SGSS	Heritage/New	No	Yes	Yes	No
SLS	Heritage/New	Yes	No	Yes	No
SMAP	Modified Heritage	No	No	Yes	Yes
SPP	Heritage/New	Yes	Yes	Yes	No
TDRS Replenishment	Heritage	Yes	Yes	Yes	Yes
TESS	New	Yes	Yes	No	Yes
WISE	Modified Heritage	Yes	Yes	Yes	No

The CADRe system data from 33 NASA missions is comprised of TRL values for 94 instruments. Table 4.3 lists the 33 NASA missions with assigned TRL values based on the associated instrument with the lowest TRL value obtained from the CADRe system. Approximately 70 percent of the NASA missions obtained from the CADRe systems were also reported in the annual reports by GAO for the assessment of major NASA missions. Table 4.4 contains the reported TRL values as a function of design types for the 94 instruments from the 33 NASA missions.

Table 4.3: CADRe System - 33 NASA Missions

NASA Mission	TRL	NASA Mission	TRL	NASA Mission	TRL
AIM	4	IBEX	6	MAVEN	6
Astro-H	6	ICESat-2	6	NICER	6
CALIPSO	6	ICON	6	OCO	6
CloudSat	6	InSight	5	OCO-2	7
CYGNSS	6	IRIS	6	OSIRIS-Rex	6
Dawn	6	Juno	6	RBSP	6
GLAST	6	JWST	6	SAC-D	6
Glory	5	Kepler	7	SGSS	5
GOES-R	6	LADEE	5	SMAP	5
GPM	6	LDCM	6	SPP	7
GRACE-FO	6	LRO	6	TESS	6

Table 4.4: TRL Values of 94 NASA Instruments Associated with the 33 NASA Missions by Design Types

ID	TRL for Heritage Design Type	ID	TRL for Heritage Design Type	ID	TRL for Heritage-New Design Type	ID	TRL for Heritage-New Design Type	ID	TRL for New Design Type
1	6	20	5	39	6	58	6	77	6
2	6	21	6	40	6	59	6	78	6
3	6	22	7	41	6	60	6	79	6
4	6	23	7	42	6	61	5	80	6
5	6	24	7	43	6	62	6	81	6
6	6	25	9	44	6	63	6	82	4
7	8	26	7	45	6	64	6	83	6
8	6	27	9	46	6	65	6	84	6
9	7	28	9	47	6	66	6	85	4
10	7	29	6	48	6	67	6	86	5
11	6	30	7	49	6	68	6	87	6
12	7	31	7	50	7	69	6	88	5
13	6	32	6	51	6	70	6	89	6
14	6	33	6	52	6	71	7	90	6
15	6	34	6	53	6	72	6	91	6
16	6	35	5	54	6	73	6	92	6
17	7	36	7	55	6	74	7	93	6
18	6	37	6	56	5	75	6	94	6
19	7	38	6	57	6	76	6		

4.1 Attribute Correlation Assessment

Binary logistic regression analysis was the statistical method used to evaluate the relationships among technology maturity and the acquisition attributes. Regression analysis requires the identification of a single dependent variable. The designated dependent variable for this study is technology maturity. The other acquisition attributes were designated as the independent variables for the binary logistic regression analysis. The purpose of this evaluation is to determine if there are any correlations between technology maturity and the other attributes.

Binary logistic regression analysis was performed on the acquisition attributes data collected at PDR. The significance and strength of the relationship among the acquisition attributes was assessed through the evaluation of the regression analysis results. The binary responses, along with the names of the NASA projects and the acquisition attribute headings, were imported as “Yes” and “No” data into the Minitab® 17 software for statistical analysis. Regression analysis was performed first on acquisition attribute data at PDR.

4.1.1 Binary Logistic Regression Analysis

Binary logistic regression analysis was conducted on the collected attributes data at PDR. The acquisition attributes identified as independent variables were complexity of heritage technology development, new technology development, and technical challenges. The logistic regression table revealed that only one attribute, no complexity of heritage technology development challenge, had a p-value less than 0.05. Table 4.5 contains the results from the regression run. The analysis was run a second time, eliminating “no technical challenges”. The second run revealed “no complexity of heritage technology challenges” having a p-value of 0.022 and “no new technology challenges” having a p-value of 0.060. However, the goodness-of-fit test displayed evidence that the reduced model may not adequately fit the binary data.

Table 4.5: Acquisition Attributes Binary Logistic Regression Analysis at PDR

Acquisition Attribute	PDR		
	Coefficient	Z-Value	P-Value
Constant	-3.55	-1.51	0.130
No Complexity of Heritage Technology Development	2.87	2.10	**0.035**
No New Technology Development Challenges	2.94	1.76	0.079
No Technical Challenges	1.71	1.31	0.189

Complexity of heritage technology developments displayed the strongest correlation to technology maturity and was the only attribute with a statistically significant relationship to technology maturity. The attribute of new technology developments did not demonstrate a statistically significant relationship with technology maturity, however the p-value does reflect a strong inclination towards technology maturity.

4.1.1.1 Goodness-of-Fit for PDR Data

Table 4.6 contains the results from the goodness-of-fit tests. The goodness-of-fit tests conveys whether the model adequately fits the binary data. P-values less than 0.05 for a 95% CL would indicate a significant difference in the model output from the actual binary data output. After performing the logistic regression analysis, the resulting goodness-of-fit tests' p-values ranging from 0.707 to 0.936. These p-values show that there are no significant differences between the predicted probabilities from the model and the observed probabilities from the binary data or insufficient evidence to assert that the predictive model does not adequately fit the binary data.

Table 4.6: Goodness-of-Fit Tests Results for Attributes at PDR

Test	Degrees of Freedom	Chi-Square	P-Value
Deviance	29	22.48	0.800
Pearson	29	24.43	0.707
Hosmer-Lemeshow	6	0.42	0.936

4.1.1.2 Odds Ratio for PDR Data

The odds ratio is another data point in the quantification of how strongly the presence or absence of an acquisition attribute influences the achievement of technology maturity by PDR. The odds ratio for each acquisition attribute is listed in Table 4.7. Level A represents the presence of or a "Yes" response for the attribute. Level B represents the absence of or a "No" response for the attribute. Interpretation of the odds ratio is as follows [Szumilas, 2010]:

- If the OR=1, then the presence of the event compared to the absence of the event does not affect odds of achieving the outcome (the neutral state)
- If the OR>1, then the presence of the event compared to the absence of the event is associated with higher odds of achieving the outcome
- If the OR<1, then the presence of the event compared to the absence of the event is associated with lower odds of achieving the outcome

Table 4.7: Odds Ratio for Categorical Predictors at PDR

Acquisition Attribute	Level A	Level B	Odd Ratio	95% CI	
				Lower	*Upper*
No Complexity of Heritage Technology Development Challenges	Yes	No	17.659	1.218	256.103
No New Technology Development Challenges	Yes	No	18.882	0.711	501.748
No Technical Challenges	Yes	No	5.511	0.432	70.349

The odds ratio for no complexity of heritage technology development challenges indicates that there is an approximately 18:1 odds of achieving technology maturity in the presence of having no heritage technology development problems. There is an approximately 19:1 odds of achieving technology maturity in the presence of no new technology development challenges. In the presence of no technical challenges, there is an approximately 6:1 odds of influencing the achievement of technology maturity. According to Szumilas (2010), the 95% CI associated with the odds ratio should be used as follows in the interpretation of odds ratio findings [Szumilas, 2010].

> *"The 95% confidence interval (CI) is used to estimate the precision of the OR. A large CI indicates a low level of precision of the OR, whereas a small CI indicates a higher precision of the OR. It is important to note however, that unlike the p value, the 95% CI does not report a measure's statistical significance. In practice, the 95% CI is often used as a proxy for the presence of statistical significance if it does not overlap the null value (e.g. OR=1). Nevertheless, it would be inappropriate to interpret an OR with 95% CI that spans the null value as indicating evidence for lack of association between the exposure and outcome"* [Szumilas, 2010].

