Beyond Integration Readiness Level (IRL): A Multidimensional Framework to Facilitate the Integration of System of Systems

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Dedication

I dedicate this dissertation to my wife, Stacy North Eder, and my two beautiful children, Haley North Eder and Colin Kekoa Eder, who continue to provide their unconditional love to me, and provided their relentless support throughout this program while I balance many other responsibilities.

I also want to dedicate this to my mother, Lucrecia Lacar Eder, who passed away prior to me starting this program. She has been the source of motivation and positive thinking throughout my life, and her spirit continues to inspire me to accomplish great things.

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Abstract of Dissertation

Beyond Integration Readiness Level (IRL):
A Multidimensional Framework to Facilitate the Integration of System of Systems

Integration Readiness Level (IRL) can be an effective systems engineering tool to facilitate integration of System of Systems (SoS). Further research in systems integration, analysis of major SoS integration data, and analysis of expert survey inputs to SoS integration can enhance the current IRL principles for systems integration use. The enhanced IRL assessment can help address Department of Defense's (DoD) uncontrollable cost growth of space systems as well as deliver systems in short timelines in support of DoD's goal to expedite the deployment of capabilities. IRL was developed to complement Technology Readiness Level (TRL), but DoD never implemented IRL. This research explains how IRL can be a separate tool to assess integration of systems as opposed to just integration of technologies. To enhance IRL evaluation, data of past DoD space systems' major integration issues were collected, aligned with integration variables, and then grouped into attributes. The resulting attributes and their refined definitions are the basis to calculate an enhanced IRL through a systems integration assessment framework. The IRL assessment identifies integration areas of emphasis that need to be addressed throughout the system development effort before the system becomes operational.

Keywords:

Integration Readiness Level (IRL), Technology Readiness Level (TRL), systems integration, Department of Defense (DoD) Acquisitions, System of Systems (SoS), DoD Space Systems

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CHAPTER 1: INTRODUCTION

1.1 Problem Statement

Integration Readiness Level (IRL) was introduced to help understand the maturity of integrating one system to another (Sauser B et al., 2010). The need to expand the use of IRL is increasingly becoming more relevant in the United States' Department of Defense (DoD) Acquisitions as programs try to acquire integrated systems with the intent to have multiple capabilities and interfaces.

When discussing about integration in systems engineering, it usually falls into the latter part of the Systems Engineering Life Cycle process as depicted in the Systems Engineering V-Model. The model can be implemented in many different ways; however, according to MITRE's Evolution of Systems Engineering (2009), "they all share fundamental elements" as depicted in Figure 1-1.

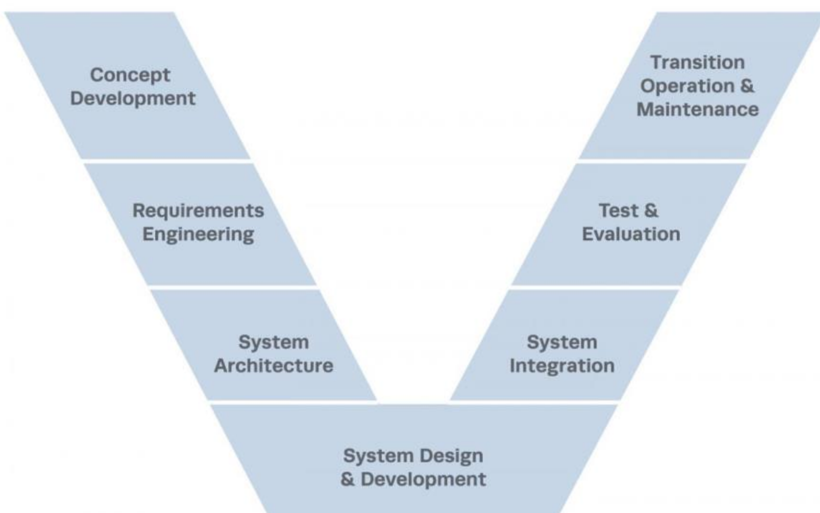

Figure 1-1. Systems Engineering V-Model (Mitre Corporation, 2009)

In the Systems Engineering V-Model, the process starts with Concept Development to System Design and Development, and then to Transition Operations and Maintenance. The application of integrating the system becomes the focus only after System Design and Development. System Integration, however, needs to be planned for earlier in the systems engineering lifecycle to improve success of overall system delivery. Understanding integration feasibility early in the program would be beneficial in managing and planning for the success of overall integration of complex systems or System of Systems (SoS).

Further research in systems integration, analysis of integration data, and the development of systems architecture framework can help enhance IRL principles for SoS integration. Enhanced IRL can improve to facilitate SoS integration, and the research will focus on Department of Defense (DoD) SoS to derive integration assessment framework.

1.2 History of Problem

The need to understand integration feasibility is necessary for integrating systems into a Family of Systems. Systems Engineers need to understand all necessary dependencies for successful integration. Throughout the years, DoD Acquisitions implemented several systems engineering processes and tools to help meet budgetary requirements while still trying to produce the best weapon systems available. There are two major reasons why integration feasibility would be beneficial to include into the systems engineering processes in DoD:

1) Uncontrollable Cost Growth:

SoS such as DoD space systems acquisitions have increased in actual system costs from the initial estimates while the capability of the system decreased from original intent. According to Government Accountability Office (GAO) report (2011), "the total estimated costs for major space programs increased by about $13.9 Billion from initial estimates for fiscal years 2010 through 2015, which is an increase of about 286 percent." This need to be managed better within DoD and additional tools are needed to understand future impacts to system delivery.

2) Expediting Deployment of Capabilities:

DoD also implemented initiatives in place to expedite the deployment of capabilities into operations as part of the Urgent Warfighter Needs efforts. Based on a GAO report (2012), various practices have been implemented by program offices in order to meet challenges to deliver capabilities within short time lines. Having additional integration tools available to understand the feasibility of weapon systems deployment on aggressive timelines could prevent schedule delays.

The DoD acquisition issues of uncontrollable cost growth and the need to expedite the deployment of capabilities into operations trigger the drive to improve systems engineering processes and tools that program managers can depend on when making program decisions. Acquiring weapon systems with the right capability, under budget, and deploy on schedule is the balance that DoD program managers need to make decisions on in order to be successful with their programs. The right capability can be defined to defeat current threats, which usually means applying the latest technology into the weapon systems. Maturity of the technologies used into these systems becomes critical to acquiring these systems. Understanding technology maturity helps with overall planning because it explains the availability of those technology that supports the development of the system.

In order to make decisions about systems and technology availability, DoD Acquisitions adopted the use of Technology Readiness Level (TRL) in 2002 (DoDI 5000.02, 2013). TRL provides measurement for explaining the maturity of a system based on the technology used for that system.

To further the use of TRL, IRL was introduced as an integration tool to complement TRL as illustrated in Table 1-1 (Sauser B et al., 2010). IRL was developed to align with the TRL definitions, but it was never officially implemented by DoD to help with integration assessment. Other readiness levels such as System Readiness Level (SRL) and Test Readiness Level were also introduced but not officially recognized by DoD Acquisitions.

Although not implemented, the use of IRL could become a necessary tool to help reduce integration risks of complex systems. Integrating SoS are becoming more complex and the current definitions of IRL do not allow it to be independent of the TRL process, which could be one reason why IRL is heavily scrutinized in current systems engineering literature. IRL was developed to support TRL's limitation of evaluating complex interfaces. According to London, M.A. et al. (2014), while TRL is used for "considering discrete technology elements, IRL is only limited to connecting these technology links between components."

Lvl	TRL	IRL
1	Basic principles observed and reported	An interface between technologies has been identified with sufficient detail to allow characterization of the relationship
2	Technology concept and/or application formulated	There is some level of specificity to characterize the interaction between technologies through their interface
3	Analytical and experimental critical function and/or characteristic proof of concept	There is compatibility between technologies to orderly and efficiently integrate and interact
4	Component and/or breadboard validation in laboratory environment	There is sufficient detail in the quality and assurance of the integration between technologies
5	Component and/or breadboard validation in relevant environment	There is sufficient control between technologies necessary to establish, manage, and terminate the integration
6	System/subsystem model demonstration in relevant environment	The integrating technologies can accept, translate, and structure information for its intended application
7	System prototype demonstration in relevant environment	The integration of technologies has been verified and validated with sufficient detail to be actionable
8	Actual system completed and qualified through test and demonstration	Actual integration completed and mission qualified through test and demonstration in the system environment
9	Integration is mission proven through successful mission operations	Execute a support program that meets operational support performance requirements and sustains the system in the most cost-effective manner over its total life cycle

Table 1-1. IRL and TRL Definitions (Sauser, B. et al., 2010)

Based on Sauser, B. et al. (2010), IRL was introduced as, "a metric for systematic measurement of the interfacing of compatible interactions for various technologies and the consistent comparison of the maturity between integration points." The concept itself could be more useful, but it is currently limited to support TRL concepts (as shown in Table 1-1). IRL's main concept is to be used to evaluate integration of two technologies that were evaluated by TRL process.

The principles of IRL can be used and enhanced to facilitate the integration of SoS. As indicated by Ge, B. et al. (2013), "SoS is defined as a large-scale integrated systems that are heterogeneous and independently operable on their own, but are networked together for a common goal." Many commonly used SoS terms such as interoperable and synergistic are important factors that need to be considered when integrating SoS (Madni A, Sievers M, 2014). The challenges of SoS integration is constant in DoD acquisitions as technology continues to improve and new capabilities emerge as better options for the warfighter. Understanding the feasibility of integration early in the process can help temper the expectations needed throughout the development and deployment of new systems.

1.3 Problem Focus

The focus of the research is to understand integration issues and challenges of prior SoS systems, and extract data to improve IRL assessment and facilitate future SoS integration. As challenges continue when integrating new capability into an existing family of systems, the need for understanding the overall effort is necessary for upfront planning. The components that make up SoS usually have different purposes, and the different organizations associated with those purposes typically use different terminologies and concepts. Thus, SoS integration must be able to address the differences in semantic and syntactic between their organizations. Identifying these issues ahead of time help highlight areas that need additional focus of IRL assessment.

Understanding systems integration itself is a very challenging task due to several factors that impact the integration processes. Systems integration can be interpreted differently, and although integration is a commonly used word, it is not clearly defined by both industry and academia on its application (Djavanshir G, Khorramshahgol R, 2007). As explained by Tien, J. (2008), "integration can occur through functional, physical, organizational, and temporal dimensions, which can also include management and processes of the actual system." Elements involved in integration tend to be multidimensional, which can be more complicated than evaluating technologies. Also, most current systems integration efforts focus on products instead of the process, which can lead to inadequate analyses when trying to understand the impacts of integrating components (Magnaye R, Sauser B, Ramirez-Marquez J, 2010). Integration of SoS is complicated, which goes beyond just "putting together" components.

The focus of the research is to develop a framework to help address SoS integration issues using IRL principles. The subjectivity of TRL and IRL processes has been widely criticized through several journals. They have been argued to oversimplify facets of system readiness and maturity. The risk and effort required for higher readiness levels does not factor into the current assessment of TRL and IRL (Kujawski E, 2013). However, the process of getting an initial assessment of the system prior to system design and development is beneficial in understanding overall integration feasibility. Defining feasibility of integration early enough in the process can impact decisions that could avoid integration pitfalls later in the process.

1.4 Initial Research Approach

The initial research approach was to understand what major integration issues that were encountered on different major systems. Several experienced systems engineers in the space industry were interviewed in order to get additional information on different integration issues that greatly impacted the systems they worked on. This initial process was the path to understanding what type of data would be used for this research.

Interviewing several systems engineers, however, would not suffice as good data due to small sample size and insufficient and inconsistent information. Thus, the focus quickly changed to collecting hard integration data that have been recorded through the years. The next challenge was finding the right systems with available integration data.

