Methods for Efficient Integration of Rapid Response Projects into Large Weapon Systems

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A Praxis 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 Engineering

August 31, 2020

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Acknowledgements

I would like to thank the faculty and staff at George Washington University, the School of Engineering and Applied Sciences Off Campus Program, and particularly Drs. Sarkani and Fossaceca, for the wonderful experience of reliving my younger days as a student. I am grateful for the Subject Matter Expert reviewers, particularly Dr. James Lyneis who, in addition to mentoring my efforts in prior degree programs, was very supportive in guiding this research. I'd like to thank my work mentors: Dr. John Balaguer, Brad Whittington, and Jon Goding who provided critical feedback and Subject Matter Expertise in shaping the organizational issues for this research. Last, but not least, I'd like to thank my wife Anna and our three boys Chris, Costa, and Anthony, who were incredibly supportive throughout the program. I hope my boys have gained a better appreciation for the study habits, drive, and determination necessary for success.

Abstract of Praxis

Methods for Efficient Integration of Rapid Response Projects into Large Weapon Systems

The military has attempted to keep up with the rapid pace of commercial change by employing rapid acquisition guidance, but with limited success. The United States military continues to struggle with integration of emerging commercial technologies into complex systems used by soldiers in unique environments. More typically, these integration strategies are plagued by unexpected delays and expenses. Current strategies are purely qualitative in nature focusing only on maturing Project technology levels, with limited success in delivering the technology into mainstream weapon systems. This research introduces a System Dynamics Model to determine the cost and schedule impacts of using different strategies to integrate Rapid Response Projects into Large Weapon System Programs. A large program is defined as complex program that spans multiple years and involves multiple phases and integration of multiple capabilities. The Model provides Engineering Managers a tool with which to assess various integration strategies in their development plans. The model is calibrated with cost and schedule data from past successful deliveries of a Project into a Program. The results show that a strategy of accepting higher TRL capabilities earlier in the integration timeline reduces overall program costs (to include the cost of the Rapid Response Capability). Integrating a capability 6 months earlier can reduce overall program costs by 2%. There is no evidence to suggest that changing management reserve from the traditional 10% has significant cost impact. Evidence exists to show that delivering an “80% Solution”

results in a defect rate of at least 30%. Finally, in comparing combinations of these factors, the best strategy is to accept a High TRL capability early in the Program, however, evidence suggest that the second-best strategy is integration of a *lower* TRL capability *early* in the Program, which beat out accepting a *higher* TRL capability *later* in the program.

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List of Acronyms

ABL	Accelerated Business Learning
AD	Anderson-Darling
CLD	Causal Loop Diagram
CvM	Cramer-Von Mises
DAP	D’gostino and Pearson
DIU	Defense Innovation Unit
DoD	Department of Defense
DUST	Deputy Under Secretary of Defense for Science and Technology
GAO	U.S. Government Accountability Office
HA	Alternative Hypothesis
HO	Null Hypothesis
INT	Integration Task
IPL	Intertwined Project Learning
JB	Jarque-Bera
KS-L	Kolmogorov-Smirnov Lilliefors
KS-Lim	Kolmogorov-Smirnov Limiting form
KS-M	Kolmogorov-Smirnov Marsaglia Method

KS-S	Kolmogorov-Smirnov Stephens Method
LE	Legitimation
LWS	Large Weapon System
MATLAB®	MATrix LABoratory
MIT	Massachusetts Institute of Technology
NASA	National Aeronautics and Space Administration
NDAA	National Defense Authorization Act
OFAT	One Factor at a Time
OTA	Other Transaction Authority
PERT	Program Evaluation Review Technique
PMBOK®	Program Management Book of Knowledge
PMI	Program Management Institute
PMO	Program Management Office
RIF	Rapid Innovation Fund
RIF	Rapid Innovation Projects
RRP	Rapid Response Project
SBIR	Small Business Innovation Research
SD	System Dynamics

SF	Shapiro-Francia
SME	Subject Matter Expert
SPDM	Software Development Performance Model
SW	Shapiro-Wilk
TRL	Technology Readiness Level
TRLA	Technology Readiness Level Assessments
U.S.	United States
VA	Validation
VE	Verification
VenSim®	Ventana Systems

Chapter 1 —Introduction

1.1 Background

The Information Age has been characterized as an explosion of technology that is transporting humanity into a world of automation, artificial intelligence, and ubiquitous computation. Technology is an expectation like clean air, water, and electricity. Yet the military continues to struggle with integration of emerging commercial technologies into large systems (e.g. Air Force Distributed Common Ground Segment, Peace Shield Air Defense System, Joint Precision Approach and Landing System) that must operate in very complex and unique environments. More typically, these integration efforts are plagued by unexpected delays and expenses. The U.S. Government Accountability Office Weapon Systems Annual Assessment report GAO-18-366SP assessed the Department of Defense (DoD) 2018 portfolio consisting of 82 Large Weapon System Programs totaling $1.69 trillion (GAO 2018). The report attributed "Knowledge Gaps" (e.g. technology maturity, timing of capability integration) as the major cause of DoD program cost overruns totaling $569.4 billion across the portfolio of U.S. Army, Air Force, and Navy Programs. These "Knowledge Gaps" set context for the factors chosen to assess the strategies in this research. The National Defense Authorization Act calls for the DoD to reform acquisition practices to implement rapid acquisition methodologies and shorten the time required to select vendors, execute projects, and field capabilities (NDAA 2019, 2018, 2017). These changes are driven by NDAA TITLE VIII sections and are outlined in DoD web sites such as http://acqnotes.com/rapid-acquisitions. However, the acquisition process seldom considers commercialization of Rapid Response

Capabilities (e.g. integration into a Large Weapon System) until late in the development cycle.

1.2 Research Motivation

The DoD established the Rapid Innovation Program in Fiscal Year 2011 with the Ike Skelton National Defense Authorization Act (NDAA 2010) to address the lack of successful transition of Rapid Response Projects into military use. The Rapid Innovation Program is one of the military's many attempts to replicate the commercial rapid adoption of new technologies. DoD Rapid Innovation Program report GAO-15-421 performed an assessment of this transition process to discover that only 42.3% (22 of 52) project successfully transitioned by July 2014 (GAO 2014). The report listed the primary causes of transition failure as: "No user commitment", "Project needs further development or testing", and "Technology failed to meet the requirements".

In many cases Rapid Response Projects are executed with little consideration for transition success, where transition success is broadly defined as, a "technology which is inserted into an acquisition program of record, incorporated into a weapon system manufacturing process, adopted for use by a depot or logistics center, or available for purchase on the General Services Administration federal supply schedule or in the commercial market" (GAO 2015). The effort focuses on creating or adapting a technology to solve a very specific problem. The common theme across these attempts is the reduction of time to deliver the technology as a prototype capability. These capabilities are then handed over to a Large Weapon System Program to be integrated with a suite of other, often incompatible, technologies.

This Praxis offers strategies and tools to better assess Rapid Response Projects, and help Engineering Managers better plan for integration of these Capabilities into Large Weapon System Programs.

1.3 Problem Statement

The current DoD process for integrating Rapid Response Projects into DoD Large Weapon Systems Programs results in a less than 43% success rate.

1.4 Thesis Statement

A System Dynamics Model for integration of Rapid Response Project into a Large Weapon System Program will identify key technical and management factors for successful delivery and inform strategies for efficient resource utilization.

This research uses a System Dynamics approach (Sterman 2000, Lyneis 2001, 2007, 2020) to model the work performed when integrating a Rapid Response Capability into a Large Weapon System Program. The System Dynamics (SD) Model consists of three major sub models. The Rapid Response Project sub model captures the work performed to mature a technology to a chosen Technology Readiness Level (TRL) as defined by DoD guidance (DUST 2005, NASA 2008). The work is typically performed by either a small business or an independent group within a larger company. The result of a Rapid Response Project is a Rapid Response Capability. The Large Weapon System Program sub model captures the work performed to build the Large Weapon System to completion. The Integration sub model captures the work effort to integrate the Rapid Response Capability as a cohesive part of the Large Weapon System.

1.5 Research Objectives

This Praxis aims to provide Engineering Managers with a modeling tool they can use to assess the cost and schedule impact of four main decision factors: (1) Maturity of the Rapid Response Capability when accepted by the Integration team to begin integration, captured as Technology Readiness Level (TRL), (2) Time to start the integration effort relative to the Large Weapon System build timeline (Integration Time), (3) Management Reserve allocated to each of the three efforts, and (4) the Level of Completion considered a deliverable capability (e.g. 100% solution, or 80% solution). Research Objectives are as follows:

1. Create a System Dynamics Model managers can use to assess the overall cost and schedule impact of integration of Rapid Response Project with their Large Weapon System Programs.
2. Determine the overall cost and schedule impact of technical management decisions required to deliver a complete Large Weapon System to the DoD.

1.6 Research Questions and Hypotheses

Research Questions

RQ1: What strategies can help managers better plan for Rapid Response Projects integration into Large Weapon System Programs?

RQ2: How does the technology maturity of a Rapid Response Project (when delivered) impact the overall cost and schedule of a Large Weapons System Program?

RQ3: How does the timing of integration between a Rapid Response Project and a Large Weapon System Program impact the overall cost and schedule?

RQ4: How does changing the allocation of management reserve to the integration effort impact the overall cost and schedule of a Large Weapon System Program?

RQ5: What is the impact of delivering incomplete solutions of Large Weapon Systems to the overall cost and schedule of a Large Weapon System Program?

Research Hypotheses

H1: Rapid Response Projects which increase TRL by one level result in an overall Program cost reduction (overall cost change less than zero). *Overall Program cost includes the cost of Rapid Response Project, Integration activity, and Large Weapon System costs combined.*

H2: Rapid Response Project integrations with Large Weapon System that start 6 months earlier than the planned integration point lowers the integration costs by more than 2%.

H3: Integration efforts that increase management reserve by 5% lead to a lower overall integration costs of greater than 5%.

H4: Integration efforts that deliver 80% solutions result in Large Weapon System that are less than 70% complete.

1.7 Scope of Research

This Praxis uses a three phase System Dynamics Model approach (Lyneis 2020) to simulate the work performed to deliver a Large Weapon System to the warfighter. The three phases are the Rapid Response Project (RRP) phase, Integration phase (INT), and Large Weapon System (LWS) Program phase. Figure 1-1 shows the relative timeline of each phase. The Rapid Response Project phase operates independent from the other two phases but must complete prior to the start of the integration phase. The Integration phase captures all work performed to integrate the Rapid Response Capability, so it performs as part of the Large Weapon System and operates in the military environment. The Large Weapon System Program phase captures all other work performed to deliver the system.

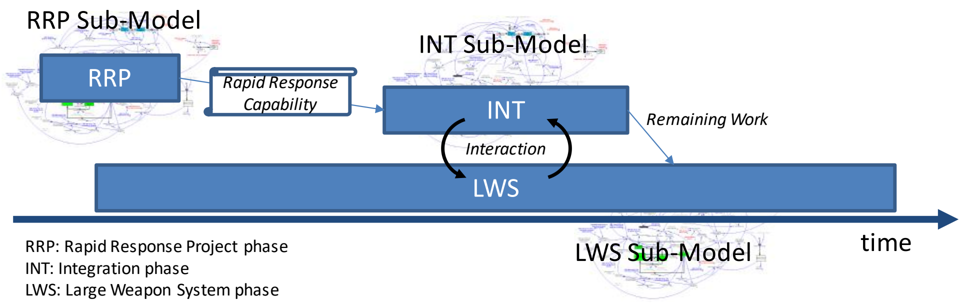

Figure 1-1. Model Timeline.

Four case studies are used to calibrate the model and analyze results. One case study is a “small” Large Weapon System project where the Rapid Response Project scope is 2.4% of the Large Weapon System scope. Two case studies are “medium” Large Weapon Systems projects, where the Rapid Response project scope is 1% of the Large Weapon System project Scope. The last case study is a “large” Large weapon system project where the Rapid Response project scope is 0.25% of the Large Weapon System project Scope. Monthly cost and schedule data for each of these four case studies is used to calibrate the System Dynamics Model. All data has been cleansed and approved for public release. Due to the financial nature, all data have been converted into “tasks” such as not to reveal any proprietary information. The same data conversion is used across all case studies to preserve relativity of results.

1.8 Research Limitations

This research is limited to programs using Department of Defense or similar procurement methodologies where a relatively small Rapid Response Project is integrated into a Large Weapon System. The research uses real world data for model calibration to validate model performance for historical relevance. The calibration data (e.g. time series events that occurred in the actual system) is limited by available and releasable data sources. The ratio of Project to Program is less than 2.4%, and all integration activity is performed within the timeline of the large weapon system. Employing the model where integration activity occurs after completion of the large weapon system would require additional calibration data that was not available during this research. Also, cases where integration activity begins prior to the completion of the Rapid Response Project, that is, where the two efforts overlap in time, is not modeled due to lack of available calibration data.

The research did not use publicly available data since the resolution of financial data is not detailed enough to break out integration activities for any large program, nor is the time resolution of public data suitable for model calibration. Public data is typically reported on an annual basis where the model requires at least monthly resolution. Rapid Response Projects are mentioned in the GAO reports, but financial data is not categorized in any detail to support model calibration.

The valid range for TRL of Rapid Response Projects is TRL4, through 8. Model results for less mature Projects (TRL 1-3) are outside the calibrated range.

1.9 Organization of Praxis

Chapter 1 introduces the problem of Rapid Response Project integration with Large Weapon Systems, providing the motivation and foundation of the research, as well as providing scope and limitation of the research. Chapter 2 provides a literature review of the foundational concepts and issues surrounding the problem. This includes a foundation of current Management Strategies to Project integration, Organizational Dynamics surrounding Project integration, and a foundation of Organizational and System Dynamics along with the pedigree of models adapted for this research.

The research methodology in Chapter 3 introduces the System Dynamics Model, an overview of the data sources used to calibrate the model, and the data cleansing process. The design of experiments methodology is explained, and an overview of how an Engineering Manager would use the model in the planning process.

Chapter 4 provides the research results and Chapter 5 provides the findings, conclusions and recommends areas of future research.

Chapter 2—Literature Review

2.1 Introduction

A focused literature review relevant to this Praxis draws from prior research in three bodies of knowledge as shown in Figure 2-1. Complex System Integration Management Strategies are covered in section 2.2. This section covers a focused analysis of complex system integration strategies including Technology Readiness Level (TRL) Assessments, as well as strategies the U.S. Governments has previously attempted to accelerate the Department of Defense (DoD) acquisition process. The section sheds light on the four factors chosen for this research: Technology Readiness Level (TRL), Integration Time, Management Reserve, and Level of Completeness. Section 2.3 covers Organizational Dynamics where management of complex systems and DoD Weapons System Project Management is covered as it applies to the current research. This section motivates the Causal Loop Diagrams used for this research, specifically the incorporation of organizational dynamics and human behavior. Lastly a brief overview of System Dynamics, describing foundations for the modeling technique as applied to this research, and a review of the Project Management System Dynamics Modeling leveraged for this Praxis.

Figure 2-1. Literature Research Overview of Modeling Integration Strategies

2.2 Complex Project Management Strategies

This section focuses on Complex Project Management Strategies relevant to this research, and the factors that are important to defining these strategies. Emphasis is placed on strategies relevant to large complex systems such as DoD Weapon system. Chew (1997), Cooke-Davies (2002) and Milosevic (2002) provide an overview of Management Strategies and provide an assessment of the factors for consideration when creating strategies to deliver projects on time and within budget. Pich et al. (2002) then provides a mathematical assessment of these factors.

Chew (1997) compares commercial acquisition strategies against DoD acquisition strategies. He compares Chrysler's burning platform to produce "better, faster, cheaper" products or risk extinction, with the DoD’s cost and timeline acquisition challenges. He recommends leveraging factors from a commercial strategy of applying Continuous Improvement, Delivery Requirements, Benchmarking, Cross Functional Platform Teams, Independent & Aggressive Advanced Concept Development, Program Stability, and Up-Front Quality to ensure project success. He concludes that commercial strategies are transferable to DoD environments.

Cooke-Davies (2002) identifies three key areas where management strategies need to be effective (Project Management Success, Individual Project Success, and Consistency in Successful Projects). The author identifies 12 factors for success categorized in these three areas focusing on metrics collected as "hard data" or "softer evidence". The 12 factors do not capture "human factors". The author argues that human factors are woven into the very nature of the factors collected. The strategies do not consider the organizational dynamics of strategies, focusing primarily on only what can be observed or measured.

Milosevic (2002) highlights the cultural features (factors) of project management. He identifies a range of attributes for each of 11 features (e.g. Time Orientation, Activity Orientation, Uncertainty Avoidance). The author then combines these features at selected attribute values to recommend management strategies when interacting with various cultures.

Pich et al. (2002) provide a general mathematical foundation for optimizing decision variables and apply the model to three management strategies. The strategies are dependent on the type of uncertainty and the complexity of the project. The authors classify the three strategy groups as Instructionism (planning and contingency), Learning (ability to modify policies) and Selectionism (multiple efforts, hedging against unanticipated events). They also define strategies as a combination of factors.

These articles support the modeling approach in this Praxis in identifying factors of interest to this research, and strategies for combining and analyzing factors to deliver greater value. TRL, Integration Time, Management Reserve, and Level of Completeness, although named slightly differently across the articles, are all common factors in assessing management strategies.

2.2.1 Integration Strategies

Where the previous section focused on strategies in general, this section focuses specifically on Integration Strategies where articles identify factors contributing to integration strategy analysis. Atto et al. (2011), Tahan (2005) and Hobday (2000, 2005) provide an overview of the factors specific to integration strategies. Friedman and Sage (2004), Thomas (2009), and Thomas and Utley (2006) provide a focused assessment of complex DoD Projects and the factors relevant to integration strategies for programs of comparable complexity. Specific attention is given to one of the four factors in this research, TRL, where Mankins (2009), and Conrow (2011) provide methodologies for TRL assessment. Conrow specifically provides a methodology for using TRL values in computational models.

Artto et al. (2011) describe the Program Management Office as an integrative arrangement with a variety of management controls to provide an integrative organizational arrangement. The authors present a framework for management control defined by four types of systems: belief, boundary, diagnostic control, and interactive control. They then use these four types of management control systems to categorize control mechanisms representing specific organizational arrangements (e.g. vertical, lateral, cross functional, incentive/social), and recommend integration strategies based on these factors.

Tahan et al. (2005) propose a strategy of incremental integration as a more robust method to process uncertainties. The authors propose two modes, statistical and design based, to compare single integration versus incremental integration. They found that incremental integration led to shorter integration times. Factors identified in this article are consistent with the factors used for this research.

Hobday (2000) compares a project-based organization strategy with a matrix-based organization under various project conditions to determine the optimal strategy. Although several factors are addressed specific to project integration strategy, they conclude that matrix organizations offered the greater transfer of knowledge and resources to produce "good" products. The article describes the interactions between various stages of a project in terms of the ability to share information Upstream and Downstream in the value chain. Upstream requirements impacting Downstream activity are affected by this ability to share information. The reverse flow of information is likewise enhanced by a matrix organization the enables flow of information. This article supports the model structure used to capture the interactions between different phases of the model used for this research.

Hobday et al. (2005) discuss integration strategy in terms of supply chain, where factors are considered in terms of internal and external integration activities. They discuss how upstream and downstream integration strategies impact the value stream of high-technology goods. The authors stress the importance of supply chain leadership as a factor in integration strategy. This factor specifically impacts the TRL factor used in this research.

Friedman and Sage (2004) explore three distinct strategies for complex program integration. (1) A single large company performing all integration work, (2) Several separate contracts where the government acts as the system integrator, and (3) strategy #2, where a single contractor is assigned to integrate the separate contracts. The authors examined 27 case studies covering the Systems Engineering Process from Requirements Management through System Deployment. Specific to integration strategy, the authors pointed out common failures in all three strategies resulting from the inability to understand issues beyond the components or sub-systems being integrated. Additionally, Thomas (2009) and Thomas and Utley (2006) explored an expanded set of integration strategies to determine common factors for successful (or unsuccessful) integration.

These integration strategy articles support the modeling approach in this Praxis. Factors used in this research are common factors discussed in this focused set of Articles. Integration Time, Management Reserve, and System Completeness are relatively straight forward factors and are captured simply as time, cost, or tasks respectively. TRL is slightly more complex as the ordinal values (1-9) do not easily translate to values useful to mathematical manipulations. The following articles provide a foundation for TRL concluding with the methodology used in this research to transform ordinal TRL values into cardinal values for use in the model.

TRL was first developed by NASA in the mid 1970's as a discipline independent way of assessing the maturity of new technology (Mankins 2009). Mankins provides a timeline of TRL early concepts and adoption from the 1960's through 2000's, with DoD adopting TRL in the 1990's. The assessment is an ordinal scale that captures the maturity of a technology ranging from one to nine. The DoD uses Technology Readiness Level Assessments (TRLA) as "a formal, systematic, metrics-based process and accompanying report that assesses the maturity of critical hardware and software technologies to be used in systems" (DoD 2009).

The assessment does not capture the difficulty to transition from one level to the next, but rather a set of criteria and/or events required to achieve the rating. Conrow (2011) points out that the ordinal TRL coefficient scale limits usefulness. He performed an analytic hierarchy process to produce non-integer technology readiness level values for use in mathematical operations. The cardinal values are computed based on prior DoD and NASA project cost metrics to move up on the ordinal TRL value scale (Conrow 2011). These coefficients are used in the model for this Praxis, but more importantly, Conrow outlines the process by which any organization can develop their own coefficients based on organizational data.

Consistent across the literature for management and integration strategies is the lack of applying predictive models such as System Dynamics in assessing Management strategy effectiveness. In particular, quantitative assessment of the factors chosen for this research (TRL, Integration Time, Management Reserve, and Level of Completeness) are not quantifiably addressed, nor is a useful and predictive model presented that manager can adapt to their organizations and use for internal predictive assessments.

2.2.2 Department of Defense Acquisition Strategies

This section focuses on strategies the DoD has used in an attempt to accelerate and improve the delivery of Large Weapon Systems. The articles first provide a historical perspective on the buildup of accelerating procurements and concludes with articles that provide a performance assessment of the strategies employed. References in this section describe challenges with Weapon System acquisition and sets context for Large Weapon Systems addressed in this Praxis.

The DoD provides the military forces needed to deter war and ensure our nation's security (defense.gov). Major defense acquisition programs play a key role in enabling the DoD mission, producing Large Weapon Systems that account for a large share of the total DoD budget. These systems are technologically advanced products, often designed to achieve performance levels never before realized (Ferrara 1993).

Formal DoD acquisition process guidance was established in 1971 with DoD Directive 5000.1. The directive admonished readers to focus on making the right decisions at the right time; wrong decisions create problems not easily overcome later in the program (Fox 2009). Since then, fourteen revisions were released through 2009 (Ferrara 1993, Fox 2009), culminating in the latest release of DoD 5000.02 on January 23, 2020 which further accelerates acquisition using an Adaptive Acquisition Framework designed to "improve process effectiveness" (DoD 2020).

The Government Accountability Office (GAO) conducts annual assessments and special reports on the DoD acquisition system. One GAO report found that by 2011 Major Defense Acquisition Programs experienced a 40 percent cost overrun ($446B) and a 32 percent schedule overrun (23 months) from initial estimates (GAO 2012). To combat these overruns, the GAO proposed in 2000 a Knowledge-Based Approach to support making the right decision at the right time, with the right knowledge. (GAO 2006) The Knowledge points consist of (1) matching resources to needs, including determining if technology maturity is suitable to meet requirements, (2) Stable product designs to ensure stable cost, schedule and performance to meet requirements, and (3) mature production processes (GAO 2006). The report concluded that the knowledge-based process is regularly bypassed resulting in limited knowledge about critical technologies, with the programs lacking a solid foundation about cost schedule and performance (GAO 2006). In 2019, GAO reported that DoD programs continue not to fully implement knowledge-based acquisition practices, leading to increased risk of undesirable cost and schedule outcomes. This foundation is relevant in defining challenges, and points to root causes (e.g. technology maturity, integration readiness) that are addressed in this research. The Knowledge Points described in these reports set the context for the factors chosen for this research.

Rapid Acquisition for government contracting first appeared in the NASA space program with the enactment of Public Law 85-568 (NASA 1958). The law introduced procurement flexibility with Other Transaction Authority (OTA). These OTAs allowed for rapid acquisition and encouraged the participation of small business. DoD was first authorized to use OTAs for research and development projects in 1989 with Public Law 101-189 (NDAA 1989). In 1994, the scope was expanded to include Prototype projects (NDAA 1993). The Ike Skelton National Defense Authorization Act for Fiscal Year 2011 established the Rapid Innovation Program (NDAA 2010) with the charter to "stimulate innovative technologies and … rapidly insert such products directly in support of primarily major defense acquisition programs, but also other defense acquisition programs that meet critical national security needs". Since then Rapid Acquisition has evolved to be a popular procurement methodology with organizations such as the

Defense Innovation Unit (DIU) and Rapid Innovation Fund (RIF). Many opportunities are available in the Defense Innovation Marketplace (https://defenseinnovationmarketplace.dtic.mil).

Yet, with the focus on rapid transition, technology innovation moves too slowly from the lab to the field (GAO 2013). Completion timeframes for technology transition range from 6 months to 6 years, with 3-6 years being typical, and acquisition programs can take additional years to integrate, deploy, and deliver the technologies to the warfighter. Although over 70 percent of these projects transition into acquisition programs, there are very few metrics collected on the success of Rapid Response Projects once they are handed over to Large Weapon Systems. (GAO 2013)

A 2015 GAO report on the DoD Rapid Innovation Program studied the transition of 52 Rapid Innovation Projects awarded in 2011 and 2012 to discover that only 22 successfully transitioned. Transition success is broadly defined as, a "technology which is inserted into an acquisition program of record, incorporated into a weapon system manufacturing process, adopted for use by a depot or logistics center, or available for purchase on the General Services Administration federal supply schedule or in the commercial market" (GAO 2015). No data is collected on the success of transition programs once they are handed over to the receiving organization (e.g. Large Weapon Systems). GAO performed a limited study on the 52 Projects to determine three primary causes of transition failure. (1) Technology Maturity: Projects with less mature technology were accompanied by higher risk for project transition, (2) User Commitment: Defined as the lack of a transition partner or a key stakeholder for the Project. The lack of participation in project reviews contributes to the lack of alignment with user requirements, and (3) Program Support: The lack of a support process for transition planning. This foundation is relevant in defining challenges with Rapid Response Projects addressed in this research, and supports the factors selected for this research, as well as the gaps in effectiveness of current DoD strategies.

2.3 Organizational Dynamics

Organizational dynamics is generally defined as the process of continuously improving business practices and strategic management. The focus of this research is on the control feedback structure that captures the interactions of humans as they build complex systems. This section captures the foundation of Organizational Dynamics with Richardson (1991, 1999, 2011) describing the origins of social dynamics application to System Theory, then dives into the methodology chosen for this Praxis (Servomechanism) as described by the founder of System Dynamics (Forrester). A few examples are provided that describe dynamic behavior exhibited by social dynamics in Project Management by Ford and Sterman (2003), Eden et al. (2000), and Repenning (2001). Tako and Robinson (2018) provide an argument for the use of System Dynamics as compared to Discrete Event Simulations. Finally, Sterman (1998, 2000) discusses Business Dynamics as the specific methodology used in this Praxis. Organizational dynamics and human behavior motivate the Causal Loop Diagrams used for this research.

Richardson (1991, 1999, 2011) captures the foundation for social sciences in system theory in his textbook, as well as in several follow-on publications. He captures two foundational camps of thought for modeling the social feedback concepts rooted in six intellectual traditions (Biology-Math Models, Econometrics, Engineering, Social Science, Biology - Homeostasis, and Logic). He reformulates these six traditions into two school of thought: (1) Servomechanism which captures the role of feedback as a mathematical model in creating the patterns of movement in dynamic systems, and (2) Cybernetic which captures feedback as a mechanism for homeostasis and control, typically represented as messages from output to input with less mathematical analysis. Cybernetics is useful when investigating individual events, decision, and actions, where servomechanism is useful to understand the feedback structure underlying patterns of behavior in aggregate systems. This Praxis uses Servomechanism for its research methodology in order to model the internal behaviors of project organizations. A further dive into Servomechanism follows, to highlight the concept motivating the Causal Loop Diagrams presented in section 3.0.

Jay Forrester (1971) is frequently attributed as the creator of System Dynamics and is a key contributor to the Servomechanism school of thought (Richardson 1991). His 1971 paper summarized his address to U.S. Congress raising concerns about the "unexpected, ineffective, or detrimental results often generated by government programs". He attributes these problems to the lack of understanding of the dynamic behavior of social systems. He further goes on to say that "Orderly processes in creating human judgment and intuition lead people to wrong decisions when faced with complex and highly interacting systems". Forrester discusses that even when a single topic is being discussed that each participant employs a different mental model, and the mental models shift as the debate shifts. Fundamental assumptions and goals are different, but rarely brought into the open. He claims that a computer simulation has advantages over mental models in that these assumptions and goals are captured, and future dynamic consequences can be reliably determined.

In a series of papers, Forrester (1986, 1992, 1994) provides insights from 30 years of experience using System Dynamics Models. He recommends the model should have a clear purpose and objective and achieve a “Unifying knowledge”. He compares dynamic systems with high-order nonlinear differential equations, defying intuitive solutions. To understand the behavior, he proposes the unification of three categories of information: (1) Observed structure and policies, (2) Expectations about behavior, and (3) Actual behavior, with the greatest discrepancies between expected and actual behavior. He describes the decision-making process consisting of three parts; formulation of desired conditions, observation of actual conditions, and corrective actions to bring the two together. Distorted and delayed information about actual conditions form the basis for corrective actions which in turn are delayed and distorted when applied to the system. Forrester states that mental and written data define the purpose of the model, and that time series data should be used to compare model behavior with real life behavior. Forrester breaks down the System Dynamics process into six steps: (1) describe the system and formulate a hypothesis for how the system is creating troubled behavior. (2) build the simulation, interacting back with step 1 to refine model fidelity. (3) simulate the model, to include validation and comparison with real world data. (4) identify alternative policies and structures. (5) “Educate and Debate”, which he claims is perhaps the most challenging phase. “Implementation often involves reversing deeply embedded policies and strongly held emotional beliefs”. (6) Implement the changes. At each stage, feedback to prior steps is critical in model refinement (Forrester 1994).

Ford and Sterman (2003) describe the issues involved with iteration management and the 90% syndrome to capture the internal control feedback loops of organizational dynamics specific to interactions of various phases in a project. At the time of this article, concurrent development was considered the solution to developing products faster. Concurrent development is where projects are divided into phases with downstream phases beginning before upstream phases complete. The authors describe a multi-phase model with a workflow structure identical for each phase. Phase interaction is described in Ford & Sterman 1998. The 90% syndrome is described as “a project that reaches about 90% completion on schedule but then stalls, finally finishing after about twice the originally projected duration”. The authors model considers two key measures: planned progress, and actual progress. They then attribute the 90% syndrome to two key causes: The long distance that information must travel between project phases, and the slower rate of information transfer due to traversing between phases. The authors argue that sustained improvements in project performance requires behavioral decision rules that capture both physical and informational structure in concurrent development. These decision rules are defined by the integration of the technical attributes, the flow of information, and behavioral decision-making participants use to respond to unanticipated problems. Their recommendation is relevant to the current research in capturing the difference between planned work and actual work performed, as well as capturing the flow of information across different phases of the project.

In a companion 2003 article the authors introduce the concept of “concealment,” defining it as the difference between reported progress and actual progress. He further describes the group of managers exhibiting this behavior as a “liar’s club,” where each knew that those best able to hide their problems could escape responsibility for project failure. The authors also note that concealment reduces project quality by causing more errors that remain undiscovered when the project is complete. A key contribution of this article is the model structure for rework. Rework is defined as the effort required the complete a task that was previously believed to be complete but contained defects. Additional effort is required the complete the task above and beyond that originally planned. The model structure for rework is similar to the current research; however, malicious intent is not modeled in the current research, and is left for future efforts.