4.1.1.3 Predictive Regression Model for PDR Data

A predictive regression model was created to estimate the probability of achieving technology maturity at PDR. The regression equation is defined in Equation 4.1. The regression equation provides the probability of achieving technology maturity by PDR as a function of the various attributes. When solving for Y′, an attribute response of "Yes" equates to "1" and an attribute response of "No" equates to "0".

$$P(Technology\ Maturity) = \frac{exp(Y')}{(1+exp(Y'))} \qquad \mathbf{4.1}$$

$$where, \quad Y' = -3.55 + 2.87(No\ Complexity\ of\ Heritage\ Technology\ Challenges) + 2.94(No\ New\ Technology\ Challenges) + 1.71(No\ Technical\ Challenges)$$

A table was produced that contained the various “Yes = 1” and “No = 0” combinations of the five acquisition attributes. These combinations were used for computing the probability predictions for achieving technology maturity. The probabilities of achieving technology maturity by PDR calculated using the regression model are shown in Table 4.8.

Table 4.8: Probability of Achieving Technology Maturity by PDR

No Complexity of Heritage Technology Challenges	No New Technology Challenges	No Technical Challenges	Y'	P(Maturity at PDR)
Yes	Yes	Yes	3.97	0.9815
Yes	Yes	No	2.26	0.9055
No	Yes	Yes	1.1	0.7503
Yes	No	Yes	1.03	0.7369
No	Yes	No	-0.61	0.3521
Yes	No	No	-0.68	0.3363
No	No	Yes	-1.84	0.1371
No	No	No	-3.55	0.0279

The data shows that there is a 90 percent or greater probability of meeting or exceeding the technology maturity threshold by PDR when there are no complexity of heritage technology development issues and no new technology challenges. Additionally, there is between 73 percent to 75 percent probability of meeting or exceeding the technology maturity threshold by PDR when there are either no complexity of technology development issues or no new technology development challenges and no technical challenges. When there are two or more attribute challenges or problems, the probability of meeting or exceeding the technology maturity threshold by PDR is no greater than 35 percent.

The predictive regression equation is used to estimate the probability of a NASA project to achieve technology maturity by PDR based on the influence of the acquisition attributes. To check the validity of the regression model, the GAO binary data for each

NASA project was used to compute the probability of meeting or exceeding technology maturity using the logistic regression equation. The comparison of the observed technology maturity assessment at PDR as extracted from the GAO reports on major NASA projects and the predicted probability of meeting or exceeding the technology maturity threshold by PDR as generated using the regression equation are listed in Table 4.9.

The calculated probabilities generated using the regression equation are estimations or approximations. Twenty-eight of the 33 NASA projects' technology maturity assessments reported by GAO agreed with the predicted probability of achieving technology maturity generated from the regression model. Five regression model probabilities predicted the opposite response than the actual assessed outcome.

Table 4.9: Observed Technology Maturity and Predicted Probability of Technology Maturity

NASA Mission	Technology Design Type	Technology Maturity (Actual GAO Assessment)	Probability of Achieving Technology Maturity (Predictive Regression Model)
Aquarius	Modified Heritage	Yes	98.2%
Dawn	Heritage/New	Yes	98.2%
GLAST	Heritage/New	Yes	73.7%
Glory	New	No	75.0%
GPM	Modified Heritage	Yes	90.6%
GRAIL	Heritage	Yes	75.0%
GRACE-FO	Modified Heritage	Yes	98.2%
Herschel	New	No	73.7%
ICESat-2	Heritage/New	Yes	98.2%
ICON	Modified Heritage	Yes	98.2%
InSight	Heritage/New	Yes	98.2%
Juno	Heritage/New	Yes	98.2%
JWST	Heritage/New	Yes	90.6%
Kepler	Heritage	Yes	75.0%
LADEE	Heritage/New	No	35.2%
LDCM	New	Yes	98.2%
LRO	Heritage/New	Yes	75.0%
MAVEN	Heritage/New	Yes	90.6%
MMS	New	Yes	75.0%
MSL	New	No	2.8%
NPP	New	No	2.8%

NASA Mission	Technology Design Type	Technology Maturity (Actual GAO Assessment)	Probability of Achieving Technology Maturity (Predictive Regression Model)
OCO	Heritage/New	Yes	98.2%
OCO-2	Heritage	Yes	90.6%
OSIRIS-Rex	New	Yes	73.7%
RBSP	Heritage/New	Yes	90.6%
SDO	Modified Heritage	Yes	75.0%
SGSS	Heritage/New	No	90.6%
SLS	Heritage/New	Yes	35.2%
SMAP	Modified Heritage	No	75.0%
SPP	Heritage/New	Yes	90.6%
TDRS Replenishment	Heritage	Yes	98.2%
TESS	New	Yes	73.7%
WISE	Modified Heritage	Yes	90.6%

4.2 Adjusted Wald Technique

For this research, sample set averages will be used to evaluate the percentage of NASA missions achieving technology maturity by PDR. The technology maturity binary responses of 33 NASA projects obtained from the GAO reports were used to generate the associated sample set averages for achieving technology maturity. The confidence intervals were computed using the Adjusted Wald technique. The Adjusted Wald technique is well-known using binary data to calculate a 95% confidence interval and sample average of a small sample set. The method detailed in Chapter 3 for calculating the Adjusted Wald technique was followed to generate the sample averages and the confidence intervals associated with technology maturity in this study.

Technology maturity attribute responses of “Yes” were converted to 1 and responses of “No” were converted to 0, for determining the “margin of error” values for the data at PDR. Once all of the binary data contained 1s or 0s, then the technique was used to determine the plus/minus “margin of error” values of the technology maturity assessment for the 33 NASA projects. Table 4.10 contains the results of the Adjusted Wald calculations for PDR. Confidence intervals were generated for technology maturity assessments at PDR for all 33 NASA projects and for:

- projects with no complexity of heritage technology development issues;
- projects with no new technology issues;
- projects with no technical issues;

Table 4.10: GAO Reported 33 NASA Projects by Acquisition Attribute

Technology Maturity Assessments by Attribute	Number of Missions	Technology Maturity (Average)	Technology Maturity (Adjusted Average)	Margin of Error	Upper Confidence Interval	Lower Confidence Interval
33 NASA Projects	33	78.8%	75.7%	14.1%	92.9%	64.7%
No Complexity of Heritage Issues	21	90.5%	84.0%	14.7%	105.1%	75.8%
No Technical Issues	22	86.4%	80.8%	15.5%	101.8%	70.9%
No New Technology Challenges	28	82.1%	78.1%	14.6%	96.8%	67.5%

For the 33 NASA missions reported by GAO, the sample set average for achieving technology maturity is approximately 79 percent. The 95% confidence interval associated with achieving technology maturity by PDR for these twenty-six NASA missions is approximately 65 percent to 93 percent. There is no evidence of a significant difference in the margin of errors for the acquisition attributes. Figure 4.1 provides a graphical representation of the sample set average for achieving technology maturity and the associated confidence intervals for the 33 NASA projects by attribute at PDR. The graph shows complexity of heritage technology development as the attribute with the highest influence on achieving technology maturity by PDR, which corroborates the regression analysis results.