There are a variety of systems that have available integration data, but the focus was to get data for large SoS. The DoD has numerous major weapons systems that could be used for this research. The primary focus was gathering the right data that are available, accessible, and had the means to validate the data.

1.5 Impact to DoD Acquisitions

DoD acquisition processes continue to evolve and program managers are given multiple systems engineering tools to shape their programs. Their goal is to acquire the best weapon systems available with a limited budget while delivering on schedule. As different DoD systems continue to be complex while keeping up with the latest technology, integration of these systems to current existing systems become very critical.

Many DoD systems face multiple challenges in integration, and testing these systems are very complex and expensive.

As DoD Acquisitions learned from prior systems, many programs have implemented systems engineering divisions and directorate within their program to ensure that the necessary rigor is identified and applied throughout the design, development, integration, test, and deployment of each system. Although integration is focused heavily after development, a lot of the integration issues later in the program should be addressed early in the requirements and design phases.

The results of the research will help identifying integration feasibility once the requirements are defined. Throughout the DoD Acquisition process, there are several reviews and events that allow the program managers to make decisions on how to proceed with their program from the information received. The process of identifying how different subsystems integrate into the overall system could be a critical tool to understand the likelihood of program success.

1.6 Organization of Dissertation

Chapter 2: Literature Review

Chapter 2 summarizes the available journals and supporting documents for the research. Understanding available literature on the topics covered in this research helped define the framework and the purpose of the research. Systems integration work has been documented in multiple journal articles and published material. These supporting literatures identified different areas of focus towards IRL, Technology Readiness Assessment (TRA), systems integration, SoS, space systems, architectural framework, integration attributes, and regression analysis and supporting analysis tools. Each area is explained from the various publications and the information from those publications were leveraged to help define the purpose and the process of the research.

Chapter 3: Research Management

Chapter 3 summarizes the evolution of the research process. It explains the theory and the proposed research criteria. Based on the research criteria, it refines the data collection of DoD space systems and explains the goals of the research. The chapter also explains how a technical conference influenced the limitations of the research. The chapter ends with a list of initial assumptions of the research and a list of challenges that need to be addressed throughout the research.

Chapter 4: Methodology

Chapter 4 explains the research process and data exploration to understand the systems being researched. It describes the data collection process and what attributes were derived from the data. It covers all the integration data collected and how the data are categorized as a result of this research process.

Chapter 5: Results

Chapter 5 summarizes the data analysis and how the data has impacted the research. It covers the data validation through survey, which explained how the data could be relevant findings to this research. Chapter 5 explains the survey development and administration, and provides the survey results. It also includes the survey analysis, the comparison of results (between data collection results and survey response results), and provides the weights of attributes based on the data and survey analyses.

Chapter 6: Conclusion

Chapter 6 begins with the final criteria of the attributes based on the results of the data and survey. The weights of the attributes are key elements in the development of the Integration Assessment Framework. The chapter also provides information on the application of the framework. The chapter and the dissertation close with the discussion of the research and a summary of its limitations and future work.

CHAPTER 2: LITERATURE REVIEW

2.1 Integration Readiness Level

The use of IRL process has been documented through several literatures with different strategies of application. The most common use is an interim tool to support TRL and/or SRL processes. TRL metrics were initially developed from seven levels (NASA) in the late 1990s, and then to the nine levels that were adopted by DoD in 2002 (Mankins J, 2009). Assessment of TRL became more necessary as technology assessment moved into complex SoS, and DoD acquisition programs needed tools to help make decisions in complex environment (McConkie E, 2013). IRL's original intent was to provide a systematic analysis of integrating different technologies and understanding the maturity between the points of integration (Pittera T, Derrico M, 2011). IRL was focused on being a tool to understand the maturity of technologies used to integrate the systems as opposed to just being a tool to integrate two or more systems.

In the DoD Acquisition Process, Technology Readiness Level (TRL) are used for evaluating technology maturity. TRL level are derived using different test and verification processes, which are supplemented by Subject Matter Experts (SMEs) directed by the Program Managers. One of the goals of this research is to use IRL assessment as a separate evaluation tool from TRL and help facilitate integration of systems instead of the integration of technologies as originally intended for IRL. Both the IRL and TRL assessments could provide significant values to the programs throughout the DoD Acquisition process and improve the chances of delivering successful systems. The current IRL definitions are still useful to describe each IRL level, but the use of current IRL assessment and how the levels are derived are the changes proposed by this research.

2.2 Technology Readiness Assessment (TRA)

The DoD Acquisition Process provides detailed guidance to the Program Managers on planning for the lifecycle of their respective programs. According to the DoD Instructions 5000.02 (2015), the DoD Acquisition Process is an extensive framework that covers all the events before and after Milestones A, B, and C. As noted in Figure 2-1, a Materiel Solution Analysis and Materiel Development Decisions are two of the major activities and events that take place prior to Milestone A. The Technology Maturation & Risk Reduction Phase (Pre-Milestone B) is where the initial Technology Readiness Assessment (TRA) is conducted.

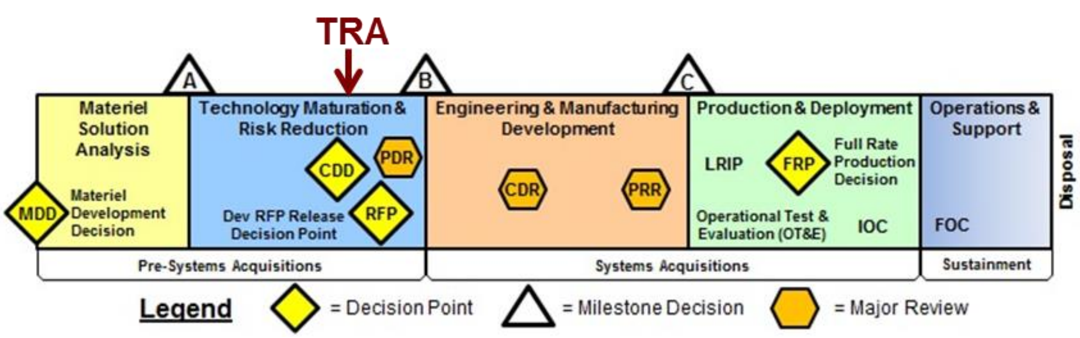

Figure 2-1. DoD Acquisition Process (DoDI 5000.02, 2015)

DoD Acquisitions use the TRA process to determine the TRL level for each critical technology that is integrated into the system that is being developed. According to the DoD TRA Guidance (2011), "TRA is a systematic, metrics-based process that assesses the maturity of, and risk associated with, critical technologies to be used by a program." TRA measures critical technologies and assess the TRL level of those technologies before they can be applied into the system design. Program Managers are responsible to assign TRA to its SMEs and conduct a TRA. The DoD TRA Guidance provides some top-level guidance on how to conduct TRAs, which are focused primarily on the technology.

TRA evaluates the system's critical technologies (potential risk areas defined by SMEs) during system development. Critical technologies are assessed using TRL Levels 1-9 (defined in Table 1-1). According to the DoD TRA Guidance (2011), "to reduce the risk associated with entering the Engineering and Manufacturing Development (EMD) phase, technology (ies) must be demonstrated adequately to attain TRL 6 or above." The TRL 6 definition is to demonstrate technology in a relevant environment, and it is a benchmark to enter EMD (Post Milestone B). Before the system becomes operational, the goal is for the system development to be completed and qualified through test and demonstration, which is the definition of TRL 8. TRL 8 can be accomplished through the Production and Deployment Phase (Post Milestone C) before it goes to Operations and Support.

IRL should follow the same TRL benchmark levels when going through the DoD Acquisition process, and it can focus on the major integration areas of the SoS as opposed to TRL's focus of critical technologies. IRL determination should also be conducted during the TRA timeframe where IRL 6 or greater is needed for the system to enter into the EMD Phase. In addition, the DoD Acquisition Process provides many other opportunities to conduct integration readiness assessment for the system after the initial assessment is conducted. Like TRL, the goal would be to ensure IRL 8 is attained prior to system operations.

2.3 Systems Integration

Systems Integration can be interpreted differently at many levels, but according to INCOSE Systems Engineering Handbook (2015), "The ultimate goal of systems integration is to ensure that the individual system elements function properly as a whole and satisfy the design properties or characteristics of the system." The INCOSE Systems Engineering Handbook (2011) describes systems integration as a process with the context diagram in Figure 2-2.

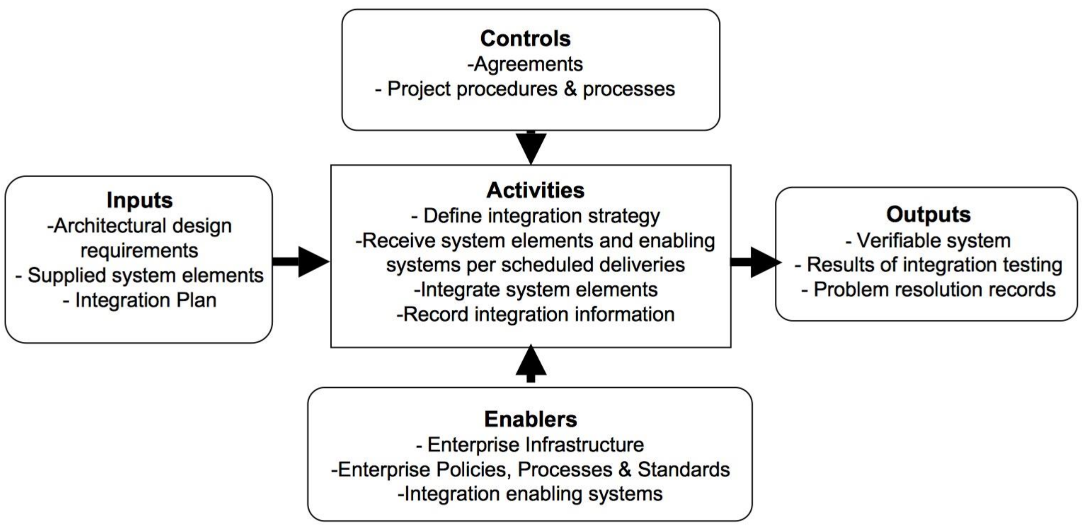

Figure 2-2. Context Diagram for the Integration Process (INCOSE Systems Engineering Handbook Ver 3.2.2, 2011)

Figure 2-2 describes the Integration Activities that are impacted by the Inputs, Enablers, and Controls to produce desirable Outputs. This process provides some context on what can be considered when executing systems integration. Integration assessment using IRL, which accounts for additional variables, can help facilitate this process. The research will focus on the integration feasibility to implement this type of process.

When the goal is to incorporate the use of IRL into systems integration processes, systems integration strategies and challenges must be identified. Systems integration is a strategy advocated in order to achieve sustainable development—it is very diverse and can be interpreted in many different ways (Vernay A, Boons F, 2015). System integration strategies have been explained in several journals, which provided different perspectives and help narrow the focus of this research from supporting technical/system maturity to readiness of integration.

According to Gagliardi, M. *et al.* (2009), "severe integration problems can arise due to inconsistencies, ambiguities, and gaps in how quality attributes are addressed in the underlying systems." One of the main reasons for this is not identifying the right quality attribute that supports the integration activities early in the process. This is where a set of quality attributes derived from the DoD space system integration issues can be identified to help with systems integration.

2.4 System of Systems

Application of systems integration processes can be enhanced when additional systems, processes, and organizations are involved in order to integrate SoS. SoS can be defined as a collection of interoperating components and systems producing results that are not achievable by each of the individual systems. Adding capabilities to an already complex system epitomizes the definition of SoS (Zhang Y *et al.*, 2012). In order to fully realize the analysis of SoS, engineering and systems architecture must be used to address allocation of functionality to component interaction as opposed to just dealing with individual components (Ender T *et al.*, 2010).