Repenning (2001) describes firefighting as a self-reinforcing phenomenon and that multi-project development systems are far more susceptible to this dynamic. He argues that current tools are not effective in managing projects to avoid the firefighting phenomenon, highlighting that humans are not capable of managing complex systems effectively. He states that human psychology makes firefighting a common occurrence, and tools are needed that can account for both benefit and cost of management decision. The ultimate source of firefighting is the faulty mental models of setting resource levels and allocating resources amongst competing projects. (Repenning 2001)

Tako and Robinson (2018) provide an empirical study to compare Discrete-Event Simulation with System Dynamics. They assessed the perception of two simulation models (Discrete Event Simulation and System Dynamics) of the same problem (a Prison Population problem). The survey addressed factors of Model Understanding, Complexity, Model Validity, Model Usefulness, and Model Results. The authors discovered similar levels of confidence in either approach, however, System Dynamics Models were determined to be more representative of real-world problems and provided a higher level of contextual learning. (Tako, Robinson 2018)

Eden et al. (2000) review feedback effects of disruption and delays in major projects. The authors state that small disruptions and delays can cause serious consequences in the life of a project. Dynamic feedback is described in terms of delay avoidance because management actions are taken to accelerate the project. Eden describes these feedback loops as impacts that are difficult for human cognition. The resulting dynamic behavior causes more disruption and delays, leading to feedback that amplifies the opposite of the intended results, and small disruptions can lead to tremendous consequences that are not intuitive. The authors describe several categories that contribute to these loops (e.g. excessive client interest in details, changing legal requirements, poor communication, and changing customer requirements). The authors then present an influence diagram (a.k.a. Causal Loop Diagrams) that captures some of the feedback loops resulting from managerial actions (Eden 2000).

Sterman's 1989 paper summarizes the results from trials using the "Beer Game" where the goal is to optimize a Stock management system and minimize overall costs. The game assigns four roles (retailer, wholesaler, distributor, and factory). Each manager only controls the inflow and/or outflow of their part of the system. The results showed that the average team resulted in total system costs ten times greater than the baseline (optimal) solution. More interesting was the character of these departures from the baseline. Oscillation is characterized as inventory levels with large amplitude variation. Amplification effects, where amplitude and standard deviation of Stock orders grew significantly down the supply chain. Lastly, Phase Lag of orders between factory and retailer, that is the peak order rate, varied across the supply chain. The author concludes that these "misconceptions of feedback" account for poor performance, and that subjects are insensitive to feedback from their decisions to the environment (Sterman 1989). This paper is useful to the current research in that it highlights the types of problems managers face with multi-phase integration efforts, and the shortcomings of traditional decision-making strategies.

John Sterman provides an in-depth textbook on System Dynamics as applied to Business Dynamics (Sterman 2000). Sterman states that accelerating change challenges managers to accelerate learning that causes unanticipated side effects from past actions. Since humans are unable to create complete mental models of complex systems, managers rely on currently available data to make decisions. Decisions made in the past on limited sets of data impact the current state in ways that managers could not have foreseen at the time of the decision. The resulting impact (a.k.a side effect) has dramatic effects over the lifecycle of the program. Effective decision making in a world of growing dynamic complexity requires us to become system thinkers (Sterman 2000). More recently courses are becoming available through channels such as MIT OpenCourseWare who provide several resources on System Dynamics (Sterman, Rahmandad 2013, de Weck, Lyneis, Braha 2012). All these resources are foundational for the Causal Loop Diagrams and System Dynamics Model used in this praxis.

2.3.1 Managing Complex Systems

Where section 2.2 focuses on general management of complex systems, this section focuses on specifically on complex DoD Program management and focuses on the Organizational Dynamics aspects of this complexity. This section captures the foundation of managing complex systems as it applies to DoD Programs, and provides motivation for the application of complex system management strategies to Large

Weapon Systems. These articles motivate the interactions between the Rapid Response Project, Integration, and Large Weapon System sub-models, and the challenges faced in modeling the complex system interactions.

GAO 2019 defines DoD’s largest weapon systems as “complex programs”. We start with an overview of what makes a complex system (PMI 2004, Söderlund 2002). Flagstad (2013), Mcgrath and Martin (2017), and Ford (1998) describe several methods of managing complexity. Finally, Sterman (2002) and Wolstenholm (1999) provide perspective on using models to manage complexity.

PMI (2004) provides guidance for managing integration for complex systems. They recommend any integration strategy must include the three dimensions of complexity: System behavior (interdependencies of components and systems), Human behavior (interplay between diverse individuals and groups) and ambiguity (Uncertainty of emerging issues and lack of understanding or confusion). Complexity itself is based on an individual’s perception formed by personal experience, observation, and skill. Rather than being complex, a project is more accurately described as containing complexity.

Söderlund (2002) presents a case study on managing complex development projects where he describes management of complex systems as a tension between (1) separating activities and making thought out plans -vs- (2) enabling the crossing of functions and knowledge bases. He claims that complex interrelations make it hard to make clear inferences and recommends organizing in a manner that follows "coupling logic" to stress the inter-functional responsiveness. "Right" is measured based on overall efficiency, rather than individual criteria (Söderlund 2002).

Flagstad et al. (2013) provide an assessment of using Balanced Scorecards to manage complexity using a feedback structure. They argue that Balanced Scorecards do not provide performance monitoring at the project level. The authors present a methodology for enhancing the balanced scorecard model in a feedback loop structure as a process improvement methodology. They recommend gathering additional metrics focused on the feedback structure in complex systems and highlight gaps in commonly used Project Management Tools.

Mcgrath and Martin (2017) claim that project failure is due to a lack of visibility in obtaining a single version of the truth. The authors recommend creating a structure for success that includes Governance, Transparency, Quality Assurance, Elimination of Redundancy, and Reporting to better obtain a view of the single version of truth. They claim that early failure can build into success if the manager has clear visibility, and can provide clear communication, transparency, and direction. The article highlights the need for clear visibility into the single version of the truth which the model for this praxis aims to provide.

Ford and Sterman (1998) describe dynamic modeling of the product development processes for a semiconductor chip development plant. The model captures the flows of work among development phases and the completion of tasks within each phase. The authors claim that traditional tools such as Critical Path Method and PERT are limited by using time as an indirect measure. They bundle scope, resources, and processes into a single measure. The authors introduce a multi-phase model where tasks are performed in stages (e.g. Design, Build, Test). An Inter-phase interaction concept is introduced that captures how “upstream” and “downstream” phases impact each other. The authors state that phases can be linked in an arbitrarily complex network of concurrence relations (e.g. sequential, parallel, partially concurrent). The authors later describe a calibration methodology, in which proprietary data was sanitized and used to fit model parameters to real world observations. This paper is an early version of the phased methodology used in this research, as well as the methodology for calibrating the research model with real world calibration data.

Wolstenholme (1999) encourages the balance between quantitative and qualitative models. He encourages the use of Causal Loop Diagrams (CLDs) as a qualitative System Dynamics approach claiming they provide a high-level means of conceptualizing models in terms of their feedback loop structure. He proposes an organizational implementation of an Intertwined Project Learning (IPL) process called the Accelerated Business Learning (ABL) process". The Causal Loop Diagram and elements of the IPL concepts are used for the current research.

Sterman' 2002 paper instructs that becoming an effective systems thinker requires mastery of feedback, stocks and flows, time delays, and nonlinearity concepts. The skill requires rigor and disciplined use of scientific inquiry to uncover hidden assumptions and biases. The bulk of his paper is a high-level summary of his Business Dynamics Book (Sterman 2000). He concludes the paper by encouraging the question "Why?" He states that "It's by asking those 'why' questions that we gain insight into how we are both shaped by, and shape, the world where we can act most effectively, where we can make a difference". This paper and his 2000 textbook are a key motivator for the current research methodology.

2.3.2 DoD Weapon Systems Project Management

Whereas section 2.2.2 captures prior attempts are managing DoD Programs, this section captures the Organizational Dynamics and the foundation of challenges that exist in managing DoD Weapon System. This section highlights shortcoming in current methodologies that provide motivation for portions of the model used for this research. White (2002) provides an overview of the inadequacies of Project Management tools. Khamooshi and Cioffi (2009), and Atkinson et al. (2006) describe the uncertainties and risk with large programs. Trammell et al. (2016) describes the effects of disruptions commonly found in DoD Projects. Eden, et al. in a series of articles (1998, 2005) highlight the effects of disruptions. Finally, Jessen (1988) provides a view on the ability to model these systems beyond simple "rule of thumb" techniques.

White and Fortune (2002) provide a survey of how well project management is performed across various industries. They discovered several inadequacies in current tool suites including inadequacy of the tools to model complex projects, difficulty in modeling "real world" effects, failing at claims of predicting performance, and only providing a constrained view of activities, that is, lacking a holistic project view.

Khamooshi and Cioffi (2009) describe a risk-based approach to program contingency planning. The presence of uncertainty drives the need for budget flexibility. They claim that traditional programs set aside an arbitrary level of resources (e.g. 10%, 20%, 30%) to cover program risks and unknowns. This approach is an integral part of Risk Management. The author develops an algorithm to determine the contingency budget based on number of risks, probability of risks, cost impact, and ranking of risks. The author provides a methodology for contingency planning but not a methodology for predicting the impact of these decision. This research supports the current research in defining and setting context for contingency budget (a.k.a. management reserve)

Atkinson et al. (2006) provide a discussion on the management of uncertainty in projects. They provide a framework to assess the “hard and soft” dimensions that contribute to uncertainty. They claim that learning from experience and data from past projects (e.g. lessons learned, previous performance data) can be used to determine the uncertainty rating of a project. They authors measure programs on a spectrum of difficulty, where harder projects are more amenable to uncertainty reduction than softer projects where focus is on ambiguity reduction. (Atkinson, Crawford, Ward 2006) This paper supports the current research approach to include modeling of uncertainty.

Trammell et al. (2016) examine the effects of funding delays on software projects. They built a “Government-Funded Software Development Performance Model” to examine the effects of funding decisions on software project performance. The authors continue with a description of their System Dynamics Model based on Abdel-Hamid and Madnick (1991) who presented a Software Development Performance Model (SPDM). The authors include an enhanced staffing model which considers the effect of experienced staff leaving and returning to a project. (Trammell 2016) This paper supports the current research modeling approach for the staffing model, and highlights opportunities for further research in the management of staff cost and experience.

Eden et al. (1998) provides an approach to modeling the traditional Wright’s Law learning curve in the highly disruptive environments typical of practical projects. The authors claim that Wright’s Law is a good rule of thumb for idealistic scenarios but must be dismantled to account for wasted learning, changing requirements, and other disruptions. A case study is presented based on the "Channel Project" where the author proposes a model for capturing the learning behavior exhibited in team environments. They propose a System Dynamics approach to model and validate their claims (Eden 1998).

Eden et al. (2005) compare two techniques for measuring cost overruns in projects: The Measured Mile technique and System Dynamics Models. Their goal was to model what would have happened in a troubled project if the disruptive events causing the problems had not happened. The analysis was limited by the fact that data only supports actual events. Their analysis showed that the measured mile approach needs a perfect start, a clear understanding of all events that will cause change, and a linear predictive association to all events. A "perfect start" never exists in the real world. The authors prefer the System Dynamics approach which does not exhibit these limitations. When the SD Model is calibrated with real data (time series events that occurred in the actual system), it can be used as an effective tool to model "what if" analysis.

Jessen (1988) provides an analysis of project modeling stating that a systems approach is preferred to traditional "rules of thumb". The author recommends that modeling in combination with experience can help identify and determine best courses of action for decision making under pressure. The author states that project quality, cost and time need constant change as a project matures, but there is no practical guidance or tools to know which to adjust. Models need to be simple, correct, and realistic to be useful. Jessen proposes a Project Dynamic Model that includes concepts of "rework," perceived progress, and team confidence. Jessen proposes his causal loop diagram as a foundation for future project models.

These articles provide motivation to capture the challenges and behaviors exhibited by DoD programs. The System Dynamics Model approach for this Praxis aims to fill research gaps formulated by these articles in providing a predictive System Dynamics Model that accounts for the complex interactions identified as challenges in literature. Elements of this section are combined with the System Dynamics foundation described in section 2.4 to complete the model used for this research.

2.4 System Dynamics for Project Management

This section captures the foundation of System Dynamics as it is applied to modeling complex systems, providing direct motivation for the model used in this research. Sterman (2000) and Richardson (1991) provide a backdrop connecting systems thinking with control theory and System Dynamics methodologies. Rodrigues and Bowers (1996) and Cooper (1980) assess the suitability of System Dynamics to Project Management. Lyneis et al. with various co-authors (2001, 2007, 2020) describe the challenges with using System Dynamics models, specifically the Project Dynamics model, for complex DoD Large Weapon Systems.

Although there are many schools of system thinking, a system view of the world is still rare (Sterman 2000). Jay Forrester first developed the field of System Dynamics in the 1950’s at MIT as a way of addressing this gap. Richardson (1991) provides a history of System Dynamics and relates the field to other approaches, starting with practical applications from ancient Greece (a water barrel control loop for keeping time with water drops) to the 1990’s. Richardson’s book captures the loop concept underlying feedback and circular causality by anchoring the concept in social sciences.

The first use of System Dynamics for Project Management appeared in 1964, but project specific applications did not appear until the 1980 (Rodrigues, Bowers 1996). Typical applications are in areas where budget and risk are high (e.g. aerospace, defense, software development). System Dynamics applied to Project Management played a key role in settling a $500 million claim against the U.S. government. Ingalls Shipbuilding used a System Dynamics Model to quantify delays and design changes attributed to U.S. Navy decisions, outside the control of the contractor. Cooper recommends proactive use of System Dynamics Models for project management as a means by which adversarial relationships can be avoided. (Cooper 1980)

Rodrigues and Bowers (1996) in two articles compare traditional project management methods with a System Dynamics approach. The authors describe Program Managers as excellent fire-fighters focusing on the here-and-now and avoiding strategic decisions. System Dynamics is recommended as a holistic approach to augment traditional project management tools. The approach focuses on the feedback process that occur within a complex project system. Three major areas are addressed: project monitoring and control, rework generation, and human resource management. The authors describe a "Project control cycle" that defines several of the terms used in this research.

Lyneis and Ford (2007) provide a survey, assessment, and direction for future research of System Dynamics as applied to project management. The authors highlight the challenges involved with project dynamics, both in terms of traditional resource constraints (e.g. Scope of project, Time limits, Funding limits, Resources) and the complex non-linear feedback loops. They survey a variety of published system dynamic structures and summarize four key “structure groups”. (1) Project features: model features found in real world systems. (2) Rework Cycle: in which work generates rework. The authors emphasize the rework cycle’s recursive nature creating problematic behaviors over the duration of the project, and the source of many project management challenges. (3) Project Controls: the parameters (factors) managers can control during project execution. (4) Ripple and knock-on effects: capture policy resistance and unintended consequences. “Ripple effects” capture the unintended consequences of well natured program control efforts. “Knock-on effect” refer to secondary impacts resulting from ripple effects (e.g. moral reduction due to increased overtime). The authors continue the paper with examples of models that exhibit these structure groups. (Lyneis, Ford 2007)

Ford, Lyneis, and Taylor (2007) discuss enhancing the System Dynamics project modeling approach to address shortcoming and provide project managers guidance on policy to control project performance. Three policy driven decision criteria are addressed: (1) Pressure on staff: realized when staff is pressured into working faster, (2) Working overtime: leading to lowered productivity from exhaustion, and (3) Introduction of new staff to the project: with the effect of reducing overall productivity both in new staff, and experienced staff needed to train new staff. The authors go on to introduce four drivers that generate typical project dynamics leading to cost and schedule overruns: (1) Rework Cycle: where undiscovered errors in current work are discovered later in the project and reworked, which may loop through the cycle multiple times before work is finally performed correctly, (2) Controlling feedback loops: where managers attempt to bring troubled programs back on track, yet have negative consequences (e.g. overworked staff, new staff, schedule pressure), (3) Ripple-effects: described as vicious circles (e.g. skills dilution, fatigue, “haste makes waste”), and (4) “secondary” or “knock-on” effects: caused by errors propagating between different phases of work (e.g. design errors not discovered until build phase).

Lyneis, Cooper, and Els (2001) discuss a System Dynamics Model for strategic project management in a DoD environment. They define strategic project management as covering five key areas: (1) Designing the project to include initial planning, (2) determining what indicators to measure, (3) Risk Management, (4) Incorporating lessons learned, and (5) making mid-course corrections. Lynes et al. introduce the “rework cycle,” a four-stock model that was used in the Ingalls Shipbuilding lawsuit (Cooper 1980). The authors propose that almost all dynamic-project models have a rework cycle in some form. The authors then continue with a project dynamics model that captures the dynamic behaviors of quality and productivity and the complex interactions that move work between the four work stocks.

Lyneis, Cooper, and Els (2001) provide a case study where System Dynamics was applied to a large military application: The Peace Shield Air Defense System. The model was used for the initial bid, to identify and manage risks, and to assess process and organizational changes implemented on the project. The authors describe a proactive role of System Dynamics Models to provide strategic/tactical management of design, construction, and development projects. The authors describe strategic project management as decisions taken up front in the design of a project that then impacts downstream performance of the project. The authors present a high-level diagram that shows the structural reasons for dynamic behavior of productivity and quality.

Lyneis (2020) describes a three-phase model approach for modeling large complex programs. He states that many projects conduct work in phases, describing a three-phase model which captures “Front End Engineering”, “Design”, and “Build/Test”. Each phase contains a rework cycle, staffing allocation, rework discovery, productivity loops, and quality loops, and is identical in structure except for interaction points between the phases. He goes on to describe the interaction points in terms of rework generation and rework discovery, and how these loops interact across the phases. A rework co-flow structure is introduced that captures and classifies rework generation to account for which phase generates the rework, and which phase can discover the rework. The rest of the paper describes the details of a model based on a construction project.

The articles discussed in this section inform the structure of the System Dynamics Model used in this research, both for the structure inside each of the three sub-models and the interactions between sub-models. This research fills research gaps by providing a System Dynamics model to fill the connective tissue across these articles.

2.4.1 System Dynamics Model Validation

This section captures the foundation of System Dynamics Model validation to provide the basis from which the model built for this research is validated.

Coyle (1983) provides a historical summary of the processes by which System Dynamics Models are constructed, validated, and analyzed. The six-step process starts with (1) A definition of real-world symptoms to be understood and improved, (2) Create a system description using influence diagrams, which he compares to control theory signal flow graphs. Key to these diagrams is that they are easily explained to managers, can be drawn quickly, and can be converted into a simulation model. (3) Build the model.

(4) Validation, defining a series of 8 tests as summarized in Table 2-1 to verify, and validate. (5) Simulate the model, and (6) Redesign the structure of policies to improve behavior.

Table 2-1. Coyle Validation Steps

Test	Type	Description
1	LE	Model Structurally coherent
2	VE	Can individual relationships be defended
3	LE	Dimensions valid
4	VE	Parameters consistent with known data
5	LE	Flows working correctly
6	VA	Silly values? (Negative people, etc.)
7	VA	Historical Validity
8	VA	Shock Testing

VE: Verification - Real world mechanisms correct

VA: Validation - Overall behavior

LE: Legitimation - Model obeys 'laws' of system structure

Sharp and Price (1984) propose that the characteristics of a System Dynamics Model is best understood by examining the paradigm. The authors group System Dynamics paradigm into three key areas: Assumption related to the model structure, assumptions related to the policy analysis, and assumptions related to the practice of System Dynamics. The paper is yet another view of validation that is useful to this research, however Sterman’s (2000) validation model is more complete.

Qudrat and Seong (2010) address structural validity of System Dynamics Models declaring that models must build the right behavior for the right reasons. The structural validity of the model must build confidence regardless of how well the model passes behavior validity tests. The authors describe two forms of validation: behavioral and structural. Behavioral validity is supported by the quantitative model (e.g. System Dynamics Model) and informs the qualitative model (e.g. Causal Loop Diagrams), while structural validity is supported by the qualitative model and informs the quantitative model. The purpose of the model informs both qualitative and quantitative models. The authors describe five structural validation procedures as boundary adequacy, structure verification, dimensional consistency, parameter verification, and extreme conditions. Behavioral validity is simply described as a comparison of model behavior to the real-world system.

Barlas (1996) provides a discussion of the formal aspects of model validity and validation in System Dynamics. He proposes a set of tests starting with direct-structure tests (e.g. empirical, theoretical, inspection) followed by structure-oriented behavior tests (e.g. extreme conditions, behavior sensitivity, modified-behavior prediction, boundary test, phase relationship tests, qualitative feature analysis, and a Turing test). Both sets of tests support structure validity. After structure validity, behavior validity tests measure how well the model can reproduce real system behavior. Barlas then describes a logical sequence of formal steps to guide the validation process.

Sterman (2000) published a System Dynamics textbook titled "Business Dynamics" where he provides a comprehensive set of material on System Dynamics. He describes a 12-step process for model validation that is used for this research. The 12 steps summarized in Table 2-2 are comprehensive of the articles discussed in this section.

Table 2-2. Sterman's Validation Steps

Step	Description
1. Boundary Adequacy	Important concepts endogenous to model, Behavior or policy recommendations change when boundary assumptions relaxed
2. Structure Assessment	Model structure consistent with knowledge of system, Level of aggregation appropriate, conforms to basic physical laws, Decision rules capture behavior of the actors in the system
3. Dimensional	Each equation dimensionally consistent
4. Parameter Assessment	Parameter values consistent knowledge of the system, Have real world counterparts
5. Extreme Conditions	Equation make sense with extreme values, Model plausibly with extreme policies, shocks, and parameters
6. Integration	Results sensitive to time step or numerical integration method
7. Behavior Reproduction	Model reproduces the behavior of interest in the system (qualitatively and quantitatively), Endogenously generates symptoms of difficulty motivating the study, Model generates behavior observed in real system, Frequencies and phase relationships among the variables match the data
8. Behavior Anomaly	Do anomalous behaviors result when assumptions of the model are changed or deleted
9. Family Member	Model generates the behavior observed in other instances of the same system

Step	Description
10. Surprise Behavior	Model generates previously unobserved or unrecognized behavior Model successfully anticipates response of the system to novel conditions
11. Sensitivity Analysis	Numerical sensitivity, Behavioral sensitivity, Policy sensitivity
12. System Improvement	Did the modeling process help change the system for the better

Table summarized from Sterman (2000) Table 21-4: Tests for assessment of dynamic models.

2.5 Conclusion

The current state of the art in Integration Strategies for Complex Systems provides components of research necessary to support the development of this Praxis. A key theme through the literature shows that complex systems are beyond the ability of human cognition to manage without tools, techniques or models that employ strategies that humans can understand. Major gaps in the literature include the use of predictive models such as System Dynamics to quantitatively assess the impacts of decisions that inform integration strategies. The four factors chosen for this research (Technology Readiness Level, Integration Time, Management Reserve, and Completeness of Solution) have been loosely discussed but have not been integrated together into a predictive model based on real world data. TRL has been exclusively assessed as a qualitative factor, rather than integrated into a predictive model using a quantitative methodology. Predictive modeling of the quantitative effects of delivering incomplete integration solutions is not addressed in the literature.

This research builds on the foundation outlined in this literature review, and fills the gaps identified to create a System Dynamics Model, calibrated with available real-world data. The model is used to determine the effectiveness of various integration strategies by varying 4 factors (the independent variables). These factors: Technology Readiness Level, Integration Time, Management Reserve, and Completeness of Solution are well founded in the literature as factors that influence integration strategy as discussed in section 2.2. Causal Loop Diagrams capture the Organizational Dynamics discussed in section 2.3. Lastly, the model used for this research is founded in the motivation provided in section 2.4.

Chapter 3—Methodology

3.1 Introduction

This chapter provides a detailed overview of how the research was conducted. It begins with an introduction of a conceptual model used to define the three phases of activity and explains how System Dynamics was chosen to implement the model. A brief tutorial of System Dynamics is followed by an overview of the System Dynamics Model structure used for this research. Next, the data cleansing process used to release company proprietary data for this research is discussed. The Design of Experiments methodology is discussed which describes the valid ranges of the model. Finally, the model verification and validation methodology are discussed.

3.2 Overview of the three-phase model

This research follows a Servomechanism methodology using a simulation research method to model the interaction between three distinct phases of work. The first phase is the Rapid Response Project phase. In this phase, a team of engineers build a technology capability to achieve the criteria to meet a chosen Technology Readiness Level (TRL) as defined by DoD guidance (DUST 2005, NASA 2008). The work performed to build the technology is called the Rapid Response Project (RRP). The RRP generates an output from the work effort which is called the Rapid Response Capability. An example of a capability may be a facial recognition application. A commercial company originally plans to build the application to pass the criteria for TRL 5, but in order to make the application available to the military end user, it must be brought to a higher TRL (e.g. TRL 9). The second phase is the Integration phase, and is abbreviated as INT. The INT phase accepts the capability output from the RRP as a starting point with which to begin integration work. Integration is defined as the work performed to make the capability work as required in the end user environment. As an example, the facial recognition capability requires additional work so that is operates in a Weapon System environment (e.g. interface with databases, user interface added to large system display, algorithm enhancements so it works with more noisy data). The third phase is called the Large Weapon System (LWS) Program. This phase captures the work required to build all the weapon system, except of course, the integration work. For example, a data processing system is built to collect video information from a variety of sources and provide a security system for a base. LWS is responsible for the complete delivery of this system. RRP delivers the facial recognition capability, and INT is the work to make that capability work in the system built by LWS.

The RRP and the INT phases interact using a transactional approach. The model assumes there is no overlap in time between the two phases. When the RRP is complete, the resulting capability, along with all defects (known and unknown), is inherited by the INT phase. The INT and LWS phases interact using Lyneis (2020) phased modeling approach for defect generation and discovery. RRP and LWS have no direct interaction. The goal of this research is to model the cost and schedule impacts of management decisions related to the interaction of the three phases. System Dynamics was chosen as the simulation method.

3.3 System Dynamics Overview – The Basics

System Dynamics Modeling uses control theory to model complex system behavior. Before any modeling begins, an understanding of the System Stocks, and the Causal Loop Diagrams (CLD) that capture high level behavior for a system are defined. Figure 3-1 shows an example of a CLD that captures the relationship of chickens and eggs. More eggs lead to more chickens, and more chickens lead to more eggs. This loop is called a Reinforcing loop, indicated by the circular arrow with a "R", because the levels of chickens and eggs continue to grow uncontrolled. An easy way to determine this is by multiplying all the signs (++), a positive product indicates a reinforcing loop. Chickens and eggs do not grow exponentially in nature, so we are clearly missing a balancing loop to the system. Figure 3-2 adds "Road Crossings" to the system. More chickens lead to more of those chickens crossing the road, which leads to fewer chickens surviving the experience. Counting the signs in this loop, we see an overall negative product (+-), which indicates a Balancing loop shown by the circular arrow with the letter "B". The

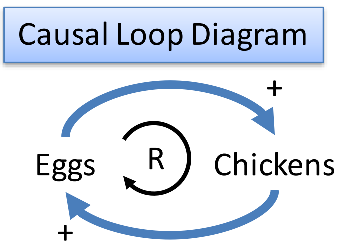

Figure 3-1. Causal Loop Diagram – Chickens and Eggs

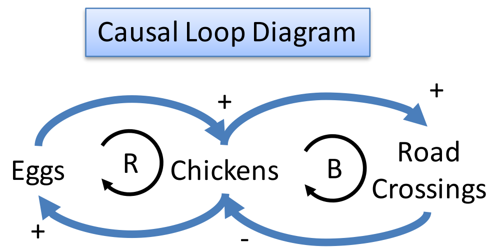

Figure 3-2. Causal Loop Diagram – Chickens, Eggs, and Road Crossings

direction of the arrow simply shows the flow of logic.

Translating CLDs to Stocks and Flow diagrams is the next step in the process. Our example results in the Stock and Flow diagram in Figure 3-3. The boxes indicate Stocks, which are defined as a countable object in the system. One can count the number of eggs, or chickens. Flows are indicated by the thick arrows (e.g. Eggs Hatched per Day, Chickens Surviving per Day). Flows measure the rate at which Stocks move from one location to another. Stocks either flow to another Stock (e.g. eggs become chickens), or Stocks expire from the system (e.g. chickens expiring). The latter is depicted with a "cloud" shape indicating flow across the system boundary. The box labeled "Probability of Chicken Death" is an equation capturing the relationship between the flow of chickens crossing the road and the chickens surviving.

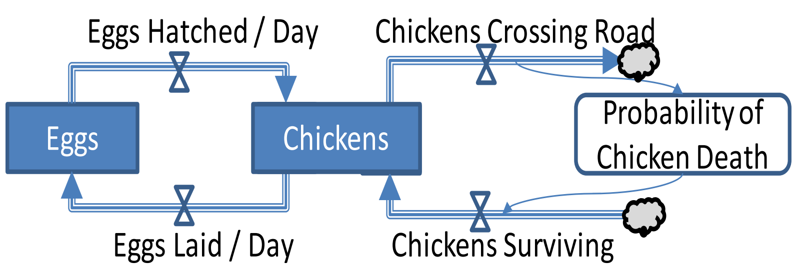

Figure 3-3. Chickens and Eggs Stock and Flow Model

Expanding the chicken and egg example further, we can begin to capture system behavior, adding one loop after another until the model captures the effects of interest to the modeler. Figure 3-4 shows an expanded model which begins to capture the effects of chicken density and behavior on the chicken population. The model has two independent variables, "Size of Farm", and "Size of Road", (green outlined boxes) with dependent variables of "chickens" and "eggs". The other boxes (blue outlines) capture the relationships of each of the control loops as equations that model the behavior of these loops.

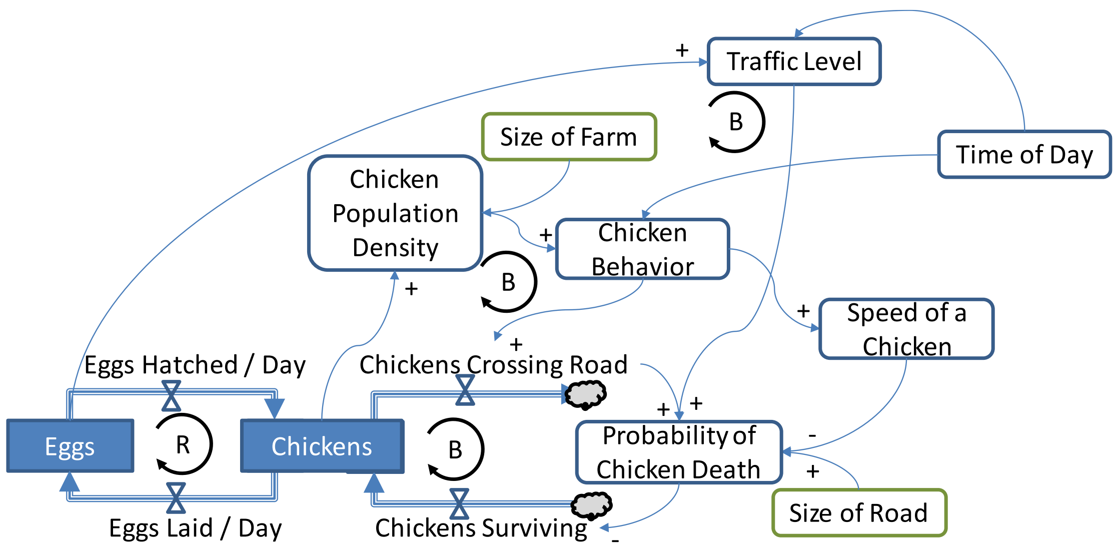

Figure 3-4. Expanded Chickens and Eggs Stock and Flow Model

Modeling Time Delay Between Two Events

In the case where a farmer wishes to determine how many eggs he wishes to sell, and how many eggs he wishes to let hatch, he may model the system with two separate egg Stocks as shown in Figure 3-5. One Stock captures “Eggs to Hatch”, and the second Stock captures “Eggs to Sell”. The farmer must make this decision as soon as the eggs are laid. He relies on a time varying sales forecast (S) to determine which flow the egg takes. “S” eggs flow into “Eggs to Sell” while (1-S) eggs flow into “Eggs to Hatch”. Since eggs are sold later in time, this model captures the time difference between making the egg decision, and the later event of “Eggs Sold”. The cascading of stocks captures the time delay effect. This concept becomes important in the Project SD Model discussed later in this chapter. The model pattern is applied when the modeler wishes to capture the dynamics of two dependent events separated by time.