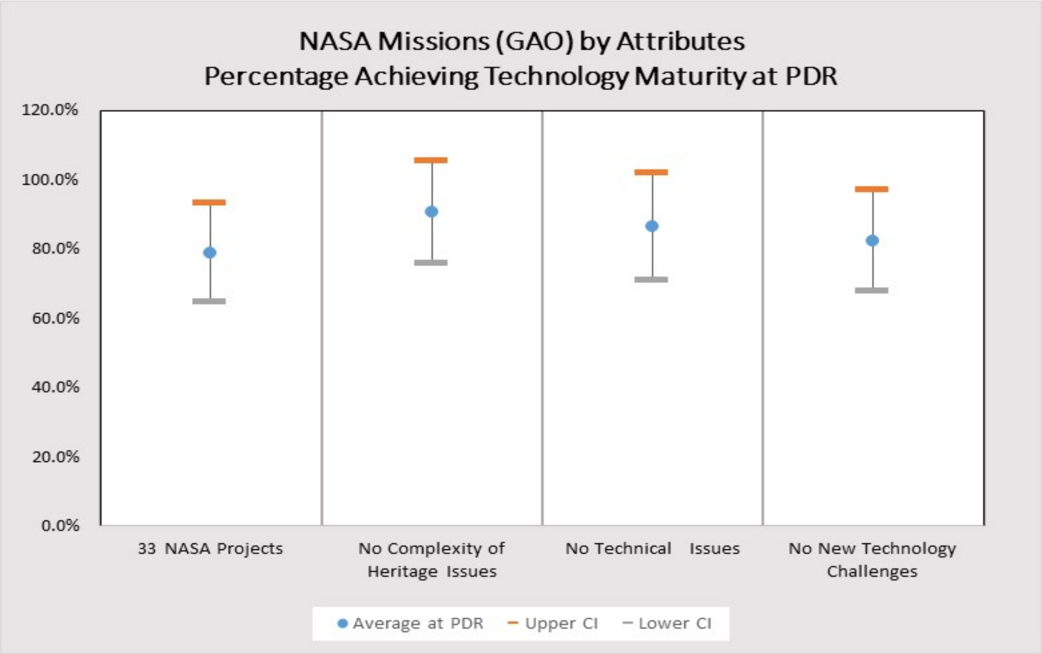


Figure 4.1: Percentage of NASA Missions Achieving Technology Maturity by Attribute

Table 4.11 displays the GAO sample set as a function of development type. Eleven of the 33 NASA missions evaluated by GAO solely utilized heritage technology designs. Approximately 91 percent of the missions that utilized heritage technologies significantly increased the average percentage of projects achieving maturity by PDR. The data also revealed that 50 percent of the missions utilizing new technologies achieved maturity by PDR. These results are consistent with the recommended practice of GAO to leverage heritage technology development to achieve technology maturity by PDR.

Table 4.11: GAO Reported 33 NASA Missions by Development Type

Technology Maturity Assessments by Development Type	Number of Missions	Technology Maturity (Average)	Technology Maturity (Adjusted Average)	Margin of Error	Upper Confidence Interval	Lower Confidence Interval
33 NASA Projects	33	78.8%	75.7%	14.1%	92.9%	64.7%
Heritage Developments	11	90.9%	80.0%	20.7%	111.6%	70.3%
Heritage & New Developments	14	85.7%	77.8%	19.6%	105.3%	66.1%
New Developments	8	50.0%	50.0%	28.9%	78.9%	21.1%

A graphical representation of achieving technology maturity by PDR as a function of development type is depicted in Figure 4.2. The analysis shows a difference in the margin of error for new technology developments in comparison to both heritage technology developments and heritage-new technology developments. However as noted in Figure 4.2, there is an overlapping of the confidence intervals for the three development types, which requires further investigation to determine the significance of the difference in the margin of errors. It should be noted that increases in the margin of error may be due to small sample size evaluations. Therefore, in an effort to determine the significance of this difference in the margins of errors, the 94 NASA instruments are also examined in Section 4.3.

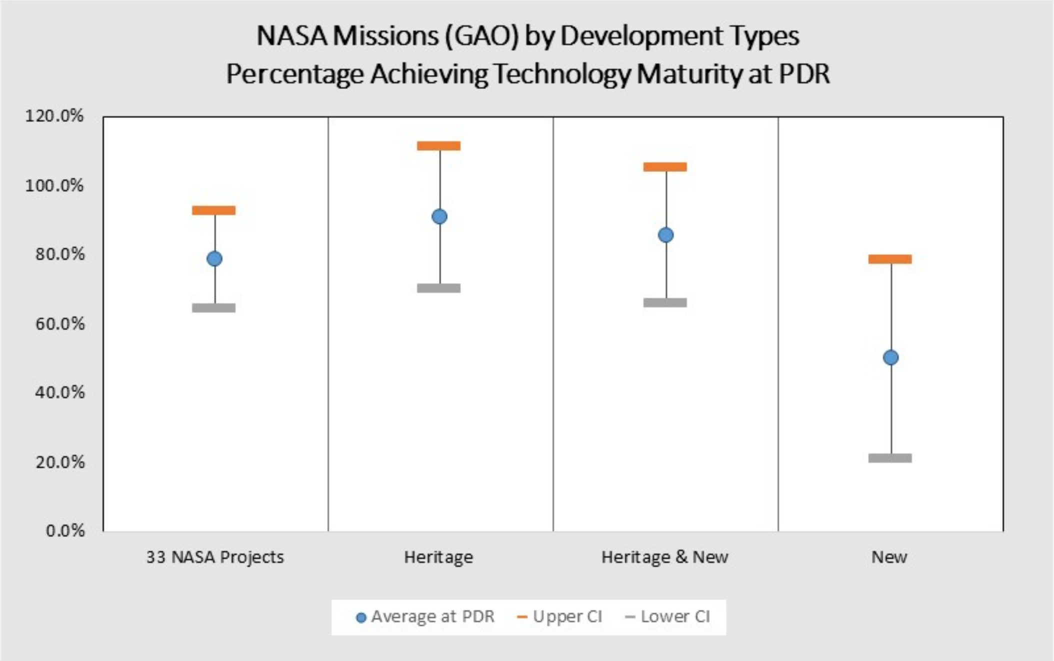


Figure 4.2: Percentage of NASA Missions Achieving Technology Maturity by Development Type

4.3 Comparison of Sample Sets

A statistical nonparametric method for comparing the medians of multiple populations is the Kruskal-Wallis method. The Mann-Whitney test is a statistical method that was used to evaluate two sample sets, which can be used as an alternative for the *t*-test when analyzing ordinal data. Table 4.12 contains the results from the Mann-Whitney test.

Table 4.12: Mann-Whitney Test on Two Sample Sets of 33 NASA Missions

NASA Data Set	N	Median
NASA Missions (CADRe)	33	6.0000
NASA Missions (GAO)	33	6.0000
Point estimate for η1 - η2 is -0.0000 95.0 Percent CI for η1 - η2 is (0.0001,-0.0001)		
W = 1103.5		
Test of η1 = η2 vs η1 ≠ η2 is significant at 0.9847		
The test is significant at 0.9810 (adjusted for ties)		

The test revealed sample medians of 6, with the 95% confidence interval for the difference in medians for the two samples sets of 0.0001 to -0.0001. The test statistic W = 1103.5 has a *p*-value of 0.9847 and when adjusted for ties is 0.9810. The p-values of 0.9847 and 0.9810 were not less than the selected level of 0.05, therefore there is insufficient evidence to support that the medians for the two samples sets are different. Figure 4.3 shows the frequency of TRL values within each of the two sample sets. The analysis results validate the methodology used for comparison purposes to assign TRL values to the binary responses, especially since 70 percent of the sampled missions are the same.