2.5 Space Systems

To understand the properties of SoS, DoD space systems can be used as examples of complex SoS. DoD satellites are complex SoS that cannot be accessed for upgrade or changes after they have been placed on orbit. DoD space systems have to satisfy integration requirements that may include affordability, reliability, security, resilience, and adaptability (Madni A, Sievers M, 2014). Conducting technical demonstration also requires significant funding and resources for these types of complex SoS (Dubos G, Saleh J, 2010). Thus, it is imperative that integrating them right the first time becomes a high priority.

2.6 Architectural Framework

To understand the comprehensive processes involved in the integration of complex SoS, one must understand how complex SoS are managed. Several architectural frameworks have been proposed in literature to design, develop, and manage these types of systems (Suh E, Chiriac N, Hotta-Otto K, 2015). Many of these larger systems involved multiple organizations as stakeholders, and according to Rebelo, L. et al. (2012), "large scale organizations, which have significant operations management needs, seek out and execute complex projects that involve a very large number of resource and schedule requirements." In addition to the wide range of factors involved in complex SoS, recent SoS development requires intensive information technology software, which also triggers the use of architectural framework (Piaszcyk C, 2011).

Architectural frameworks are developed to illustrate operations and functions to help clearly define roles of entities within complex SoS. Understanding and implementing the right architecture and component design will help perform faster integration processes and help reduce complexity (Jain R et al., 2008). The resulting data from this research will provide the components needed to develop an architectural framework. This framework will help explain how major attributes will contribute to the assessment of enhanced IRL and will help illustrate the different factors needed for consideration during evaluation of IRL at certain specific timelines.

2.7 Integration Attributes

Major attributes to support the integration assessment framework will be finalized based on the results of the data collection. As explained by Jain, R. *et al.* (2013), "attribute is a property or characteristics of an entity that can be distinguished quantitatively or qualitatively by human or automated means; the attributes of a system or architecture are used to describe the properties of the system or system architecture in a unique distinguishing manner." Attributes are usually basic elements related to requirements, which can be interpreted that a requirement consists of multiple attributes (Lung C, Xu X, Zaman M, 2007).

For attributes to be an effective tool for integration, they need to be integrated into the framework and optimized to balance complexity and simplicity. Organizations can adopt these attributes when integrating capabilities into the family of systems. Complex systems can have unpredictable behaviors and using multiple attributes can help measure the performance of these behaviors by quantitatively and qualitatively weighing the individual attributes (Gifun J, Karydasb D, 2005).

The initial list of attributes that will be considered for this research are derived from discussions with space systems integration experts, and journal articles on integration variables (Jain R, Chandrasekaran A, Erol O, 2010) and key integration process areas (Djavanshir G, Khorramshahgol R, 2007). The list of attributes considered were:

- System Availability
- Architecture and Design
- Commercial-off-the-Shelf (COTS)
- Complexity
- Configuration Management
- Concept of Operations
- Documentation
- Functionality
- Hardware/Software Verification and Validation
- Interface Control
- Information Assurance
- Interoperability
- Internal/External Organizations and Coordination
- Processes & Procedures
- Planning and Scheduling
- Programmatic and Risks
- Quality Assurance
- Requirements Management

- Resources (Funding)
- Risk Analysis and Management
- Semantic consistency
- Standards, Schedule Control
- Strategic Planning
- Technology Insertion
- Testing
- Training

These potential attributes will be used to help define each integration issue data that is aligned to specific integration variable. Some of these attributes may overlap or become part of another attribute. Collecting DoD Space Systems data will help identify and provide the criteria for the major attributes associated with each data.

2.8 Regression Analysis and Supporting Analysis Tools

The data collected for this research can be manipulated to examine the relationship with the research goals. One way to determine the trend of the integration issues data collection is through regression analysis. According Lattin, J., Carroll, J., Green, P. (2002), "Regression analysis is the most widely used for analysis of dependence, for which to examine relationship between a set of independent variables (x's) and single dependent variable (y)." Regression analysis can be used to examine data relationships and model the relationships that would help with prediction. It is used for predicting trends given a set of data and test hypothesis. Regression tries to produce the "best fit" equation to explain a group of data using linear equation. The equation of a straight line is:

$$y = a + bx$$

where a is the intercept and b is the slope. The line that gives the best fit to the data is called least squares line or sample regression line.

If the scatter plot of a sample data suggests a linear relationship between the two variables, drawing a straight line on the plot can summarize a relationship. Linear regression calculates an equation that minimizes the distance between the fitted line and all of the data points. Least squared method gives the best-estimated line for the set of sample data. Regression estimates are more reliable if it has a large dataset, sample variance of the independent variables is high, small variance error, and the less closely related are the independent variables (Greene W, 2010).

Normal Distribution

When collecting data, it is important to understand the relationship between independent variables and the dependent variable. To understand how they are distributed throughout the sample size, Normal Distribution is used. Normal Distribution is a probability distribution that plots all of its values in a symmetrical fashion and most of the results are situated around the probability's mean (Lane D et. al., 2007). Normal distributions are defined by two parameters, the mean (μ) and the standard deviation (σ) (Lane D et. al., 2007). Understanding these properties will help determine how the data will be used in the research.

Null Hypothesis Test

The P-value is used for hypothesis tests, where the null hypothesis is either rejected or fail to be rejected (Abell M, Braselton J, Rafter J, 1998). When doing a hypothesis test for a set of data, P-value can help measure the evidence against the null hypothesis, and it has a calculated value from 0 to 1. A P-value less than 0.05 often explain evidence that the null hypothesis is rejected (Minitab Support, 2016). To calculate the P-value, it is established that sample mean has a normal distribution, where the test statistic = (sample mean – hypothesized mean) / (sample standard deviation / square root of sample size). The test statistic is the value under the normal distribution curve. The P-value is the sum of the values outside of the test statistic under the normal distribution curve. When the P-value is less than 0.05 (this is derived with 0.95 test statistic), the null hypothesis is rejected.

Predictors in Regression Analysis

R-squared is a statistical measure of how close the data are to the fitted regression line. It is defined as the percentage of the response variable variance that is explained by a linear model (Lattin J, Carroll J, Green P, 2002).

R-squared = 1 – ((sum of squares about regression line) /

(sum of squares about mean of Y))

According to Lattin J., Carroll, J., Green, P. (2002), "R-squared with a value of 75% or higher is a good fit."

Adjusted R-squared is a modified version of R-squared that has been adjusted for the number of predictors in the model more than would be expected by chance. It imposes a penalty for adding additional explanatory variables if the fit is poor.

Adjusted R-squared = 1 – {(sum of squares about regression line) /

{[(samples size – number of predictors) – 1)] x

(sum of squares about mean of Y)}

In multiple regression, when a new variable is added it affects the coefficients of the existing variables. The coefficients of the multiple regression model are estimated using sample data with a defined number of independent variables. Adjusted R-squared can help with goodness-of-fit measurement using additional variables.

Other data analysis tools provide a different value of statistical predictor. The Minitab Analysis Software Tool provides the standard error of the regression (S) value, which like the R-squared, provides a measure of how well the model fits the data. The overall value of S is the average distance from the regression line. The smaller the value of S, the better it would be because it is closer to the fitted regression line (Lattin J, Carroll J, Green P, 2002).

CHAPTER 3: RESEARCH MANAGEMENT

3.1 Theory

IRL can be an effective systems integration assessment tool and given the right multidimensional framework, it can facilitate the integration of SoS. Utilizing other integration variables and expanding the current notional definitions of IRL can significantly impact the assessment of SoS integration. IRL was also proposed as an intermediate step by making it part of a matrix function with TRL in order to determine the SRL (McConkie E *et al.,* 2013). When IRL is used as a function of SRL, IRL could be overlooked from being a significant independent assessment value, and the IRL level may be influenced by what is needed as the SRL value. Current IRL definitions can be useful as an input to the framework as opposed to just being an intermediate assessment to understand technology or system maturity.

There are others who determine integration readiness can be assessed as part of DoD Acquisition's TRA process, but this process does not capture the purpose of integration. TRL was never intended to measure integration maturity (Magnaye R, Sauser B, Ramirez-Marquez J, 2010). A system with mature technology does not automatically equate to having a high IRL when interfacing with another system with mature technology. However, with time and more opportunities to resolve integration issues, the assumption is that the IRL value becomes higher.

3.2 Research Criteria

In determining the research criteria, the focus was to find relevant integration data for major systems across DoD Acquisitions. Integration of SoS becomes very challenging as the system becomes larger and more expensive with multiple parts to consider. There is significant value in understanding macro level SoS and be able to understand their integration properties into other SoS. Thus, the focus of the research and data collection was refined with the following criteria:

1) The systems have to be an ACAT I program due to it being a macro level integration. As defined in the DoD Instructions 5000.02 (2015), ACAT I programs are “Major Defense Acquisition Programs (MDAP) Acquisition Category I (ACAT I), which are defined as overall program procurement cost of over $2.79 Billion (using fiscal year 2014 constant dollars).”
2) There is available and accessible unclassified integration data. Collecting the right data and being able to access that data is critical to any research. There are also several classified systems in DoD, and although their integration data would be relevant to this research, it would not be available for use and for release.
3) There is available literature to support the data, and there is prior research that can help develop the framework of this research and provide background information. As the different concepts and effective processes in systems engineering are introduced through renowned journals, the information can be leveraged to support future work or identify gaps in the processes that could help with systems integration.
4) There are available and accessible expert personnel to validate the data collected as well as to provide additional background information. The expert personnel also need to be available to provide other considerations when categorizing the data as well as provide different perspectives based on their experiences.

3.3 DoD Space Systems Data

With the defined criteria, the focus of the research was refined to DoD Space Systems since they continue to provide examples of complex System of Systems. With very limited opportunities to do operational tests and analyses for satellite systems and rocket launches, space systems provide a platform to incorporate the latest technologies and processes to attain successful operational systems. As part of space system complexity, space systems also factors in the need for expediting the insertion of "cutting-edge" technology while adapting to new evolution of new technology and reducing qualification timelines (Pittera T, Derrico M, 2011). IRL can be used to assess the integration of these type of complex SoS given a rigorous process that account for other variables.

The DoD space systems that will be used for data collection have been or planned to be integrated into the space mission area family of systems as illustrated in Figure 3-1:

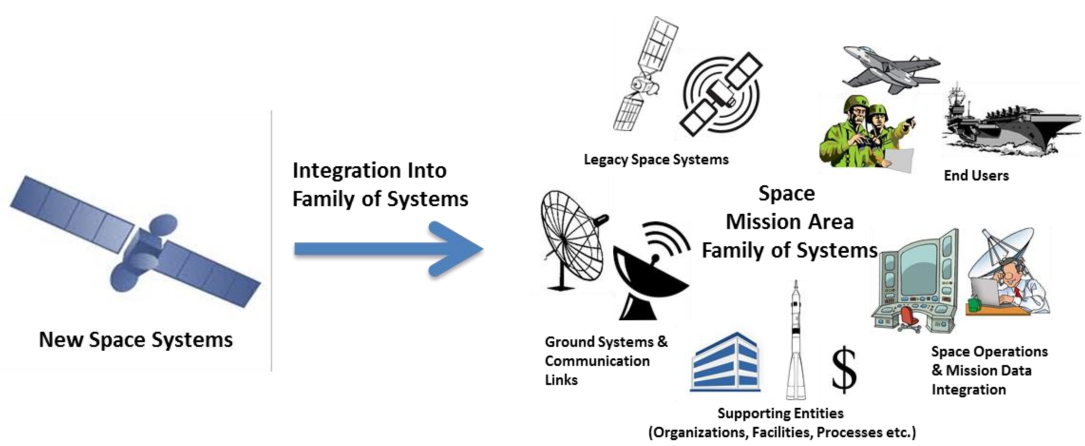

Figure 3-1. Space Capability Integration Into Family of Systems (Notional View)

The integration data will be collected from six major DoD space systems that are considered ACAT I programs. The major space systems are: 1) Advanced Extremely High Frequency (AEHF) satellite communications (SATCOM); 2) Evolved Expendable Launch Vehicle (EELV); 3) Global Positioning Satellite (GPS); 4) National Polar-Orbiting Operational Environment Satellite System (NPOESS); 5) Space Based Infrared Systems (SBIRS); and 6) Wideband Global SATCOM (WGS).