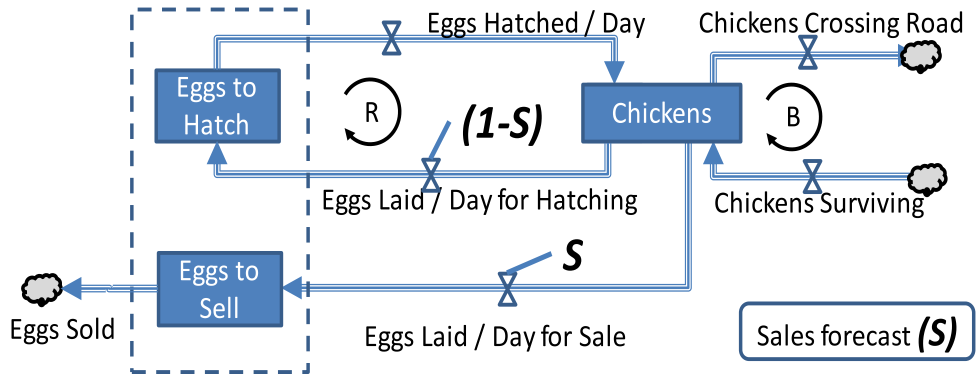

Figure 3-5. Eggs sold based on Sales Forecast

3.4 Model Overview

The System Dynamics (SD) Model consists of three major sub models capturing the Rapid Response Project (RRP), the Integration Activity (INT), and the Large Weapon System (LWS) phases. Before describing the three sub models, it is important to understand the Stocks and flows in the model used for this research. The two Stocks are The Work Cycle, and the Staff Model. The flow in model is Activity which consists of two factors: how fast work is performed (Productivity) and how well work is performed (Quality). Each of these Stocks and Flows are described in more detail in the following sections.

3.4.1 Work Cycle

A small glossary of commonly used terms is provided in Table 3-1 to aid the reader in following along with the discussion in sections 3.4.1.

Table 3-1. Glossary of terms used in Work Cycle

Term	Definition
Activity	A specific deed or action
Defect	A Task that has not been completed correctly

Term	Definition
Flows	Capture the Actions in the SD Model (Tasks / Unit Time)
Known Work	Tasks that are known to be incomplete (Work to Do + Rework to Do)
Productivity	The rate at which Tasks are completed (Task/Unit Time)
Quality	The ratio of Tasks worked that are done correctly
Rework to Do	Captures all the Tasks that have known defects, where defects have been discovered.
Stocks	Capture the Tasks in the SD Model
Task	The product of an Activity
Undiscovered Rework	Captures all the Tasks that contain defects, but defects are not yet discovered.
Work	A set of Actions and the Tasks those action produce
Work Complete	Captures all Tasks that have been worked to a level considered to be complete (Work Done + Undiscovered Rework)
Work Cycle	A sequence of tasks, operations, and processes, or a pattern of manual motions, elements, and activities that is repeated for each unit of work.
Work Done	Captures all the Tasks that are completed and contain no defects
Work to Do	Captures all the Tasks that have not been started

The Work Cycle is an industrial engineering term defined as "A sequence of tasks, operations, and processes, or a pattern of manual motions, elements, and activities that is repeated for each unit of work". (encyclopedia2.thefreedictionary.com) The basic unit of measure in the Work Cycle is the "Task". Cooper (2003) claims that work can be managed by decomposing the total work effort into smaller chunks of work, which are called activities and tasks. Cooper states that the Program Management Book of Knowledge (PMBOK®) Guide reveals that activities and tasks are the unit of analysis in the core processes of project management. Activity in this case is defined as a verb, "a specific deed or action" (dictionary.com). For example, an Activity would be the act of writing software for an interface to a new database. Task is then defined as the subject (or product) of the action, or the object to be acted upon. For example, the Task is new interface. Work is then defined as the set of actions and the respective tasks those actions produce. In mapping this definition to System Dynamics, Tasks are the measure of work, realized as "stocks", and actions determine the flows between the stocks. This research follows Cooper's strategy of decomposing work into smaller chunks (Tasks). One Task is set to equal the result of activity done by an experience staff in a fixed period of time. Activity (flow) is then measured as the number of Tasks performed per unit of time. This approach aligns with the available real-world data used to validate the research SD Model.

Although there are several methods in previous literature for modeling the work cycle, the approach described in Lyneis, Ford (2007) was chosen for this research. The Work Cycle model is structured is shown in Figure 3-6. Four stocks capture the states of a Task. (S1) Task has not been started, (S2) Task has been worked correctly and contains no defects, (S3) Task has been worked incorrectly, contains defects, but defects are not yet discovered, and (S4) Task has been worked incorrectly, contains defects, but defects have been discovered and are known. The separation of "Work Complete" into (S2) "Work Done" and (S3) "Undiscovered Rework" follows the similar logic in separating

Eggs in the tutorial example, with the purpose of modeling the time lag effect between defect generation and defect discovery.

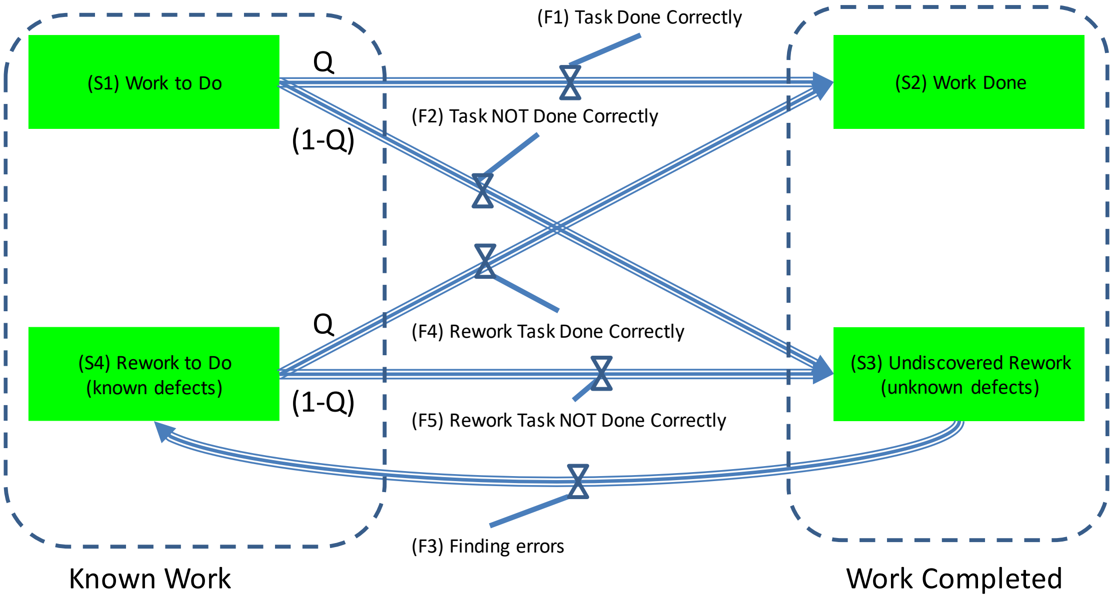

Figure 3-6. Work Cycle Model

When work is accomplished, the resulting Task is either performed correctly, or incorrectly. An incorrect Task is said to contain defects, and defects are either known, or not known. In this research, we assume that all staff work to the best of their abilities. A Task will not be considered complete with known defects. This assumption eliminates the path from (S1) to (S4). Defects are produced based on the Quality (Q) of the staff performing the work. Quality is a variable that captures the percentage of Tasks performed correctly. We may not know which specific Tasks contain defects, but we can capture the ratio, and route tasks to either (S2) or (S3) as a function of Quality. For example, if Q = 0.8, then for every 10 Tasks performed, 8 of those Tasks will flow from (S1) to (S2), and 2 of those Tasks will flow from (S1) to (S3). (S2) "Work Done" captures the percentage (Q) of Work Completed that is done correctly, while (S3)

“Undiscovered Rework” captures the percentage (1-Q) of work that contains defects. Undiscovered Rework highlights the fact that defects exist in work that is *believed* to be completed, but there is not yet a mechanism to determine the nature of the defect, thus the qualifier “Undiscovered”. Key to this concept: An Engineering Manager will view both stocks (S2) and (S3) as a single list of completed tasks. There is no clear way to distinguish which *specific* tasks contain defects, only that some percentage of those tasks (determined by the Quality variable) will have defects. Quality (Q) varies with time and is discussed with the CLDs later in this chapter.

As the Work Cycle progresses, downstream events (e.g. Subject Matter Expert review, Unit or System level testing, End User testing) will reveal the undiscovered defects. The Tasks that are discovered by this process follow path (F3), into the Stock called (S4) “ReWork to Do”. This Stock (S4) keeps track of reworked Tasks as a separate metric for analysis. Future research could classify (S4) as rework that requires a different level of effort to complete than (S1), however for this research they are treated the same. Activity on rework follows the exact same strategy as “Work to Do”, where Tasks completed correctly follow path (F4), and Tasks completed incorrectly follow path (F5). Since the same Staff works all “Known Tasks”, the same flow structure applies to (S4) “Rework to Do” as with (S1) “Work to Do”.

3.4.2 Staff Model

A small glossary of commonly used terms is provided in Table 3-2 to aid the reader in following along with the discussion in sections 3.4.2.

Table 3-2. Glossary of terms used in Staff Model

Term	Definition
Experienced Staff	People that have gained enough experience to perform at expected quality and productivity
New Staff	People joining the Program from outside the system boundary'
Staff	People performing Work

Staff are people performing the activity defined in the Work Cycle. As shown in Figure 3-7, the model captures Staff as a Stock, with two types of Staff based on a measure of experience. (S1-s) “New Staff” and (S2-s) “Experienced Staff” are defined in units of “Person”. The primary difference between the two Staff Stocks is in the relative quality and productivity of new staff with respect to experienced staff. Relative Quality is a measure of the quality of a new staff as compared to an experienced staff and is captured as a ratio (e.g. New Staff is 75% as good as Experienced Staff). Productivity is a relative measure of speed of new staff compared with Experienced Staff (e.g. New Staff works 50% slower than Experienced Staff).

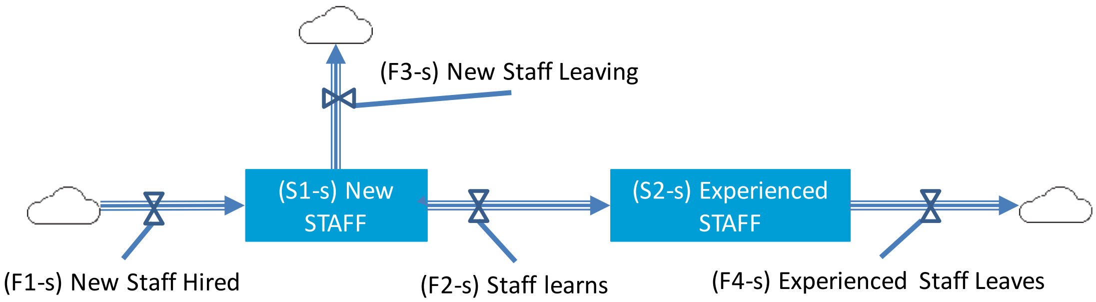

Figure 3-7. Staff Model

New Staff are hired from outside the project (F1-s) and enter based on the staffing needs of the project, delayed by the ability of the organization to hire people. For example, the project may need 10 new staff, but the company can only hire 2 staff per month. Staff leave (S1-s) "New Staff" Stock either by gaining experience (F2-s) and transitioning into (S2-s) "Experienced Staff" Stock, or by leaving the project (F3-s). New Staff leave the project when they are no longer needed. This is driven by staffing needs, and the speed with which the organization can transition staff off the project. In this model when staffing needs are less than actual staff, (S1-s) "New Staff" are released from the project (F3-s) before any (S2-s) "Experienced Staff" are released (F4-s).

3.4.3 Productivity and Quality CLDs

A small glossary of commonly used terms is provided in Table 3-3 to aid the reader in following along with the discussion in sections 3.4.3.

Table 3-3. Glossary of terms used in Productivity and Quality CLDs

Term	Definition
Average Quality	The long-term average of quality captured over the project timeline.
Experience	The level of ability of Staff, measured in productivity and quality.
Productivity	The rate at which Tasks are completed (Task/Unit Time).

Term	Definition
Progress	The status of the project compared to expected status (e.g. schedule, cost).
Quality	The ratio of Tasks worked that are done correctly.
Schedule Pressure	The pressure exerted on Staff when the Project falls behind schedule. (e.g. overtime, adding staff).
Schedule Status	The status of the project compared to expected completion time.
Uncertain Customer Requirements	The impact on quality when requirements are not yet well understood.

Activity consists of two factors: how fast work is performed (Productivity) and how well work is performed (Quality). Productivity is easily observed by simply counting the number of Tasks completed in a unit of time. Quality is not as easy to observe. The effects of quality are not immediate and only discovered later in time. This is comparable to the time delay modeling for eggs in the tutorial model of section 3.2. The model captures time delay between defects being generated, and defects being discovered. Unlike the egg example, we cannot directly associate which Task contains defects, but the Quality variable is designed to help determine what percentage of tasks will contain defects.

The Work Cycle and the Staff Cycle are intertwined by a set of feedback loops that center on two controlling factors: Productivity and Quality. As described previously, Quality is a measure of how well work is performed and has a dimensionless range of zero to one. Quality determines which path a Task takes in the Work Cycle. Productivity, on the other hand, is a measure of speed and is measured as “Tasks per Month per Person”. Productivity determines the rate at which tasks flow from one Stock to another. For example, a case where Quality is perfect (Q=1) and Productivity is zero (e.g. No staff available to work) would show no Task movement over time. This section describes the feedback loops in terms of CLDs: Two CLDs describe Productivity, and four CLDs describe Quality.

Productivity CLDs

First, we address Productivity, defined as the speed at which work is performed. There are two primary feedback loops that control productivity. The Schedule Pressure CLD captures the effect of pressure on the staff when the project is running ahead of, or behind schedule. The Staff Experience CLD captures the effect of changing the staff ratio of experienced and new staff members.

The Productivity CLD for Schedule Pressure is described in Figure 3-8. Following the loop starting at Productivity, we see that (1) Productivity trends with Progress, where improved productivity leads to improved progress. Work is getting done faster so more Tasks are accomplished. (2) Improved Progress leads to improved Schedule Status. (3) Improved Schedule Status reduces the schedule pressure on the Staff. Staff will not be pressured if deadlines are being met, and work is not falling behind schedule. (4) Reduced Schedule pressure allows the Staff to work slower (e.g. no overtime, no rushed work), which reduces productivity. By counting the negative signs in this loop, we end up with an overall negative loop, which classifies the loop as a Balancing Loop. Notice that the *quality* of the Work is not addressed in this CLD, only the speed of the Work.

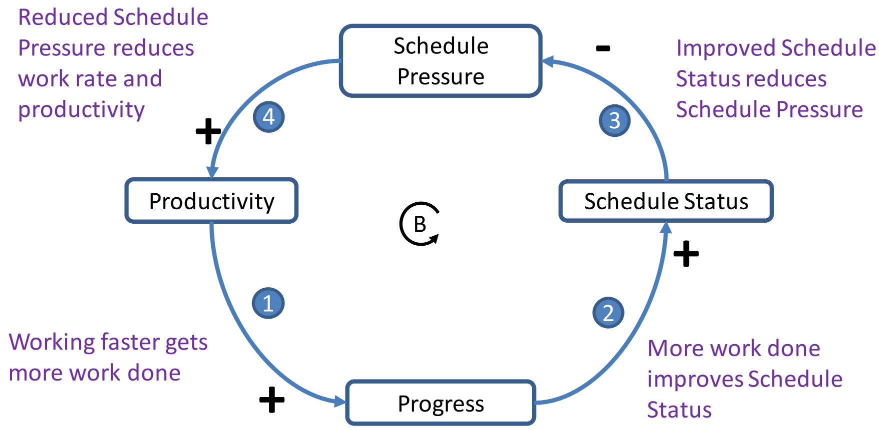

Figure 3-8. Productivity CLD – Schedule Pressure

The Productivity CLD for Staff Experience is described in Figure 3-9. Following the loop starting at Productivity, we see that (1) improved Productivity leads to improved Progress. (2) Improved Progress results in lower staffing needs. (3) Lower staffing needs reduces the amount of New Staff, either less new staff are hired, or New Staff are released from the project to meet staffing level needs. (4) Less New Staff improves staff experience which in turn (5) improves Productivity. By counting the negative signs, we end up with an overall positive loop, which classifies the loop as a reinforcing loop. In the case where we have zero new staff and can hire no new staff, the loop becomes a balancing loop, but this is not the normal state.

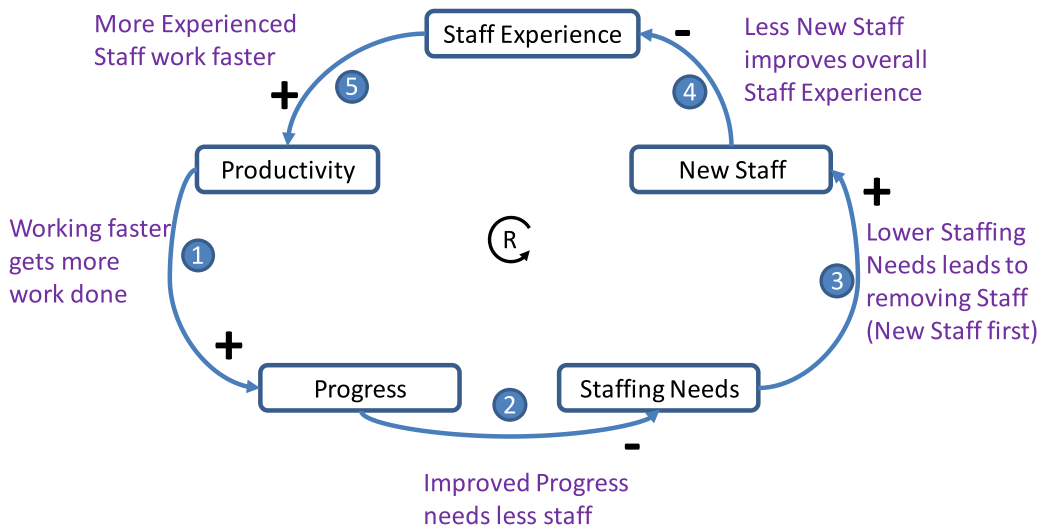

Figure 3-9. Productivity CLD – Staff Experience

Quality CLDs

Quality is defined as the percentage of tasks that are completed without defects. Quality is modeled using four CLDs impacting overall quality: Schedule Pressure, Staff Experience, Uncertain Customer Requirements, and Prior Quality impact on Quality.

The Quality CLD for Schedule Pressure is described in Figure 3-10. Following the loop starting at Quality, we see that (1) Quality trends with Progress, where improved quality improves the number of correct Tasks. (2) Improved Progress leads to improved Schedule Status. (3) Improved Schedule Status reduces the schedule pressure on the Staff. (4) Reduced schedule pressure allows the Staff to work at a higher quality, which improves overall quality. By counting the negative signs in this loop, we end up with an overall positive loop, which classifies the loop as a reinforcing loop.

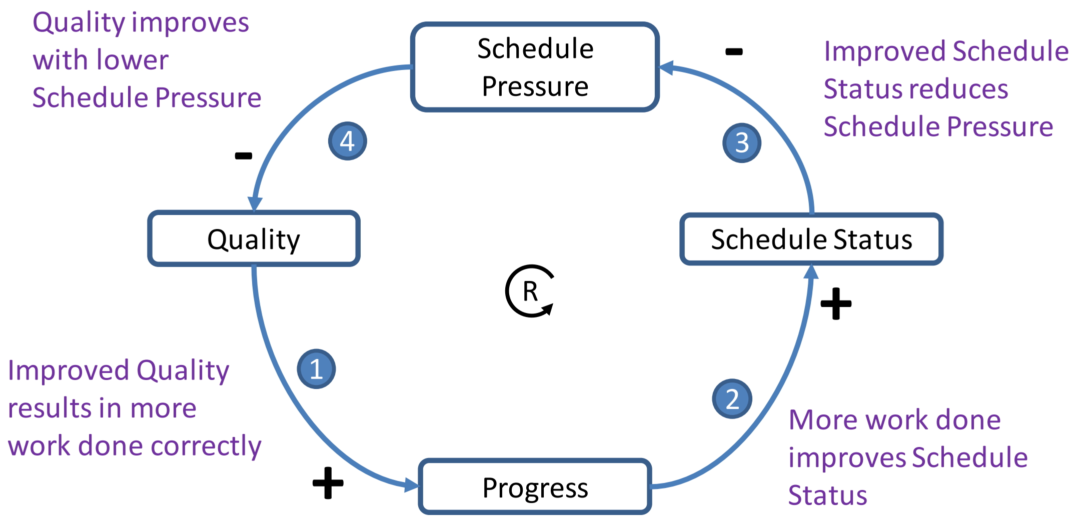

Figure 3-10. Quality CLD – Schedule Pressure

The Quality CLD for Staff Experience is described in Figure 3-11. Following the loop starting at Quality, we see that (1) improved Quality leads to improved Progress, where improved quality improves the number of correct Tasks. (2) Improved Progress results in lower staffing needs. (3) Lower staffing needs reduces the amount of new staff, either less new staff are hired, or new staff are released from the project. (4) Less New Staff improves Staff Experience which in turn (5) improves Quality. By counting the negative signs, we end up with an overall positive loop, which classifies the loop as a reinforcing loop. In the case where we have zero new staff and can hire no new staff, the loop becomes a balancing loop, but this is not the normal state.

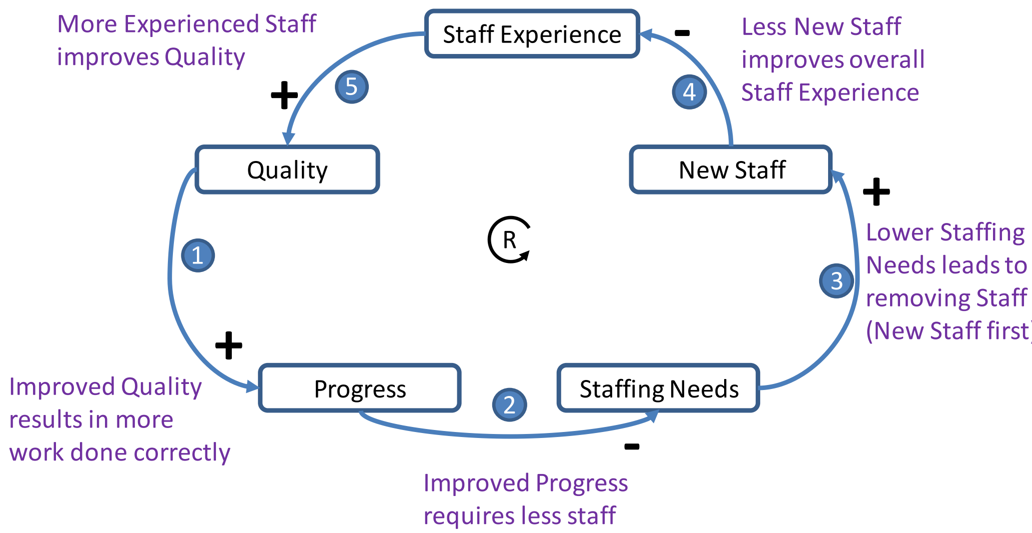

Figure 3-11. Quality CLD – Staff Experience

The Quality CLD for Uncertain Customer Requirements is described in Figure 3-12. The purpose of this loop is to capture the startup effect of the project, where even experienced staff must orient themselves to the project requirements before improved quality can occur. Following the loop starting at Quality, we see that (1) improved Quality leads to improved Progress, where improved quality improves the number of correct Tasks. (2) Improved Progress results in less requirements uncertainty, which then leads to (3) improved quality. By counting the negative signs, we end up with an overall positive loop, which classifies the loop as a reinforcing loop.

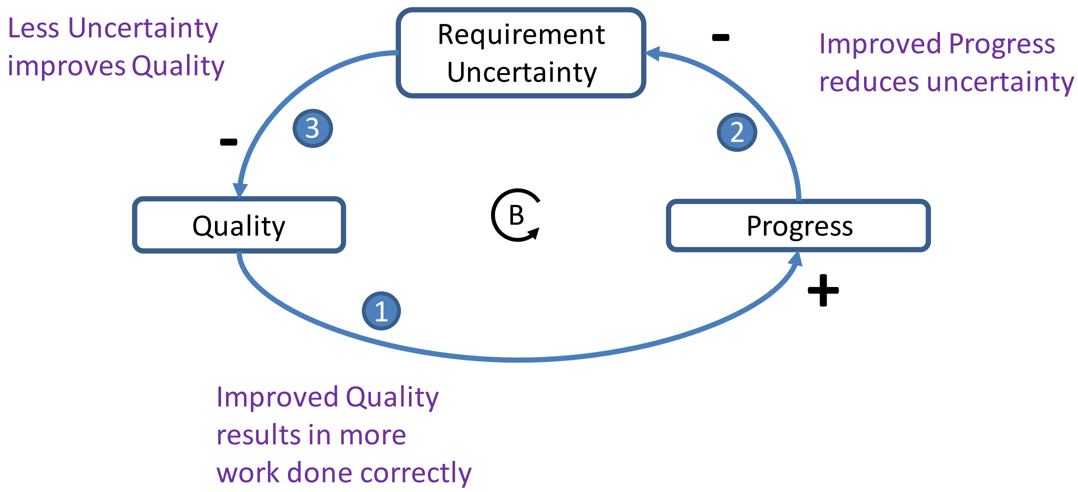

Figure 3-12. Quality CLD – Uncertain Requirements

Lastly, Prior Quality impact on Quality is a control loop that has been found necessary to act as a dampening loop against sudden quality changes in the system. The loop tracks a running average of quality, with the argument that regardless of the effects of other loops, an organization cannot dramatically change quality overnight. (Lyneis 2007). Prior Quality on Quality is described with the Causal Loop Diagram in Figure 3-13. Following the loop starting at Quality, we see that (1) improved Quality leads to improved Progress, where improved quality improves the number of correct Tasks. (2) Improved Progress results in improved Prior (average) Quality, which then leads to (3) improved Quality. By counting the negative signs, we end up with an overall positive loop, which classifies the loop as a reinforcing loop.

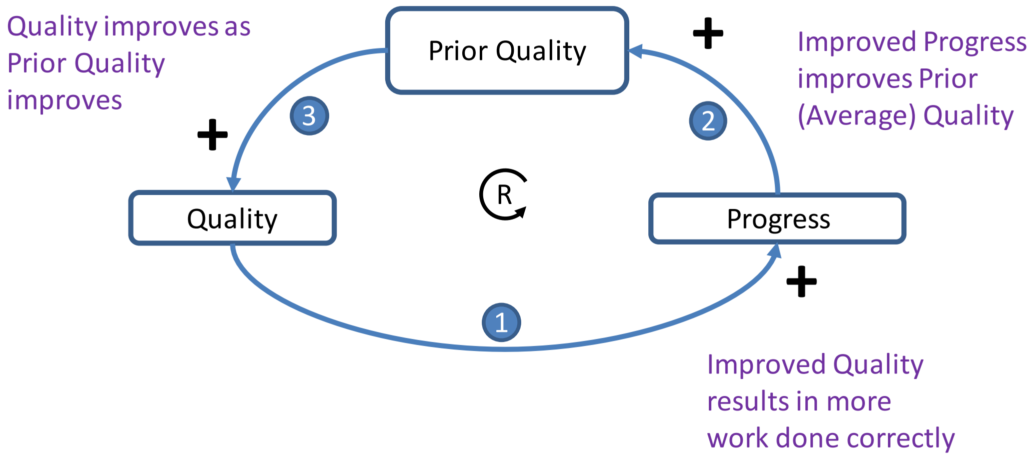

Figure 3-13. Quality CLD – Prior Quality

3.4.4 Overall Sub-Model:

Figure 3-14 shows the combination of all the previously described CLDs and the Work and Staffing Stocks into one diagram. Although each CLD is assessed as an isolated interaction, when working together there are higher order dynamics that interplay to simulate project execution. Productivity is captured with the brown components in the diagram. The two productivity loops are labeled as P1 and P2. P1 captures Schedule Pressure effect on Productivity, and P2 captures Staff Experience effect on Productivity. Quality is captured with the orange components in the diagram. The four Quality loops are Q1-Q4. Q1 captures Schedule Pressure effect on Quality, and Q2 captures Staff Experience effect on Quality, Q3 captures Requirements Uncertainty effect on Quality, and Q4 captures Prior Quality (a.k.a average quality) effect on Quality. Green captures the Work Cycle, and Blue captures the Staffing Model.

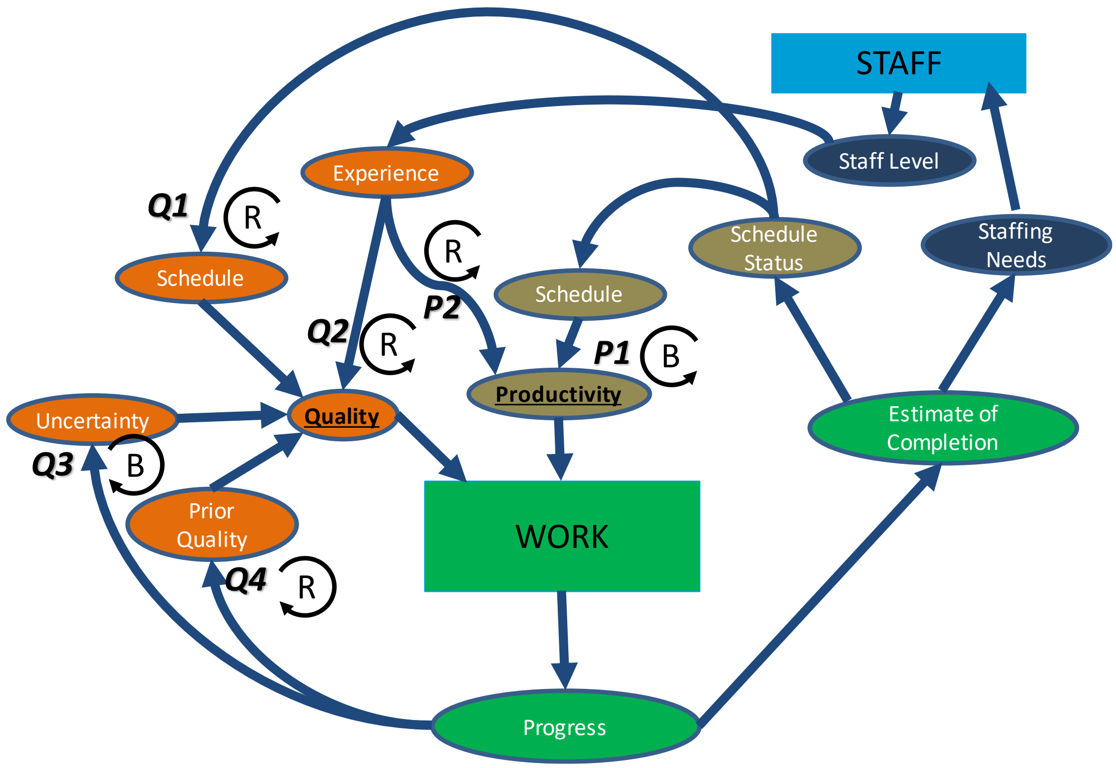

Figure 3-14. CLDs, Work and Staff Stocks combined in a single project model

Work Cycle, Staff, Productivity and Quality interactions all exist as internal constructs within each of the three sub-models. These three sub-models capture the three phases (RRP, INT, and LWS) with mostly symmetric model structure. The primary differences between these three sub-models are the interaction points.

3.3.5 Three Phase Interactions

The interactions are driven by and limited to the four Hypothesis in this research, summarized as (H1) Technology Readiness Level (TRL), (H2) Integration Time, defined as the start time of integration activity (relative to LWS), (H3) Management Reserve captures as a percentage of the initial work scope, and (H4) Level of Completion, defined as the percentage of work *believed* to be complete and the resulting defect level. (e.g. defect level of 30% when 80% complete).