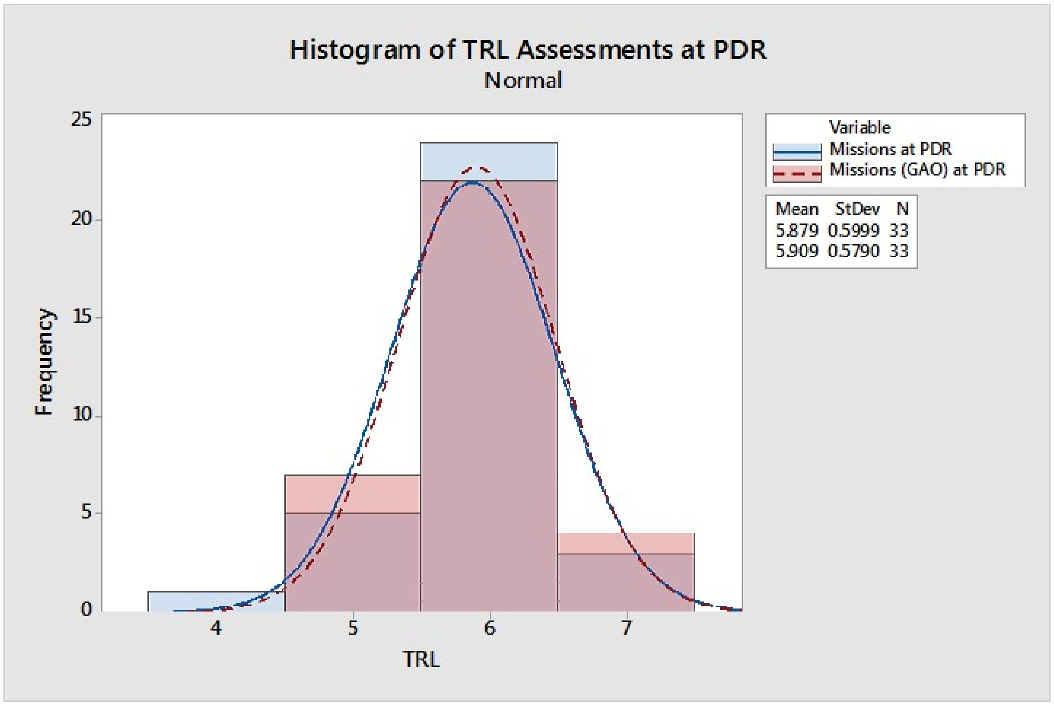


Figure 4.3: Histogram of the Two NASA Missions Populations

The sample data from the CADRe system was further analyzed by performing a Kruskal-Wallis test on the 94 instruments as a function of development type. Table 4.13 contains the results of the statistical analysis for the two sample sets of 33 NASA missions and the 94 NASA instruments.

Table 4.13: Kruskal-Wallis Test on 94 NASA Instruments

Development Type	N	Median	Average Rank	Z
Heritage	38	6.000	58.3	3.17
Heritage/New	38	6.000	43.3	-1.23
New	18	6.000	33.4	-2.43
Overall	94		47.5	
H = 11.68	DF = 2	*P* = 0.003		
H = 18.43	DF = 2	*P* = 0.000 (adjusted for ties)		

The Kruskal-Wallis test disclosed that the calculated sample medians for the three development types were the same. The average rank, also known as the mean rank, shows that the new development types differs the most from the overall 94 instruments' average rank. The test reveals that the heritage development types has a higher average rank than the average rank for the overall 94 instruments. The p-value and the adjusted p-value for the test statistic (H) are less than the significant level of 0.05. Therefore, the p-values indicate that the population medians of technology development types differs for at least one development type. Figure 4.4 displays the distribution of the TRL assessments for the 94 NASA instruments as a function of development type.

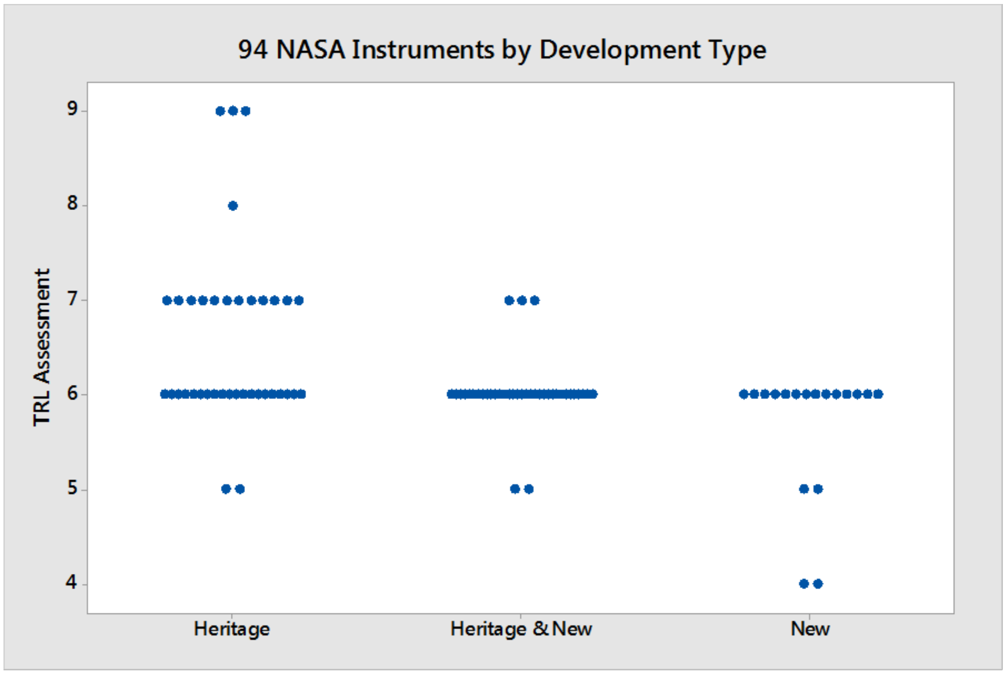


Figure 4.4: Comparison of TRL Assessment for the 94 NASA Instruments by Development Type

Chapter 5 – RESEARCH FINDINGS

This study sought to investigate the impact of critical technologies on technology maturity through the evaluation of acquisition attributes and development types at a specified KDP and the application of a predictive probabilistic regression model. The specified KDP examined in this study was PDR. As previously stated in Chapter 2, critical technologies refer to heritage technology developments and new technology developments. Binary logistic regression analysis was used to evaluate the relationship between technology maturity and the independent acquisition attributes. The Adjusted Wald technique was used to establish the average percentage for achieving technology maturity and confidence intervals associated with technology maturity. The Mann-Whitney test was used to compare the medians of two sample sets for the 33 NASA missions. Kruskal-Wallis was used to evaluate the sample set of 94 NASA instruments as a function of development type. This chapter discusses the findings contained in Chapter 4 – Data Analysis.

5.1 First Hypothesis – Heritage Technology Developments

As previously stated in Chapter 2 – Literature Review, a GAO recommended best practice is to leverage the application of heritage designs to attain technology maturity by PDR, reducing the uncertainty associated with new critical technology developments [GAO, 2009]. The recommendation is based on the premise that heritage designs or technologies have been shown to be technologically mature. The first hypothesis addresses this belief. The first hypothesis proposes - $H1_0$: Heritage technology developments significantly increases a project’s ability to achieve technology maturity by PDR.

The findings, as shown in Table 4.11 of Chapter 4, from the GAO reports for NASA missions as a function of technology development type revealed that missions using “heritage designs only” did significantly impact the average percentage of missions achieving technology maturity at PDR. The average percentage of missions utilizing heritage developments is approximately 91 percent in comparison to 79 percent for all GAO reported 33 NASA assessed projects. The average percentage of missions achieving technology maturity by PDR significantly decrease to 50 percent when using primarily or solely new developments.

Findings from the Adjusted Wald technique when using primarily or solely heritage technology developments reveal an increase in the percentage of NASA missions achieving technology maturity at PDR. Analysis of the 94 NASA instruments as a function of development type from the Kruskal-Wallis test also confirms a higher increase in the average rank (mean rank) of NASA instruments achieving technology maturity that utilize heritage technology developments in comparison to the overall 94 NASA instruments. Based on the research analysis findings presented in this dissertation, there is evidence with a 95% confidence that heritage technology developments significantly increase a project’s ability to achieve technology maturity by PDR. Thus, the first hypothesis is not rejected.

5.2 Second Hypothesis – Acquisition Attributes and Technology Maturity

Since heritage designs have previously been assessed as technologically mature, it is commonly believed that a heritage technology development will have little to no influence on technology maturity assessments at PDR. New technology developments are also believed to have significant influence on technology maturity assessments at PDR, especially since the new technology had not previously met the technology maturity threshold for transitioning from the formulation phase to the implementation phase in the NASA life cycle. Having a better understanding of how acquisition attributes influence a mission's ability to achieve technology maturity could provide systems engineers and project managers with needed information for satisfactorily managing technical, cost, and schedule performance. For this research, the relationship between acquisition attributes and technology maturity were examined to gain a more comprehensive understanding of their significance. The data was evaluated as a function of acquisition attributes at PDR. The second hypothesis proposes - $H2_0$: At PDR, the relationships between critical technologies attributes and technology maturity are significant.