3.4 Research Goals

The goal is to develop a systems integration assessment framework tool based on the attributes identified through data analysis. It is imperative that assessment of complex systems must address common interfaces, interoperability, reliability, and operations (Bhasin K, Hayden J, 2008). Methods and processes in system engineering are used for defining requirements and provide the framework to identify a generalized architecture (Bhasin K, Hayden J, 2008). One of the major goals is to understand how integration issues can be addressed early in the acquisition process or planning stages in order to reduce the number of integration challenges and complexities later in the systems engineering process (Jain R, Chandrasekaran A, Erol O, 2010).

Cost for systems integration can increase substantially, and implementing processes to understand enterprise-wide systems integration requirements must be considered before deciding on a solution and architecture (Bolloju N, 2009). Based on Kruchten, P., Capilla, R., and Duenas, J. (2009), architectural elements are the primary constituents of describing “components and connectors while nonfunctional properties shape the final architecture.”

To support the goal of this research, data will be collected on six DoD major space systems integration issues in past 16 years, the data will be aligned with items that impact integration (as integration variables), the items will be grouped into major attributes, and the attributes will be analyzed to understand how they could be used to influence the SoS IRL score. Each derived attribute will provide a dimension into an integration assessment framework that will determine the enhanced IRL score for SoS integration. The framework will evaluate the overall integration feasibility, which will be able to help identify risks and mitigation strategies. To validate the data collected, an expert survey will be conducted. The results of the survey will help influence how the attributes are defined and weighted as they become components of the integration assessment framework.

The DoD Space Systems goal of integrating desired capabilities into family of DoD space/satellite systems is illustrated notionally in Figure 3-2 with the major integration points. The desired capability of DoD space system is usually integrated into a sensor, which becomes the payload of a satellite. The payload is integrated into a satellite bus and both systems become the satellite system. The satellite system is integrated into ground systems for communications and data exchange. The ground systems are the satellite operations centers, ground antennas, tracking stations, and the locations that process the mission data coming from the satellite system.

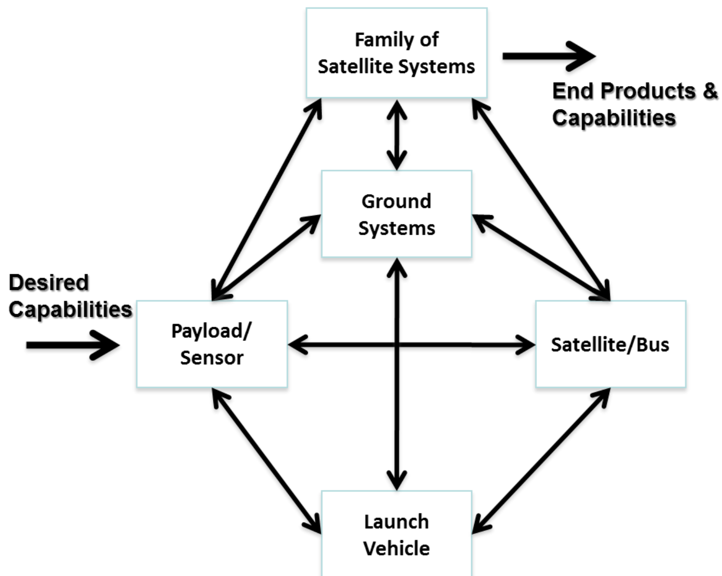

Figure 3-2. Notional DoD Space Systems Architecture and Major Integration Points

Due to its uniqueness, the integration of desired capabilities into the payload is usually the most challenging efforts in development and integration of space systems. After the payload has been developed and integrated into the satellite bus, they are rigorously tested on the ground. The satellite bus (or spacecraft bus) is the infrastructure of a spacecraft, usually providing locations for the payload, power source, and other instruments. From there, the satellite system is integrated into a launch vehicle (its ride to get on orbit). The satellite system is also integrated into the family of systems to ensure interoperability with existing systems and produce the final product/data to its users. The launch vehicle is integrated into the Ground Systems and the satellite system. The Ground Systems enable communication with all systems throughout launch, deployment, and operations of satellite system. The desired end state or successful SoS integration includes successful launch and deployment of satellite system on orbit that meet (or exceed) performance of all systems involved.

3.5 Limitations of Research

Excluding Integration Requirements

This research provides a tool to facilitate the integration of SoS; however, it does not focus on the development of systems integration requirements. Integration Requirements are critical but this research assumes that the stakeholders have agreed to the requirements before planning the scope that allows integration activities to be executed. Requirements need to be clearly defined to the lowest level and the assumption is to have clear requirements before conducting integration assessment(s). The proposed IRL assessment process will be iterative based on the changes in scope (if any) by the stakeholders. Understanding enterprise-wide integration requirements is necessary before developing a specific architectural framework to help with the integration process (Bolloju N, 2009). Understanding integration requirements processes can help with traceability of derived requirements during the integration planning and implementation stages.

Feedback from DEPEND Conference

When the research process began to mature and the target data for collection became more defined, an extended abstract of the research was developed. The reason for this was to get additional feedback through a technical conference on the focus of the research. The extended abstract helped refine the research and the path to complete it. Part of the focus of the research was to improve process dependability of systems integration. The result of the research was to provide a dependable systems engineering tool that decision makers can use to facilitate systems integration. Therefore, an extended abstract was submitted for presentation to the International Academy, Research, and Industry Association (IARIA) Eighth International Conference on Dependability in March 2015 (DEPEND 2015).

The DEPEND 2015 conference focused on dependability of processes including integration and specific systems. The extended abstract was reviewed by IARIA panel reviewers to be considered as part of the Doctoral Forum of the conference, which provided the opportunity to discuss and receive feedback on the thesis research from peers and senior practitioners in the field. Feedback from the panel were provided and adjudicated for extended abstract update. The updated extended abstract was approved and published by IARIA (Eder C, 2015), which was presented at the DEPEND 2015 conference on August 2015 in Venice, Italy.

The extended abstract review process and feedback from the conference presentation panel helped to clarify the focus of the research and understand the limitations and assumptions of the research. Based on the feedback and additional research, the initial list of attributes identified in Paragraph 2.6 has been truncated. As mentioned in the Beyond IRL Extended Abstract (Eder C, 2015), "Initial integration variables that are being considered include: 1) Schedule (need date, allowed timeline to integrate); 2) Resources (Funding, Personnel, Available tools); 3) Processes (Documented approach, Binding Agreements, Testing); 4) Policies (Directives, Guidance); 5) Communication (Documentation, Semantics, Expectations); and 6) Risks (Cost, Schedule, Technical)." Initial research into the space systems data provided this list of integration variables, which was later refined into integration attributes.

Two research limitations were identified based on the review panel and presentation feedback:

1) Provide a detailed description of each attribute and distinguish between them. The research process needs to define how each attribute is different from each other by different users and applications. This feedback was accepted and applied during the data collection process and during the development of the survey questions to validate the data.
2) Distinguish between complex SoS Integration (integration of macro or major systems that accounts for many factors) and small systems integration approaches that focus mostly on interoperability issues. The conference feedback highlighted the difference of these two views and how different they should be handled during the research process. Another topic was presented at the conference that focused on smaller integration process, which involved just the interoperability of two systems and the resources to make that happen. Understanding that process helped differentiate the focus of this research, which involves a much larger and more complex integration.

3.6 Assumptions:

The initial assumptions to the research, which is also closely related to the research criteria identified in Section 3.2, include the following:

1) The data collected would be clearly define the integration attributes
2) There is integration data available every year during the timeframe identified
3) There are available software tools to help analyze the data

4) Experts are available to validate data and provide survey results to enhance the definitions and the use of the data

3.7 Challenges

As the research process continued to be defined, there were some anticipated challenges that were documented. The goal was to address these challenges throughout the research process and determine ways to make them advantageous for the research:

1) Determining the scope of research (types of data to collect, limitations of data, availability of data, and releasability of data)
2) Understanding the relationships of the attributes and how they are different from one another
3) Applying different mathematical tools and supporting software tools to help analyze the data and understand how the results are applied into the integration assessment framework
4) Identifying the right SMEs to validate the integration data
5) Convincing the right SMEs to participate in the survey process to validate the data

CHAPTER 4: METHODOLOGY

4.1 Research Process

In support of the research goals of improving SoS integration assessment, the research process needed to be defined. The research process is as follows:

1. Collect high level integration issues data from six DoD major space systems from 1999–2014
2. Identify the integration variable that is impacted by each integration issue
3. Group the integration variables based on common focus areas
4. The integration variables will define the parameters for the final set of attributes
5. Analyze how each attribute is distributed throughout all six major space systems in the 16 years of data sets
6. Complete regression analysis of the attributes and determine weights of each attribute (The Minitab software tool will be used to assist with data analyses)
7. Validate attributes and the type of integration variable associated with each attribute by completing a survey of systems engineering, integration, and acquisitions experts in DoD
8. Analyze survey results using regression and correlations (The Minitab Version software tool will be used to assist with survey results analyses)
9. Compare both data analysis and survey analysis; identify final criteria for each attribute and determine the weight of each attribute
10. Based on the analyses, develop a systems integration framework tool using the weighted attributes

Once the integration assessment framework is developed, it can be used to help facilitate SoS integration. The output of the framework is the IRL score for the entire SoS, and as each major attribute matures, the IRL score improves. The framework can be used throughout the design, development, and deployment of the SoS. The stakeholders or designated Subject Matter Experts (SMEs) will have to provide upfront analysis, and agree on what the initial IRL level for each of the major attribute.

4.2 Data Exploration

In looking for a large sample size, the research for integration data led to the understanding of the major impacts to each DoD space system. Most of the DoD space systems were just ending the Research phase of the system in 1999. The pre-acquisition planning to procure the systems have either started or have matured in 1999, and integration issues surfaced during that timeframe. Each of the major systems were all budgeted for by the DoD in planning for their procurement reflecting on early cost estimates.

Throughout the years from 1999, multiple major decisions were made, which considered many factors that included financial disconnects (cost growth, budget support), schedule slippage, requirement changes, and technology risks. As evident through the reports highlighted in the Department of Operational Test & Evaluation (DOT&E) and other supporting documents (Aerospace annual reports, GAO, and program documents), significant integration issues were identified throughout the years. The 2014 reports were published in 2015, and therefore, 2014 was the last year these integration issues were considered for this research. The data collection for this research started in 2015, which focused on six major DoD space systems: 1) AEHF; 2) EELV; 3) GPS; 4) NPOESS; 5) SBIRS; and 6) WGS.

4.3 Data Collection

For 16 years from 1999–2014, major integration data from DOT&E reports with additional GAO supporting documents were collected (DOT&E Annual Reports, 1999–2014), which explained major integration issues encountered by the six major space programs for each year. The DOT&E annual reports are formal U.S. government documents that are consistently written to capture all the major issues throughout the DoD programs. The reports have specific guidelines for approval before it can be signed by the Director of Operational Test and Evaluation, and published in the DOT&E website for the United States Congress to review as needed. The reports, which satisfy the provisions of Title 10, United States Code, Section 139, summarize the operational test and evaluation activities of the DoD. Each annual report captures the previous fiscal year activities.