H1: *Rapid Response Projects which increase TRL by one level result in an overall Program cost reduction (overall cost change less than zero). Overall Program cost includes the cost of Rapid Response Project, Integration activity, and Large Weapon System costs combined.*

Our first Hypothesis models Technology Readiness Level as the independent variable, and cost is the dependent variable. The RRP performs work to mature a capability to a planned TRL (e.g. TRL 6). Changing the planned TRL (e.g. TRL 5) results in a different level of work required to complete the RRP tasking before it is transitioned to INT. As an example, when the RRP TRL is reduced from a 6 to a 5, “Work to Do” is transferred from RRP into INT. RRP requires less effort, and INT must now perform additional Tasks to bring the capability to a TRL 9. Figure 3-15 shows the transfer of work where the solid arrow (T1) indicates the transfer of Tasks between RRP and INT. The change in TRL selected by the Engineering Manager controls the number of Tasks transferred and the direction of the transfer. The Engineering Manager controls this variable during the planning stage of the program.

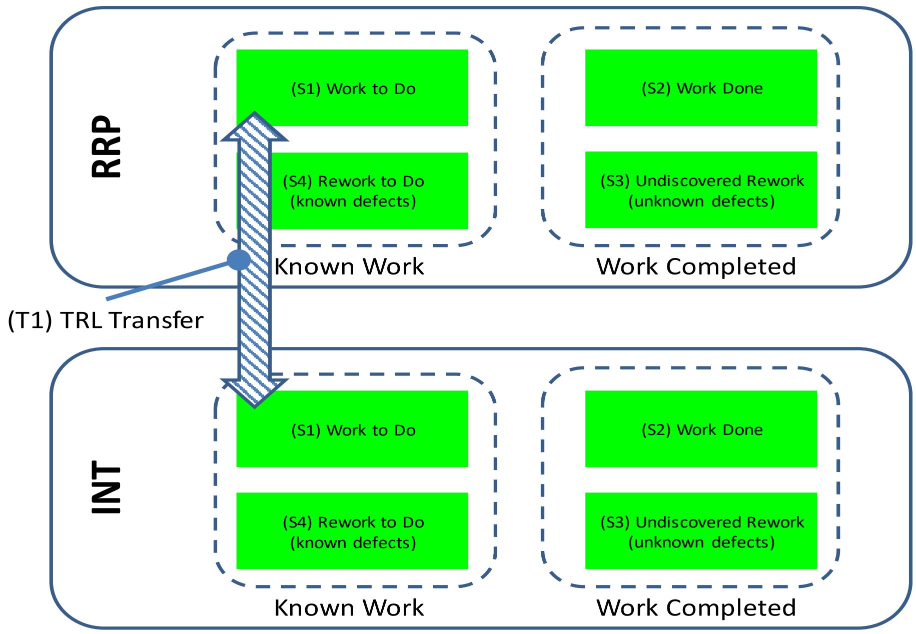

Figure 3-15. Transfer of Task RRP to INT based on TRL

The Task Transfer interaction is modeled using Conrow's (2011) coefficients to transfer work between RRP and INT. Conrow performed a study to produce quantitatively useful coefficients for TRL using data from past DoD and NASA programs. These coefficients capture the cumulative cost as technology is created to meet the criteria of the nine TRLs. For example, a complete capability, TRL 9, has a value of 9, where a TRL 6 capability has a value of 2.74. The TRL 6 capability will have resulted in 2.74/9.0 (~30%) of the cost required to complete the capability to a TRL 9. The curve transforms ordinal scale TRL values into cardinal scale coefficients useful for computation. This research uses the coefficients as shown in Figure 3-16 to derive the percentage of Tasks to transfer between RRP and INT as a

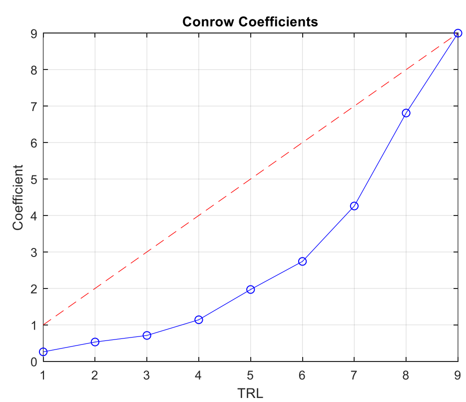

Figure 3-16. Conrow Coefficients

function of TRL change. The X-Axis indicates the TRL of a capability. The Y-Axis indicates the coefficient. The blue curve captures the Conrow Coefficients, where the red curve captures the linear relationship of TRLs. The gap between red and blue curves shows the cost gap. Where a manager may incorrectly believe that a TRL 6 capability is 67% complete, historical data indicates that the capability is only 30% complete. Suppose the Engineering Manager wishes to determine the impact of changing the planned TRL of the RRP from 6 to 5. Conrow's coefficients are respectively 2.74 and 1.97. As an example, we would like to compute the number of tasks to shift from RRP to INT when we change the planned TRL of the RRP from a 6 to a 5. Suppose the estimated work for RRP is 100 Tasks, and the estimated work for INT is 200 Tasks at a planned TRL 6. We capture the amount of work to shift from RRP to INT as *Work to Shift*.

$$Work\ to\ Shift = (RRPwork + INTwork) * \left(\frac{Conrow(TRL6)}{9} - \frac{Conrow(TRL5)}{9}\right)$$

Where RRPwork is 100 Tasks and INTwork is 200 Tasks. Conrow(TRL6) is the value obtained using the data in figure 3-16 where the x-axis is 6, and likewise Conrow(TRL5) for an x-axis value of 5 (2.74 and 1.97 respectively). Thus:

$$Work\ to\ Shift = (100 + 200) * \left(\frac{2.74}{9} - \frac{1.97}{9}\right) = 25.66\ Tasks$$

We conclude for this example that 25.66 Tasks must be shifted from RRP into INT. RRP would start with 74.66 Tasks, and INT would start with 225.66 Tasks.

H2: *Rapid Response Project integrations with Large Weapon System that start 6 months earlier than the planned integration point lowers the integration costs by more than 2%.*

Our second Hypothesis models the relative time that INT work begins with respect to the timeline of LWS. The independent variable is Integration Start Time, and the dependent variable is cost. This is modeled by controlling the start time for the INT work with respect to LWS. The start time for INT is restricted to start after RRP completes, and after LWS begins. The model controls the start and end times of each of the three phases. An Engineering Manager will input the planned start times and durations. The INT start time is then shifted earlier or later to determine the cost and schedule impacts.

Interaction between INT and LWS is designed to follow Lyneis (2020) phase interaction model. The approach recognizes that some defects generated by INT can only be discovered by LWS, and some defects generated by LWS can only be discovered by INT. Figure 3-17 describes the methodology to track “Undiscovered Rework” (containing defects) in the rework generation process. This figure shows the LWS sub-model tracking methodology, and the INT sub-model reflects this structure. “Undiscovered Rework” is now classified into two stocks (S3a) and (S3b). (S3a) captures the percentage of LWS “Undiscovered Rework” that LWS can discover. (S3b) captures the percentage of LWS “Undiscovered Rework” that INT can discover. The variable “L” captures this further breakdown. “L” is currently determined by a ratio of qualities between the two phases and is captured in a table that controls this ratio.

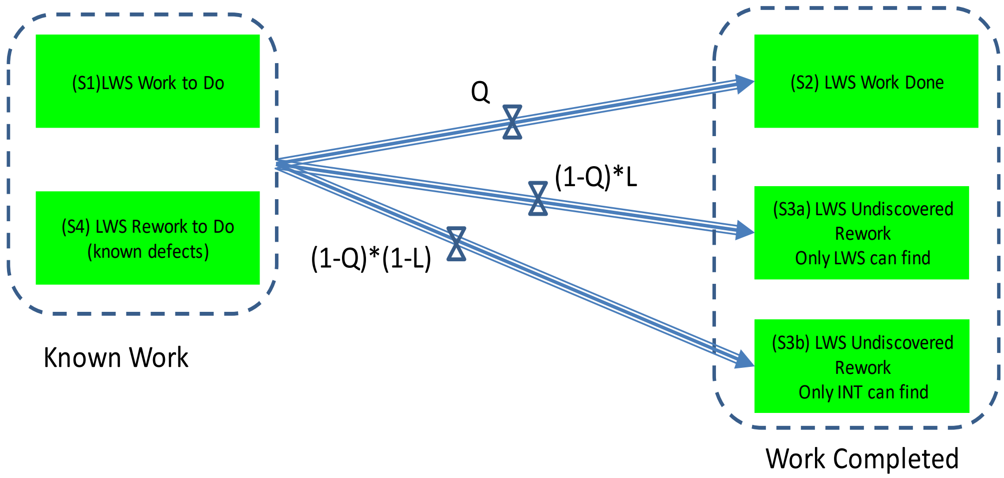

Figure 3-17. Defect Generation between INT and LWS

Table 3-4 shows an example of a table for L. In this example, the table entry of 0.5 indicated the case when LWS has a significantly lower quality than INT. LWS quality is half that of INT. LWS has a lower ability to discover rework than INT. The resulting L value is 0.35, which indicates that 35% of the rework generated is discoverable by LWS, and the other 65% is discoverable by INT.

Table 3-4. Ratio of Rework Discoverable by LWS (example)

Quality Ratio (LWS/INT)	L
0.25	0.25
0.5	0.35
1	0.5
2	0.9
4	0.95

The table reflects a relationship where a poorly performing organization (e.g. low quality) will tend to generate more defects that the higher performing organization must discover. More in depth organizational data describing work processes can further clarify this relationship, but for the purposes of this research, a simple relationship suffices. Additionally, calibrating the model to real world data captures the relationship between INT and LWS interactions.

The ability to discover defects improves as progress is made, where each phase improves the discovery of defects (e.g. Improved progress in LWS improves the ability to discover LWS defects in both LWS and INT phases). Figure 3-18 shows the CLD for the interdependence of defect discovery between LWS and INT. Following the loop starting at LWS Progress, we see that (1) improved LWS Progress leads to improved ability to find defects in both LWS and INT, where (2) the more defects discovered leads to higher Quality. (3) Improved Quality results in improved Progress. (4) Improved LWS ability to find INT defects improves INT Quality, which then leads to (5) improved INT Progress. The relationship holds from INT to LWS as well, where (6,7, and 8) follow the same logic as (1, 2, and 4). By counting the negative signs, we end up with overall positive loops across the board, which classifies these loops as reinforcing loops.

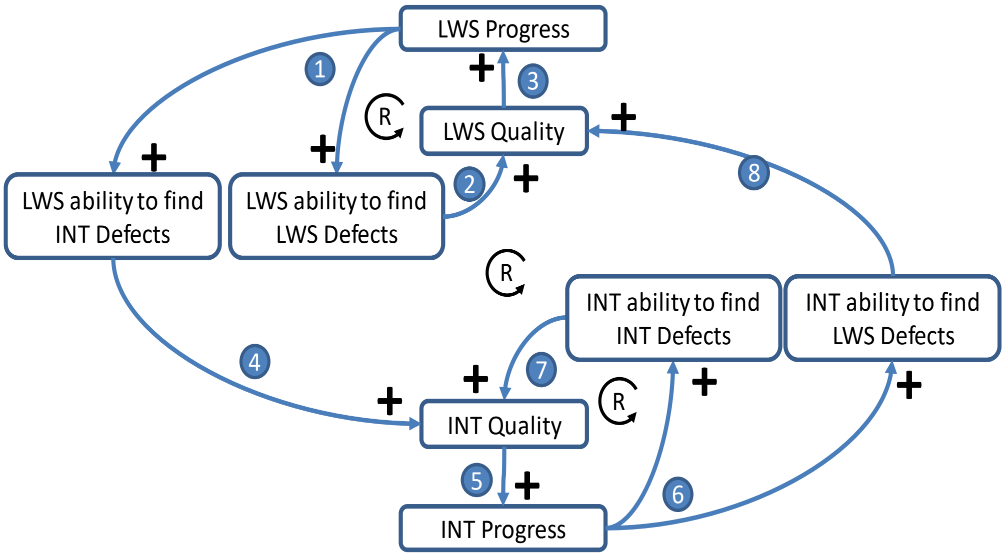

Figure 3-18. Defect Discovery CLD between INT and LWS

H3: *Integration efforts that increase management reserve by 5% lead lower overall integration costs of greater than 5%.*

Our third Hypothesis models the management reserve allocated to each phase of the program. The independent variable is "percentage of reserve", and the dependent variable is cost. The "progress" discussed in our CLDs is computed based on a cost to complete estimate. This estimate is initially based on the planned estimate, and transitions to a progress-based estimate as the work matures over time. The initial estimate is based on the initial "Work to Do" plus a management reserve called "Estimated Rework" in the Model. Varying this ratio impacts both quality and productivity loops in the model. The Engineering Manager will vary the "Estimated Rework" variable to determine overall cost and schedule impact. Future research can enhance the fidelity of how management reserve is release during project execution. For example, a Risk Management Process may release management reserve in fixed time slots, or conditional based on other programmatic thresholds. For this model, a simple linear strategy is employed.

H4: *Integration efforts that deliver 80% solutions result in Large Weapon System that are less than 70% complete.*

Lastly, our fourth Hypothesis models the level of completion an Engineering Manager *believes* is complete. The independent variable is “Work Believed to be Complete”, and the dependent variable is “Work Actually Complete”. Recalling the four stocks from our work model are grouped into two primary categories: “Known Work” and “Work Completed”. When an Engineering Manager wishes to compute the level of completion the following equation is used:

$$Completion\ Level\ based\ on\ belief = \frac{Work\ Complete}{Work\ Complete + Known\ Work}$$

This equation is based on observed metrics and is the work percentage *believed* to be complete. However, when this equation is expanded to show all Stocks we get:

$$Completion\ Level\ based\ on\ belief$$
$$= \frac{Work\ Done + Undiscovered\ Rework}{Work\ Done + Undiscovered\ Rework + Work\ to\ Do + Rework\ to\ Do}$$

“Undiscovered Rework” is *not* complete. To compute the actual completion level, we need to remove “Undiscovered Rework” from the numerator resulting in the following:

$$Actual\ Completion\ Level$$
$$= \frac{Work\ Done}{Work\ Done + Undiscovered\ Rework + Work\ to\ Do + Rework\ to\ Do}$$

These equations are tracked throughout the model timeline. This research stops model execution time at the chosen completion rate (e.g. Completion Level based on belief = 80%) and measures the Actual Completion Level that results. The Engineering Manager chooses the completion criteria for the model. The first choice is to either complete work based on a scheduled completion date or based on a chosen completion percentage based on belief. If the latter decision is made, then the Engineering Manager must choose the level of completion (e.g. 80%, 90%, 100% complete). These decisions determine the resulting cost and schedule impact.

3.3.6 Cost and Schedule

Cost and Schedule are collected and tracked for each of the three phases. Cost is calculated in units of Person-Months and is computed by accumulating the monthly effort over time. Schedule is computed as the time when the effort is considered complete. There are two options for defining complete. Option 1 determines completion based on a scheduled completion time. For this option, all remaining work is collected, and a defect ratio is calculated. Option 2 determines completion based on “Completion Level based on Belief” and is controlled based on the desired outcome. For example, if the Engineering Manager desires zero defect, a “stop at 100% complete” is chosen. A choice of 80% would finish sooner and result in some level of defects. Defect ratio is calculated as:

$$Defect\ ratio = 1 - Actual\ Completion\ Level$$

3.5 Data available for research

The data available for this research captures four cases where a Rapid Response Capability was built by one organization, delivered to an LWS in a different organization. The integration into the LWS was performed by a dedicated team in LWS organization. Cost over time was captured for each of the three phases. The RRP tracked cost separately as an independent activity. The LWS Program tracked cost with the detail required to isolate the integration team efforts from the rest of the Program activity.

Since the data came from within a commercial organization, it was put through a cleansing process, vetted, and approval was received from the organization to release the data for this research. The cleansing process included scaling the data so that relating the values back to original currency was not possible. Also, any information associating the data to the accompanying real LWS or RRP has been sanitized. What can be said about the four cases is that they would all classify as Large Programs per DoD definition, and that all four programs were successfully delivered to the end user. Cost Data is provided in Appendix C.

3.6 Design of Experiments

This section describes the Design of Experiments for the model. Each Hypothesis is addressed in terms of valid range, and the range exercised in the model to generate the results in Chapter 4.

TRL

TRL can range from 1 to 9, however, it is very rare that an LWS will choose to accept TRL 1-3. These technologies are in very early stages of discovery and are generally considered too risky for integration into an LWS. TRL 9 capabilities are considered to not need integration with the LWS and this value is outside the range for simulation. The data used for this research included RRP ranging from 4 to 6. Using Conrow's coefficients, we can extend the valid range for TRL in this simulation model from TRL 4 through TRL 8.

Integration Time

Integration time must start after the RRP completes, and after the LWS begins. The data includes four different integration start times relative to LWS. The valid range for start time is bounded by available data and shown in Table 3-5.

Table 3-5. Integration Start Time Valid Range

	RRP End	INT Start	LWS Start	LWS End	Valid Range
USECASE1	11	20	11	47	11 - 47
USECASE2	12	49	30	61	30 – 61
USECASE3	11	22	18	45	18 – 45
USECASE4	17	25	1	50	17 – 50

Units in Months.

Management Reserve

Management Reserve is only bounded by the willingness of the organization to allocate a percentage of the effort. The value cannot be negative. For this research we explore the range from 0% in steps of 5% through 30%.

Level of Completion

Level of completion is explored in the range from 80% to 100%. 80% was chosen as the lower range based on an unsubstantiated theory that the military can work with an 80% solution today, rather than waiting for a 100% solution tomorrow. In future research, that data point could be used in conjunction with other expert interviews to determine DoD utility curves for acceptable technology completion rates. This research only focuses on the measure of defects at a chosen completion rate. Since there are three phases to this model, each phase can choose a completion rate, and the cascade effect is analyzed using One Factor at a Time (OFAT) analysis. Table 3-6 shows the OFAT trials used for simulation. Trials 1-5 vary the completion of RRP, where INT and LWS each deliver at an 80% completion level. Trials 6-10 vary the completion of INT, where RRP delivers a complete solution, and LWS delivers and 80% solution. Trials 11-15 vary the completion of LWS, where RRP and INT deliver complete solutions, and LWS completes to the desired level. Trial 1 is an example where an 80% delivery standard is consistent with all three phases.

Table 3-6. Completion Level based on Belief OFAT Trials

	Completion Level based on Belief (%)			
	Trial No.	RRP	INT	LWS
OFAT Run 1	1	80	80	80
	2	85	80	80
	3	90	80	80
	4	95	80	80
	5	100	80	80
OFAT Run 2	6	100	80	80
	7	100	85	80
	8	100	90	80
	9	100	95	80
	10	100	100	80
OFAT Run 3	11	100	100	80
	12	100	100	85
	13	100	100	90
	14	100	100	95
	15	100	100	100

All values in %

3.7 Model Validation and Verification

Model validation and Verification follows the process described in Sterman (2000). The validation steps in Table 2-2 are discussed in this section. For each step, the methodology is discussed, followed by the results of that methodology.

Step 1: Boundary Adequacy

Boundary Adequacy determines if the important concepts the research is addressing are endogenous to the model. Does the behavior or policy recommendations change when boundary assumptions relaxed. The four hypotheses in this research are used to define the research boundary for the system. That boundary is extended to ensure that any decisions that Engineering Managers make in the model have impacts contained within the system bounds. The model used for this Praxis includes the two productivity and four quality CLDs, and the Stocks and Flows discussed in section 3.4. Model boundaries are established using cloud symbols. The structure of the Work Cycle and Quality and Productivity loops are well founded in literature, as well as the inter phase model interactions. SME review was also used to validate this step.

Step 2: Structure Assessment

Structure Assessment determines if the structure of the model is consistent with relevant descriptions of the system. Do the decision rules in the system capture the behavior of actors in the system? This assessment uses similar techniques as with Boundary Adequacy with the focus on internal workings of the model. The Quality, Productivity, and Interaction CLDs in section 3.4 capture Model behavior under the conditions relevant to this research. The impact of Engineering Manager decisions is captured within the system boundaries. All behavior is self-contained in the model. Staff entering and leaving the system are the only variables that cross the system boundary and are considered a reasonable flow. SME review was also used to validate this step.

Step 3: Dimension Consistency

Dimensional Consistency ensures that each equation in the model is dimensionally consistent. VenSim performs this function. The resulting analysis found no inconsistencies in the model equations.

Step 4: Parameter Assessment

Parameter Assessment determines if the variables are consistent with knowledge of the system and have real world counterparts. The model uses Tasks as a unit of work, as defined by Cooper (2003). Productivity is defined as the speed with which Task are performed. Quality is defined as the correctness of Tasks performed. Each CLD is discussed with respect to real world behavior. SME review was also used to validate this step.

Step 5: Extreme Conditions

Extreme Conditions determine if the equations make sense with extreme values. The model is most sensitive to startup effects and “divide by zero” errors when values trend outside the valid range for the simulation. Each equation was analyzed for extreme behavior. In several places, equations are provided with “safety bumpers” to avoid impractical behavior (e.g. divide by zero, negative staff). Several of these cases are easily found by examining the provided VenSim model. The addition of two CLDs, Uncertain Requirements, and Average Quality were also found necessary to account for startup conditions and to dampen model response to extreme inputs. SME review was also used to validate this step.

Step 6: Integration Error

Integration Error determines the response of the model when the resolution of integration is changed in the model. For example, this model is simulated with 0.25 month time steps. The model was run with 0.125-month and 0.5-month time steps with no difference in results or model behavior.

Step 7: Behavior Reproduction

Behavior Reproduction determines if the model reproduces the behavior of interest in the system (qualitatively and quantitatively). Does the model endogenously generate symptoms of difficulty motivating the study, and generates behavior observed in real systems? Data from four use cases was used to calibrate the model. The model was able to replicate the resulting cost and schedule with R^2 values at reflected in Table 3-7.

Table 3-7. Calibration Results matching Model to Real World Data

	R^2 fit to Calibration Data		
	RRP	INT	LWS
USECASE1	0.9913	0.9961	0.9877
USECASE2	0.9539	0.9928	0.9534
USECASE3	0.9967	0.9720	0.9259
USECASE4	0.9941	0.9964	0.9934

Step 8: Boundary Anomaly

Behavior Anomaly determines if anomalous behaviors result when assumptions of the model are changed or deleted. Loop knockout was used both for the purpose of behavior anomaly and to determine model parsimony. Removing the Average Quality loop and Uncertain customer requirement loop changed the respective R^2 values to less than 0.76. The inclusion of these two loops was determined necessary to maintain model validity.

Step 9: Family Member

Family Member determines if the model behavior is observed in other instances of the same system. The four use cases were used for model calibration and analysis to satisfy that the model is calibrated to a range of systems. The data provided captures the size ratio of RRP to LWS, and ranges from 0.28% to 2.4%. That is, the number Tasks planned for RRP divided by the number of Tasks planned for LWS adheres to this range. No data is available to validate the Model outside this range. The Model does provide the ability for organizations to use internal data to calibrate the model for desired scenarios.

Step 10: Surprise Behavior

Surprise Behavior determines if the model generates previously unobserved or unrecognized behavior. For all simulation runs across all four hypothesis and simulation ranges, including loop knock out tests, no surprise behavior was observed. VenSim provides warnings and errors when undesired behavior occurs. No such errors were observed for the experiments run for this research.

Step 11: Sensitivity Analysis

Sensitivity Analysis determines if the model exhibits numerical or behavioral sensitivity. The model was run over a range of decision criteria described in section 3.5. As will be seen in the results section there are no significant variations from the expected results (e.g. no unexplained jumps or deviations in the model results).

Step 12: System Improvement

System Improvement determines if the modeling process helped change the system for the better. The conclusion section of this research provides the author's assessment of the utility of this research. True validation of step 12 can only occur within the organization leveraging this research.

3.8 Conclusion

VenSim DSS Version 8.0.7 x64 SD Modeling software was used to generate the overall SD Model and MATLAB was used to automate the execution runs for each of the 4 use cases and plot the results for further analysis. The complete model in VenSim, as well as the Matlab scripts used to automate are available. A graphical version of the VenSim model used for this research is presented in Appendix A, and the equations used for the model are presented in Appendix B.

Chapter 4—Results

4.1 Introduction

This chapter provides the results of each of the Design of Experiment trials performed to test the four Hypothesis presented in chapter 1. The System Dynamics (SD) model was run for each of the four case studies and results are tabulated in Appendix D. The results are presented here graphically, and a statistical analysis is presented for each Hypothesis to either fail to reject or reject each of the null hypothesis.

Figure 4-1 shows the flow of the experiments starting with Model generation discussed in section 3.4. The model calibration is discussed in Section 3.7 where the data used for calibration is presented in Tables C-1, C-3, C-5, and C-7 for each Use Case. The results of calibration are shown in Table 3-3 where R^2 statistics capture the wellness of model fit to real world data. The resulting model parameters are presented in Tables C-2, C-4, C-6, and C-8. The design of experiments is shown in section 3.6 which sets up the results presented in this chapter. Sections 4.2, 4.3, 4.4, and 4.5 present the results of Technology Readiness Level (TRL), Integration Time, Management Reserve, and Level of Completeness experiments respectively.

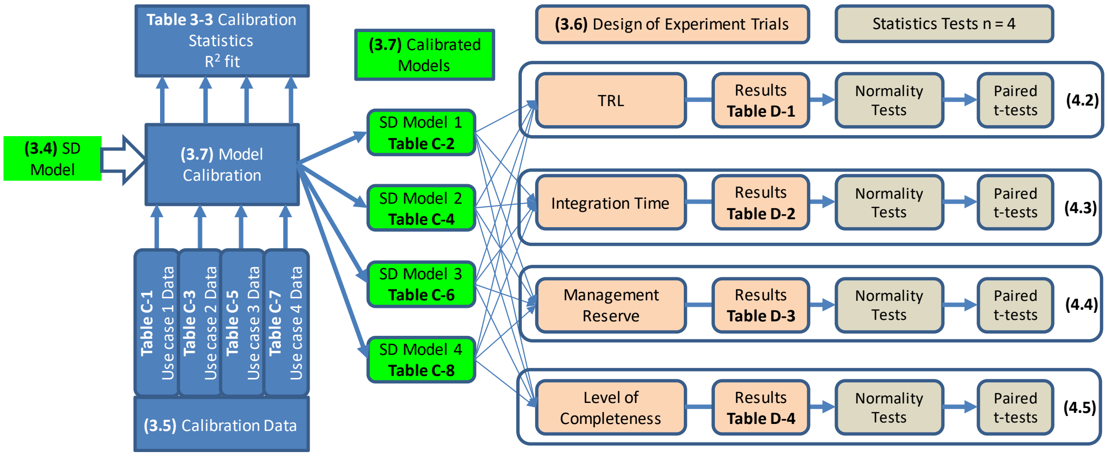

Figure 4-1. Experiments flow of information mapped to Praxis sections

Cost Normalization – Level setting results for comparison

The Real-World Cost Data is presented in Appendix C. Since the scale of cost data across the four Use Cases varies, all model output cost data is normalized for comparison. The cost data is presented as a ratio of model output to the real-world costs where:

$$Cost\ Ratio = \frac{Cost\ Data\ produced\ by\ SD\ Model}{Real\ World\ Cost\ Data}$$

Real World Cost Data is captured from each Use Case as the value in the final row (total cumulative cost) of the data provided in Appendix C. This value captures the actual cost it took to complete each of the three phases. For example, for Use Case 1, the total costs to integrate a TRL-6 capability into that Large Weapon System are categorized by RRP, INT, LWS, and Total are 56.47, 71.8, 3441.41, and 3569.68 respectively. The model results for Use Case 1 are normalized by these values. Use Cases 2 – 4 are likewise normalized by the similar values from the respective tables in Appendix C. This normalization allows comparison across the four Use Cases.

4.2 Technology Readiness Level Results

H1: Rapid Response Projects which increase TRL by one level result in an overall Program cost reduction (overall cost change less than zero). Overall Program cost includes the cost of Rapid Response Project, Integration activity, and Large Weapon System costs combined.

Null Hypothesis: A higher TRL level has no impact on total program costs

Alternate Hypothesis: A Higher TRL level reduces total program costs

$$H_0: \mu_1 = \mu_2 \qquad H_A: \mu_1 > \mu_2$$

The SD Model was run by changing the independent variable "New TRL" from 4 to 8. For all four Use Cases, TRL-6 was the real-world data point. Results are presented in Figure 4-2, with the tabulated results presented in Table D-1. Four graphs are shown that capture Rapid Response Project (RRP), Integration Tasks (INT), Large Weapon System (LWS), and Total costs (sum of RRP, INT, and LWS). In each Graph, four curves plot results of each Use Case. Values above 1.0 indicates that the Cost produced by the SD Model experiment exceeded the actual costs, and values less than 1.0 indicate lower cost. For example, 0.8 indicates that the SD Model experiment cost resulted in 80% of the Real-World cost, 1.2 indicates the SD Model experiment resulted in 20% higher cost.

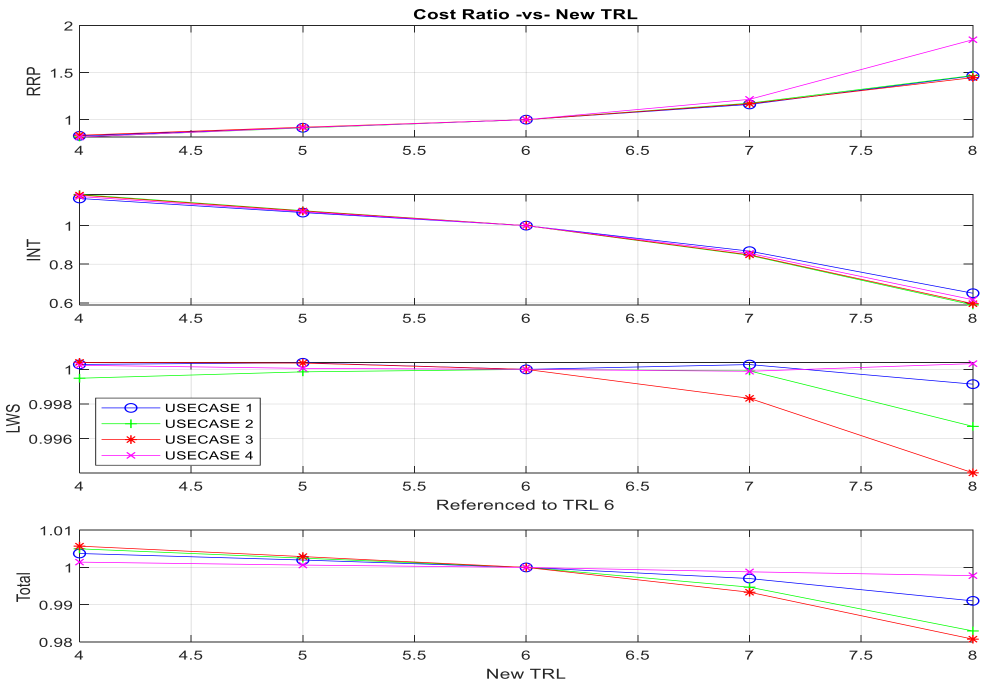

Figure 4-2. Cost Impact of Changing delivered RRP TRL

Since there are four Use Cases, we can analyze the results using paired t-tests with a sample set of four points, and a t-distribution with 3 degrees of freedom. First, we perform an analysis of normality for the resulting data points. Ten normality tests were performed on each data set: Kolmogorov-Smirnov test (Limiting form (KS-Lim), Stephens Method (KS-S), Marsaglia Method (KS-M), Lilliefors test (KS-L)), Anderson-Darling (AD) test, Cramer-Von Mises (CvM) test, Shapiro-Wilk (SW) test, Shapiro-Francia (SF) test, Jarque-Bera (JB) test, D'gostino and Pearson (DAP) test. These tests were all performed using Matlab scripts. The results of these tests are tabulated using an alpha value of 0.05. Table 4-1 shows the number of tests that fail to reject the Null Hypothesis that the data set is Normal, that is, there is not enough evidence to support that the data is not Normal. A value of 10 indicates that all 10 of the listed tests resulted in a P-value greater than an alpha of 0.05. Since TRL-6 is the reference point used for data normalization, Normality tests are not applicable since those values are all 1s.