The findings from the binary logistics regression analysis of the GAO reported data showed complexity of heritage technology development as the only acquisition attribute at PDR with a p-value less than 0.05. The remaining independent acquisition attributes, which includes new technology developments, had p-values greater than 0.05. However, the p-value for new technology developments was 0.079. Although the p-value for new technology was not determined to be significant at $\alpha = 0.05$, it does exhibit a very strong relationship to technology maturity. Based on these binary logistic regression analysis results of the GAO reported 33 NASA missions, there is a 95% confidence that the "complexity of heritage technology development" acquisition attribute has a statistically significant relationship with technology maturity and new technology development acquisition attribute has an extremely strong relationship to technology maturity at PDR. Thus, the second hypothesis is partially rejected.

5.3 Predictive Probability Regression Model

The predictive probability regression model serves as a tool, in conjunction with the confidence intervals, for gauging the accuracy of the technology maturity assessments. The regression model was developed for estimating the probability of achieving technology maturity by PDR. If the model is a good fit, then binary responses can be entered for independent variables to predict the probability of a specific outcome for the dependent variable. Goodness-of-fit tests have limitations, especially for small data sets, when assessing if a data set is a good fit for a specific model. Based on the goodness-of-fit tests' p-values, the predictive model is asserted as a good fit for the binary sample data set for this research. Determining the adequacy of the predictive model is through a comparison of the actual or observed response versus the predictive model's response. Table 5.1 contains the actual technology maturity responses at PDR reported in the GAO reports and the calculated probabilities using the predictive model.

Table 5.1: Differences between Observed and Modeled Responses

NASA Mission	Technology Design Type	Technology Maturity (Actual GAO Assessment)	Probability of Achieving Technology Maturity (Predictive Regression Model)
Glory	New	No	75.0%
Herschel	New	No	73.7%
SGSS	Heritage/New	No	90.6%
SLS	Heritage/New	Yes	35.2%
SMAP	Modified Heritage	No	75.0%

The predictive model provided a different response then the actual reported response for five of the 33 NASA projects obtained from the GAO annual reports. The predictive model is an estimator with a 95% confidence and is not an absolute predictor of the project's maturity state. The predictive regression model was accurate for 85% of the responses. On the surface, this represents a 15% discrepancy in the model response. The predictive model is a guide, which should trigger the need for further investigation when the technology maturity assessment response is at odds with the predictive model's probability of the response. Additionally, the predictive model is demonstrating its benefit as a tool for gauging the accuracy of technology maturity assessments. These results reflected in this study should indicate to the system engineers that additional examination is required when the regression model predicts a lower probability for a mission that is assessed as technologically mature or a high probability for a mission that is assessed as technologically immature.

Upon further examination of these projects, additional scrutiny could benefit management and technical execution of the projects. For example, one of the five projects had a GAO reported response of technology immaturity at PDR, however, the predictive model provided a 90.6 percent probability of the project achieving technology maturity by PDR. The SGSS project management reported the project as being technology mature, however, the management review panel identified two critical technologies as immature. Using the NASA's rule of thumb for assessing system level maturity, the project must be reported as immature at PDR.

Investigation into the difference between the predictive probability and the actual state of the project's technology maturity could provide systems engineers and managers with previously uncovered issues or awareness of resolved issues or challenges that may have not been reported. This predictive probability has the potential to provide system engineers with supplemental information concerning the accuracy of maturity state of the technology. The predictive model provides system engineers and project managers with the ammunition to question the state of technology maturity.

5.4 Subjectivity of Technology Maturity Assessments

The Adjusted Wald technique findings for the NASA missions as a function of acquisition attribute show no significant difference in the margin of error percentage between complexity of heritage development challenges and new technology development challenges. As displayed in Table 4.10 of Chapter 4, the margin of errors are 14.1 percent for all 33 NASA missions, 14.7 percent for missions with no complexity of heritage technology development challenges and 14.6 percent for missions with no new technology development challenges. The margin of error measures accuracy. These findings seems to suggest that both complexity of heritage technology development and new technology development are measured with the same level of accuracy. Further investigation of the margin of error as a function of critical technology development is needed to determine if engineers use the same subjectivity when assessing heritage technology developments and new technology developments.

Chapter 6 - CONCLUSIONS

The assessment of technology maturity is an essential component of the systems engineering decision-making process for aerospace mission acquisitions and defense weapon acquisitions. The purpose of this study is to investigate the relationship between critical technologies and technology maturity assessments. However, there is a commonly accepted premise within the systems engineering community that using TRL for evaluating technology maturity has its limitations. Moreover, unsatisfactory or reduced technical performance and programmatic overruns can result from inaccurate technology maturity assessments. Accurate and trustworthy information is required by systems engineers and project managers for making good decisions. Gaining a more comprehensive understanding of the relationship between critical technologies and technology maturity assessments will provide systems engineers with valuable information for making informed decisions. This research examined technology maturity assessments at PDR and its relationship to critical technologies. Aerospace systems are frequently designed utilizing heritage technologies. The use of heritage technologies give systems engineers an overly optimistic view of technology maturity. Utilization of heritage technology developments is a recommended practice by GAO for the reduction of risk associated with cost and schedule growth. Leveraging the application of heritage designs is also recommended by GAO to achieve technology maturity by PDR, minimizing the uncertainty associated with the development of new technologies. This research confirmed with a 95% confidence that the attribute, complexity of heritage technology development, significantly influences a mission's ability to achieve technology maturity by PDR [Sauser, 2009]. Additionally, this study indicated with a

95% confidence that there was not a statistically significant relationship between new technology developments and achieving technology maturity by PDR. However the new technology development attribute does exhibit a strong tendency towards a significant relationship with technology maturity based on the logistics regression analysis findings disclosing a p-value of 0.079. The research clearly demonstrated that the application of heritage developments increases the average number of NASA missions that achieved technology maturity by PDR. Therefore, the first hypothesis – "$H1_0$: Heritage technology developments significantly increases a project's ability to achieve technology maturity by PDR" – is not rejected. Furthermore, the second hypothesis - $H2_0$: At PDR, the relationships between critical technologies attributes and technology maturity are significant – is partially rejected.

A regression equation was generated and there was no evidence to conclude that the model was not a good fit. The regression model is limited to predicting the probability of achieving technology maturity by PDR for aerospace missions. Findings from the regression model discloses a 90 percent or better probability of obtaining technology maturity by PDR in the absence of complexities of heritage technology development challenges and new technology challenges. In the presence of complexities of heritage technology development challenges, the regression model predicts a 74 percent probability of achieving maturity by PDR. If technical challenges and technology development challenges exist, than the probability of achieving maturity by PDR ranges from 35 percent to 33 percent. In the presence of both complexity of heritage technology development challenges and new technology development challenges, the probability of achieving technology maturity by PDR is below 14 percent. Based on the findings in this study, as long as there are no complexities of heritage technology development challenges and/or new technology development challenges, there is a high probability that the maturity can be obtained by PDR.

After examining all of the findings, the following conclusions were reached. This research examined the relationship between critical technologies and technology maturity at PDR as a function of GAO acquisition attributes and by technology development type. The analysis of technology maturity as a function of technology development type revealed that there is no statistical difference between the margin of errors associated with the TRL assessments of missions based on heritage technology developments and missions based on new technology developments. This research validates the recommendation to utilize heritage technology developments to achieve technology maturity by PDR. The findings show a significant increase in the average percentage of missions achieving technology maturity by PDR when solely utilizing heritage technology developments. Heritage technology developments refer to the application of the technology as originally designed or only modified due to obsolesces. As referenced in the NASA Systems Engineering Handbook [2007], heritage designs that are modified in form, fit, and function should be treated as either a new or hybrid technology development. If heritage technology developments are not utilized as originally designed, the technology development may not reduce unsatisfactory technical and programmatic performance.

The study identified with a 95% confidence that there are no significant differences in the margin of errors of heritage developments and new developments by PDR. The margin of error represents the maximum amount an assessment is expected to differ from the actual assessment. The margin of error is used to measure the accuracy of the technology maturity assessments. However, it cannot evaluate the amount of subjectivity or bias associated with the technology maturity assessments.