The issues identified in the reports are explained, but additional background information was gathered from the U.S. Air Force Space & Missiles Systems Center (SMC) program offices. Additional interviews of SMC personnel to gather background information were also conducted for better understanding of some of the issues. These space acquisitions programs have encountered challenges that directly impacted integration activities throughout the 16 years. Each major issue identified per year was counted as one issue (i.e. if one issue persisted through 4 years, it will be counted as 4 issues). Below is the description and data collection summary of each of the DoD space system:

1) AEHF: AEHF is a communication satellite SoS that provides secure and survivable communication capability to U.S. military during any level of conflict. According to DOT&E *Annual Reports* (1999–2014), it serves "as the protected backbone of the DoD military communication architecture." The AEHF capability ensures continuous secure communication during all levels of conflict for warfighters.

There were 79 major integration issues identified for AEHF during the 16-year span. Some of AEHF major integration issues included: testing processes for digital processors, and integrating nuclear hardening and shielding, electric propulsion, phased array antenna, and nuller spot beam.

2) EELV: EELV is a SoS launch vehicles and services provided to DoD and commercial customers. It was developed to provide launch capability that reduces the cost of alternative launch options while meeting mission assurance requirements.

There were 24 major integration issues identified for EELV during the 16-year span. Some of the major issues were data availability to the stakeholders for test verification processes, documentation of flight analysis plan, and integration of several design processes.

3) GPS: GPS is a major SoS that provides data dependent by DoD and civilian users. It has 24-satellite constellation that provides real-time and highly accurate positioning and location data. It can function through all weather and provides passive data to worldwide users. DoD is dependent on this data to precisely determine their velocity, time, and position.

There were 71 major integration issues identified for GPS during the 16-year span. Some of the major issues were communication between cross-link systems, development and integration of GPS Military-Code and civil signal capabilities, integration of receivers into major platforms (i.e. ships and aircraft), and refinement of end-to-end test strategy.

4) NPOESS: NPOESS was an enhanced weather SoS program that were administered by three different government organizations: DoD's Air Force; Department of Commerce's (DoC) National Aeronautics and Space Administration (NASA); and DoC's National Oceanic and Atmospheric Administration (NOAA). NPOESS provided the platform to acquire satellite SoS to collect and disseminate environmental data for the three organizations. Although development planning and integration started in 1999, the program was eventually cancelled in 2011. There are many valuable integration lessons learned derived throughout the years.

There were 18 major integration issues identified for NPOESS during its existence. Some of the major issues included field terminal integration and interoperability, integration of quality environmental data record, and integration challenges of program sensor design and algorithm development.

5) SBIRS: SBIRS are remote sensing satellite SoS that supports DoD by providing unprecedented timely and improved infrared data quality. SBIRS top missions of improving missile warning and missile defense have been realized through complex development and integration processes. It has also greatly enhanced the other mission areas of technical intelligence and battlespace characterization.

There were 46 major integration issues identified for SBIRS during the 16-year span. Some of the major integration issues included defining multiple test strategies, development of Model & Simulation systems to support operations of integration and testing, ground software development and integration, flight software integration into satellite.

6) WGS: WGS SoS enables communication to U.S. military and Coalition partners and allies during war and all levels of conflicts. Its wideband capability provides greater bandwidth to transfer data during conflicts.

There were 33 major integration issues identified for WGS during the 16-year span. Some of the major issues included integration complexity of X-band and Ka-band cross-banding on the on-board satellite, integration technical issues on orbital placement, frequency reuse, and launch services integration, interoperability complexity of control software development.

4.4 Attributes Derived from Data Collection

To understand the impact of each major integration issue, each issue was aligned with an integration variable to best describe the major area impacted by the issue. The integration variables were then grouped together based on similar focus areas and aligned with contributing attribute. Interviews with integration experts and additional research were conducted to define the right number of attributes from the initial list. The definition of each potential attribute continued to be refined based on the different groups of integration variables supporting them. After identifying the integration issues and integration variables, the list of contributing attributes was finalized. Each integration variable was assigned to a major attribute, which also helped define the criteria for that attribute. The result was seven final attributes, which are defined below:

Availability:

Availability is the attribute that was designated to understand the accessibility of supporting hardware, software, documentation, and expertise in order to enable integration activities. Integrating into legacy systems may not have proper support documentation and expert personnel may not be readily available, and this attribute will help to identify those supporting entities. The items derived from the integration issues that support this attribute are access to high TRL supporting systems, subsystems, and components, and access to supporting documentation and expertise.

The availability of the right supporting systems is critical to the success of the overall system delivery. To help address Availability, the reuse of existing infrastructure and the use of Commercial-Off-the-Shelf (COTS) items are identified before integration activities. To meet time commitments, the reuse of systems, subsystems, and components from the current infrastructure are highly encouraged with the possibility of replacing them with COTS items on future updates (Tyree J, Akerman A, 2005).

Complexity:

Complexity is the attribute that manages the technical risks of integration. The items derived from the integration issues that support this attribute are managing low technical maturity of system design, development, and integration, and determining complex interfaces. According to Jain, R. *et al.* (2008), "complexity can be defined as the degree to which a system or component has a design or implementation that is difficult to understand and verify." The complexity of systems integration has significant influence on driving schedule delays (Dubos G, Sale J, Braun R, 2008). Complexity affects the degree of complication of several factors such the number of interfaces and intricacies of different components (Jain R *et al.,* 2008). Although it has been widely studied, there is no defined mathematical model for systems related to complexity (Haghnevis M, Askin R, 2012).

Interoperability:

Interoperability is the attribute that will address compatibility, connectivity, and communication between systems, subsystems, and components. The items derived from the integration issues that support this attribute are understanding compatibility and interface issues, addressing semantic/syntactic issues, and managing communication issues between systems. Interoperability assessments can be very challenging in SoS because of the different testing involved to verify their functionality (Lin C *et al.,* 2009).

According to Madni A, Sievers M (2014), "interoperability is the ability of distinct systems to share semantically compatible information and then process and manage the information in semantically compatible ways, enabling users to perform desired tasks." Interoperability can be improved, which means that the metrics to measure it can be defined. However, interoperability is still a complex and broad topic, and its condition may not be easily quantified (Rezaei R, Chiew T, Lee S, 2013).

Management:

Management is the attribute that plans, develops, and directs integration strategies. The items derived from the integration issues that support this attribute include leading coordination between stakeholders, providing guidance and directives, determining scope, managing requirements, and developing and implementing policies and agreements. Management ensures that the stakeholders' derived integration requirements are met throughout the integration process. Managing stakeholders' decisions is critical in shaping the final design of the system (Booch G, 2006). Management must be able to navigate through the challenges of diminishing budgets, changing politics, and evolving technologies to support integration activities.

The management methods for integration address issues of philosophy, operation, and collaboration (Tien J, 2008). Management addresses requirements traceability. As indicated by Piaszcyk, C. (2011), "traceability is used to evaluate the impact of top-level requirements changes" that can help eliminate requirements creep.

Processes:

Processes is the attribute that enables the development, documentation, and execution of all integration activities. The items derived from the integration issues that support this attribute are processes that develop, document and execute the following: testing, verification and validation, configuration management, training, model and simulation activities, information assurance, mission assurance, model and simulation, communication and decision making, security, safety, quality assurance, and manufacturing and assembly. Processes implemented during integration must be clearly defined and documented. Many organizations' efforts in key process areas for integration did not have much success due to ill-defined processes (Djavanshir G, Khorramshahgol R, 2007). Processes for integration include standards, procedures, and algorithms associated with integration activities (Tien J, 2008).

The goal is to identify necessary processes needed for successful integration and the impacts to the integration requirements. Great examples from the space integration data also explains how the integration issues are impacted due to the different test and verification processes that have been implemented. Using Model and Simulation (M&S) as part of the integration process will help minimize risks. Computer based simulation M&S early in the process can help thrust systems engineering methods throughout the integration process (Ender T *et al.*, 2010).

Resources:

Resources is the attribute that enables integration of SoS through funding and providing the right integration tools. The items derived from the integration issues that support this attribute are having sufficient funding to support all integration activities, providing the right amount of trained personnel, and providing the right tools and facilities throughout the integration activities. Resource planning throughout SoS integration is critical to the overall success. During the early phase of integration, information is scarce but SMEs would have great inputs to address life cycle cost of development and overall integration of that system (Tien J, 2008).

Schedule:

Schedule is the attribute that manages schedule impacts throughout the integration activities. The items derived from the integration issues that support this attribute are understanding timeline goals (i.e. need dates, expected deliveries, and milestones), understanding scheduling parameters, and understanding critical path and impacts to schedule delays. Schedule can be impacted by several of the attributes mentioned;

however, an independent assessment is needed in order to understand how different changes impact scheduled milestones and activities. Need date and allowed time of integration must be established early on with analysis for fluctuations and critical path. Usually, the more time given for integration, the better the IRL score, which can be attributed to system maturity through time and processes.

Schedule delay usually increases the overall cost of the system and may impact the current requirements (i.e. launching a satellite at a certain month/year as required). Based on Dubos, G., Saleh, J., and Braun R. (2008), "schedule slippage plagues the space industry and is autonomic with the recent emphasis on space responsiveness; the GAO has repeatedly noted the difficulties encountered by the DoD in keeping its acquisition of space systems on schedule, and they identified the low TRL of the system/payload under development as the primary culprit driving schedule risk and slippage."

4.5 Results of Data Collection

Some of the attributes derived from the data may slightly impact the other attributes based on how they are interpreted. Therefore, the stakeholders need to establish clear definitions (as summarized above), understand the distinctions between attributes, and document assumptions being made for each major attribute. Each integration issue is aligned with an integration variable and then grouped with one of the seven major attributes based on their focus areas. Tables 4-1a to 4-6a capture the data of each attribute from each Space System. The tables show how a specific integration issue is aligned to an integration variable and how it becomes a subset to one of the seven attributes. Tables 4-1b to 4-6b also provide the number of years that the issue impacted for each of the space systems.

Table 4-1a: AEHF Data

Major Integration Issue from 1999-2014

#	Integration Issue	Type of Issue	Contributing Attribute	# of Years Impacted
1	Insufficient integration & test processes of satellite's digital processor	Testing Process	Processes	1
2	Nuclear hardening and shielding integration into system	System Design Maturity	Complexity	6
3	Nuller spot beam performance and integration	System Design Maturity	Complexity	6
4	Phased array antenna performance and integration	System Design Maturity	Complexity	6
5	Electric propulsion development and integration	System Design Maturity	Complexity	6
6	Integration of turbo coding into system is susceptible to nuclear fading	Interface	Interoperability	3
7	Lack of terminal synchronization within systems	Communication between systems	Interoperability	4
8	Insufficient software testing	Testing Process	Processes	3
9	Need for a payload simulator for integration, test, and verification	HW/SW Availability	Availability	2
10	Compatibility of payload and new terminals (standardization and consistency)	Compatibility between systems	Interoperability	2
11	Cryptographic capability to support AEHF data rate	Compatibility between systems	Interoperability	2
12	Manufacturing of complex circuit	Manufacturing Process	Processes	2
13	Model & Simulation for development, integration, test, and operations of nuller spot beam (testing single & multiple jammer scenarios)	Test and Verification	Processes	2
14	Fidelity of available system test simulator	Supporting System Availability	Availability	2
15	Increased system throughput capacity	Communication between systems	Interoperability	1
16	Schedule of legacy system testing inclusion to Mission Control segment	Schedule impacts	Schedule	1
17	Planning of space, mission control, and user segment integration & synchronization strategy	Strategy Development	Management	3
18	Insufficient specialized Model & Simulation validation process	Validation Process	Processes	2
19	Satellite to satellite payload cross-links, theater-to-theater communications, network control interoperability,	Communication between systems	Interoperability	2

	spacecraft system control, and user segment terminal configuration compatibility; integration of interim command & control system			
20	Lack of compatibility with the terminal and both the payloads, and with each payload	Communication between systems	Interoperability	1
21	Problems with low data rate for legacy users; degradation in performance during system communications	Communication between systems	Interoperability	2
22	Schedule issues by development contractor to resolve first-time test article and text fixture problems	Schedule impacts	Schedule	1
23	Testing anti-jam capabilities; test processes to evaluate AEHF Capabilities	Testing Process	Processes	3
24	Breached certification due to increase in cost and integration	Cost increase	Resources	1
25	Schedule slips prior to launch	Schedule impacts	Schedule	1
26	Multi-service interoperability of improving system performance	Interoperability of systems	Interoperability	1
27	Software availability to support integration of mission planning	Software Availability	Availability	1
28	Model & Simulation strategy to assess nulling antenna performance supporting integration and test	Strategy Development	Management	3
29	Sufficient ground control software is not available (insufficient sparing and logistics support)	Software Availability	Availability	1
30	Schedule delays of satellite vehicle development causing test delays	Schedule Delays	Schedule	1
31	Schedule delays to maneuvering of anomaly in orbit (delay test schedule)	Schedule Delays	Schedule	2
32	Insufficient budget to fund additional filters to meet High-Altitude Electro Magnetic Pulse (HEMP) testing and certification	Insufficient Funding	Resources	1
33	System downtime issues to support Mission Control element suitability	Software Availability	Availability	2
34	Scintillation testing processes capability to deter atmospheric effects and nuclear detonation	Testing Process	Processes	2
			TOTAL	**79**