Table 4-1. Normality Table for TRL Model Results

	TRL-4	TRL-5	TRL-6	TRL-7	TRL-8
RRP	6	10	N/A	4	4
INT	10	10	N/A	10	9
LWS	4	6	N/A	4	10
TOTAL	10	10	N/A	10	10

The results range from 4 to 10 out of 10 tests passing. With such a small data set normality is generally not expected, however the results show that we can reasonably proceed with performing paired t-tests on the resulting data.

One tailed paired t-tests were performed pairwise on each data set to determine if the mean level of each cost ratio is significantly greater than the other. The P-Values of these tests are presented in Table 4-2 through Table 4-5. The tables compare all combinations of TRL-4 through TRL-8 for RRP, INT, LWS and Total costs. The columns indicate the initial TRL level data point while the rows capture the change in TRL data point. For example, column TRL-5 - row TRL-7 indicates a comparison between an initial TRL of 5, and the change to a TRL of 7. The diagonal indicates no change and the cell is left blank. Tables 4-2 through Table 4-4 capture the cost comparisons for RRP, INT, and LWS efforts individually. Table 4-5 captures combined costs.

Table 4-2. P-Value Table for TRL Model Results – Comparing RRP Cost Deltas

		Initial RRP TRL				
		TRL-4	TRL-5	TRL-6	TRL-7	TRL-8
Target RRP TRL	TRL-4		0.0001	0.0000	0.0001	0.0026
	TRL-5			0.0000	0.0001	0.0036
	TRL-6				0.0003	0.0053
	TRL-7					0.0109
	TRL-8					

Table 4-3. P-Value Table for TRL Model Results – Comparing INT Cost Deltas

		Initial RRP TRL				
		TRL-4	TRL-5	TRL-6	TRL-7	TRL-8
Target RRP TRL	TRL-4					
	TRL-5	0.0000				
	TRL-6	0.0000	0.0000			
	TRL-7	0.0000	0.0000	0.0000		
	TRL-8	0.0000	0.0000	0.0000	0.0001	

Table 4-4. P-Value Table for TRL Model Results – Comparing LWS Cost Deltas

		Initial RRP TRL				
		TRL-4	TRL-5	TRL-6	TRL-7	TRL-8
Target RRP TRL	TRL-4					
	TRL-5	0.6809				
	TRL-6	0.3241	0.1400			
	TRL-7	0.2138	0.1683	0.2139		
	TRL-8	0.0836	0.0822	0.0891	0.0742	

Table 4-5. P-Value Table for TRL Model Results – Comparing TOTAL Cost Deltas

		Initial RRP TRL				
		TRL-4	TRL-5	TRL-6	TRL-7	TRL-8
Target RRP TRL	TRL-4					
	TRL-5	0.0110				
	TRL-6	0.0122	0.0136			
	TRL-7	0.0168	0.0189	0.0226		
	TRL-8	0.0233	0.0254	0.0279	0.0312	

The results are color coded to show Alpha Value thresholds of 0.01, 0.05, and 0.1 with the colors blue, green and yellow respectively. As expected, the tables for RRP (Table 4-2) and INT (Table 4-3) show significant mean deviations since the result of a TRL shift moves Tasks from one to the other. Shifting from TRL 5 to a TRL 6 moves work from INT into RRP. It is expected that in this case, INT will be less expensive and

RRP will be more expensive. In that case, the RRP table shows a P-Value of 1.0, and the INT table shows a P-Value of 0.0. What is interesting about the results is that even though the same amount of work is shifted between RRP and INT, the two tables, and also the curves in Figure 4-2, are not symmetrical. A TRL shift from 7 to 8, for example, shows a less significant impact in the RRP table than the INT table, where an alpha of 0.05 is required rather than an alpha of 0.01. This suggests that changes in TRL have greater impact on the INT phase than the RRP phase.

Examining the LWS P-Table (Table 4-4), we see that there is no significance to changing TRL levels until a TRL of 8 is selected as the target TRL for RRP. However, when examining Total cost deltas (Table 4-5), we see that all TRL changes show significance reduction of cost for an alpha of 0.05.

Although the data set is small, only 4 points, the results indicate that there is evidence to reject the Null Hypothesis, and that an increase in TRL does reduce Total program cost. Examining the trend in Figure 4-2, we also see that an increased TRL of an RRP capability does suggest reduced total program costs. Keep in mind that total program costs *include* the cost of RRP.

Conclusion: There is evidence to reject the null Hypothesis for an alpha of 0.05. We accept the alternative Hypothesis that an increase in RRP TRL level reduces overall program cost.

4.3 Integration Time Results

H2: Rapid Response Project integrations with Large Weapon System that start 6 months earlier than the planned integration point lowers the integration costs by more than 2%.

Null Hypothesis: An integration start time accelerated by 6 months will not reduce total program costs by 2%. H_O: Savings are no more that 2%

Alternate Hypothesis: An integration start time accelerated by 6 months will reduce total program costs by 2%. H_A: Savings are greater than 2%

$$H_0: \mu_1 - \mu_2 = 0.02 \qquad H_A: \mu_1 - \mu_2 > 0.02$$

The SD Model was run by changing the integration start time to range from 5 months earlier than the actual integration time to 5 months later. For integration times earlier than 5 months or later than 5 months the sample set of data drops below 4 points. The time window chosen maintained the valid range of all four Use Cases. For each Use Cases, month zero indicates the actual integration month. Results are presented in Figure 4-3, with the tabulated results presented in Table D-2. Three graphs are shown that capture Integration Tasks (INT), Large Weapon System (LWS), and Total costs (sum of RRP, INT, and LWS). Note that RRP costs are not impacted by this independent variable, and not shown. In each Graph, four curves plot results of each Use Case. Values above one indicates that the Cost produced by the SD Model experiment exceeded the actual costs, and values less than one indicate lower cost.

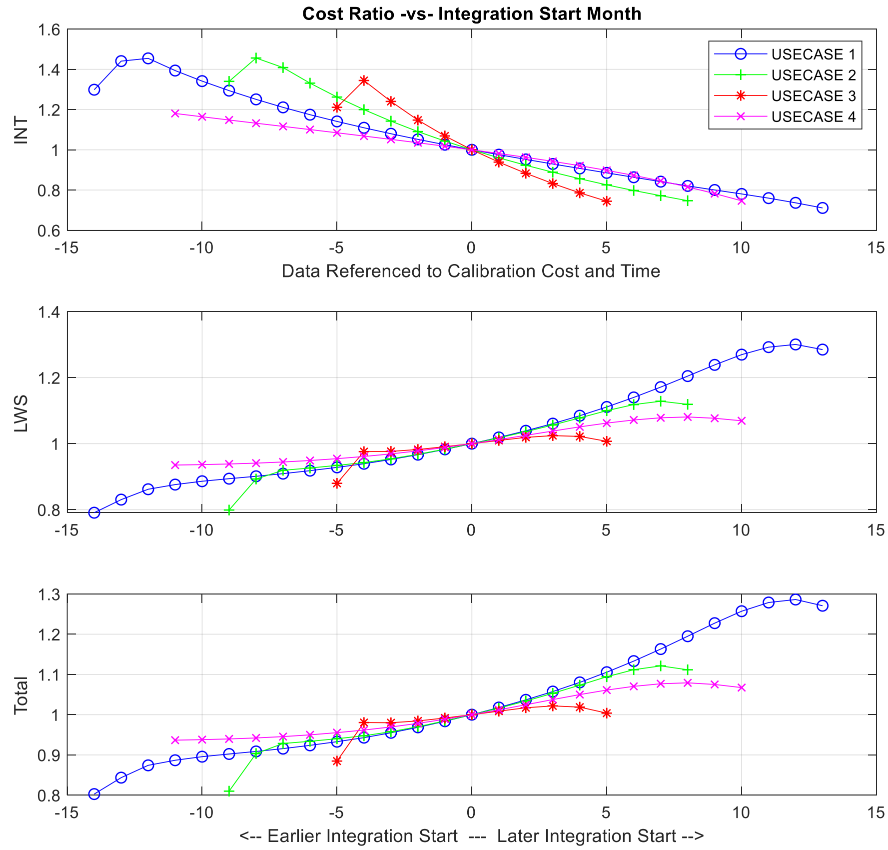

Figure 4-3. Cost Impact of Changing Integration Time

Since there are four Use Cases, we can analyze the results using paired t-tests with a sample set of four points, and a t-distribution with 3 degrees of freedom. First, we perform an analysis of normality for the resulting data points. The same ten tests are used as with Hypothesis 1. The results of these tests are tabulated using an alpha value of 0.05. Table 4-6 shows the number of tests that fail to reject the Null Hypothesis that the data set is Normal, that is, there is not enough evidence to support that the data is not Normal.

Table 4-6. Normality Table for TRL Model Results

	Months Shifted										
	-5	-4	-3	-2	-1	0	1	2	3	4	5
RRP	10	10	10	10	10	N/A	10	10	10	10	9
INT	7	10	6	5	5	N/A	10	10	10	10	10
LWS	4	10	10	10	9	N/A	10	10	10	10	9
TOTAL	10	10	10	10	10	N/A	10	10	10	10	9

The results range from 4 to 10 out of 10 tests passing. With such a small data set normality is generally not expected, however the results show that we can reasonably proceed with performing paired t-tests on the resulting data.

One-tailed paired t-tests were performed on each data set to determine the p-value of each cost ratio with respect to H_O and H_A above. The P-Values of these tests are presented in Table 4-7 through Table 4-9. The table compares all combinations of Integration Times from -5 months to +5 months for RRP, INT, LWS and Total costs. The rows are the initial month trial, the columns are the comparison month trials. The Entry of 1, -5 indicates a trial where integration at month 1 is compared to integration at month -5 (a six-month delta).

Table 4-7. P-Value Table for Integration Time Shift Model Results – Comparing INT Cost Deltas

Change in Integration Month Rows = Initial Month, Columns = Comparison Month											
	-5	-4	-3	-2	-1	0	1	2	3	4	5
-5		0.702	0.230	0.037	0.018	0.014	0.013	0.012	0.011	0.010	0.009
-4			0.099	0.058	0.046	0.039	0.035	0.031	0.028	0.025	0.022
-3				0.101	0.053	0.040	0.034	0.029	0.025	0.022	0.019
-2					0.099	0.046	0.034	0.027	0.023	0.020	0.017
-1						0.098	0.040	0.028	0.022	0.018	0.015
0							0.098	0.034	0.023	0.017	0.014
1								0.096	0.028	0.018	0.013
2									0.091	0.022	0.013
3										0.083	0.015
4											0.066
5											

Table 4-8. P-Value Table for Integration Time Shift Model Results – Comparing LWS Cost Deltas

Change in Integration Month Rows = Initial Month, Columns = Comparison Month											
	-5	-4	-3	-2	-1	0	1	2	3	4	5
-5											

Change in Integration Month

Rows = Initial Month, Columns = Comparison Month

	-5	-4	-3	-2	-1	0	1	2	3	4	5
-4	0.331										
-3	0.203	0.989									
-2	0.099	0.577	0.990								
-1	0.044	0.088	0.228	0.985							
0	0.019	0.030	0.031	0.100	0.976						
1	0.009	0.017	0.015	0.020	0.069	0.957					
2	0.004	0.013	0.011	0.012	0.019	0.064	0.921				
3	0.002	0.013	0.011	0.012	0.017	0.030	0.099	0.858			
4	0.002	0.017	0.016	0.018	0.024	0.037	0.071	0.212	0.810		
5	0.003	0.029	0.029	0.034	0.043	0.061	0.098	0.181	0.379	0.793	

Table 4-9. P-Value Table for Integration Time Shift Model Results – Comparing Total Cost Deltas

Change in Integration Month

Rows = Initial Month, Columns = Comparison Month

	-5	-4	-3	-2	-1	0	1	2	3	4	5
-5											
-4	0.341										
-3	0.220	0.990									
-2	0.112	0.701	0.992								

Change in Integration Month

Rows = Initial Month, Columns = Comparison Month

	-5	-4	-3	-2	-1	0	1	2	3	4	5
-1	0.050	0.134	0.353	0.990							
0	0.021	0.041	0.043	0.152	0.984						
1	**0.010**	0.021	0.018	0.025	0.096	0.972					
2	0.004	**0.015**	0.013	0.014	0.023	0.083	0.947				
3	0.002	0.015	**0.013**	0.014	0.019	0.035	0.122	0.892			
4	0.001	0.020	0.019	**0.021**	0.027	0.041	0.081	0.244	0.839		
5	0.002	0.033	0.033	0.038	**0.048**	0.068	0.108	0.200	0.409	0.813	

The results are color coded to show Alpha Value thresholds of 0.01, 0.05, and 0.1 with the colors blue, green and yellow respectively. A P-Value above the chosen Alpha indicates that there is not enough evidence to reject H_O, and thus not enough evidence to support that cost savings are not greater than 2%. A P-Value below the chosen alpha value allows us to reject H_O and accept H_A, proving that cost savings are at least 2%.

Each table is divided by a diagonal in which values above the diagonal indicate later integration times, and values below the diagonal indicate earlier integration times. Table 4-7 shows P-Values below alpha for later integration times (above the diagonal) for INT, while Table 4-8 shows P-Values below alpha for earlier integration times (below the diagonal) for LWS. This indicates that later integration times reduce cost for INT, where earlier integration times reduce cost for LWS. Table 4-9 also shows P-Values below alpha for earlier integration times for total program costs. This suggests that earlier integration times are more expensive for INT, but cheaper for LWS, with a total lower cost for earlier integration times. Said differently, earlier integration times increase the cost of integration, but reduce the cost to the Large Weapon System effort, and in doing so, reduces total program costs.

The bolded values in Table 4-9 indicate the 5 instances where integration occurred 6 months earlier. The P-Values of 0.01, 0.015, 0.013, 0.021, and 0.048 are all lower than an alpha of 0.05, thus all instances indicate we can accept the alternative hypothesis that cost savings are at least 2% when integration occurs 6 months earlier. The results were also run for candidate savings values ranging from 0% to 6% with the results shown in Table 4-10.

Table 4-10. P-Value Table for Integration Time Shift Model Results – Comparing 6 months earlier integration

		Change in Integration Month				
		-5,1	-4,2	-3,3	-2,4	-1,5
Cost Savings	0%	0.005	0.006	0.006	0.010	0.025
	1%	0.006	0.009	0.008	0.014	0.034
	2%	0.010	0.015	0.013	0.021	0.048
	3%	0.015	0.027	0.021	0.032	0.070
	4%	0.024	0.051	0.038	0.053	0.106
	5%	0.044	0.110	0.073	0.092	0.162

		Change in Integration Month				
		-5,1	-4,2	-3,3	-2,4	-1,5
	6%	0.085	0.248	0.154	0.166	0.248

The results show that a 2% savings is a reasonable expectation for an alpha value of 0.05. Also, for an alpha of 0.05, 4 of 5 samples indicate that a 3% cost saving could be expected.

Conclusion: Evidence exists to reject the null Hypothesis. The Alternate Hypothesis is accepted to indicate that a 2% cost savings can be expected by starting integration 6 months earlier.

4.4 Management Reserve Results

H3: Integration efforts that increase management reserve by 5% lead lower overall integration costs of greater than 5%.

Null Hypothesis: A 5% increase in management reserve has no impact on total program costs

Alternate Hypothesis: A 5% increase in management reserve will reduce total program costs by 5%, H_O: Savings are no more that 5%, H_A: Savings are greater than 5%

$$H_0: \mu_1 - \mu_2 = 0.05 \qquad H_A: \mu_1 - \mu_2 > 0.05$$

The SD Model was run by changing the independent variable "Estimated Rework" (variable used to capture Management Reserve) from 0% to 30% in increments of 5%. For all four Use Cases, Estimated Rework for the real-world data point was at 10%. Results are presented in Figure 4-4, with the tabulated results presented in Table D-3. Four graphs are shown that capture Rapid Response Project (RRP), Integration

Tasks (INT), Large Weapon System (LWS), and Total costs (sum of RRP, INT, and LWS). In each Graph, four curves plot results of each Use Case. Values above one indicates that the Cost produced by the SD Model exceeded the actual costs, and values less than one indicate lower cost.

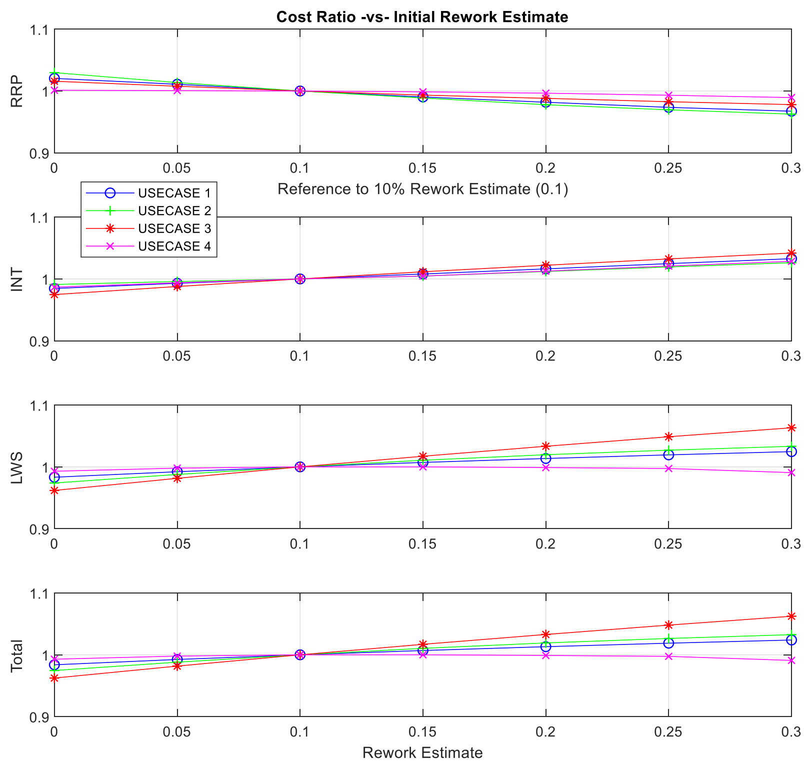

Figure 4-4. Cost Impact of Changing Management Reserve

Since there are four Use Cases, we can analyze the results using paired t-tests with a sample set of four points, and a t-distribution with 3 degrees of freedom. First, we perform an analysis of normality for the resulting data points. The same ten tests are used as with Hypothesis 1. The results of these tests are tabulated using an alpha value of 0.05. Table 4-11 shows the number of tests that fail to reject the Null Hypothesis that the data set is Normal, that is, there is not enough evidence to support that the data is not Normal.

Table 4-11. Normality Table for Management Reserve Model Results

	0%	**5%**	**10%**	**15%**	**20%**	**25%**	**30%**
RRP	10	10	N/A	10	10	10	10
INT	10	7	N/A	5	7	9	10
LWS	10	10	N/A	10	10	10	10
TOTAL	10	10	N/A	10	10	10	10

The results range from 5 to 10 out of 10 tests passing. With such a small data set normality is generally not expected, however the results show that we can reasonably proceed with performing paired t-tests on the resulting data.

One-tailed paired t-tests were performed pairwise on each data set to determine if the mean level of each cost ratio changed significantly by 5%. All paired t-tests resulted in P-values of 0.5 or greater, indicating that there is not enough evidence to reject the null hypothesis.

The results were also run for savings values ranging from 0% to 5% with the results shown in Table 4-12. The columns collect the P-Values where management reserve was increased by 5%, for example column 10% indicates a change from 5% to

10% in management reserve. The rows are the P-Values resulting when compared for a cost savings of the indicated percentage.

Table 4-12. P-Value Table for Management Reserve Model Results – Comparing 5% management reserve

		Management Reserve					
		5%	10%	15%	20%	25%	30%
Cost Savings	0%	0.0167	0.0312	0.0464	0.0622	0.0732	0.1740
	1%	0.3200	0.5057	0.6403	0.7406	0.8005	0.8454
	2%	0.9632	0.9696	0.9758	0.9813	0.9851	0.9810
	3%	0.9952	0.9950	0.9955	0.9962	0.9968	0.9951
	4%	0.9986	0.9984	0.9985	0.9987	0.9989	0.9981
	5%	0.9994	0.9993	0.9993	0.9994	0.9995	0.9991

The results show that any cost savings from increasing management reserve is minimal. The 0% row indicates that there is a non-zero savings, as can somewhat be seen in Figure 4-4, however, this is far less than the 5% hypothesized.

Conclusion: There is no evidence to reject the null Hypothesis. The data indicates that for a Large Weapon System Program, there is no evidence to support that increasing management reserve by 5% will reduce overall program costs by 5%.

4.5 Delivery Completeness Results

H4: Integration efforts that deliver 80% solutions result in Large Weapon System that are less than 70% complete.

Null Hypothesis: An integration effort delivering an 80% solution deliver less than a 30% defect rate. H_O: Defect Rate is not greater than 30%

Alternate Hypothesis: An integration effort delivering an 80% solution will deliver at least a 30% defect rate. H_A: Defect Rate is at least 30%

$$H_0: \mu_1 - \mu_2 = 0.3 \qquad H_A: \mu_1 - \mu_2 > 0.3$$

The SD Model was run by changing the independent variable "Fraction Complete to Finish" (variable used to capture when to stop work based on completion level) from 80% to 100% in increments of 5% for each of the sub-models (RRP, INT, and LWS) using the OFAT design presented in Table 3-2. For each OFAT set of trials, data was normalized to the calibration data as with previous trials. Results are presented in Figure 4-5 through Figure 4-7, with the tabulated results presented in Table D-4. Figure 4-5 shows the OFAT trials where RRP completion is varied from 80% to 100%, and INT and LWS are fixed at 80%. Figure 4-6 shows the OFAT trials where INT completion is varied from 80% to 100% and RRP is fixed at 100%, LWS if fixed at 80%. Figure 4-7 shows the OFAT trials where LWS completion is varied from 80% to 100% and RRP and INT are fixed at 100%. In each figure, four graphs are shown that capture Rapid

Response Project (RRP), Integration Tasks (INT), Large Weapon System (LWS), and Total costs (sum of RRP, INT, and LWS). In each Graph, four curves plot results of each Use Case. Values above one indicates that the Cost produced by the SD Model exceeded the actual costs, and values less than one indicate lower cost.

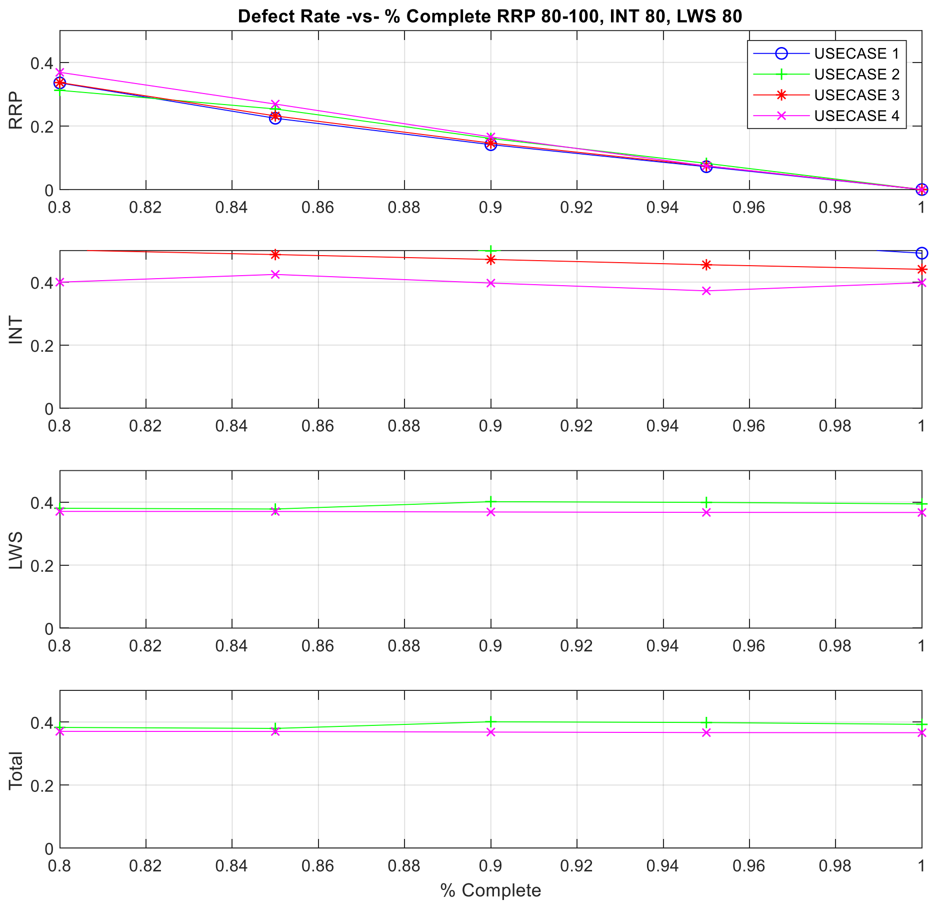

Figure 4-5. Defect Rate for OFAT Trial Set 1 Varying RRP Completion

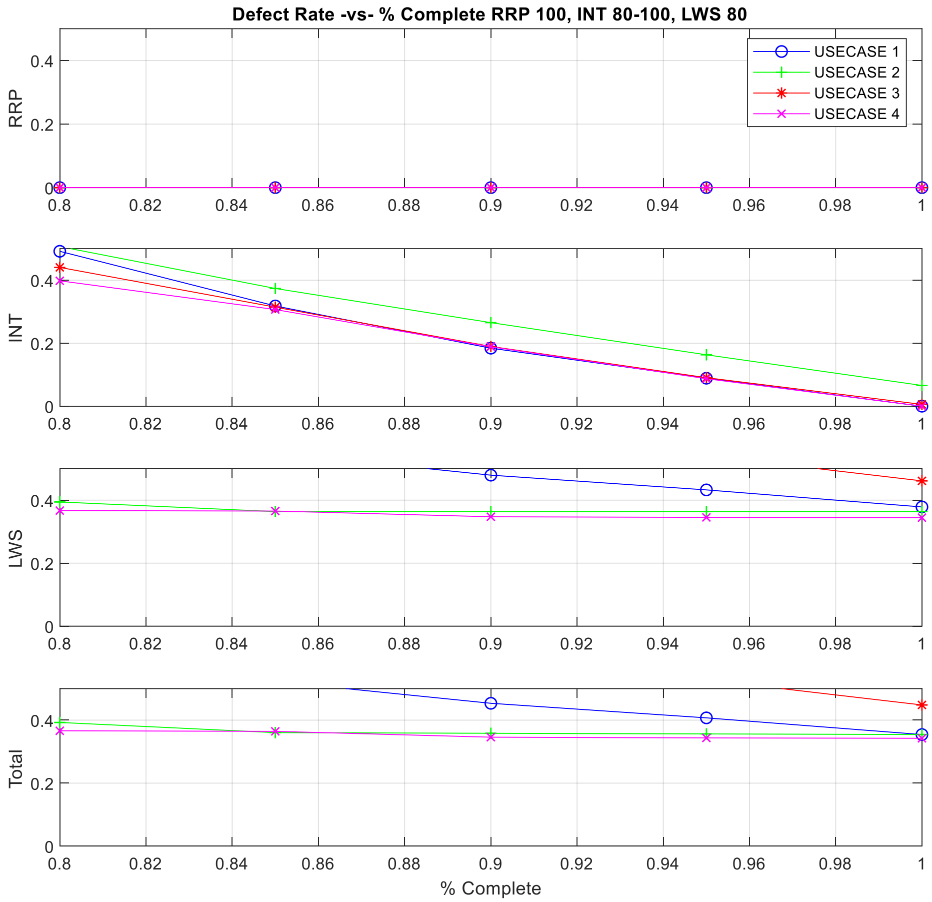

Figure 4-6. Defect Rate for OFAT Trial Set 2 Varying INT Completion

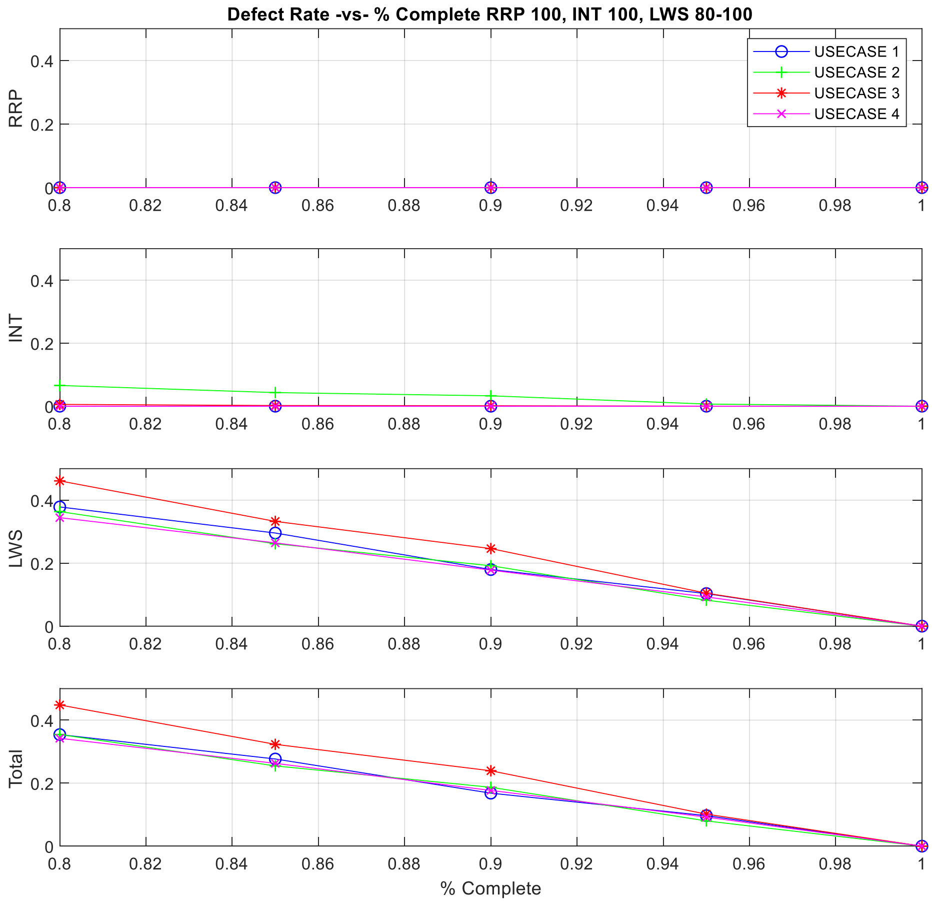

Figure 4-7. Defect Rate for OFAT Trial Set 3 Varying LWS Completion

Since there are four Use Cases, we can analyze the results using paired t-tests with a sample set of four points, and a t-distribution with 3 degrees of freedom. First, we perform an analysis of normality for the resulting data points. The same ten tests are used as with Hypothesis 1. The results of these tests are tabulated using an alpha value of 0.05. Table 4-13 shows the number of tests that fail to reject the Null Hypothesis that the data set is Normal, that is, there is not enough evidence to support that the data is not Normal.

Table 4-13. Normality Table for Delivery Completeness Model Results

	80%	85%	90%	95%	100%
OFAT Trial 1 – Vary RRP (INT 80%, LWS 80%)					
RRP	9	10	9	4	0
INT	4	6	8	8	10
LWS	3	3	3	3	3
TOTAL	3	3	3	3	3
OFAT Trial 2 – Vary INT (RRP 100%, LWS 80%)					
RRP	N/A	N/A	N/A	N/A	N/A
INT	10	4	4	4	4
LWS	3	3	7	9	4
TOTAL	3	3	8	6	4
OFAT Trial 3 – Vary LWS (RRP 100%, INT 100%)					
RRP	N/A	N/A	N/A	N/A	N/A
INT	4	4	4	4	3
LWS	4	8	4	7	3
TOTAL	4	5	4	10	3

The results range from 3 to 10 out of 10 tests passing. With such a small data set normality is generally not expected, however the results show that we can reasonably proceed with performing paired t-tests on the resulting data.

One-tailed paired t-tests were performed on each data set to determine if the mean level of defects was significantly greater than 30%. The P-Values of these tests are presented in Table 4-14. The tables present P-Values with each column representing an OFAT trial, and the rows representing the defect rate for comparison. Our Hypothesis focuses on the 30% rows in each trial, but additional defect rates are examined for comparison.