The knowledge expanded from this research provides an approach for systems engineers to use as a gauge when assessing a NASA mission's ability to achieve technology maturity by PDR. This research provides system engineers with a tool to weigh if a mission's assessed technology maturity is highly likely or highly unlikely. The predictive probabilistic regression model can be used as supplemental information along with previously established method for assessing technology maturity. Thus, this investigation adds to the body of knowledge available to the systems engineering community for making informed decisions by providing a more comprehensive understanding of technology maturity assessment.

6.1 Limitation and Future Work

As with all studies, there are some limitations associated with this research. This study investigated the technology maturity of two sample sets of NASA missions. The findings from this research apply to the NASA life cycle process for product development. The conceptual framework was developed and is limited to the acquisition attributes identified in GAO annual reports on the assessment of NASA large missions. The number of missions investigated in this study was constrained by the availability of TRL data, the quantity of technology maturity information, and the frequency of GAO publications on the assessments of selected NASA missions.

The sample size of 33 missions is considered statistically small. Due to the small population size, statistical analysis was also performed on the TRL data from the 94 instruments that were payloads on the 33 missions acquired from the NASA CADRe system. Future work should include the analysis of larger sample set sizes of NASA missions to improve the reliability of the confidence interval associated with achieving technology maturity by PDR. This recommendation includes expanding the sample population size of binary data obtained from GAO annual assessments of NASA major projects.

Future work may also be considered in the area of heritage technology developments to determine when the complexity of a legacy design significantly alters the technology development in a manner that is no longer consistent with the definition of heritage. As previously stated, the utilization of heritage technologies is a recommended best practice by GAO. What is the threshold for a heritage technology that constitutes sufficient changes in form, fit, and the function to no longer assert or quantify it as heritage? Regression analysis indicated a statistically significant relationship between complexity of heritage technology development and achieving technology maturity by PDR. The findings show an increase in the average number of NASA missions obtaining maturity when using heritage technology developments. Therefore, the determination of whether a technology development is considered heritage or not will directly correlate to the ability of a mission to achieve maturity.

Another challenge facing systems engineers is quantifying the accuracy of the technology maturity assessment. The ability to quantify a technology maturity assessment through the application of confidence interval or margin of error would be beneficial to the systems engineering community. Confidence intervals provide an understanding concerning the amount of trust one should place in a sample estimate or the level of uncertainty associated with the estimate. Confidence intervals are used when there is only a small sample of the overall population. Usually the true population estimate is within the upper and lower confidence limits. The margin of error measures accuracy of the average associated with the assessed sample group and are used to determine confidence intervals. The larger the margin of error, the greater the uncertainty associated with the measured average. Future work may include the development of a methodology for evaluating the accuracy of technology maturity assessments. Methods for gauging the accuracy of technology maturity assessments will provide systems engineers with valuable information.

Additionally, future research could be expanded to include assessing the accuracy of technology maturity assessments at CDR. Expansion of this research will assist in answering questions such as: What is the significance of the relationships between the various acquisition attributes and the technology maturity assessments at CDR? Which attributes significantly influence achieving technology maturity assessments at CDR?

REFERENCES

Amer, T. R. (2011). Development of risk uncertainty factors from historical NASA projects. (Ph.D., Old Dominion University).

Anderson, M. J. (2001). A new method for non-parametric multivariate analysis of variance. Austral ecology, 26(1), 32-46.

Azizian, N. (2011). A framework for evaluating technology readiness, system quality, and program performance of U.S. DoD acquisitions. (Ph.D., The George Washington University).

Azizian, N., Mazzuchi, T., Sarkani, S., & Rico, D. F. (2011). A framework for evaluating technology readiness, system quality, and program performance of U.S. DoD acquisitions. *Systems Engineering*, *14*(4), 410-426.

Brown, L. D., Fu, X., & Zhao, L. H. (2011). Confidence intervals for nonparametric regression. Journal of Nonparametric Statistics, 23(1), 149-163.

Buckland, S. (1984). Monte Carlo Confidence Intervals. Biometrics, 40(3), 811-817.

Chang, L. (2012). Integration-centric approach to system readiness assessment based on evidential reasoning. *Journal of Systems Engineering and Electronics, 23*(6), 881; 881-890; 890.

Clausing, D., & Holmes, M. (2010). Technology readiness. *Research Technology Management, 53*(4), 52-59.

Collins, M., & Williams, L. (2014). A three-stage filter for effective technology selection. *Research Technology Management*, *57*(3), 36-42.

Conrow, E. H. (2011). Estimating technology readiness level coefficients. *Journal of Spacecraft and Rockets*, *48*(1), 146-152.

Conrow, E. H. (2011). Technology readiness levels and space program schedule change. *Journal of Spacecraft and Rockets, 48*(6), 1068-1071.

Cornford, S. L., and Sarsfield, L. (2004). Quantitative methods for maturing and infusing advanced spacecraft technology, 2004 IEEE Proceedings, 2004 Aerospace Conference.

de Almeida, A., Morais, D., Alencar, L., Clemente, T., Krym, E., & Barboza, C. (2014). A multicriteria decision model for technology readiness assessment for energy based on PROMETHEE method with surrogate weights. Paper presented at the *Industrial Engineering and Engineering Management (IEEM), 2014 IEEE International Conference on,* 64-68.

DiCiccio, T. J., & Efron, B. (1996). Bootstrap confidence intervals. *Statistical Science, 11*(3), 189-212.

Donaldson, L., Charlier, S. D., & Qiu, J. X. J. (2012). Organizational portfolio analysis: Focusing on risk inside the corporation. *Long Range Planning, 45*(4), 235-257.

Doskey, S. C. (2014). A measure of systems engineering effectiveness in government acquisition of complex information systems: A bayesian belief network-based approach. (Ph.D., The George Washington University).

Dubos, G. F., & Saleh, J. H. (2011). Spacecraft technology portfolio: Probabilistic modeling and implications for responsiveness and schedule slippage. *Acta Astronautica, 68*(7), 1126-1146.

Dubos, G. F., Saleh, J. H., & Braun, R. (2008). Technology readiness level, schedule risk, and slippage in spacecraft design. *Journal of Spacecraft and Rockets, 45*(4), 836-842.

Dubos, G. F. (2011). Stochastic modeling of responsiveness, schedule risk and obsolescence of C systems, and implications for design choices. (Ph.D., Georgia Institute of Technology).

Eggstaff, J. W. (2013). Technical performance measurement and technical risk analysis utilizing the assessment of probability distributions from expert judgment. (Ph.D., The George Washington University).

El-Khoury, B., & Kenley, C. (2012). An analysis of TRL-based cost and schedule models. Paper presented at the *Monterey, California: 9th Annual Acquisition Research Symposium.*

Evans, J. D., & Johnson, R. O. (2013). Tools for managing early-stage business model innovation. *Research Technology Management, 56*(5), 52-56.

Fiondella, L. (2009). Statistical inference and uncertainty assessment for multi-state systems. *International Journal of Reliability, Quality and Safety Engineering, 16*(05), 453-467.

Ford, S. J., Mortara, L., & Probert, D. R. (2012). Disentangling the complexity of early-stage technology acquisitions. *Research Technology Management, 55*(3), 40-48.

Ganguly, A., Nilchiani, R., & Farr, J. V., PE. (2010). Defining a set of metrics to evaluate the potential disruptiveness of a technology. *Engineering Management Journal, 22*(1), 34-44.

Georgiadis, D. (2013). Using multi criteria decision making in analysis of alternatives for selection of enabling technology. (Ph.D., The George Washington University).

Ghasemzadeh, F., & Archer, N. P. (2000). Project portfolio selection through decision support. *Decision Support Systems, 29*(1), 73-88.

Giasolli, R., Marinakis, Y. D., Tierney, R. H., & Walsh, S. (2014). Using technology readiness levels in the pharmaceutical landscape: the next generation of technology roadmapping. CMM international= Commercial micro manufacturing international, 7(6), 46-48.

Golberg, M. A., & Cho, H. A. (Hokwon A.). (2004). *Introduction to regression analysis*. Southhampton, UK : Billerica, MA: WIT Press ; Computational Mechanics Inc.