Table 4-1b: AEHF Data

Major Integration Issue (Number of Attributes by Year)

YEAR	AVAIL	COMP	INTER	MGMT	PROC	RESO	SCHED
1999							
2000					1		
2001	1	4	2		1		
2002	1	4	4		2		
2003		4	4		3		
2004	1	4	2		1		
2005	1	4	2	1	1		1
2006		4	2	1	1		
2007			1	1	1		1
2008			2		1	1	1
2009	2			1	1		1
2010	1			1		1	1
2011	1			1	1		1
2012							
2013							
2014							
Totals	**8**	**24**	**19**	**6**	**14**	**2**	**6**
TOTAL	**79**						

Table 4-2a: EELV Data

Major Integration Issue from 1999-2014

#	Integration Issue	Type of Issue	Contributing Attribute	# of Years Impacted
1	Availability of modified Ground Operations System	Supporting System Availability	Availability	1
2	Insufficient testing processes on performance of rocket components	Test Processes	Processes	1
3	Requirement changes to rocket engine design	Requirement Changes	Management	1
4	Integration of legacy upper stage to the new launch vehicle design	System Interfaces and Compatibility	Interoperability	1
5	Legacy commonality from legacy launch vehicle to new launch vehicle (avionics, subsystems, parts, and engine)	System Compatibility	Interoperability	1
6	Integration processes of space launch operations (deploy, sustain, augment)	Operations Processes	Processes	1
7	Accessing agreement issues of development contractor's integration and test information/data	Contracted Agreement and Policies	Management	1
8	Insufficient processes to obtain data of system qualification tests for verification	Verification Processes	Processes	2
9	Lack of contractual requirement for test reporting	Contracted Agreement and Policies	Management	2
10	Processes for improving the documentation of post-flight analysis plans	Documentation Processes	Processes	2
11	Lack of additional development and integration funding to satisfy government and industry launches	Insufficient Funding	Resources	1
12	Insufficient use of Models and Simulations to predict systems integration and mission performance	Implementation of Processes	Processes	1
13	Interoperability and standardization issues of supporting two launch ranges	Interoperability between systems	Interoperability	1
14	Design issues on reliability, logistics supportability, multiple payload interfaces, and information assurance	System Design Maturity	Complexity	2
15	Insufficient rocket engine and subsystem testing	Testing Process	Processes	1
16	Ill-defined combined system test processes	Testing Process	Processes	1
17	Ill-defined systems engineering processes for system anomaly resolution	Verification Processes	Processes	1

18	Rocket engine design and integration issues impacting timing shut-off	System Design Maturity	Complexity	1
19	Characterization of integrated booster system performance	System Design Maturity	Complexity	1
20	Insufficient integrated review and analysis on avionics, flight mechanics, loads & dynamics, and environments	Verification Processes	Processes	1
			TOTAL	**24**

Table 4-2b: EELV Data

Major Integration Issue (Number of Attributes by Year)

YEAR	AVAIL	COMP	INTER	MGMT	PROC	RESO	SCHED
1999	1		1		1		
2000			1	2	1		
2001				1	2		
2002		1	1	1	3	1	
2003		1			1		
2004					1		
2005		2			2		
2006							
2007							
2008							
2009							
2010							
2011							
2012							
2013							
2014							
Totals	**1**	**4**	**3**	**4**	**11**	**1**	**0**
TOTAL	**24**						

Table 4-3a: GPS Data

Major Integration Issue from 1999-2014

#	Integration Issue	Type of Issue	Contributing Attribute	# of Years Impacted
1	Issues of cross-link systems (spurious radio frequency interference/noise was being sensed by new cross-link system)	Communication between systems	Interoperability	5
2	Availability of integrating a replacement ground system	Ground System Availability	Availability	1
3	Schedule margin issues on implementing ground system upgrades	Schedule impacts	Schedule	1
4	Operations Control segment availability	Software Availability	Availability	1
5	Integration of Prime contractor initiative (one contractor for both space and control segments)	Contract Agreement and Policies	Management	1
6	Funding availability to system development and integration causing event delays	Insufficient Funding	Resources	1
7	Configuration Management process issues on operations control system development and integration	Configuration Management Process	Processes	3
8	Availability of M-code and civil signal capabilities through development and integration	Supporting System Availability	Availability	7
9	Design issues on Control Software Integration	System Design Maturity	Complexity	1
10	Backward compatibility of modernization of new systems with legacy systems	Compatibility between systems	Interoperability	3
11	Integration of two different satellite models into launch vehicle	Compatibility between systems	Interoperability	1
12	Software integration and testing of control segment	Test Processes	Processes	3
13	Satellite signal power test process issues	Test Processes	Processes	2
14	On-going issues with the integration of GPS receivers into different platforms (ships, aircraft, etc.)	Communication between systems	Interoperability	8
15	Updated refinement of subsystem to support GPS Receivers	Hardware Availability	Availability	1
16	Integrating compatible electronic warfare environment into system for testing software	Compatibility between systems	Interoperability	1
17	Insufficient information assurance testing	Testing Process	Processes	3
18	Operational testing for new and legacy integration of system capabilities	Testing Process	Processes	2

19	Planning and refinement of integration and test strategy; insufficient rigorous end-to-end planning	Planning Test Strategy	Management	7
20	Schedule delays impacting integration, tests, and supporting resources	Schedule Impacts	Schedule	3
21	Synchronization of the development and integration of space, control, and user segments (risks to test new GPS capabilities into operational platforms)	Compatibility between systems	Interoperability	6
22	Test processes and assessment of new system capabilities	Test Processes	Processes	1
23	Prototype military receiver not available for development and integration testing	Hardware Availability	Availability	1
24	Lack of documentation for interface control documents, requirement documents, and test plan	Documentation Process	Processes	1
25	Lack of mission planning tool; limited operational realism when integrating and testing different subsystems	Hardware and Software Availability	Availability	2
26	Insufficient details to the documentation of integration, test, and evaluation plan; hindered strategy of test planning and integration	Documentation Process	Processes	1
27	Updates needed for Crypto-keyed GPS receivers design to enhance utility in jammed environment	System Design Maturity	Complexity	1
28	Lack of Documentation for Selective Availability Anti-Spoofing Module (SAASM) and updated GPS receivers	Documentation Process	Processes	1
29	Inaccurate, Implausible, and Incoherent schedule	Schedule impacts	Schedule	1
30	Updated Military GPS User Equipment receiver availability for integration and testing	Hardware Availability	Availability	1
			TOTAL	**71**

Table 4-3b: GPS Data

Major Integration Issue (Number of Attributes by Year)

YEAR	AVAIL	COMP	INTER	MGMT	PROC	RESO	SCHED
1999	1		1				1
2000	2		1	1	1	1	
2001	1		1				
2002	1	1	2		1		
2003	1		4		3		
2004	1		2		2		
2005	2		2	1	4		
2006	1		1	1	1		1
2007			2	1			1
2008			2	1	1		1
2009	2		2	1	2		
2010	1		2	1	2		
2011		1	1	1			
2012							
2013							
2014	1		1				1
Totals	**14**	**2**	**24**	**8**	**17**	**1**	**5**
TOTAL	**71**						

Table 4-4a: NPOESS Data

Major Integration Issue from 1999-2014

#	Integration Issue	Type of Issue	Contributing Attribute	# of Years Impacted
1	Availability of Critical Imager & Sounding systems	Systems Availability	Availability	1
2	Compatibility of legacy ground systems and operational system	Compatibility between systems	Interoperability	1
3	Development of acceptable integration and test strategy	Strategy Development	Management	1
4	Documented processes on the integration of space segment, command & control segment and communication segment; interface data processor segment; and launch support	Documentation Process	Processes	1
5	Designing and developing algorithm performance to new systems	System Design Maturity	Complexity	1
6	Funding issues to support interoperability of high rate data in X Band and low rate data in L Band	Insufficient Funding	Resources	1
7	Integration of different elements, multiple vendors, teams, and success is lacking definition and rigorous systems engineering	System of Systems Challenges	Complexity	1
8	Inconsistent agreement and definitions of different decision makers' roles and responsibilities	Stakeholder Agreements	Management	1
9	Design issues with the quality of Environment data record on algorithm, sensor performance, quality control of interface data processing segment	System Design Complexity	Complexity	2
10	Insufficient interoperability of field terminals and ground systems	Interoperability between systems	Interoperability	2
11	Design viability of delivering three sensors that can support ground segment capability	Design Complexity	Complexity	1
12	Technical challenges on subsystems: program sensor design, integration, and algorithm development	System Design Maturity	Complexity	2
13	Satellite control compatibility to existing network	Compatibility between systems	Interoperability	1
14	Lack of documentation process of adequate threshold definitions in data terminals	Documentation Processes	Processes	1
15	Lack of available space environment sensors that can be used for integration, test, and upgrades	Supporting Subsystem Availability	Availability	1
			TOTAL	**18**

Table 4-4b: NPOESS Data

Major Integration Issue (Number of Attributes by Year)

YEAR	AVAIL	COMP	INTER	MGMT	PROC	RESO	SCHED
1999							
2000	1		1				
2001				1			
2002		2			1	1	
2003		2	1	1			
2004		1	2		1		
2005	1	2					
2006							
2007							
2008							
2009							
2010							
2011							
2012							
2013							
2014							
Totals	**2**	**7**	**4**	**2**	**2**	**1**	**0**
TOTAL	**18**						