Table 4-14. P-Value Table for Delivery Completeness Model Results

OFAT Trial 1 – Vary RRP (INT 80%, LWS 80%)						
		RRP Level of Completeness (%)				
		80%	**85%**	**90%**	**95%**	**100%**
Defect Rate	**10%**	0.0027	0.0028	0.0023	0.0024	0.0026
	15%	0.0041	0.0043	0.0036	0.0037	0.0039
	20%	0.0067	0.0069	0.0058	0.0060	0.0064
	25%	0.0119	0.0123	0.0102	0.0107	0.0113
	30%	**0.0236**	0.0244	0.0202	0.0211	0.0224
	35%	0.0543	0.0563	0.0466	0.0487	0.0517
	40%	0.1477	0.1524	0.1286	0.1338	0.1413
	Defect Sample Mean	46.33%	46.25%	46.73%	46.62%	46.47%
OFAT Trial 2 – Vary INT (RRP 100%, LWS 80%)						
		INT Level of Completeness (%)				
		80%	**85%**	**90%**	**95%**	**100%**
Defect Rate	**10%**	0.0026	0.0031	0.0029	0.0026	0.0008
	15%	0.0039	0.0048	0.0046	0.0043	0.0014
	20%	0.0064	0.0080	0.0080	0.0078	0.0029
	25%	0.0113	0.0145	0.0157	0.0163	0.0074

	30%	**0.0224**	0.0299	0.0359	0.0406	0.0280
	35%	0.0517	0.0720	0.1001	0.1284	0.1942
	40%	0.1413	0.2003	0.3134	0.4245	0.8093
	Defect Sample Mean	46.47%	44.94%	42.46%	40.87%	37.48%

OFAT Trial 3 – Vary LWS (RRP 100%, INT 100%)

		LWS Level of Completeness (%)				
		80%	**85%**	**90%**	**95%**	**100%**
Defect Rate	**10%**	0.0008	0.0007	0.0051	0.8926	1.0000
	15%	0.0014	0.0017	0.0374	0.9994	1.0000
	20%	0.0029	0.0069	0.6584	0.9999	1.0000
	25%	0.0074	0.0751	0.9814	1.0000	1.0000
	30%	**0.0280**	0.8646	0.9966	1.0000	1.0000
	35%	0.1942	0.9904	0.9989	1.0000	1.0000
	40%	0.8093	0.9979	0.9995	1.0000	1.0000
	Defect Sample Mean	37.48%	27.94%	19.28%	9.28%	0.00%

The results are color coded to show Alpha Value thresholds of 0.01, 0.05, and 0.1 with the colors blue, green and yellow respectively. The results of interest are the values where the OFAT trial completed to an 80% belief level (80% column), and the comparison is made for a 30% defect rate (row 30%). When all three efforts (RRP, INT, and LWS) are completed to 80%, the resulting P-Value is 0.0236, and the sample mean defect rate is 46.33%. For the case where RRP is completed to 100%, INT and LWS are completed to 80%, the resulting P-Value is 0.0224, with a sample mean defect rate of 46.47%. For the third case where RRP and INT are completed to 100%, and LWS is completed to 80% the resulting P-Value is 0.0280, with a sample mean defect rate of 37.48%. In all three cases we can reject the Null Hypothesis with an alpha of 0.05. We also note that comparisons of 35% and 40% result in not enough evidence to reject the null hypothesis, and comparisons of 10% through 25% are solidly above a 0.05 alpha. We also see that 80% completion of RRP and INT as compared with 100% completion has some impact, but not enough to change the overall conclusion. Said differently, comparing the results of the three OFAT runs, we see little change in the overall results. We can conclude that 30% or above defect rate is a reasonable expectation for delivery of 80% solutions.

Conclusion: There is sufficient evidence to reject the null Hypothesis. We can accept the alternative hypothesis that an integration effort delivering an 80% solution will deliver at least a 30% defect rate.

4.6 Conclusion

Quantitative analysis of the four factors chosen for this research indicate that there are more effective strategies for Efficient Integration of Rapid Response Projects into Large Weapon Systems. Three of the four factors in this research showed significant cost savings could be accomplished by employing the strategies proposed.

Integrating technology of higher maturity does indicate overall cost saving to deliver a Large Weapon System to the end user, when including the cost of maturing the technology by RRP. When RRP matures capability to a higher TRL, INT has less interactive work to do with LWS. INT Staff must go through the requirements uncertainty phase, at the same time as working interactively with the LWS, which can lead to inefficiencies and increased costs.

Integration of capabilities started earlier does reduce overall cost. As seen in section 4.3, starting Integration 6 months earlier reduces cost by at least 2%. Although the cost of the integration task increases when this time shift is introduced, the impact to the LWS is a cost reduction that more than offsets the cost increase in INT. Resolving integration defects early in the program allows LWS to concentrate effort on completing the core weapon system. This factor can conflict with the TRL factor, where giving RRP more time to mature the Capability is inconsistent with starting INT earlier. An Engineering Manager should balance these two factors to determine a strategy suitable to the overall end goals.

Changes in Management Reserve did not have a significant impact on overall program costs. There was no observed impact to the overall cost outcome. Management reserve is modeled as a linear release of resources, held early in the program and released slowly as defects arise that need additional funding to resolve. Since the model captures the overall quality of the project, Management reserve is only useful to the model in the early stages, when not enough effort has been expended to compute an accurate estimation of progress. Any impacts are only observed early in the timeline and are less impactful for longer duration projects. Future research can integrate different methodologies for management reserve release to determine if different strategies can impact total program cost. For example, a strategy where management reserve is held until defect rates exceed a threshold may show some impact to total program by increasing the staffing level at key points in the project.

The Level of Completeness experiment measures the defect level at the point in time when the Engineering Manager considers the Project complete. When assessing the impact of “80% solutions” it is important to understand the difference between what is believed to be complete, and what portion of the completed work contains defects. The OFAT experiments resulted in showing that at least a 30% defect is to be expected when the overall Project is believed to by 80% complete.

These four factors are key elements in a decision strategy. Discounting Management Reserve, since it has little impact, Strategies can be developed to determine different approaches to integration challenges. The Engineering Manager can choose between eight strategies varying TRL, Integration Time, and Level of Completeness. Table 4-15 captures the overall cost impact of each of the eight strategies for the Use Cases presented in this research. The “delta costs” are computed based on the calibrated data points, as with the cost comparisons in section 4.0. For the 80% solution values, the cost deltas are referenced to the calibrated data as if the project had been run back to 80% completion, thus normalizing all comparisons.

Table 4-15. Strategy Comparisons – Cost Impacts

		LOW TRL	High TRL
100% Completion	**Early Integration**	-6.80%	-8.27%
	Late Integration	7.05%	5.36%
80% Completion	**Early Integration**	-4.76%	-5.79%
	Late Integration	4.93%	3.75%

Cost Deltas: negative indicates lower cost

The lowest cost strategy is High TRL, Early Integration Time, both for a 100% and an 80% solution. This is achievable under conditions where there is enough time to mature the Rapid Response Capability to a high TRL, and enough time exists to perform the integration tasking early in the LWS project. Although this strategy is most optimal, the time constraints may force the Engineering Manager into accepting a Low TRL capability, with the ability to integrate early in the LWS Program. This strategy is still preferred to integration of a higher TRL capability later in the LWS Program. The most expensive option is integration of a low TRL capability late in the LWS Program. The 80% solution version of these strategies reflects the same cost relationship, with slight variations. To put this into perspective, for a $100M Large Weapon System Program, a cost savings of 8.27% is $8.27M.

Chapter 5—Discussion and Conclusions

5.1 Discussion

This research accomplished all research objectives identified in section 1.5. A System Dynamics Model was created for Engineering Managers to assess the impact of Rapid Response Project integration with their Large Weapon System Programs in terms of overall cost and schedule. The Model allows Engineering Managers to determine the impact of technical management decisions on the overall cost and schedule required to deliver a complete Large Weapon System to the DoD. Strategies are formulated as a combination of the factors addressed in this research. These strategies are devised to help managers better plan for Rapid Response Projects integration into Large Weapon System Programs. The research questions are assessed with three of the four hypotheses proven. The impact of technology maturity, captured as Technology Readiness Level (TRL), Integration Time, Management Reserve, and Completeness Level on overall Large Weapon System (LWS) cost and schedule is assessed. Practical results provide Engineering Managers eight strategies along with the benefits and risks of each. Lastly, a System Dynamics Model is provided, as well as the methodology to adapt the model to real world data specific to an organization. This provides organizations the capability to predict integration program performance and plan programs with a predictive tool.

5.2 Conclusions

Integration of Rapid Response Capabilities into Large Weapon Systems are fraught with interdependencies that defy the ability of human cognition. Simple "Rules of Thumb" are not enough to accurately predict Program performance. The System Dynamics Model presented in this research is a tool that Engineering Managers can use to manage the complexity of large integration Programs. Engineering Managers can use organizational data to verify and validate the model to match performance for their organizations. They can then use the model to predict the impact of engineering management decisions. Although only four factors were addressed in this research, the model can incorporate many more factors, and is limited only by the ability of the organization to provide the data needed to verify and validate the model. A well-maintained model allows Engineering Managers the freedom to make decisions based on predictive information, rather than the tradition reactive information provided by current state of the art management tools.

5.3 Contributions to Body of Knowledge

Engineering Managers may use the results of this research to formulate integration strategies by considering the effect of how modifying four factors (TRL, Integration Time, Management Reserve, and Level of Completeness) impact cost and schedule for LWS Programs. Significant contributions of this research include:

- System Dynamics Model that organizations can use with their own data sources to predict the cost and schedule performance of Large Weapon Systems integrating Rapid Response Capabilities.
- A method to assess the impact of changing Technology Readiness Level of a Rapid Response Capability when it begins integration with a Large Weapon System in terms of cost.
- A method of assessing the impact of Integration Time on cost with respect to integrating a rapid response capability early or late in the timeline of an LWS Program.

- A method to assess the impact of management reserve, as well as the conclusion that Management Reserve changes do not significantly impact the overall cost and schedule of an LWS Program for the strategy chosen in this research.
- A method to assess the impact of delivering incomplete solutions in terms of defect rates.
- A case study that concluded that accepting Higher TRL Rapid Response capabilities into Large Weapons Programs does reduce total program costs.
- A case study that concluded that integration of capabilities 6 months earlier in the Large Weapon Program timeline reduces overall program costs by at least 2%.
- A case study that concluded that accepting an 80% solution is expected to have at least a 30% defect rate.
- A case study that concluded that accepting a High TRL capability early in a program is the most cost effective approach but accepting a lower TRL early in the program is preferred to accepting a high TRL capability later in the program.

5.4 Recommendations for Future Research

Future research recommendations focus on following the methodology of this research by enhancing the System Dynamics Model in three main areas. (1) Sub-Model enhancements to capture organizational process within an organization. (2) Model enhancements to capture interaction process between the three phases of the model, and (3) Capturing different integration configurations.

Sub Model future research

- Enhancing the "work" model to capture a wider variety of defect types. The current model captures all defects in the same Stock and assumes the same productivity and quality factors. Future research can capture defects into multiple classes and adjust the flows to accommodate these differences.
- The "Staff" model can be enhanced to capture various staffing strategies (e.g. New people -vs- expensive people, rotational assignments, agile sprint groups)
- The Quality loops can capture additional factors to assess game theory strategies (e.g. cooperative -vs- competitive strategies)
- Integration of the Model with Risk Management Approaches. Build out the Management Reserve factor to more closely align with risk management strategies and assess the impact of risk reduction strategies.

Interaction Model future research

- Capture additional factors specific to organizational processes and capture inter phase complex loop diagrams. Assess strategies for combining these factors into additional strategies. For example, a Rapid Response Project performed by an internal organization would have more dynamic interaction that an outside organization where contractual issues set up barriers in information sharing. Internal organizational processes are typically held as proprietary information. This research may be better captured as an internal company project which may not be permitted to publish.

- Model the differences between an agile methodology and a waterfall methodology to determine if the process chosen impacts the strategies developed. For example, a more detailed time phased review approach (e.g. waterfall) would group defect discovery into specific events, rather than capturing discovery as a continuous process (e.g. agile).
- Model different strategies for upstream and downstream information flow between project phases. Capture the factors associated with speed of information sharing and determine strategies to control information flow to optimize performance. This would require a time delay model of information flow between each sub-model. (see section 3.3)

Integration Configurations:

- Capture the interaction of multiple RRPs integrated into the same LWS. Determine the factors involved with managing multiple integration efforts and model the cost and schedule impact. This would require building and calibrating additional sub models for RRP. Also, an assessment of INT strategies could be performed where either a single INT task handles all RRPs, or each RRP is aligned with a separate INT task. In this case, interaction would need to be modeled not only between RRP and INT, but between the INT tasks as they compete for resources.
- For the case of multiple INT tasks, the phase interaction model would need to be enhanced where relationships exist not just between LWS and each INT, but between each INT as they interact with defect generation and discovery. This would result in a complex web of interactions that would require real

world data for calibration, or very clear and specific process control to capture the relationships.

- Modeling the interaction where RRP and INT overlap in time. This would be more closely aligned to Lyneis's three phase model. This could also be included in the above research or be more simply performed by itself.

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Appendix A – Graphical VenSim Models

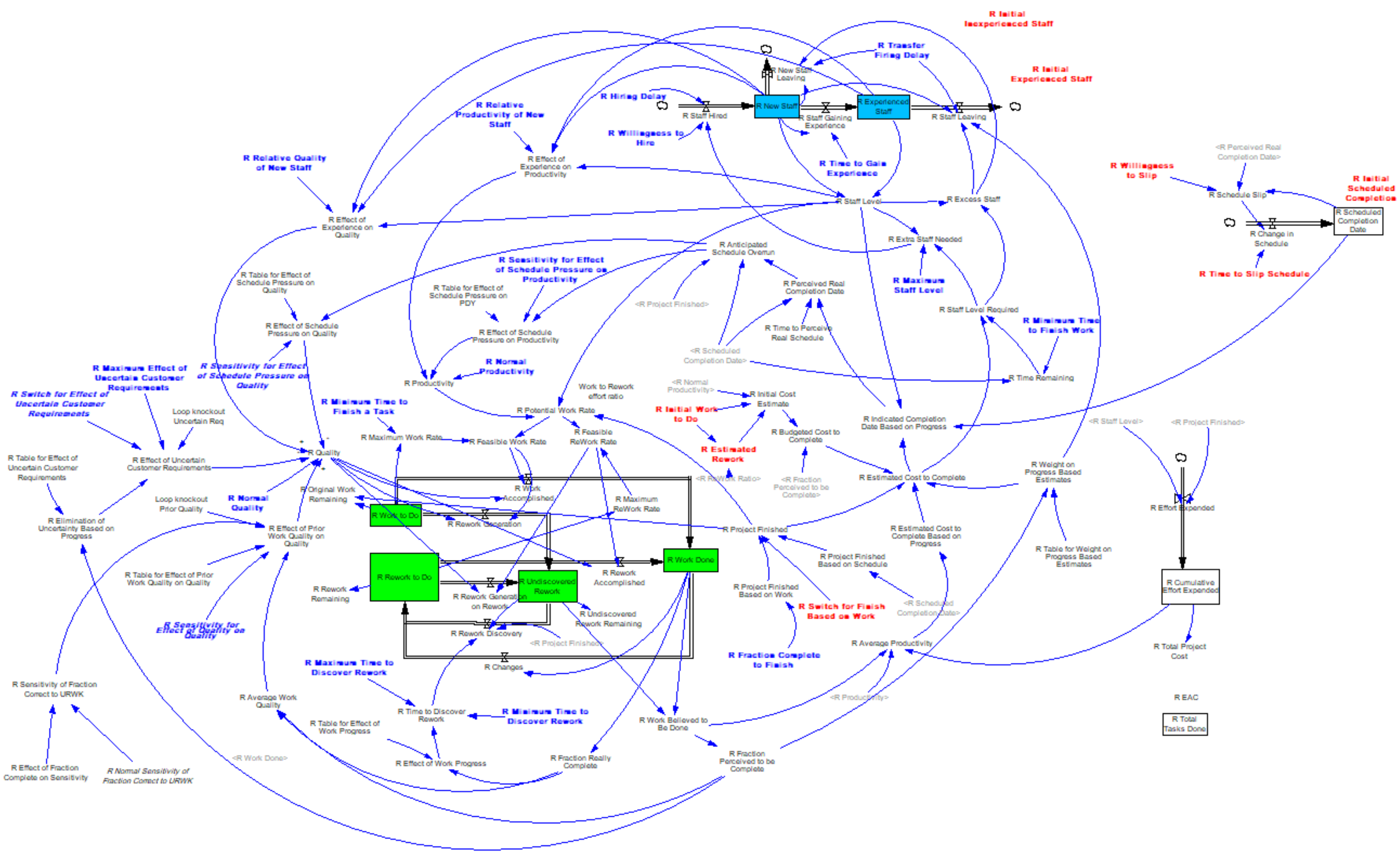

Figure A-1. RRP Sub-Model

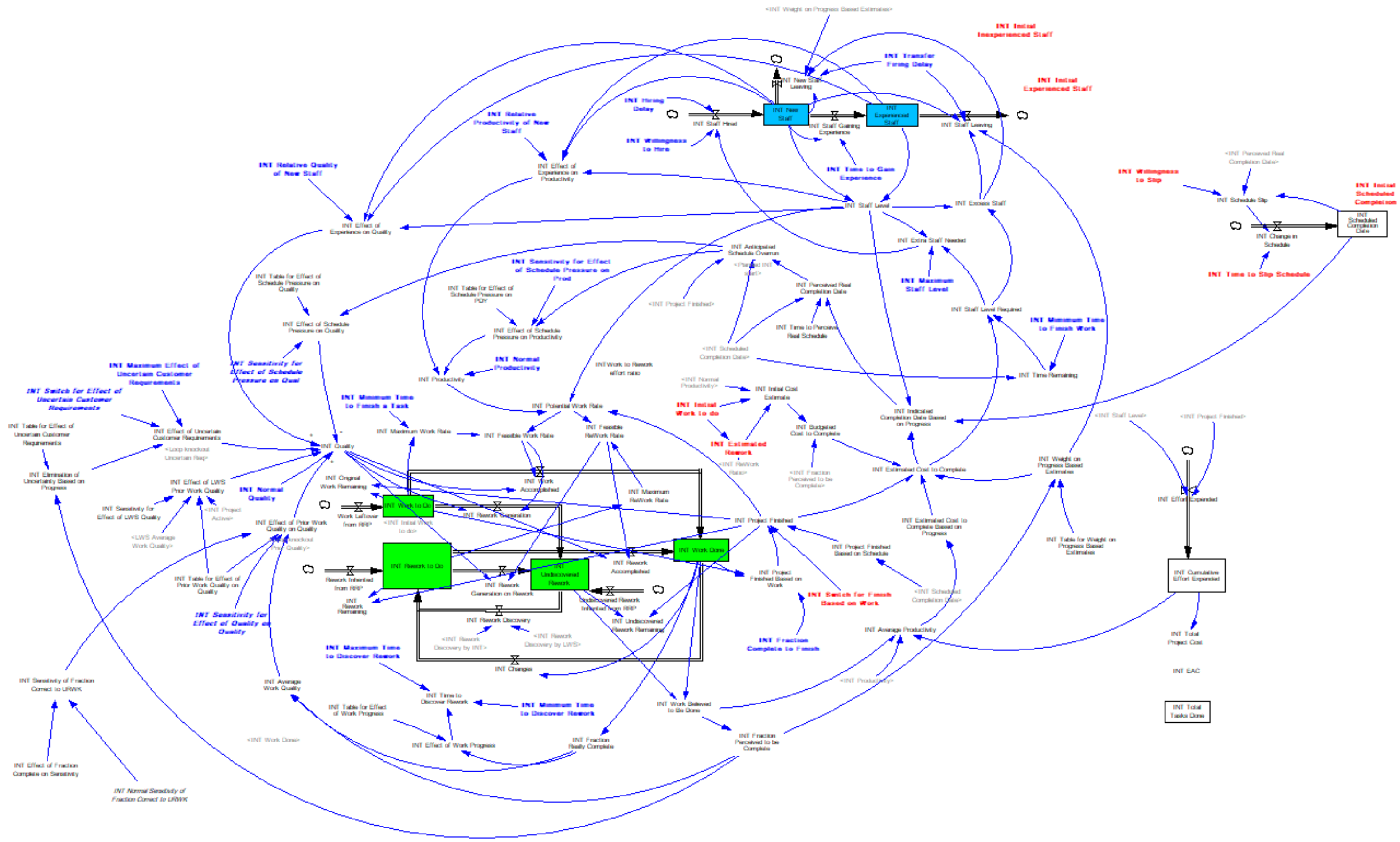

Figure A-2. INT Sub-Model

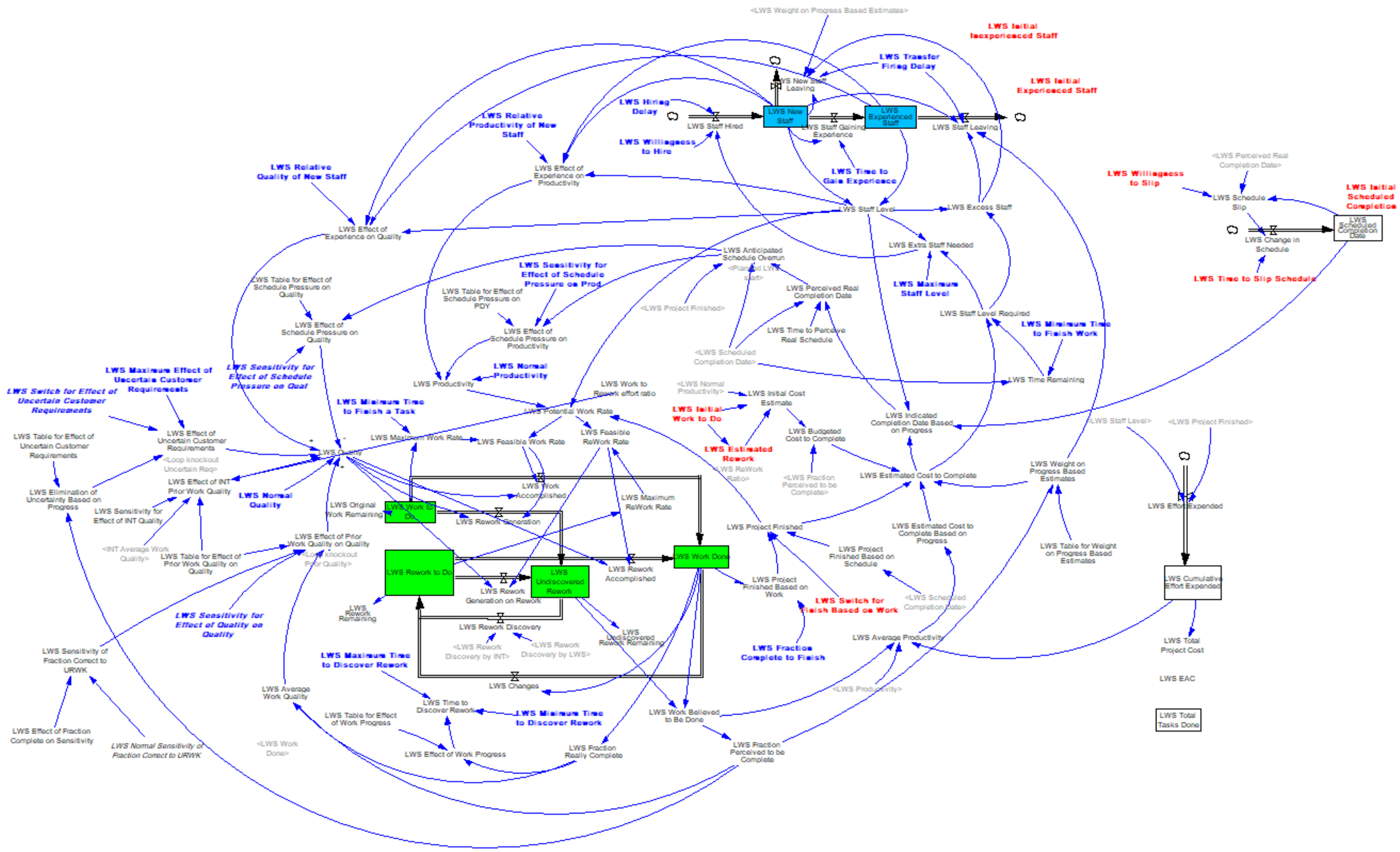

Figure A-3. LWS Sub-Model

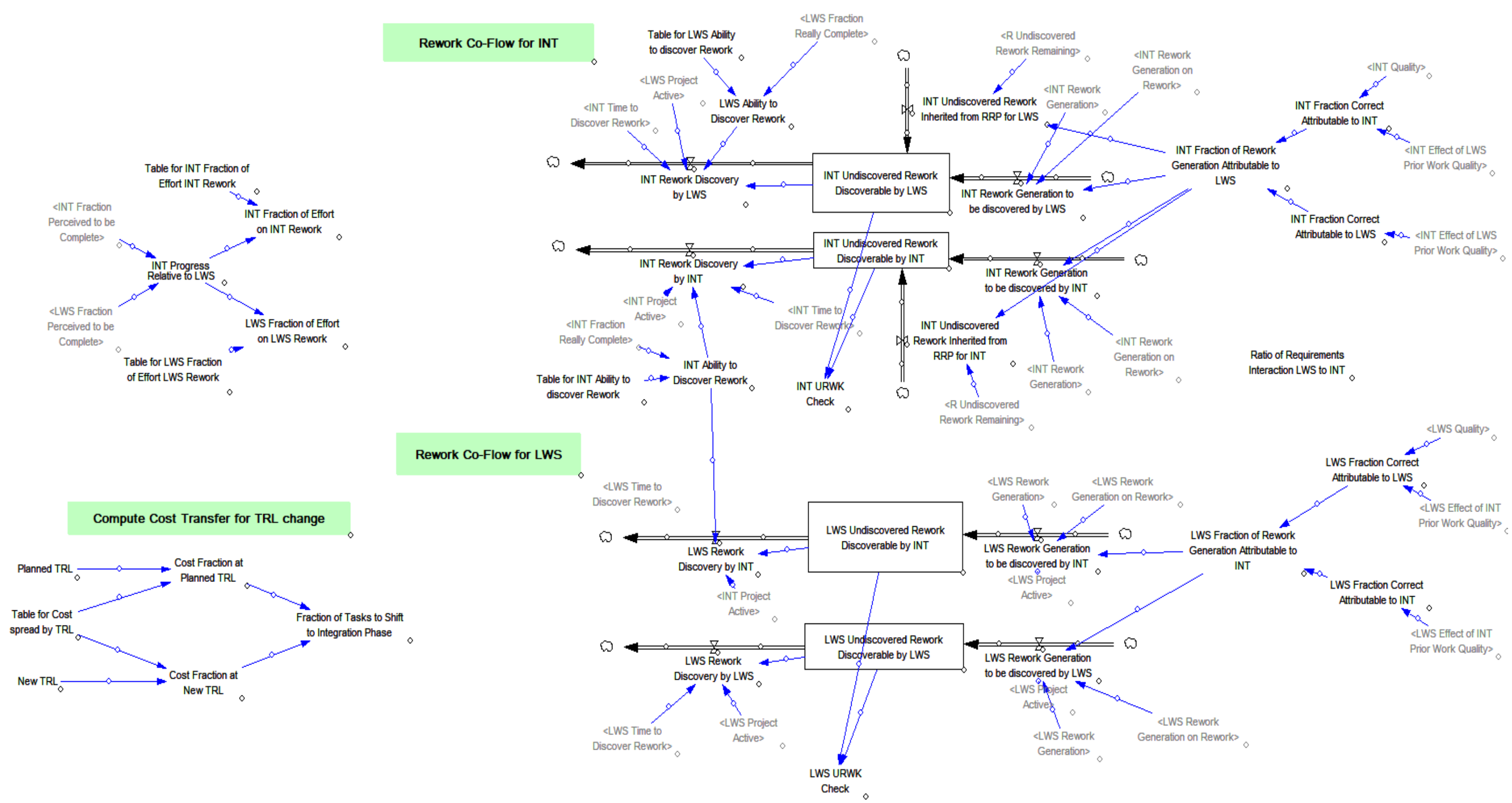

Figure A-4. Interaction Model Components

Appendix B – Model Variables

VenSim Model contains 376 variables. The variables are grouped in the following tables to capture the primary section of the model they support. The grouping is subjective and presented only to compartmentalize the model equations into digestible groupings.

Table B-1. Work Cycle Equations

Variable Name	Equation -or- Value	Dimensions	Purpose
Original Work Remaining	TAG Work to Do * (1- TAG Project Finished)	Tasks	Captures remaining original work when Project shuts down
Rework Accomplished	TAG Quality * TAG Feasible ReWork Rate	Task/Month	Rate at which rework is done correctly
Rework Remaining	TAG Rework to Do * (1- TAG Project Finished)	Tasks	Capture remaining Rework when Project shuts down
Time to Discover Rework	TAG Maximum Time to Discover Rework * TAG Effect of Work Progress + (1 - TAG	Month	Time to discover rework. Scales from maximum time early in Project, to minimum time at end of Project.

Variable Name	Equation -or- Value	Dimensions	Purpose
	Effect of Work Progress) * TAG Minimum Time to Discover Rework		
Total Tasks Done	INTEG (TAG Rework Accomplished+TAG Rework Generation+TAG Rework Generation on Rework+TAG Work Accomplished, 0)	Tasks	Stock that captures tasks complete
Undiscovered Rework Remaining	TAG Undiscovered Rework * (1-TAG Project Finished)	Tasks	Capture Remaining Undiscovered Rework when Project Finishes
Work Done	INTEG(TAG Rework Accomplished + TAG Work Accomplished - TAG Changes ,0)	Task	Work completed correctly on the Project - includes original work and rework done correctly
Initial Work to do	Value based on estimated calibration data	Tasks	Initial Estimate of Work to Perform (Three variables, one for each stage)
INT Rework Discovery	(INT Rework Discovery by INT+INT Rework Discovery by LWS)	Task / Month	Rate at which undiscovered rework is discovered

Variable Name	Equation -or- Value	Dimensions	Purpose
LWS Rework Discovery	(LWS Rework Discovery by INT+LWS Rework Discovery by LWS)	Task / Month	Rate at which undiscovered rework is discovered
R Rework Discovery	(R Undiscovered Rework / R Time to Discover Rework) * R Project Finished	Task / Month	Rate at which undiscovered rework is discovered
INT Rework to Do	INTEG (INT Changes+INT Rework Discovery+Rework Inherited from RRP-INT Rework Accomplished-INT Rework Generation on Rework,0)	Task	Recognized rework stock - Note, if INT Project finishes, and LWS is still active, LWS will discover INT rework, and raise the stock after INT is complete.
LWS Rework to Do	INTEG(LWS Changes + LWS Rework Discovery - LWS Rework Accomplished - LWS Rework Generation on Rework , 0)	Task	Recognized rework stock - Note, if INT Project finishes, and LWS is still active, LWS will discover INT rework, and raise the stock after INT is complete.
R Rework to Do	INTEG(R Changes + R Rework Discovery - R Rework Accomplished - R Rework Generation on Rework,0)	Task	Recognized Rework Stock

Variable Name	Equation -or- Value	Dimensions	Purpose
INT Undiscovered Rework	INTEG (INT Rework Generation+INT Rework Generation on Rework+Undiscovered Rework Inherited from RRP-INT Rework Discovery,0)	Task	Undiscovered rework stock
LWS Undiscovered Rework	INTEG (LWS Rework Generation + LWS Rework Generation on Rework - LWS Rework Discovery,0)	Task	Undiscovered rework stock
R Undiscovered Rework	INTEG (R Rework Generation + R Rework Generation on Rework - R Rework Discovery,0)	Task	Undiscovered rework stock
R Work to Do	INTEG (- R Rework Generation - R Work Accomplished, R Initial Work to Do *(1-Fraction of Tasks to Shift to Integration Phase))	Task	Original work to do stock, also accounting for TRL change in planning

Variable Name	Equation -or- Value	Dimensions	Purpose
LWS Work to Do	INTEG (- LWS Rework Generation - LWS Work Accomplished, LWS Initial Work to Do)	Task	Original work to do stock
INT Work to Do	INTEG (Work Leftover from RRP-INT Rework Generation-INT Work Accomplished, INT Initial Work to do *(1+ Fraction of Tasks to Shift to Integration Phase))	Task	Original work to do stock
Rework Inherited from RRP	STEP(R Rework Remaining/TIME STEP, Planned INT start)- STEP(R Rework Remaining/TIME STEP, Planned INT start+TIME STEP)	Task/Month	Inherit Rework left behind by RRP
Undiscovered Rework Inherited from RRP	STEP(R Undiscovered Rework Remaining/TIME STEP, Planned INT start)- STEP(R Undiscovered Rework	Task/Month	Inherited undiscovered rework

Variable Name	Equation -or- Value	Dimensions	Purpose
	Remaining/TIME STEP, Planned INT start+TIME STEP)		
Work Leftover from RRP	STEP(R Original Work Remaining/TIME STEP, Planned INT start)- STEP(R Original Work Remaining/TIME STEP, Planned INT start+TIME STEP)	Task/Month	Captures RRP tasks remaining when RRP shuts down. Step function transfers these tasks via a flow into the INT Work Stock
Undiscovered Rework Inherited from RRP	STEP(R Undiscovered Rework Remaining/TIME STEP, Planned INT start)- STEP(R Undiscovered Rework Remaining/TIME STEP, Planned INT start+TIME STEP)	Tasks/Month	Captures RRP tasks remaining when RRP shuts down. Step function transfers these tasks via a flow.