Greenfield, M.L., Kuhn, J., and Wojtys, E. (1998). Correlation and regression analysis. *The American Journal of Sports Medicine, 26*(2).

H, G., Mary Lou V. (1998). A statistics primer. correlation and regression analysis. *The American Journal of Sports Medicine, 26*(2), 338.

Han, S. Y. (2014). System-of-systems architecture analysis and design using bayesian networks. (Ph.D., Purdue University).

Hantos, P. (2011). Systems engineering perspectives on technology readiness assessments in software-intensive system development. *Journal of Aircraft, 48*(3), 738.

Hendrickson, P. D. (2014). Benchmark requirement decision making tool to optimize effectiveness of weapon system modifications. (Ph.D., The George Washington University).

Heslop, L. A., McGregor, E., & Griffith, M. (2001). Development of a technology readiness assessment measure: The cloverleaf model of technology transfer. *Journal of Technology Transfer, 26*(4), 369.

Hosmer, D. W., Hosmer, T., Le Cessie, S., and Lemeshow, S. (1997). A comparison of goodness-of-fit tests for the logistic regression model. *Statistics in Medicine*, *16*, 965-980.

Ilas, C. (2013). Technology readiness impact on high-tech RD projects. *Scientific Bulletin, Series D (Mechanical Engineering), 75*(2), 241-50.

Islam, N., & Brousseau, E. (2014). Implementing a multi-staged methodology to micro and nanotechnology. *International Journal of Productivity and Performance Management, 63*(2), 170-193.

James, J. W. (1964). Comparing regression and correlation coefficients. *Journal of the Royal Statistical Society.Series C (Applied Statistics), 13*(2), 127-132.

Jimenez, H., & Mavris, D. N. (2013). Assessment of technology integration using technology readiness levels. Paper presented at the *51st AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition 2013,* American Institute for Aeronautics and Astronautics (AIAA), 583.

Jones, M., Webb, P., Summers, M., & Baguley, P. (2012). A manufacturing technology readiness impact assessment transitional framework. Paper presented at the *Aerospace Conference, 2012 IEEE,* pp. 1-9.

Katz, D. R., Sarkani, S., Mazzuchi, T., & Conrow, E. H. (2015). The relationship of technology and design maturity to DoD weapon system cost change and schedule change during engineering and manufacturing development, *Systems Engineering*, *18*(1), 1-15.

Katz, D. R. (2014). The relationship of technology and design maturity to DoD weapon system cost change and schedule change during engineering and manufacturing development. (Ph.D., The George Washington University).

Kenley, C. R., & Creque, T. R. (1999). Predicting technology operational availability using technical maturity assessment. *Systems Engineering, 2*(4), 198-211.

Kirby, M. R., & Mavris, D. N. (2000). A method for technology selection based on benefit, available schedule and budget resources. Paper presented at the *5th World Aviation Congress and Exposition, San Diego, CA,*

Kleinbaum, D. G., and Klein, M. (2010). Logistic regression: a self-learning text, Springer Science and Business Media, Springer New York.

Kujawski, E. (2013). Analysis and critique of the system readiness level. *IEEE Transactions on Systems, Man, and Cybernetics: Systems, 43*(4), 979-987.

Leemis, L. M. (1986). Relationships among common univariate distributions. *The American Statistician, 40*(2), 143-146.

Leete, S. J., Romero, R. A., Dempsey, J. A., Lively, C. F., Carey, J. P., Cline, H. P., & Millar, P. S. (2015). Technology readiness level assessment process as applied to NASA earth science missions, AIAA Space 2015, 4596.

London, M. A. (2015). Evaluating system readiness level reversal characteristics using incidence matrices. (Ph.D., The George Washington University).

London, M. A., Holzer, T. H., Eveleigh, T. and J., Sarkani, S. (2015). Incidence matrix approach for calculating readiness levels, *Journal of Systems – Science Systems Engineering 23(4),* 377-403.

Lourenço, J. C., Morton, A., & Bana e Costa, C. A. (2012). PROBE—A multicriteria decision support system for portfolio robustness evaluation. *Decision Support Systems, 54*(1), 534-550.

Loxley, E. S. (2014). Innovation in a New Energy Landscape-How Radical Technology can increase Commercial Viability in the Oil and Gas Industry (Master's Thesis).

Lucy, L. B. (2014). Frequentist confidence intervals for orbits. *Astronomy & Astrophysics*, 565, A37

Magnaye, R. B., Sauser, B. J. and Ramirez-Marquez, J. E. (2009). System development planning using readiness levels in a cost of development minimization model, *Systems Engineering* 13(4), 311-323.

Mankins, J. C. (1995). Technology readiness levels. White Paper, NASA Office of Space Access and Technology, Advanced Concepts Office.

Mankins, J. C. (2002). Approaches to strategic research and technology analysis and road mapping. *Acta Astronautica 51*(1-9), 3-21.

Mankins, J. C. (2009). Technology readiness assessments: A retrospective. *Acta Astronautica 65*(9), 1216-1223.

Mashunin, K. Y., & Mashunin, Y. K. (2013). Simulating engineering systems under uncertainty and optimal decision making. *Journal of Computer & Systems Sciences International, 52*(4), 519-534.

McConkie, E. B. (2013). A systems engineering approach to mathematical properties of system readiness levels. (Ph.D., The George Washington University).

McConkie, E., Mazzuchi, T. A., Sarkani, S., & Marchette, D. (2013). Mathematical properties of system readiness levels. *Systems Engineering, 16*(4), 391-400.

Minning, C. P., Moynihan, P. I., & Stocky, J. F. (2003). Technology readiness levels for the new millennium program. Paper presented at the *Aerospace Conference, 2003. Proceedings. 2003 IEEE, 1,* 1-426.

Nakamura, H., Kajikawa, Y., & Suzuki, S. (2013). Multi-level perspectives with technology readiness measures for aviation innovation. *Sustainability Science, 8*(1), 87-101.

NASA Procedural Requirements. (2012). NASA Space Flight Program and Project Management Requirements, NPR-7120.5E.

NASA Systems Engineering Handbook. (2007). NASA/SP-2007-6105.

Nolte, W. L., Kennedy, B. C., & Dziegiel, R. J. (2003). Technology readiness level calculator. In NDIA Systems Engineering Conference (Vol. 20).

Parasuraman, A., & Colby, C. L. (2015). An updated and streamlined technology readiness index TRI 2.0. *Journal of Service Research, 18*(1), 59-74.

Parkin, T., Chester, S., and Robinson, J. (1990). Calculating confidence intervals for the mean of a lognormally distributed variable, *Soil Science Society of America Journal, 54*(2), 321-326.

Philbin, S. P. (2013). Managing university-industry research partnerships through a process of alignment. IEEE *2013 Proceedings of PICMET'13: Technology Management in the IT-Driven Services (PICMET),* 1848-1859.

Prado Lopez, V. (2013). Decision analysis for comparative life cycle assessment. (M.S., Arizona State University).

Prado-lopez, V., Seager, T. P., Chester, M., Laurin, L., Bernardo, M., & Tylock, S. (2014). Stochastic multi-attribute analysis (SMAA) as an interpretation method for comparative life-cycle assessment (LCA). *The International Journal of Life Cycle Assessment, 19*(2), 405-416.

Ramirez-Marquez, J. E., and Sauser, B. J. (2009). System development planning via system maturity optimization, *Engineering Management*, IEEE Transactions *56*(3), 533-548.

Robinson, J. W., Levack, D., Rhodes, R. E., and Chen, T. (2009). The need for technology maturity of any advanced capability to achieve better life cycle cost (LCC), 45th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, AIAA 2009, 5347.

Reeves, J. D., Eveleigh, T., Holzer, T. H., & Sarkani, S. (2013). Risk identification biases and their impact to space system development project performance. *Engineering Management Journal, 25*(2), 3-12.

Reeves, J. D., Jr. (2013). The impact of risk identification biases and trends on space system project performance. (Ph.D., The George Washington University).

Russo, F. (2011). Correlational data, causal hypotheses, and validity. *Journal for General Philosophy of Science / Zeitschrift Für Allgemeine Wissenschaftstheorie, 42*(1), 85-107.