Table 4-5a: SBIRS Data

Major Integration Issue from 1999-2014

#	Integration Issue	Type of Issue	Contributing Attribute	# of Years Impacted
1	Availability of ground software delivery for integration (delayed in development)	Supporting Software Availability	Availability	3
2	Degraded test data from Sensor Test Integration Lab due to starer sensor and telescopic assembly process	Assembly Process	Processes	3
3	Scanner anomalies on current system design: periodic noise, background levels, and velocity errors	System Design Maturity	Complexity	1
4	Lack of planning to implement National Institute of Standards (NIST)-traceable calibration	Planning and Strategy Development	Management	1
5	Schedule delays impacting delivery of adequate processor and government provided communications	Schedule impacts	Schedule	1
6	Software instability in tracking, telemetry, and control functions	Software Design Maturity	Complexity	1
7	Management of integrating old and new software systems; development of configuration management system	Managing Integration	Management	2
8	Interoperability and supportability of existing ground systems with new software deliveries	Interoperability between systems	Interoperability	1
9	Integration of Ground Control Station backup with updated space systems	Communication between systems	Interoperability	2
10	Inadequate deficiency correction process; need new strategy for integration and test process	Strategy Development	Management	1
11	Funding to update inadequate Model & Simulation tool; expert resources to determine most effective tool	Inadequate Resources	Resources	2
12	Space sensor development and integration capability to meet current threshold	System Design Maturity	Complexity	1
13	Complication of coverage capability due to Solar flyer configuration for GEO satellites	System Design Complexity	Complexity	1
14	Availability of Ground Segment software upgrades and maintainability	Software Availability	Availability	1
15	Lack of appropriate tools to conduct threat scenario simulations (require	Insufficient Tools	Resources	1

	new simulation tool and message injector)			
16	Assembly rework and parts fabrication of High Voltage Power Supply in gyro assembly	Manufacturing Process	Processes	1
17	Lack of requirements definition on the integration of SBIRS control segment, CONOPS, and operational dependability	Requirements Development	Management	2
18	Availability of subsystems to support the development of overall system (concerns with degree of concurrency between space and ground segment development and operational impact of any further program delays)	Hardware and Software Availability	Availability	1
19	Insufficient definition of integrated test strategy to meet current schedule, ground architecture, and overall systems operational requirement	Strategy Development	Management	6
20	Lack of accredited software test models available for test scenarios and simulations	Software Availability	Availability	2
21	Insufficient definitions of operational concepts and development/operations phases	Requirements Management	Management	2
22	Lack of tools and resources to support Model and Simulation development of operational integration and testing	Insufficient Tools and Resources	Resources	3
23	Compressed schedules to accreditation of operational test scenarios increased software integration issues	Schedule Impacts	Schedule	2
24	Communication Issues of space control and telemetry and Flight Software integration in Satellite	Communication between systems	Interoperability	3
25	Limited ground software tools to determine limitations of software capabilities	Insufficient Tools	Resources	1
26	Insufficient processes for data collection of deficiencies, fixes, and impacts to mission capability	Data Collection Process	Processes	1
			TOTAL	**46**

Table 4-5b: SBIRS Data

Major Integration Issue (Number of Attributes by Year)

YEAR	AVAIL	COMP	INTER	MGMT	PROC	RESO	SCHED
1999	1	2		2	1		1
2000	1		2	1	1		
2001	1	1		1	2	1	
2002		1	1			1	
2003	1				1	1	
2004	1			1			
2005	1			3			
2006	1			2			
2007			1	1		1	1
2008			1	1		2	1
2009			1	1		1	
2010							
2011							
2012				1			
2013							
2014							
Totals	**7**	**4**	**6**	**14**	**5**	**7**	**3**
TOTAL	**46**						

Table 4-6a: WGS Data

Major Integration Issue from 1999-2014

#	Integration Issue	Type of Issue	Contributing Attribute	# of Years Impacted
1	Complexity of designing and integrating effective cross-banding between X-band and Ka-band on board the satellite	System Design Maturity	Complexity	4
2	Lack of software tools to support development of system configuration control element	Insufficient Tools	Resources	2
3	Software development complexity to support the interoperability requirements for control software control	Software Complexity	Complexity	2
4	Insufficient communication network between operational system users	Communication	Interoperability	1
5	System interoperability issues of WGS and transmission system	System Interoperability	Interoperability	2
6	Lack of workable communication payloads in WGS; need to ensure consistent communication between different bands (Ka and X bands) and between users	Communication between systems	Interoperability	1
7	Insufficient documentation processes to support development and integration	Documentation Processes	Processes	1
8	Ill-defined requirement definitions to separate legacy and new systems on orbit	Strategy Development and Requirement Management	Management	1
9	Updating requirements on the integration of solar panels into design; decisions on payload weight issues	Strategy Development	Management	1
10	Insufficient schedule assessment to account for development and integration	Schedule Impacts	Schedule	1
11	System availability to enable linkage between space and ground systems	Hardware and Software Availability	Availability	1
12	Insufficient Operator workload; highly trained personnel needed for increased responsibilities	Insufficient Personnel	Resources	1
13	Support to operations from different organizations and DoD services; insufficient number of personnel	Insufficient Personnel	Resources	1

14	Lack of upgraded automation software operations center networks	Supporting System Availability	Availability	1
15	Design and integration complexity of frequency reuse, satellite orbital placement, and launch service availability	System Design Maturity	Complexity	4
16	Schedule requirements are insufficient for integration and test assessment	Schedule impacts	Schedule	1
17	Oscillator component issues with payload channelizer subsystem; controls payload switching and crossbanding	Compatibility between systems	Interoperability	1
18	Quality control production of wrongly integrated fasteners	Production Process	Process	1
19	Updating connectivity between related systems such as the Global Broadcast System to improve interoperability	System Connectivity	Interoperability	2
20	Quality control testing at production facility caused problems with assembly of first two WGS satellites	Manufacturing Process	Processes	1
21	Insufficient management controls to address current satellite issues	Management Standards	Management	1
22	Unavailable software for users on WGS communication using Common Network Planning	Software Availability	Availability	1
23	Interoperability of legacy baseband equipment	Interoperability between systems	Interoperability	1
			TOTAL	**33**

Table 5-6b: WGS Data

Major Integration Issue (Number of Attributes by Year)

YEAR	AVAIL	COMP	INTER	MGMT	PROC	RESO	SCHED
1999							
2000		2	3			1	
2001		2	1				
2002		1		2	1		1
2003	1					2	
2004	1	2				1	
2005		1	2		1		1
2006		1	1		1		
2007		1					
2008	1		1	1			
2009							
2010							
2011							
2012							
2013							
2014							
Totals	**3**	**10**	**8**	**3**	**3**	**4**	**2**
TOTAL	**33**						

4.6 Summary of Data Collection Results

The result of the data collection based on the attributes gathered from the six major DoD space systems is summarized in Table 4-7. The total number of major integration issues collected from the six DoD space systems for the 16 years is 271 with a total of 35 for Availability, 51 for Complexity, 64 for Interoperability, 37 for Management, 52 for Processes, 16 for Resources, and 16 for Schedule.

TOTAL (Int Issues/Year)	**Year #**	**Avail**	**Comp**	**Interop**	**Mngmt**	**Process**	**Resource**	**Sched**
1999	1	3	2	2	2	2	0	2
2000	2	4	2	8	4	4	2	0
2001	3	3	7	4	3	5	1	0
2002	4	2	10	8	3	8	3	1
2003	5	3	7	9	1	8	3	0
2004	6	4	7	6	1	5	1	0
2005	7	5	9	6	5	8	0	2
2006	8	2	5	4	4	3	0	1
2007	9	0	1	4	3	1	1	3
2008	10	1	0	6	3	2	3	3
2009	11	4	0	3	3	3	1	1
2010	12	2	0	2	2	2	1	1
2011	13	1	1	1	2	1	0	1
2012	14	0	0	0	1	0	0	0
2013	15	0	0	0	0	0	0	0
2014	16	1	0	1	0	0	0	1
TOTALS		**35**	**51**	**64**	**37**	**52**	**16**	**16**
Total Major Integration Issues		**271**						

Table 4-7. Summary of DoD Space Systems Integration Data from 1999-2014

CHAPTER 5: RESULTS

5.1 Data Analysis

To determine the relationships between the seven attributes for the given years, a multivariable regression analysis was completed with the help of the Minitab software tool. The summary of analysis for each attribute is highlighted in the Normal Probability Graph in Figure 5-1. The resulting numbers are provided in Tables 5-1a to d. Table 5-1a shows the Mean and Standard Deviation (StDev) for each of the seven Attributes with the N number of years (16 total years). It also shows the Minimum and Maximum values for each attribute.

According to the Normal Probability Graph in Figure 5-1 and the resulting values in Table 5-1a, the value of the attributes are distributed in 3 groups with closely related plots: 1) Processes, Interoperability, and Complexity have the highest means and highest standard deviations; 2) Management and Availability values lie in the middle; and 3) Resources and Schedule have the lowest mean values (1.0) and with Schedule having a lower standard deviation. The analysis explained that although Interoperability has the highest mean from the collective space systems integration issues, Complexity had the highest standard deviation. Complexity had the highest variance from 0 to as much as 10 issues per year.

Table 5-1b provides the P-value calculation. The null hypothesis is that the attribute's set of data follows a normal distribution. According the results, Complexity, Resources, and Schedule have P-values less than 0.05, which rejects the null hypothesis. These attributes do not follow a normal distribution. The other attributes (Availability, Interoperability, Management, and Processes) have P-values greater than 0.05, which shows that the data follow a normal distribution. The P-value was calculated in order to understand how each of the attributes' data set is compared against each other. Further investigation explains why the three attributes do not have normal distribution:

- Complexity related issues were not distributed normally since there were 49 Complexity related issues of the DoD space systems in the first 8 years of the 16-year sample and there are only 2 issues in the next 8 years. This is consistent to the assumption in Section 3.1 that as more time is given to address complex issues and allowing the program to mature, the less of these Complexity related issues would occur, which also impacts the overall IRL assessment. In addition, from 2011 to 2014, these DoD space system programs have either matured through the Systems Engineering Life Cycle or have been cancelled (NPOESS); therefore the major integration issues for those years are minimal compared to the years before that.
- Resources related issues throughout the 16 years had a maximum of 3 per year (in 3 years) while having 7 years with the value of 0. There are a total of 16 Resources related issues in the 16 years, which explains why it is not normally distributed.
- Schedule, like Resources, also shows 16 Schedule related issues in the 16 years. Based on the data collection, both Resources and Schedule are lower valued attributes, and it may be due to how they are reported in the DOT&E annual reports. Resources may not be an issue for that year if additional funding was provided, and Schedule issues may be caused by other attributes.

For statistical measure, R-squared helps explain how close the data are to the fitted regression line. Table 5-1c shows the calculated values for the Standard Error for the Regression (S), the goodness of fit (R-squared or R-sq), and the modified version of R-squared (R-sqAdj). R-squared is calculated at 68.0%, which is just below the acceptable 75% “good fit” value (Lattin J, Carroll J, Green P, 2002). This shows that there is correlation between the variables and the Year. A modified version of the R-squared value is the Adjusted-R-squared, which accounts for the number of predictors in the model. In this case, the Adjusted-R-squared significantly drops the R-squared value. The Regression Equation have also been calculated in Table 5-1d, which helps with predicting the year for the given attributes. However, the goal of this research is to identify and define the attributes and their relationships among each other. Therefore, the Regression Equation will not be used.