Note. Variables repeated for RRP, INT, and LWS sub models

Table B-2. Staff Stocks Equations

Variable Name	Equation -or- Value	Dimensions	Purpose
Excess Staff	Max (0, TAG Staff Level - TAG Staff Level Required)	People	Given the estimated cost to complete, the number of excess staff on the Project
Experienced Staff	INTEG(TAG Staff Gaining Experience - TAG Staff Leaving , TAG Initial Experienced Staff)	People	Stock of how many staff are experienced
Extra Staff Needed	Max (0, MIN (TAG Maximum Staff Level , TAG Staff Level Required) - TAG Staff Level) * TAG Project Active	People	Given the estimated cost to complete, the number of additional staff on the Project
New Staff	INTEG(TAG Staff Hired - TAG Staff Gaining Experience - TAG New Staff Leaving , TAG Initial Inexperienced Staff)	People	Stock to capture new staff level
New Staff Leaving	((MIN (TAG Excess Staff , TAG New Staff) / TAG Transfer Firing Delay) *	People/Month	New staff that leaves the Project, either short term staff or excess staff. Gauged by

Variable Name	Equation -or- Value	Dimensions	Purpose
	TAG Weight on Progress Based Estimates)*TAG Project Active		the perceived completion estimate of the project
Staff Gaining Experience	(TAG New Staff / TAG Time to Gain Experience)*TAG Project Active	People/Month	Staff transitioning to experienced staff at the rete defined by Time to gain experience
Staff Hired	(TAG Willingness to Hire * TAG Extra Staff Needed / TAG Hiring Delay)* TAG Project Active	People/Month	New Staff being hired on to Project
Staff Leaving	((Max (0, (TAG Excess Staff - TAG New Staff)) / TAG Transfer Firing Delay) * TAG Weight on Progress Based Estimates)*TAG Project Active	People/Month	Staff leaving the project based on perceived project completion. Higher confidence on the required staffing level as the Project matures
Staff Level	IF THEN ELSE (TAG Project Active , TAG New Staff + TAG Experienced Staff,0)	People	Total number of people on the Project

Variable Name	Equation -or- Value	Dimensions	Purpose
Staff Level Required	(TAG Estimated Cost to Complete / TAG Time Remaining) * TAG Project Active	People	Required staff level based on estimated cost to complete spread over remaining time available
Hiring Delay	Calibrated for Real World Data	Months	Time it takes from when hiring need is identified until new staff enters project
Initial Experienced Staff	Calibrated for Real World Data	People	Initial experienced staff on the Project
Initial Inexperienced Staff	Calibrated for Real World Data	People	Initial inexperienced staff on the Project
Maximum Staff Level	Organizational Size	People	Maximum Staff on the Project - Organizational parameter
Time to Gain Experience	Calibrated for Real World Data	Months	Time it takes for a new hire to perform at the experienced level.
Transfer Firing Delay	Calibrated for Real World Data	Months	Time it takes to ramp down staffing level, providing advanced notice.

Variable Name	Equation -or- Value	Dimensions	Purpose
Willingness to Hire	Management Control (Set to 1)	Dimensionless	Flag variable to indicate if PM is willing to bring new staff on to the project.
Willingness to Slip	Control Variable for Simulation (0, 1)	Dimensionless	Management control on willingness to slip schedule

Note. Variables repeated for RRP, INT, and LWS sub models

Table B-3. Productivity Equations

Variable Name	Equation -or- Value	Dimensions	Purpose
Sensitivity for Effect of Schedule Pressure on Prod	Range [0, 1]	Dimensionless	Schedule pressure effect on productivity. Control parameter for calibration to adjust impact.

Variable Name	Equation -or- Value	Dimensions	Purpose
Average Productivity	IF THEN ELSE (TAG Cumulative Effort Expended > 0, TAG Work Believed to Be Done / TAG Cumulative Effort Expended , TAG Productivity)	Task/(Month*Person)	Computed average productivity based on work believed to be done
Effect of Experience on Productivity	IF THEN ELSE (TAG Staff Level > 0, (TAG New Staff * TAG Relative Productivity of New Staff + TAG Experienced Staff) / TAG Staff Level,1)	Dimensionless	Effective productivity level with a mixed staff of experienced and new staff.
Effect of Schedule Pressure on Productivity	TAG Table for Effect of Schedule Pressure on PDY (TAG Anticipated Schedule Overrun) * TAG Sensitivity for Effect of Schedule Pressure on Prod + (1 -	Dimensionless	Overall effect of schedule pressure on productivity

Variable Name	Equation -or- Value	Dimensions	Purpose
	TAG Sensitivity for Effect of Schedule Pressure on Prod)		
Feasible ReWork Rate	MIN (TAG Maximum ReWork Rate , TAG Potential Work Rate)* TAG Project Active * (1 - TAG Work to Rework effort ratio)	Tasks/Month	Portion of work rate attributed to rework
Feasible Work Rate	MIN (TAG Maximum Work Rate , TAG Potential Work Rate) * TAG Project Active * TAGWork to Rework effort ratio	Tasks/Month	Portion of work rate attributed to original work
Maximum Work Rate	(TAG Work to Do) / TAG Minimum Time to Finish a Task	Tasks/Month	Fastest that work can be completed
Potential Work Rate	TAG Staff Level * TAG Productivity * TAG Project Finished	Tasks/Month	Work rate available to perform work, staff level at the computed productivity rate.

Variable Name	Equation -or- Value	Dimensions	Purpose
Productivity	TAG Normal Productivity * TAG Effect of Schedule Pressure on Productivity * TAG Effect of Experience on Productivity	Task / (Person * Month)	Overall Productivity on the Project
Table for Effect of Schedule Pressure on PDY	([(-1,0)-(5,2)], (-1,0.85), (-0.2,0.85), (-0.1,0.95), (0,1), (0.1,1.025), (0.2,1.075), (0.3,1.15), (0.4,1.25), (0.5,1.325), (0.6,1.375), (0.7,1.4), (5,1.4))	Dimensionless	Schedule pressure increase as a function of anticipated schedule overrun.
Work to Rework effort ratio	(Work to Do) / (Work to Do + Rework to Do)	Dimensionless	Ratio of effort spent on rework -vs-original work
Maximum Time to Discover Rework	Value for Discovery Early in Project (e.g. 1)	Months	Maximum time to discover rework (Time Constant)
Minimum Time to Finish Work	Time (e.g. 1 Months)	Month	Minimum time to complete the overall Project - Captures shut down time

Variable Name	Equation -or- Value	Dimensions	Purpose
Minimum Time to Discover Rework	Value for Discover Late in Project (e.g. 0.25)	Months	Shortest time to discover rework. 0.25 is about a week, indicating a short sprint. 2 week sprints are typical
Minimum Time to Finish a Task	Time (e.g. 0.25 Months)	Months	Shortest time to complete a task. 0.25 is about a week, indicating a short sprint. 2 week sprints are typical
Normal Productivity	Value Calibrated for Project Team	Task/(Month*Person)	Normal Productivity based on organization. Calibrated to real data
Relative Productivity of New Staff	Value Calibrated for Project Team	Dimensionless	New staff productivity level compared to experienced staff. Productivity is based on experience on the project.

Note. Variables repeated for RRP, INT, and LWS sub models

Table B-4. Quality Equations

Variable Name	Equation -or- Value	Dimensions	Purpose
Sensitivity for Effect of Quality on Quality	Range [0, 1]	Dimensionless	Control parameter to scale the effect of historical quality on current quality
Sensitivity for Effect of Schedule Pressure on Qual	Range [0, 1]	Dimensionless	Control parameter on the effect of schedule pressure
Switch for Effect of Uncertain Customer Requirements	Value [0 or 1]	Dimensionless	Control parameter to include customer uncertainty in the quality equation. 1 includes uncertainty, 0 does not.
Average Work Quality	Max(TAG Fraction Really Complete,0.01) /Max(TAG Fraction Perceived to be Complete,0.01)	Fraction	Running average of Project quality
Effect of Experience on Quality	IF THEN ELSE (TAG Staff Level > 0, (TAG New Staff * TAG Relative Quality of New Staff +	Dimensionless	Computes the effective quality of combined new and experienced staff

Variable Name	Equation -or- Value	Dimensions	Purpose
	TAG Experienced Staff) / TAG Staff Level , 1)		
Effect of Fraction Complete on Sensitivity	WITH LOOKUP (TAG Fraction Perceived to be Complete, ([(0,0)-(1,1)], (0,0), (0.025,0), (0.05,0), (0.075,0.2), (0.1,0.5), (0.125,0.8), (0.15,1), (0.2,1), (0.25,1), (0.3,1), (0.35,1), (0.4,1), (0.45,1), (0.5,1), (0.55,1), (0.6,1), (0.65,1), (0.7,1), (0.75,1), (0.8,1), (0.85,1), (0.9,1), (0.95,1), (1,1)))	Dimensionless	Phase in table that gradually introduces average quality impact. Dampens startup effects when average quality has not yet stabilized
Effect of Prior Work Quality on Quality	(TAG Sensitivity of Fraction Correct to URWK*TAG Sensitivity for Effect of Quality on Quality * TAG Table for Effect of	Dimensionless	Captures the effect of prior quality on work quality. Staff will tend to exhibit average quality level, migrating the

Variable Name	Equation -or- Value	Dimensions	Purpose
	Prior Work Quality on Quality (TAG Average Work Quality) + (1 - TAG Sensitivity for Effect of Quality on Quality * TAG Sensitivity of Fraction Correct to URWK))*Loop knockout Prior Quality		average, rather than exhibiting jumps in quality
Effect of Schedule Pressure on Quality	TAG Sensitivity for Effect of Schedule Pressure on Qual * TAG Table for Effect of Schedule Pressure on Quality (TAG Anticipated Schedule Overrun) + (1 - TAG Sensitivity for Effect of Schedule Pressure on Qual)	Dimensionless	Quality is reduced as a function of anticipated schedule overrun. Pressure to complete tasks faster result in poorer quality.

Variable Name	Equation -or- Value	Dimensions	Purpose
Effect of Uncertain Customer Requirements	((TAG Maximum Effect of Uncertain Customer Requirements + (1 - TAG Maximum Effect of Uncertain Customer Requirements) * TAG Elimination of Uncertainty Based on Progress) * TAG Switch for Effect of Uncertain Customer Requirements + (1 - TAG Switch for Effect of Uncertain Customer Requirements))* Loop knockout Uncertain Req	Dimensionless	Effect of uncertain customer requirements on Quality, transitions from maximum effect early in Project to 1 as the Project matures
Elimination of Uncertainty Based on Progress	TAG Table for Effect of Uncertain Customer Requirements (TAG Fraction Perceived to be Complete)	Dimensionless	Customer requirement uncertainty reduces as Project approaches completion, meaning impact on quality approaches 1

Variable Name	Equation -or- Value	Dimensions	Purpose
Quality	TAG Normal Quality * TAG Effect of Prior Work Quality on Quality * TAG Effect of Schedule Pressure on Quality * TAG Effect of Experience on Quality * TAG Effect of Uncertain Customer Requirements	Dimensionless	Overall quality produced by the Project. Normal Quality (organizational), prior work quality, schedule pressure, staff experience, and uncertain requirements each contributing to overall quality Equation for RRP. For INT, includes: *(INT Effect of LWS Prior Work Quality) for LWS includes: *(LWS Effect of INT Prior Work Quality)
Rework Generation	(1 - TAG Quality) * TAG Feasible Work Rate	Task / Month	Rate at which original work is done incorrectly
Rework Generation on Rework	(1 - TAG Quality) * TAG Feasible ReWork Rate	Task/Month	Rate at which rework is done incorrectly

Variable Name	Equation -or- Value	Dimensions	Purpose
Sensitivity of Fraction Correct to URWK	TAG Normal Sensitivity of Fraction Correct to URWK* TAG Effect of Fraction Complete on Sensitivity	Dimensionless	Phase in value that gradually introduces average quality impact. Dampens startup effects when average quality has not yet stabilized
Maximum Effect of Uncertain Customer Requirements	Range [0, 1], set to 0.85	Dimensionless	Worst case effect of uncertain customer requirements
Normal Quality	Range [0, 1], Calibrated Across project data (0.9 for RRP, 0.8 for INT, LWS)	Fraction	Normal Quality in the organization for Project type
Normal Sensitivity of Fraction Correct to URWK	Range [0, 1]	Dimensionless	Control switch for phase in table that gradually introduces average quality impact. Dampens startup effects when average quality has not yet stabilized

Variable Name	Equation -or- Value	Dimensions	Purpose
Relative Quality of New Staff	Range [0, 1]	Dimensionless	Quality of new staff on the Project
Table for Effect of Prior Work Quality on Quality	([(0,0)-(10,1)], (0,0.05), (0.1,0.1), (0.2,0.2), (0.3,0.3), (0.4,0.4), (0.5,0.5), (0.6,0.6), (0.7,0.7), (0.8,0.8), (0.9,0.9), (1,1), (10,1))	Dimensionless	(mostly) Linear table that captures the average work quality impact on current work quality. Quality will migrate from the average quality, rather than jump quickly to a new value.
Table for Effect of Schedule Pressure on Quality	([(-5,0)-(5,1)], (-5,1), (0,1), (0.1,0.975), (0.2,0.93), (0.3,0.87), (0.4,0.8), (0.5,0.75), (0.6,0.725), (0.7,0.7), (5,0.7))	Dimensionless	Schedule Pressure effect. Further behind schedule reduces quality of products built
Table for Effect of Uncertain Customer Requirements	([(0,0)-(1,1)], (0,0), (0.1,0), (0.2,0), (0.3,0), (0.4,0), (0.5,0), (0.6,0.1), (0.7,0.3), (0.8,0.6), (0.9,0.85), (1,1))	Dimensionless	Closer Project is to completion, the lower impact uncertain requirements have on quality. Closer to done, less to be uncertain about.

Note. Variables repeated for RRP, INT, and LWS sub models

Table B-5. Progress Equations

Variable Name	Equation -or- Value	Dimensions	Purpose
Time to Slip Schedule	Time Constant (e.g. 1 Month)	Months	Time delay to slip schedule once recognized (Time Constant)
Anticipated Schedule Overrun	((TAG Perceived Real Completion Date - TAG Scheduled Completion Date) / (TAG Scheduled Completion Date - Planned TAG start - 1)) * TAG Project Finished * TAG Project Active	Dimensionless	Fraction of schedule overrun based on the overall schedule

Variable Name	Equation -or- Value	Dimensions	Purpose
Budgeted Cost to Complete	TAG Initial Cost Estimate * (1 - TAG Fraction Perceived to be Complete)	Month*Person	Estimated cost to complete based on initial cost estimate
Change in Schedule	Max (0, TAG Schedule Slip) / TAG Time to Slip Schedule * TAG Project Finished	Months/Month	How much to slip schedule, with time delay
Cumulative Effort Expended	INTEG(TAG Effort Expended , 0)	Person*Month	Collects the total effort expended on the Project
EAC	TAG Cumulative Effort Expended+TAG Estimated Cost to Complete	Month*Person	Running Estimate at Completion (EAC)
Effect of Work Progress	TAG Table for Effect of Work Progress (TAG Fraction Really Complete)	Dimensionless	Inverse proportion, as fraction really complete increases, the effect on work progress decreases, capturing the effect that as there is less work to do,

Variable Name	Equation -or- Value	Dimensions	Purpose
			undiscovered rework is discovered faster.
Effort Expended	TAG Staff Level * TAG Project Finished * TAG Project Active	People	Captures the rate of effort expended on the project
Estimated Cost to Complete	(TAG Budgeted Cost to Complete * (1 - TAG Weight on Progress Based Estimates) + (TAG Estimated Cost to Complete Based on Progress) * TAG Weight on Progress Based Estimates) * TAG Project Finished	Month*Person	Overall estimate on cost to complete the Project - transitions from budgeted cost to complete to estimated cost to complete as Project matures
Estimated Cost to Complete Based on Progress	(TAG Work to Do + TAG Rework to Do) / TAG Average Productivity	Month*Person	Cost to complete based on known work and average productivity

Variable Name	Equation -or- Value	Dimensions	Purpose
Estimated Rework	TAG ReWork Ratio*TAG Initial Work to do	Tasks	An estimation of rework on the project to compute budgeted cost to complete
Fraction Perceived to be Complete	TAG Work Believed to Be Done/ (TAG Work Believed to Be Done + TAG Work to Do + TAG Rework to Do)	Fraction	Fraction of Work perceived to be complete based on discovered and known work
Fraction Really Complete	TAG Work Done / (TAG Work Done + TAG Work to Do + TAG Rework to Do + TAG Undiscovered Rework)	Fraction	Fraction of work really completed (includes undiscovered rework in equation)
Indicated Completion Date Based on Progress	IF THEN ELSE (TAG Project Active , Time + (TAG Estimated Cost to Complete / Max (0.0001, TAG Staff Level)) , TAG Scheduled Completion Date)	Month	Projected completion date based on estimated cost to complete and staffing available

Variable Name	Equation -or- Value	Dimensions	Purpose
Initial Cost Estimate	(TAG Initial Work to do + TAG Estimated Rework)*(1+ Fraction of Tasks to Shift to Integration Phase) / TAG Normal Productivity	Person*Month	Initial Cost estimate for the Project
Maximum ReWork Rate	TAG Rework to Do / TAG Minimum Time to Finish a Task	Tasks/Month	Maximum rework rate
Perceived Real Completion Date	SMOOTHI (TAG Indicated Completion Date Based on Progress , TAG Time to Perceive Real Schedule , TAG Scheduled Completion Date)	Month	exponential smoothing, starting at scheduled completion date, and smooths completion based on project date
Schedule Slip	TAG Willingness to Slip * Max (0, (TAG Perceived Real Completion Date - TAG Scheduled Completion Date))	Months	Compute how much to change schedule based on willingness to slip

Variable Name	Equation -or- Value	Dimensions	Purpose
Scheduled Completion Date	INTEG(TAG Change in Schedule , TAG Initial Scheduled Completion)	Month	Keeps track of completion date. Moves when Project control allows schedule to slip.
Table for Effect of Work Progress	([(0,0)-(1,1)], (0,1), (0.1,1), (0.2,0.95), (0.3,0.85), (0.4,0.75), (0.5,0.6), (0.6,0.4), (0.7,0.25), (0.8,0.15), (0.9,0.05), (1,0))	Dimensionless	Effect of Work Progress decreases as project approaches completion
Table for Weight on Progress Based Estimates	([(0,0)-(1,1)], (0,0), (0.1,0), (0.2,0), (0.3,0.1), (0.4,0.25), (0.5,0.5), (0.6,0.75), (0.7,0.9), (0.8,1), (0.9,1), (1,1))	Fraction	Captures the effect of confidence in progress based estimates. Less progress is less relied on, as progress improves, progress based estimates are given greater credibility
Time Remaining	Max (TAG Minimum Time to Finish Work , TAG Scheduled Completion Date - Time)	Month	Time left for Project execution based on either scheduled date, or minimum time to shut down

Variable Name	Equation -or- Value	Dimensions	Purpose
Time to Perceive Real Schedule	IF THEN ELSE (TAG Project Finished , 1, 1e+06)	Month	During the project, the effective time constant is 1 month; after project finishes, the time constant is set to a large number such that the equations recognize the project completion date has occurred.
Total Project Cost	TAG Cumulative Effort Expended	Month*Person	Project overall cost is the effort expended plus any penalties for late delivery
Weight on Progress Based Estimates	TAG Table for Weight on Progress Based Estimates (TAG Fraction Perceived to be Complete)	Fraction	Provides the confidence to be placed on progress based estimates. Early in the Project, low confidence, confidence raises as project matures
Work Accomplished	TAG Quality * TAG Feasible Work Rate	Task / Month	Ratio of Work accomplished correctly

Variable Name	Equation -or- Value	Dimensions	Purpose
Work Believed to Be Done	TAG Undiscovered Rework+TAG Work Done	Tasks	Amount of work believed to be done
Fraction Complete to Finish	Range [0, 1]	Fraction	How much work needs to be completed to call the Project finished based on work completed. For example, and 80% solution could set this to 0.8
Initial Scheduled Completion	Planning Estimate in Months	Month	Planned completion date
ReWork Ratio	Management Reserve Value (e.g. 0.1)	Dimensionless	Independent Variable for Management Reserve

Note. Variables repeated for RRP, INT, and LWS sub models

Table B-6. Interaction Equations

Variable Name	Equation -or- Value	Dimensions	Purpose
Table for INT Ability to discover Rework	([(0,0.5)-(1,1)], (0,0.55), (0.5,0.55), (0.6,0.65), (0.7,0.75), (0.8,0.85), (0.9,0.95), (1,1))	Dimensionless	Rework as a function of actual complete. As Project matures, rework is discovered that can not be discovered early in the Project
Table for INT Fraction of Effort INT Rework	([(-1,0)-(1,1)], (-1,0), (-0.5,0.25), (0,0.5), (0.5,0.75), (1,1))	Dimensionless	Function of Workload ratio. If INT Rework is much greater than LWS workload, focus is on INT rework. As INT rework load drops, team will shift focus to LWS rework issues
Table for LWS Ability to discover Rework	([(0,0.5)-(1,1)], (0,0.55), (0.5,0.55), (0.6,0.65), (0.7,0.75), (0.8,0.85), (0.9,0.95), (1,1))	Dimensionless	Rework as a function of actual complete. As Project matures, rework is discovered that can not be discovered early in the Project

Variable Name	Equation -or- Value	Dimensions	Purpose
Table for LWS Fraction of Effort LWS Rework	([(-1,0)-(1,1)], (-1,0), (-0.5,0.25), (0,0.5), (0.5,0.75), (1,1))	Dimensionless	Fraction of effort LWS spends on its own Rework as a function of workload
INT Ability to Discover Rework	Table for INT Ability to discover Rework(INT Fraction Really Complete)	Dimensionless	Factor to accommodate ability to discover rework as Project matures Ability to discover rework improves as progress improves
INT Effect of LWS Prior Work Quality	IF THEN ELSE(INT Project Active, INT Table for Effect of Prior Work Quality on Quality (LWS Average Work Quality)*INT Sensitivity for Effect of LWS Quality+(1-INT Sensitivity for Effect of LWS Quality),1)	Dimensionless	Captures the effect of prior LWS quality on INT work quality. Staff will tend to exhibit average quality level, migrating the average, rather than exhibiting jumps in quality

Variable Name	Equation -or- Value	Dimensions	Purpose
INT Fraction Correct Attributable to INT	MIN(1,INT Quality)/INT Effect of LWS Prior Work Quality	Dimensionless	Captures the ratio of INT rework that is attributable to INT work
INT Fraction Correct Attributable to LWS	INT Effect of LWS Prior Work Quality	Dimensionless	Impact of undiscovered rework in LWS impacting INT. As LWS rework reduces, confidence builds in INT rework
INT Fraction of Effort on INT Rework	Table for INT Fraction of Effort INT Rework(INT Progress Relative to LWS)	Dimensionless	Fraction of effort INT spends on INT rework discovery
INT Fraction of Rework Generation Attributable to LWS	MIN(1, (1-INT Fraction Correct Attributable to LWS)/Max(1e-05, (1-INT Fraction Correct Attributable to LWS)+(1-INT Fraction Correct Attributable to INT)))	Dimensionless	The fraction of INT Rework generation that is attributable to LWS

Variable Name	Equation -or- Value	Dimensions	Purpose
INT Progress Relative to LWS	INT Fraction Perceived to be Complete-LWS Fraction Perceived to be Complete	Dimensionless	Positive indicates INT is further along than LWS, Negative is LWS is further along
INT Rework Discovery by INT	INT Undiscovered Rework Discoverable by INT*INT Fraction of Effort on INT Rework*INT Ability to Discover Rework/INT Time to Discover Rework * INT Project Active	Tasks/Month	Rework discovery impacted by workload and ability to discover rework due to Project maturity
INT Rework Discovery by LWS	INT Undiscovered Rework Discoverable by LWS*(1-LWS Fraction of Effort on LWS Rework)*LWS Ability to Discover Rework/INT Time to Discover Rework * LWS Project Active	Tasks/Month	Rework discovery impacted by workload and ability to discover rework due to Project maturity. After INT Project completes, LWS will discover rework, which will shift undiscovered rework to discovered,

Variable Name	Equation -or- Value	Dimensions	Purpose
			assuming LWS is still active to discover it. INT will not be active to complete the rework, but it will raise the known rework stock at the end.
INT Rework Generation to be discovered by INT	(INT Rework Generation+INT Rework Generation on Rework)*(1-INT Fraction of Rework Generation Attributable to LWS)* INT Project Active	Tasks/Month	Fraction of INT Rework that INT can discover
INT Rework Generation to be discovered by LWS	(INT Rework Generation+INT Rework Generation on Rework)*INT Fraction of Rework Generation Attributable to LWS * INT Project Active	Tasks/Month	Fraction of INT Rework that LWS can discover

Variable Name	Equation -or- Value	Dimensions	Purpose
INT Sensitivity for Effect of LWS Quality	Range [0, 1]	Dimensionless	Control switch for LWS to INT interaction
INT Undiscovered Rework Discoverable by INT	INTEG (INT Rework Generation to be discovered by INT+INT Undiscovered Rework Inherited from RRP for INT-INT Rework Discovery by INT,0)	Tasks	Stock to capture INT Undiscovered Rework that INT can find
INT Undiscovered Rework Discoverable by LWS	INTEG (INT Rework Generation to be discovered by LWS+INT Undiscovered Rework Inherited from RRP for LWS-INT Rework Discovery by LWS,0)	Tasks	Stock to capture INT Undiscovered Rework that LWS can find
INT Undiscovered Rework Inherited from RRP for INT	(STEP(R Undiscovered Rework Remaining/TIME STEP, Planned INT start)- STEP(R Undiscovered	Tasks/Month	Captures portion of RRP tasks remaining that INT could discover.

Variable Name	Equation -or- Value	Dimensions	Purpose
	Rework Remaining/TIME STEP, Planned INT start+TIME STEP))*(1-INT Fraction of Rework Generation Attributable to LWS)		
INT Undiscovered Rework Inherited from RRP for LWS	(STEP(R Undiscovered Rework Remaining/TIME STEP, Planned INT start)- STEP(R Undiscovered Rework Remaining/TIME STEP, Planned INT start+TIME STEP))*INT Fraction of Rework Generation Attributable to LWS	Tasks/Month	Captures portion of RRP tasks remaining that LWS could discover.
INT URWK Check	INT Undiscovered Rework Discoverable by INT+INT Undiscovered Rework Discoverable by LWS	Tasks	Variable to check Undiscovered Rework tracking between INT and LWS in the interaction phase aligns.

Variable Name	Equation -or- Value	Dimensions	Purpose
LWS Ability to Discover Rework	Table for LWS Ability to discover Rework(LWS Fraction Really Complete)	Dimensionless	Factor to accommodate ability to discover rework as Project matures Ability to discover rework improves as progress improves
LWS Effect of INT Prior Work Quality	IF THEN ELSE(LWS Project Active, LWS Table for Effect of Prior Work Quality on Quality (INT Average Work Quality)*LWS Sensitivity for Effect of INT Quality+(1-LWS Sensitivity for Effect of INT Quality),1)	Dimensionless	Captures the effect of prior INT quality on LWS work quality. Staff will tend to exhibit average quality level, migrating the average, rather than exhibiting jumps in quality
LWS Fraction Correct Attributable to INT	LWS Effect of INT Prior Work Quality	Dimensionless	Fraction of LWS correct work attributable to INT

Variable Name	Equation -or- Value	Dimensions	Purpose
LWS Fraction Correct Attributable to LWS	MIN(1,LWS Quality)/LWS Effect of INT Prior Work Quality	Dimensionless	Fraction of LWS correct work attributable to LWS
LWS Fraction of Effort on LWS Rework	Table for LWS Fraction of Effort LWS Rework(-INT Progress Relative to LWS)	Dimensionless	Fraction of effort LWS spends on LWS rework discovery
LWS Fraction of Rework Generation Attributable to INT	MIN(1, (1-LWS Fraction Correct Attributable to INT)/Max(1e-05, (1-LWS Fraction Correct Attributable to INT)+(1-LWS Fraction Correct Attributable to LWS)))	Dimensionless	The fraction of LWS Rework generation that is attributable to INT
LWS Rework Discovery by INT	LWS Undiscovered Rework Discoverable by INT*(1-INT Fraction of Effort on INT Rework) *INT Ability to Discover	Tasks/Month	Captures the rate at which INT can discover rework for LWS

Variable Name	Equation -or- Value	Dimensions	Purpose
	Rework/LWS Time to Discover Rework * INT Project Active		
LWS Rework Discovery by LWS	LWS Undiscovered Rework Discoverable by LWS*LWS Fraction of Effort on LWS Rework*LWS Ability to Discover Rework /LWS Time to Discover Rework * LWS Project Active	Tasks/Month	Captures the rate at which LWS can discover rework for INT
LWS Rework Generation to be discovered by INT	(LWS Rework Generation+LWS Rework Generation on Rework)*LWS Fraction of Rework Generation Attributable to INT * LWS Project Active	Tasks/Month	Flow to capture LWS rework generation portion that INT must discover

Variable Name	Equation -or- Value	Dimensions	Purpose
LWS Rework Generation to be discovered by LWS	(LWS Rework Generation+LWS Rework Generation on Rework)*(1-LWS Fraction of Rework Generation Attributable to INT)* LWS Project Active	Tasks/Month	Flow to capture LWS rework generation portion that LWS must discover
LWS Sensitivity for Effect of INT Quality	Range [0, 1]	Dimensionless	Control switch for LWS to INT interaction
LWS Undiscovered Rework Discoverable by INT	INTEG (LWS Rework Generation to be discovered by INT-LWS Rework Discovery by INT,0)	Tasks	Stock that captures LWS rework discoverable by INT
LWS Undiscovered Rework Discoverable by LWS	INTEG(LWS Rework Generation to be discovered by LWS-LWS Rework Discovery by LWS,0)	Tasks	Stock that captures INT rework discoverable by LWS

Variable Name	Equation -or- Value	Dimensions	Purpose
LWS URWK Check	LWS Undiscovered Rework Discoverable by LWS+LWS Undiscovered Rework Discoverable by INT	Tasks	Variable to check Undiscovered Rework tracking between INT and LWS in the interaction phase aligns.