Sarfaraz, M., Sauser, B. J., & Bauer, E. W. (2012). Using System Architecture Maturity Artifacts to Improve Technology Maturity Assessment. Procedia Computer Science, 8, 165-170.

Sauser, B., Verma, D., Ramirez-Marquez, J., and Gove, R. (2006). From TRL to SRL: The concept of systems readiness levels, Conference on Systems Engineering Research, Los Angeles, CA.

Sauser, B. J., Ramirez-Marquez, J. E., Henry, D., & DiMarzio, D. (2008). A system maturity index for the systems engineering life cycle. *International Journal of Industrial and Systems Engineering, 3*(6), 673-691.

Sauser, B. J., Reilly, R. R., & Shenhar, A. J. (2009). Why projects fail? How contingency theory can provide new insights–A comparative analysis of NASA's mars climate orbiter loss. International Journal of Project Management, 27(7), 665-679.

Sauser, B., Gove, R., Forbes, E., & Ramirez-Marquez, J. E. (2010). Integration maturity metrics: Development of an integration readiness level. *Information, Knowledge, Systems Management, 9*(1), 17-46.

Sauser, B., Magnaye, R., Tan, W., Ramirez-Marquez, J., & Sauser, B. (2010). Optimization of system maturity and equivalent system mass for exploration systems development. Paper presented at the *8th Conference on Systems Engineering Research, Hoboken, NJ.*

Sauro, J., and Lewis, J. (2005). Estimating completion rates from small samples using binominal confidence intervals: comparisons and recommendations, Proceedings of the Human Factors and Ergonomics Society 49th Annual Meeting, 2100-2104.

Seablom, M. S., and Lemmerman, L. A. (2012). Measuring technology maturity and readiness for mission infusion, IEEE International Geoscience and Remote Sensing Symposium (IGARSS), 5646-5649.

Sharif, A. (2014). A multi goal multi criteria (MGMC) methodology for improving technology transition in defense systems development. (Ph.D., Southern Methodist University).

Shenhar, A., Dvir, D., Milosevic, D., Mulenburg, J., & et al. (2005). Toward a NASA-specific project management framework. *Engineering Management Journal*, *17*(4), 8-16.

Shi, R., & Conrad, S. A. (2009). Correlation and regression analysis. *Annals of Allergy, Asthma & Immunology, 103*(4, Supplement 1), S35-S41.

Shishko, R., Ebbeler, D. H., and Fox, G. (2004). NASA technology assessment using real options valuation. *Systems Engineering*, 7(1), 1-13.

Strunz, R. (2013). A risk-informed decision-making methodology to improve liquid rocket engine program tradeoffs. (Ph.D., University of Maryland, College Park).

Sun, Y., & Bhattacherjee, A. (2014). Looking inside the "it black box": Technological effects on it usage. *The Journal of Computer Information Systems*, *54*(2), 1-15.

Szumilas, M. (2010). Explaining Odds Ratios. *Journal of the Canadian Academy of Child and Adolescent Psychiatry*, *19*(3), 227–229.

Tamaskar, S. (2014). Managing complexity of aerospace systems. (Ph.D., Purdue University).

Tan, W. (2012). System maturity assessment and advancement from a multifunction multicapability perspective. (Ph.D., Stevens Institute of Technology).

Tan, W., Ramirez-Marquez, J., & Sauser, B. (2011). A probabilistic approach to system maturity assessment. *Systems Engineering, 14*(3), 279-293.

Tan, W., Sauser, B. J., Ramirez-Marquez, J. E., & Magnaye, R. B. (2013). Multiobjective optimization in multifunction multicapability system development planning. *IEEE Transactions on Systems, Man, and Cybernetics: Systems, 43*(4), 785-800.

Terrile, R. J., Doumani, F. G., Ho, G. Y., & Jackson, B. L. (2015). Calibrating the technology readiness level (TRL) scale using NASA mission data. *Aerospace Conference, 2015 IEEE*, 1-9.

Tetlay, A., & John, P. (2009). Determining the lines of system maturity, system readiness and capability readiness in the system development lifecycle. 7th Annual Conference on Systems Engineering Research (CSER).

Tetlay, A., & John, P. (2010). Clarifying the concepts of system maturity, system readiness and capability readiness through case studies.

Thamhain, H. J. (2014). Assessing the effectiveness of quantitative and qualitative methods for R&D project proposal evaluations. *Engineering Management Journal*, *26*(3), 3-12.

Thompson, B. (2007). Effect sizes, confidence intervals, and confidence intervals for effect sizes. *Psychology in the Schools*, *44*(5), 423.

U.S. Department of Defense. (2003). “Technology Readiness Assessment (TRA) Deskbook”, September 2003.

U.S. Department of Defense. (2011). “Technology Readiness Assessment (TRA) Guidance”, May 2011.

U.S. Department of Energy. (2009). “Technology Readiness Assessment Guide,” DOE G 413.3-4, October 2009.

U.S. Government Accountability Office. (1999). Best Practices: Better Management of Technology Development Can Improve Weapon System Outcomes, GAO/NSIAD-99-162, July 1999.

U.S. Government Accountability Office. (2009). NASA: Assessments of selected large-scale projects, GAO-09-306SP, March 2009.

U.S. Government Accountability Office. (2010). NASA: Assessments of selected large-scale projects, GAO-10-227SP, February 2010.

U.S. Government Accountability Office. (2011). NASA: Assessments of selected large-scale projects, GAO-11-239SP, March 2011.

U.S. Government Accountability Office. (2012). NASA: Assessments of selected large-scale projects, GAO-12-207SP, March 2012.

U.S. Government Accountability Office. (2013). NASA: Assessments of selected large-scale projects, GAO-13-276SP, April 2013.

U.S. Government Accountability Office. (2014). NASA: Assessments of selected large-scale projects, GAO-14-338SP, April 2014.

U.S. Government Accountability Office. (2015). NASA: Assessments of selected large-scale projects, GAO-15-320SP, March 2015.

U.S. Government Accountability Office. (2016). NASA: Assessments of major projects, GAO-16-309SP, March 2016.

U.S. Government Accountability Office. (2005). NASA: Implementing a knowledge-based acquisition framework could lead to better investment decisions and project outcomes, GAO-06-218, December 2005.

Vaseashta, A. (2014). Advanced sciences convergence based methods for surveillance of emerging trends in science, technology, and intelligence. *Foresight : The Journal of Futures Studies, Strategic Thinking and Policy, 16*(1), 17-36.

Viana, M. A. G. (1980). Statistical methods for summarizing independent correlational results. *Journal of Educational Statistics, 5*(1), 83-104.

Viroli, C. (2012). On matrix-variate regression analysis. *Journal of Multivariate Analysis, 111*(0), 296-309.

Volkert, R. E. (2013). A methodology for predicting operational performance during development of a system of systems. (Ph.D., Southern Methodist University).

Ward, M. J., Halliday, S. T., & Foden, J. (2012). A readiness level approach to manufacturing technology development in the aerospace sector: An industrial approach. *Proceedings of the Institution of Mechanical Engineers.Part B, Journal of Engineering Manufacture, 226*(3), 547.

Weerahandi, S. (1993). Generalized confidence intervals. *Journal of the American Statistical Association*, *88*(423), 899-905.

Wilcox, R. R. (2006). Confidence intervals for prediction intervals. *Journal of Applied Statistics*, *33*(3), 317-326.

Weigang Chen, Shunli Jin, Minfang Zhang, & Xiao Chen. (2012). Technology readiness assessment and application in the engineering development phase. Paper presented at the *Quality, Reliability, Risk, Maintenance, and Safety Engineering (ICQR2MSE), 2012 International Conference on,* pp. 1493-1496.

Wood, J. N. (2012). A framework for capturing the hidden stakeholder system. (Ph.D., The George Washington University).

Yen-Lin, K. (2013). Technology readiness as moderator for construction company performance. *Industrial Management + Data Systems*, *113*(4), 558-572.

Yin, J., & Li, H. (2012). Model selection and estimation in the matrix normal graphical model. *Journal of Multivariate Analysis, 107*(0), 119-140.