Note. Variables appear only once in Model

Table B-7. TRL Equations

Variable Name	Equation -or- Value	Dimensions	Purpose
New TRL	Range [3-8]	Dimensionless	New TRL Level of Rapid Response Project
Planned INT start	1	Month	Planned Start month of Rapid Response Project

Variable Name	Equation -or- Value	Dimensions	Purpose
Planned LWS start	1	Month	Planned Start month of Large Weapon System
Planned RRP start	1	Month	Planned Start month of Integration Effort
Planned TRL	Range [3-8]	Dimensionless	Planned TRL of Rapid Response Project
Table for Cost spread by TRL	([(0,0)-(10,1)], (1,0.029), (2,0.059), (3,0.079), (4,0.127), (5,0.219), (6,0.304), (7,0.473), (8,0.757), (9,1))	Dimensionless	Table based on Edmond Conrow study of NASA and DoD projects cost spread -vs- TRL level
Cost Fraction at New TRL	Table for Cost spread by TRL (New TRL)	Dimensionless	Fraction of Cost at the new TRL level based on Conrow ratio table
Cost Fraction at Planned TRL	Table for Cost spread by TRL (Planned TRL)	Dimensionless	Fraction of Cost at the Planned TRL level based on Conrow ratio table

Variable Name	Equation -or- Value	Dimensions	Purpose
Fraction of Tasks to Shift to Integration Phase	Cost Fraction at Planned TRL - Cost Fraction at New TRL	Dimensionless	TRL increase (e.g. 5 - 6) results in tasks taken out of integration Phase and placed into Project Phase

Note. Variables appear only once in Model

Table B-8. Control Equations

Variable Name	Equation -or- Value	Dimensions	Purpose
Project Active	IF THEN ELSE (Time >= Planned TAG start , 1, 0)* TAG Project Finished	Dimensionless	Control parameter indicating when Project is active. Controlled by start month and completion control parameters

Variable Name	Equation -or- Value	Dimensions	Purpose
Project Finished	TAG Project Finished Based on Work * TAG Switch for Finish Based on Work + (1 - TAG Switch for Finish Based on Work) * TAG Project Finished Based on Schedule	Dimensionless	Control switch for stopping the Project. Either stop based on schedule, or stop when work is near complete.
Project Finished Based on Schedule	IF THEN ELSE (Time > TAG Scheduled Completion Date,0,1)	Dimensionless	Control flag to indicate when Project is complete based on schedule parameters
Project Finished Based on Work	IF THEN ELSE (TAG Fraction Perceived to be Complete > TAG Fraction Complete to Finish , 0,1)	Dimensionless	Control flag to indicate when Project is complete based on work to do
Switch for Finish Based on Work	Value [0 or 1]	Dimensionless	Control parameter 0 indicates finishing based on schedule, 1 indicates finishing when work is complete
TIME STEP	0.25 used for all use cases	Months	Simulation Resolution

Variable Name	Equation -or- Value	Dimensions	Purpose
FINAL TIME	Value set to maximum project duration (e.g. 60 months)	Months	Simulation End Time
INITIAL TIME	Simulation Starts at Month 0	Months	Simulation Start Time
Loop knockout Prior Quality	1 enables loop, 0 knocks out loop	Dimensionless	Test Variable for Loop Knockout Validation
Loop knockout Uncertain Req	1 enables loop, 0 knocks out loop	Dimensionless	Test Variable for Loop Knockout Validation
SAVEPER	0.25	Months	Resolution to save results for export
TIME STEP	0.25	Months	Resolution for simulation

Note. Variables appear only once in Model

Appendix C – Real World Data and Calibration Parameters

Real World Data used for model calibration is presented here for each of the four Use Cases.

C.1 Use Case 1: Small - Large Weapon System

Table C-1. Use Case 1 Cost Data Table

	Cumulative Cost (Tasks)		
Month	RRP	INT	LWS
1	0.63	0	0
2	5.89	0	0
3	12.56	0	0
4	16.95	0	0
5	20.96	0	0
6	27.08	0	0
7	32.05	0	0
8	38.52	0	0
9	49.64	0	0
10	54.9	0	0
11	56.47	0	0
12	56.47	0	7.02
13	56.47	0	19.93
14	56.47	0	37.81

	Cumulative Cost (Tasks)		
Month	RRP	INT	LWS
15	56.47	0	64.51
16	56.47	0	96.31
17	56.47	0	126.33
18	56.47	0	157.17
19	56.47	0	202.41
20	56.47	0	249.46
21	56.47	7.87	312.03
22	56.47	17	377.38
23	56.47	28.27	463.41
24	56.47	40.45	553.9
25	56.47	52.37	663.68
26	56.47	63.67	785.39
27	56.47	71.8	912.96
28	56.47	71.8	1040.35
29	56.47	71.8	1170.8
30	56.47	71.8	1303.78
31	56.47	71.8	1441.87
32	56.47	71.8	1582.05
33	56.47	71.8	1720.01
34	56.47	71.8	1852.6
35	56.47	71.8	1990.49

	Cumulative Cost (Tasks)		
Month	RRP	INT	LWS
36	56.47	71.8	2129.21
37	56.47	71.8	2279.57
38	56.47	71.8	2425.72
39	56.47	71.8	2575.46
40	56.47	71.8	2722.93
41	56.47	71.8	2867.39
42	56.47	71.8	3003.88
43	56.47	71.8	3130.7
44	56.47	71.8	3240.69
45	56.47	71.8	3334.37
46	56.47	71.8	3408.39
47	56.47	71.8	3441.41

Table C-2. Use Case 1 Calibration Parameters

Calibration Data - Fixed	
Planned RRP start	1
R Initial Scheduled Completion	11
R Initial Work to Do	100
R Estimated Rework	10
Planned INT start	20

INT Initial Scheduled Completion	27
INT Initial Work to do	69
INT Estimated Rework	6.9
Planned LWS start	11
LWS Initial Scheduled Completion	47
LWS Initial Work to Do	2470
LWS Estimated Rework	247
Calibration Variables	
R Normal Productivity	2.49
R Normal Quality	0.9
R Hiring Delay	0.25
R Transfer Firing Delay	0.1
R Time to Gain Experience	0.94
R Initial Inexperienced Staff	4.73
R Initial Experienced Staff	1
INT Normal Productivity	1.64
INT Normal Quality	0.8
INT Hiring Delay	5
INT Transfer Firing Delay	0.1
INT Time to Gain Experience	1.93
INT Initial Inexperienced Staff	9.4
INT Initial Experienced Staff	1

LWS Normal Productivity	0.93
LWS Normal Quality	0.8
LWS Hiring Delay	5
LWS Transfer Firing Delay	0.1
LWS Time to Gain Experience	0.5
LWS Initial Inexperienced Staff	1
LWS Initial Experienced Staff	1

C.2 Use Case 2: Medium - Large Weapon System

Table C-3. Use Case 2 Cost Data Table

	Cumulative Cost (Tasks)		
Month	RRP	INT	LWS
1	0.19	0	0
2	0.89	0	0
3	3.18	0	0
4	6.05	0	0
5	9.84	0	0
6	31.15	0	0
7	43.94	0	0
8	56.3	0	0
9	71.27	0	0
10	82.79	0	0

	Cumulative Cost (Tasks)		
Month	RRP	INT	LWS
11	87.69	0	0
12	88.39	0	0
…			
30	88.39	0	0.94
31	88.39	0	27.71
32	88.39	0	63.42
33	88.39	0	105.55
34	88.39	0	189.66
35	88.39	0	325.44
36	88.39	0	439.41
37	88.39	0	612.56
38	88.39	0	753.59
39	88.39	0	923.98
40	88.39	0	1069.82
41	88.39	0	1264.97
42	88.39	0	1500.32
43	88.39	0	1768.34
44	88.39	0	2092.76
45	88.39	0	2496.83
46	88.39	0	2979.73
47	88.39	0	3538.58

	Cumulative Cost (Tasks)		
Month	RRP	INT	LWS
48	88.39	0	4097.76
49	88.39	5.3	4663.84
50	88.39	11.14	5275.31
51	88.39	19.55	5966.71
52	88.39	32.38	6725.49
53	88.39	46.59	7422.96
54	88.39	62.42	8049.92
55	88.39	79.96	8582.28
56	88.39	97.99	8932.13
57	88.39	116.33	9251.75
58	88.39	135.37	9452.62
59	88.39	152.35	9591.39
60	88.39	164.6	9624.53
61	88.39	173.92	9652.03

Table C-4. Use Case 2 Calibration Parameters

Calibration Data - Fixed	
Planned RRP start	1
R Initial Scheduled Completion	12
R Initial Work to Do	100

R Estimated Rework	10
Planned INT start	49
INT Initial Scheduled Completion	61
INT Initial Work to do	200
INT Estimated Rework	20
Planned LWS start	30
LWS Initial Scheduled Completion	61
LWS Initial Work to Do	9945
LWS Estimated Rework	994.5
Calibration Variables	
R Normal Productivity	1.55
R Normal Quality	0.9
R Hiring Delay	0.25
R Transfer Firing Delay	0.1
R Time to Gain Experience	1.17
R Initial Inexperienced Staff	1
R Initial Experienced Staff	1
INT Normal Productivity	1.42
INT Normal Quality	0.8
INT Hiring Delay	5
INT Transfer Firing Delay	0.1
INT Time to Gain Experience	0.5

INT Initial Inexperienced Staff	12.5
INT Initial Experienced Staff	1
LWS Normal Productivity	1.29
LWS Normal Quality	0.8
LWS Hiring Delay	5
LWS Transfer Firing Delay	0.1
LWS Time to Gain Experience	0.5
LWS Initial Inexperienced Staff	1
LWS Initial Experienced Staff	1

C.3 Use Case 3: Medium - Large Weapon System

Table C-5. Use Case 3 Cost Data Table

	Cumulative Cost (Tasks)		
Month	RRP	INT	LWS
1	7.54	0	0
2	14.27	0	0
3	27.14	0	0
4	35.54	0	0
5	43.86	0	0
6	54.11	0	0
7	62.98	0	0

	Cumulative Cost (Tasks)		
Month	RRP	INT	LWS
8	72.36	0	0
9	82.54	0	0
10	91.13	0	0
11	100.15	0	0
…			
18	100.15	0	4.53
19	100.15	0	79.34
20	100.15	0	236.47
21	100.15	0	478.01
22	100.15	6.11	772.55
23	100.15	10.64	1125.77
24	100.15	18.32	1514.13
25	100.15	28.51	1974.93
26	100.15	40.38	2469.62
27	100.15	53.14	3007.9
28	100.15	67.4	3534.79
29	100.15	82.72	4105.59
30	100.15	99.34	4656.29
31	100.15	114.52	5271.75
32	100.15	131.12	5924.34
33	100.15	147.2	6592.9

	Cumulative Cost (Tasks)		
Month	RRP	INT	LWS
34	100.15	161.49	7230.24
35	100.15	176.58	7924.4
36	100.15	187.26	8547.38
37	100.15	197.17	9138.47
38	100.15	197.17	9629.46
39	100.15	197.17	10113.11
40	100.15	197.17	10501.07
41	100.15	197.17	10840.26
42	100.15	197.17	11133.53
43	100.15	197.17	11366.51
44	100.15	197.17	11496
45	100.15	197.17	11513.31

Table C-6. Use Case 3 Calibration Parameters

Calibration Data - Fixed	
Planned RRP start	1
R Initial Scheduled Completion	11
R Initial Work to Do	98
R Estimated Rework	9.8
Planned INT start	22

INT Initial Scheduled Completion	37
INT Initial Work to do	194
INT Estimated Rework	19.4
Planned LWS start	18
LWS Initial Scheduled Completion	45
LWS Initial Work to Do	9996
LWS Estimated Rework	999.6
Calibration Variables	
R Normal Productivity	1.28
R Normal Quality	0.9
R Hiring Delay	0.25
R Transfer Firing Delay	0.1
R Time to Gain Experience	0.5
R Initial Inexperienced Staff	5
R Initial Experienced Staff	5
INT Normal Productivity	1.8
INT Normal Quality	0.8
INT Hiring Delay	5
INT Transfer Firing Delay	0.1
INT Time to Gain Experience	0.5
INT Initial Inexperienced Staff	9
INT Initial Experienced Staff	5.3

LWS Normal Productivity	1
LWS Normal Quality	0.8
LWS Hiring Delay	5
LWS Transfer Firing Delay	0.1
LWS Time to Gain Experience	0.5
LWS Initial Inexperienced Staff	20
LWS Initial Experienced Staff	10

C.4 Use Case 4: Large - Large Weapon System

Table C-7. Use Case 4 Cost Data Table

	Cumulative Cost (Tasks)		
Month	RRP	INT	LWS
1	0	0	96.37
2	0	0	401.4
3	0	0	698.63
4	0	0	1048.94
5	0	0	1434.34
6	5.78	0	1864.14
7	12.36	0	2316.23
8	23.83	0	2781.28
9	29.87	0	3261.96

	Cumulative Cost (Tasks)		
Month	RRP	INT	LWS
10	34.67	0	3837.82
11	42.24	0	4324.08
12	50.43	0	4892.52
13	56.93	0	5417.65
14	69.5	0	5979.22
15	85.43	0	6549.3
16	98.82	0	7044.77
17	113.52	0	7533.2
18	113.52	0	8096.42
19	113.52	0	8633.01
20	113.52	0	9204.22
21	113.52	0	9765.15
22	113.52	0	10338.3
23	113.52	0	10930.56
24	113.52	0	11651.87
25	113.52	11.56	12444.12
26	113.52	24.61	13351.31
27	113.52	39.82	14303.35
28	113.52	60.82	15268.87
29	113.52	89.24	16280.14
30	113.52	117.49	17247.93

	Cumulative Cost (Tasks)		
Month	RRP	INT	LWS
31	113.52	144.08	18113.7
32	113.52	172.26	19059.73
33	113.52	200.79	19976.54
34	113.52	226.77	20965.12
35	113.52	247.63	21997.58
36	113.52	247.63	23281.69
37	113.52	247.63	24604.53
38	113.52	247.63	26066.22
39	113.52	247.63	27583.28
40	113.52	247.63	29337.83
41	113.52	247.63	30900.47
42	113.52	247.63	32559.18
43	113.52	247.63	34443.07
44	113.52	247.63	36232.68
45	113.52	247.63	37724.05
46	113.52	247.63	38824.4
47	113.52	247.63	39816.58
48	113.52	247.63	40409.4
49	113.52	247.63	40763.53
50	113.52	247.63	40996.92

Table C-8. Use Case 4 Calibration Parameters

Calibration Data - Fixed	
Planned RRP start	6
R Initial Scheduled Completion	17
R Initial Work to Do	95.5
R Estimated Rework	9.55
Planned INT start	25
INT Initial Scheduled Completion	35
INT Initial Work to do	165
INT Estimated Rework	16.5
Planned LWS start	1
LWS Initial Scheduled Completion	50
LWS Initial Work to Do	43000
LWS Estimated Rework	4300
Calibration Variables	
R Normal Productivity	2
R Normal Quality	0.9
R Hiring Delay	0.25
R Transfer Firing Delay	0.1
R Time to Gain Experience	6
R Initial Inexperienced Staff	5
R Initial Experienced Staff	2

INT Normal Productivity	0.922
INT Normal Quality	0.8
INT Hiring Delay	5
INT Transfer Firing Delay	0.1
INT Time to Gain Experience	0.5
INT Initial Inexperienced Staff	16
INT Initial Experienced Staff	3
LWS Normal Productivity	1.55
LWS Normal Quality	0.8
LWS Hiring Delay	5
LWS Transfer Firing Delay	0.1
LWS Time to Gain Experience	2.9
LWS Initial Inexperienced Staff	1
LWS Initial Experienced Staff	1

Appendix D – Tabulated Model Results

Results presented in Chapter 4 are tabulated here.

D.1 Technology Readiness Level Tabulated Model Output

Table D-1. Cost Impact of Changing RRP TRL

Use Case	New TRL	RRP Cost Ratio	INT Cost Ratio	LWS Cost Ratio	Total Cost Ratio
1	4	0.828	1.141	1.000	1.004
1	5	0.914	1.068	1.000	1.002
1	6	1.000	1.000	1.000	1.000
1	7	1.162	0.868	1.000	0.997
1	8	1.465	0.650	0.999	0.991
2	4	0.817	1.162	0.999	1.005
2	5	0.912	1.078	1.000	1.002
2	6	1.000	1.000	1.000	1.000
2	7	1.175	0.846	1.000	0.995
2	8	1.469	0.589	0.997	0.983
3	4	0.835	1.158	1.000	1.006
3	5	0.920	1.076	1.000	1.003
3	6	1.000	1.000	1.000	1.000
3	7	1.169	0.849	0.998	0.993
3	8	1.446	0.595	0.994	0.981
4	4	0.816	1.151	1.000	1.001
4	5	0.915	1.072	1.000	1.001

4	6	1.000	1.000	1.000	1.000
4	7	1.216	0.857	1.000	0.999
4	8	1.849	0.616	1.000	0.998

D.2 Integration Time Tabulated Model Output

Table D-2. Cost Impact of Changing RRP Integration Time

Use Case	Integration Time Shift (Months)	INT Cost Ratio	LWS Cost Ratio	Total Cost Ratio
1	-14	1.299	0.791	0.803
1	-13	1.441	0.831	0.844
1	-12	1.455	0.862	0.874
1	-11	1.394	0.876	0.887
1	-10	1.341	0.886	0.896
1	-9	1.294	0.894	0.902
1	-8	1.251	0.901	0.909
1	-7	1.211	0.909	0.916
1	-6	1.175	0.918	0.924
1	-5	1.141	0.928	0.933
1	-4	1.110	0.939	0.943
1	-3	1.080	0.952	0.955

Use Case	Integration Time Shift (Months)	INT Cost Ratio	LWS Cost Ratio	Total Cost Ratio
1	-2	1.052	0.967	0.969
1	-1	1.025	0.983	0.984
1	0	1.000	1.000	1.000
1	1	0.976	1.019	1.018
1	2	0.952	1.039	1.037
1	3	0.929	1.061	1.057
1	4	0.907	1.085	1.080
1	5	0.885	1.111	1.106
1	6	0.864	1.140	1.133
1	7	0.842	1.171	1.163
1	8	0.820	1.205	1.195
1	9	0.800	1.239	1.227
1	10	0.781	1.270	1.257
1	11	0.760	1.292	1.279
1	12	0.736	1.300	1.286
1	13	0.711	1.285	1.271
2	-9	1.340	0.799	0.810
2	-8	1.456	0.893	0.903
2	-7	1.409	0.919	0.928
2	-6	1.331	0.926	0.934

Use Case	Integration Time Shift (Months)	INT Cost Ratio	LWS Cost Ratio	Total Cost Ratio
2	-5	1.262	0.934	0.940
2	-4	1.200	0.943	0.948
2	-3	1.143	0.954	0.958
2	-2	1.091	0.968	0.970
2	-1	1.043	0.983	0.984
2	0	1.000	1.000	1.000
2	1	0.960	1.017	1.016
2	2	0.923	1.036	1.034
2	3	0.889	1.057	1.053
2	4	0.856	1.078	1.073
2	5	0.826	1.100	1.094
2	6	0.798	1.118	1.112
2	7	0.772	1.128	1.121
2	8	0.747	1.119	1.112
3	-5	1.211	0.880	0.885
3	-4	1.344	0.976	0.980
3	-3	1.240	0.977	0.980
3	-2	1.148	0.982	0.984
3	-1	1.069	0.991	0.992
3	0	1.000	1.000	1.000

Use Case	Integration Time Shift (Months)	INT Cost Ratio	LWS Cost Ratio	Total Cost Ratio
3	1	0.939	1.010	1.009
3	2	0.883	1.019	1.017
3	3	0.832	1.024	1.022
3	4	0.786	1.022	1.019
3	5	0.744	1.007	1.004
4	-11	1.181	0.935	0.937
4	-10	1.164	0.937	0.938
4	-9	1.148	0.938	0.940
4	-8	1.132	0.941	0.942
4	-7	1.116	0.944	0.946
4	-6	1.101	0.949	0.950
4	-5	1.085	0.955	0.955
4	-4	1.068	0.961	0.962
4	-3	1.052	0.969	0.969
4	-2	1.035	0.978	0.978
4	-1	1.018	0.988	0.989
4	0	1.000	1.000	1.000
4	1	0.982	1.012	1.012
4	2	0.963	1.025	1.025
4	3	0.943	1.038	1.038

Use Case	Integration Time Shift (Months)	INT Cost Ratio	LWS Cost Ratio	Total Cost Ratio
4	4	0.921	1.051	1.050
4	5	0.898	1.062	1.061
4	6	0.873	1.072	1.070
4	7	0.846	1.078	1.077
4	8	0.815	1.081	1.079
4	9	0.782	1.077	1.075
4	10	0.746	1.069	1.067

D.3 Management Reserve Tabulated Model Output

Table D-3. Cost Impact of Changing Management Reserve

Use Case	Management Reserve	RRP Cost Ratio	INT Cost Ratio	LWS Cost Ratio	Total Cost Ratio
1	0%	1.020	0.985	0.983	0.984
1	5%	1.011	0.993	0.992	0.992
1	10%	1.000	1.000	1.000	1.000
1	15%	0.990	1.008	1.007	1.007
1	20%	0.982	1.016	1.014	1.013
1	25%	0.974	1.025	1.019	1.019
1	30%	0.967	1.033	1.025	1.024

Use Case	Management Reserve	RRP Cost Ratio	INT Cost Ratio	LWS Cost Ratio	Total Cost Ratio
2	0%	1.030	0.991	0.974	0.975
2	5%	1.014	0.996	0.988	0.988
2	10%	1.000	1.000	1.000	1.000
2	15%	0.989	1.005	1.011	1.010
2	20%	0.978	1.012	1.020	1.019
2	25%	0.970	1.019	1.027	1.026
2	30%	0.963	1.026	1.033	1.033
3	0%	1.016	0.975	0.962	0.962
3	5%	1.008	0.988	0.981	0.982
3	10%	1.000	1.000	1.000	1.000
3	15%	0.993	1.012	1.017	1.017
3	20%	0.988	1.022	1.033	1.033
3	25%	0.983	1.032	1.049	1.048
3	30%	0.978	1.042	1.063	1.062
4	0%	1.001	0.987	0.993	0.993
4	5%	1.001	0.994	0.998	0.998
4	10%	1.000	1.000	1.000	1.000
4	15%	0.999	1.005	1.000	1.000
4	20%	0.997	1.013	0.999	0.999
4	25%	0.993	1.021	0.997	0.997
4	30%	0.989	1.029	0.991	0.991

D.4 Delivery Completeness Tabulated Model Output

Table D-4. Cost Impact of Delivery Completeness

	Planned % Complete			Resulting % Complete				Resulting Defect Rate				Cost Ratio OFAT Reference Point all 1.0			
Use Case	RRP	INT	LWS	RRP	INT	LWS	TOTAL	RRP	INT	LWS	TOTAL	RRP	INT	LWS	TOTAL
1	0.800	0.800	0.800	0.804	0.821	0.802	0.803	0.335	0.515	0.550	0.550	1.000	1.000	1.000	1.000
1	0.850	0.800	0.800	0.869	0.820	0.803	0.806	0.224	0.512	0.550	0.550	1.070	0.888	0.996	0.992
1	0.900	0.800	0.800	0.916	0.816	0.804	0.808	0.141	0.514	0.550	0.550	1.134	0.802	0.992	0.986
1	0.950	0.800	0.800	0.958	0.802	0.805	0.811	0.072	0.532	0.550	0.550	1.243	0.726	0.988	0.980
1	1.000	0.800	0.800	1.000	0.826	0.810	0.818	0.000	0.492	0.550	0.550	1.392	0.695	1.004	0.995
2	0.800	0.800	0.800	0.819	0.807	0.820	0.819	0.312	0.532	0.380	0.383	1.000	1.000	1.000	1.000
2	0.850	0.800	0.800	0.854	0.810	0.820	0.821	0.253	0.520	0.378	0.380	1.037	0.992	0.999	0.999
2	0.900	0.800	0.800	0.905	0.822	0.800	0.802	0.161	0.499	0.401	0.401	1.108	0.980	0.971	0.972
2	0.950	0.800	0.800	0.952	0.802	0.805	0.807	0.082	0.526	0.399	0.398	1.230	0.930	0.971	0.972

	Planned % Complete			Resulting % Complete				Resulting Defect Rate				Cost Ratio OFAT Reference Point all 1.0			
Use Case	RRP	INT	LWS	RRP	INT	LWS	TOTAL	RRP	INT	LWS	TOTAL	RRP	INT	LWS	TOTAL
2	1.000	0.800	0.800	1.000	0.807	0.807	0.809	0.000	0.507	0.394	0.393	1.401	0.918	0.969	0.971
3	0.800	0.800	0.800	0.801	0.807	0.802	0.802	0.336	0.502	0.550	0.550	1.000	1.000	1.000	1.000
3	0.850	0.800	0.800	0.864	0.811	0.802	0.803	0.232	0.487	0.550	0.550	1.071	0.980	0.999	0.999
3	0.900	0.800	0.800	0.913	0.817	0.801	0.802	0.146	0.472	0.550	0.550	1.138	0.962	0.997	0.997
3	0.950	0.800	0.800	0.956	0.832	0.813	0.814	0.075	0.455	0.550	0.550	1.251	0.949	1.020	1.020
3	1.000	0.800	0.800	1.000	0.844	0.806	0.809	0.000	0.441	0.550	0.550	1.406	0.932	1.017	1.018
4	0.800	0.800	0.800	0.803	0.819	0.801	0.801	0.369	0.400	0.370	0.370	1.000	1.000	1.000	1.000
4	0.850	0.800	0.800	0.858	0.803	0.801	0.801	0.269	0.424	0.370	0.370	1.095	0.939	1.000	0.999
4	0.900	0.800	0.800	0.911	0.814	0.801	0.801	0.166	0.397	0.369	0.368	1.288	0.924	0.999	0.999
4	0.950	0.800	0.800	0.958	0.825	0.801	0.801	0.074	0.372	0.367	0.367	1.498	0.911	0.998	0.999
4	1.000	0.800	0.800	1.000	0.807	0.801	0.801	0.000	0.398	0.367	0.366	1.671	0.862	0.998	0.998
1	1.000	0.800	0.800	1.000	0.826	0.810	0.818	0.000	0.492	0.550	0.550	1.000	1.000	1.000	1.000
1	1.000	0.850	0.800	1.000	0.860	0.801	0.810	0.000	0.318	0.550	0.523	1.000	1.327	1.010	1.020

	Planned % Complete			Resulting % Complete				Resulting Defect Rate				Cost Ratio OFAT Reference Point all 1.0			
Use Case	RRP	INT	LWS	RRP	INT	LWS	TOTAL	RRP	INT	LWS	TOTAL	RRP	INT	LWS	TOTAL
1	1.000	0.900	0.800	1.000	0.908	0.803	0.813	0.000	0.184	0.479	0.453	1.000	1.697	1.035	1.056
1	1.000	0.950	0.800	1.000	0.952	0.810	0.820	0.000	0.089	0.433	0.407	1.000	2.053	1.060	1.091
1	1.000	1.000	0.800	1.000	1.000	0.809	0.822	0.000	0.000	0.378	0.354	1.000	2.416	1.097	1.137
2	1.000	0.800	0.800	1.000	0.807	0.807	0.809	0.000	0.507	0.394	0.393	1.000	1.000	1.000	1.000
2	1.000	0.850	0.800	1.000	0.871	0.819	0.822	0.000	0.374	0.364	0.360	1.000	1.134	1.026	1.028
2	1.000	0.900	0.800	1.000	0.912	0.813	0.817	0.000	0.265	0.364	0.358	1.000	1.290	1.026	1.030
2	1.000	0.950	0.800	1.000	0.951	0.810	0.815	0.000	0.163	0.364	0.356	1.000	1.498	1.026	1.033
2	1.000	1.000	0.800	1.000	1.000	0.808	0.814	0.000	0.066	0.364	0.354	1.000	1.759	1.026	1.038
3	1.000	0.800	0.800	1.000	0.844	0.806	0.809	0.000	0.441	0.550	0.550	1.000	1.000	1.000	1.000
3	1.000	0.850	0.800	1.000	0.860	0.808	0.810	0.000	0.314	0.550	0.550	1.000	1.202	1.008	1.012
3	1.000	0.900	0.800	1.000	0.905	0.816	0.819	0.000	0.190	0.550	0.541	1.000	1.475	1.042	1.049
3	1.000	0.950	0.800	1.000	0.953	0.804	0.808	0.000	0.091	0.541	0.528	1.000	1.782	1.048	1.060
3	1.000	1.000	0.800	1.000	1.000	0.814	0.819	0.000	0.006	0.461	0.448	1.000	2.071	1.109	1.125

	Planned % Complete			Resulting % Complete				Resulting Defect Rate				Cost Ratio OFAT Reference Point all 1.0			
Use Case	RRP	INT	LWS	RRP	INT	LWS	TOTAL	RRP	INT	LWS	TOTAL	RRP	INT	LWS	TOTAL
4	1.000	0.800	0.800	1.000	0.807	0.801	0.801	0.000	0.398	0.367	0.366	1.000	1.000	1.000	1.000
4	1.000	0.850	0.800	1.000	0.855	0.800	0.801	0.000	0.307	0.365	0.364	1.000	1.086	0.999	1.000
4	1.000	0.900	0.800	1.000	0.906	0.808	0.809	0.000	0.189	0.347	0.346	1.000	1.235	1.010	1.011
4	1.000	0.950	0.800	1.000	0.952	0.808	0.809	0.000	0.087	0.345	0.344	1.000	1.432	1.010	1.012
4	1.000	1.000	0.800	1.000	1.000	0.807	0.808	0.000	0.000	0.344	0.342	1.000	1.656	1.010	1.014
1	1.000	1.000	0.800	1.000	1.000	0.809	0.822	0.000	0.000	0.378	0.354	1.000	1.000	1.000	1.000
1	1.000	1.000	0.850	1.000	1.000	0.852	0.861	0.000	0.000	0.296	0.277	1.000	1.000	1.055	1.050
1	1.000	1.000	0.900	1.000	1.000	0.913	0.919	0.000	0.000	0.180	0.168	1.000	1.000	1.139	1.127
1	1.000	1.000	0.950	1.000	1.000	0.951	0.954	0.000	0.000	0.104	0.097	1.000	1.000	1.218	1.199
1	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.000	0.000	0.000	0.000	1.000	1.000	1.420	1.385
2	1.000	1.000	0.800	1.000	1.000	0.808	0.814	0.000	0.066	0.364	0.354	1.000	1.000	1.000	1.000
2	1.000	1.000	0.850	1.000	1.000	0.870	0.874	0.000	0.043	0.262	0.255	1.000	1.022	1.087	1.084
2	1.000	1.000	0.900	1.000	1.000	0.908	0.911	0.000	0.033	0.192	0.187	1.000	1.028	1.154	1.149

	Planned % Complete			Resulting % Complete				Resulting Defect Rate				Cost Ratio OFAT Reference Point all 1.0			
Use Case	RRP	INT	LWS	RRP	INT	LWS	TOTAL	RRP	INT	LWS	TOTAL	RRP	INT	LWS	TOTAL
2	1.000	1.000	0.950	1.000	1.000	0.958	0.960	0.000	0.007	0.082	0.080	1.000	1.048	1.337	1.326
2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.000	0.000	0.000	0.000	1.000	1.055	1.515	1.498
3	1.000	1.000	0.800	1.000	1.000	0.814	0.819	0.000	0.006	0.461	0.448	1.000	1.000	1.000	1.000
3	1.000	1.000	0.850	1.000	1.000	0.870	0.873	0.000	0.002	0.333	0.323	1.000	1.003	1.089	1.085
3	1.000	1.000	0.900	1.000	1.000	0.904	0.907	0.000	0.001	0.246	0.239	1.000	1.005	1.153	1.147
3	1.000	1.000	0.950	1.000	1.000	0.952	0.954	0.000	0.000	0.105	0.102	1.000	1.006	1.326	1.313
3	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.000	0.000	0.000	0.000	1.000	1.006	1.550	1.528
4	1.000	1.000	0.800	1.000	1.000	0.807	0.808	0.000	0.000	0.344	0.342	1.000	1.000	1.000	1.000
4	1.000	1.000	0.850	1.000	1.000	0.853	0.854	0.000	0.000	0.264	0.263	1.000	1.000	1.057	1.056
4	1.000	1.000	0.900	1.000	1.000	0.903	0.903	0.000	0.000	0.178	0.177	1.000	1.000	1.118	1.116
4	1.000	1.000	0.950	1.000	1.000	0.952	0.953	0.000	0.000	0.093	0.092	1.000	1.000	1.184	1.182
4	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.000	0.000	0.000	0.000	1.000	1.000	1.332	1.328