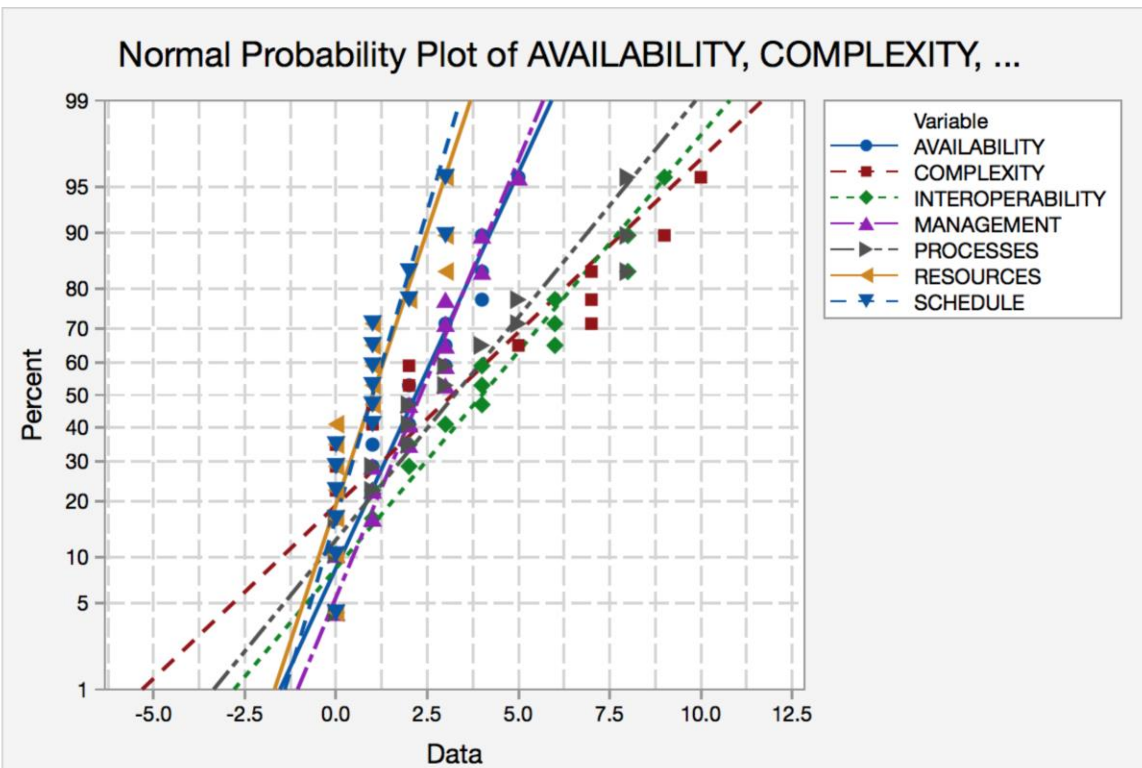

Figure 5-1. Normal Probability Graph of the Attributes Derived from Collected Data

Summary Statistics					
Variable	***N***	***Mean***	***StDev***	***Minimum***	***Maximum***
Availability	16	2.188	1.601	0	5
Complexity	16	3.188	3.656	0	10
Interoperability	16	4.000	2.921	0	9
Management	16	2.313	1.448	0	5
Processes	16	3.250	2.840	0	8
Resources	16	1.000	1.155	0	3
Schedule	16	1.000	1.033	0	3

Table 5-1a. Summary Statistics

Source	**P-Value**
Availability	0.3065
Complexity	<0.0050
Interoperability	0.4230
Management	0.3135
Processes	0.0724
Resources	<0.0050
Schedule	0.0058

Table 5-1b. Analysis of Variance

Model Summary		
S	**R-sq**	**R-sq(adj)**
3.6838	68.07%	40.13%

Table 5-1c. Model Summary

Regression Equation
Year = 15.140 − 0.070 Schedule − 2.183 Resources + 2.341 Processes − 0.5640 Management − 0.290 Interoperability − 1.5063 Complexity − 2.162 Availability

Table 5-1d. Regression Equation

5.2 Data Validation through Survey

The integration data was very useful in identifying critical attributes to support a framework for facilitating SoS integration. SoS integration is complex and being able to develop a systems integration assessment tool to determine integration feasibility is necessary for overall program planning. Although the identified attributes from the data collection can help improve the integration feasibility assessment, the attributes need to be validated by systems engineering, integration, and DoD acquisition experts.

A survey was conducted to help validate the usefulness of the seven major integration attributes. The survey was four weeks long that targeted 159 systems engineering, integration, and DoD acquisition experts with varying experiences in space systems, and/or complex SoS. From the 159 targeted participants, 88 have responded to the survey, which helped validate the attributes derived from the six major space systems data. The 88 participants were systems engineers, DoD acquisition professionals, and SMEs.

The survey was developed to ask the participants their opinions, based on their experience, of the integration attributes derived from the DoD Space Systems. They were asked to rank the attributes based on importance when considering for SoS integration. They were asked for their credentials though years of experience, field of expertise, and the types of SoS that they had experience with. The participants were targeted based on their credentials and were given the opportunity to provide feedback if they agreed or disagreed with the list of attributes. They were also given the opportunity to provide additional attributes and integration variables that helped define the original attributes. Most the participants were: systems engineers and DoD acquisition professionals working at the United States Air Force Space and Missiles Systems Center and the Missile Defense Agency; system engineers who were members of the International Council of Systems Engineers in Los Angeles; and development engineers from major companies in the space industry.

5.3 Survey Development and Administration

The process to develop and administer a survey required important steps to ensure a quality survey was produced without negative repercussions. To implement the survey, an Independent Review Board (IRB) package needed to be completed to include the intent of the survey and to ensure certain ethical and George Washington University regulations are not violated. Before any survey was initiated, a Collaborative Institutional Training Initiative (CITI Program) needed to be successfully completed, which covered ethical principles, defining research with human subjects, Federal regulations, risk assessment, and privacy and confidentiality.

IRB Package Consent Summary:

The IRB package provided very specific reasons to conduct the survey emphasizing that it was entirely voluntary for the participants to take. Participants were requested to complete the survey because of their experience in SoS and space systems integration. They needed to have had experience or are currently supporting the acquisitions (planning, design, development, test, integration, and deployment) of space systems and/or SoS. Targeted participants should have been involved in any functional capacity (i.e. systems engineering, SMEs, contracts, etc.) and/or are stakeholders in the decisions to space systems or SoS integration. Participants were advised to not continue with survey if they did not meet the qualifications provided in the introduction of the survey. Finally, the survey is restricted to only unclassified responses. Any higher security classification responses were not acceptable and are against the law, which was defined in the research criteria.

The survey would take approximately 30 minutes to complete; however, the participants may decline to answer any of the questions being asked as well as choose to stop their participation in the survey at any time. There was no known risk associated with the survey or the research. The answers from the survey would only be used for the purpose of the research and potential identifying information was kept confidential. The data derived from the survey will not include any identifying information for the survey participants, and will only be reported in an aggregate format.

The survey was administered in three different ways: 1) through Qualtrics, an online survey tool that has proven to protect encrypted data (i.e. actual names or email address of the survey participant)—this method garnered the most response; 2) through email—some of the participants were emailed a copy of the survey and they also provided their response through email; and 3) through hardcopy printouts—the surveys were distributed to experts through different meetings and system engineering conferences.

Each participant would not benefit directly or financially from his/her participation in the survey. The major motivation was to be involved with potentially improving systems engineering and integration processes within their respective organizations with the results being potentially published in scholarly paper. The participants were informed that their inputs and insight to the research would directly help challenge or validate new perspective they may have about space systems or SoS integration.

The participants would only complete the survey once and with no follow-up questions after completion. Their feedback will focus on providing feedback and comments to the data collected. The survey was administered in January 2016 and lasted for five (5) weeks. Online consent forms needed to be completed by the participants before starting the survey.

Survey Questions:

1. List the name(s) of the Space Systems (and/or complex systems) you have worked on:
2. What are your area(s) of expertise in the system(s) you mentioned above (i.e. Systems Engineering, Acquisitions, Finance, Logistics, Schedule, Contracts, Business Management, Configuration Management, Technical/Integration, Management, Subject Matter Expert, etc.)?
3. How many years of work experience do you have in your area(s) of expertise?
4. Rank the attributes identified below (derived from the DoD space systems integration data) that may help ensure successful integration of your overall system:
    a. **____ Availability** (Available Technology, Readiness of Hardware and Software components/subsystems)
    b. **____Complexity** (Technical risks, Number of interfaces, Level of effort)

c. ____**Interoperability** (Desired output/data, Semantics, Syntax, Component Communication)

d. ____**Management** (Stakeholders, Directives, Guidance, Internal/External Coordination)

e. ____**Processes** (Planning and Execution, Test and Verification, Documentation)

f. ____**Resources** (Funding, Personnel, Right Expertise/Experience, Hardware and Software tools)

g. ____**Schedule** (Need date, Allowed time, Fluctuations/Critical Path)

5. Do you agree with the 7 primary attributes listed in Question 4? Why or why not?
6. Do you agree with the list in parenthesis supporting each attribute in Question 4? Why or why not?
7. What other attribute(s) should be considered in addition to the 7 identified in Question 4?
8. Would you put Security as a separate attribute from the 7 above? Or would you include it under Processes?
9. What is your organization doing (or has done) to address major integration issues and challenges?
10. Have you heard of Integration Readiness Level (IRL) assessment before? (circle)

Yes / No

11. IRL has been used to support Technology Readiness Assessment; however, it can also be beneficial to support overall systems integration. The higher the IRL

score, the higher the integration feasibility. Do you think including the attributes above would make IRL more useful in systems integration? (circle)

Yes / No

12. IRL could be used to understand the integration challenges ahead of time and provide areas of emphasis throughout the integration process. How would you benefit if you understood the feasibility of integration before integrating the actual system? Provide examples (if any).
13. Based on your experience, what factors can hurt the system if Schedule continues to be delayed (impact of time)?
14. Would you agree that your Integration Readiness Level (IRL) score improves through time due to more opportunities to address potential risks and issues? Why or why not?
15. What do you think are some major risk areas when integrating overall System of Systems (i.e. Space Systems, Enterprise Systems, Complex Systems, etc.)?
16. Based on your experience, what do you see most often that causes systems integration failure? Why?
17. What are some recommendations you have to improve overall systems integration?
18. What has been one of the longest integration issue for the system you worked on? How long did it take to resolve (estimated in years)?

5.4 Survey Results

Summary of Survey Results

Questions 1 to 7 were the most useful responses to this research that were analyzed through the survey analysis below and compared with the data that were collected from the DoD space systems. Table 5-2 is the Key to the Survey Results Data for Questions #1 to 7. Table 5-3 is the Survey Results Data for Questions #1 to 7. Questions 8 to 18 provided additional background information of the systems that the participants were involved with and their experience. The responses received from all of the questions validated the Attributes data collected, and it helped provide additional background information for each Attribute.

Table 5-2: Key for Survey Results Data (Questions #1 to 7)

<table>
<tr><td>Q: # for each survey participant</td></tr>
<tr><td>1: System of Systems (SoS) that each participant has been involved with

MDA SoS: Missile Defense Agency (MDA) SoS
Ground-Based Midcourse Defense (GMD)
SMC SoS: Various Space & Missiles Systems Center (SMC) SoS
SBIRS, EELV, GPS, AEHF, and WGS
FAA SoS: Federal Aviation Administration SoS
Class SoS: Classified Satellite SoS
XSats: Experimental Satellites from SMC, Air Force Research Laboratory, or other organizations
Weather: Weather SoS
Defense Meteorological Satellite Program, Weather Follow On System, NPOESS
NASA: National Aeronautics and Space Administration SoS
Launch: Launch Vehicle SoS
ABR: Airborne Radars SoS
Aircraft: U.S. Air Force aircraft SoS
ABL: Airborne Laser
Navy: U.S. Navy aircraft/space SoS
</td></tr>
<tr><td>2: Area of Expertise:

SE: Systems Engineering
PM: Program Management
SME: Subject Matter Expert
Acq: Acquisitions
Req: Requirements
SI: Systems Integration
T&E: Test and Evaluation
CM: configuration Management
Ops: Operations
Log: Logistics
DE: Development Engineering
Sec: System Security
BM: Business Management (Finance, Contracts, Schedule)
MM: Manufacturing and Materials
Risk: Risk Management
</td></tr>
<tr><td>3: Number of Years on Work Related Experience</td></tr>
<tr><td>4: Ranking of Attributes: #1 to #7 (#1 is most significant to #7 least significant)</td></tr>
<tr><td>5: Response to Question if Participants agree with current List of Attributes? Why or why not (if applicable)?</td></tr>
<tr><td>6: Response to Question if Participants agree with current definitions of Attributes? Why or why not (if applicable)?</td></tr>
<tr><td>7: Response to Question List any other Attribute (if any)</td></tr>
</table>

Table 5-3: Survey Results Data (Questions #1 to 7)

Q	1	2	3	4							5	6	7
#	**SoS**	**Exp**	**Yrs**	**R 1**	**A 2**	**N 3**	**K 4**	**I 5**	**N 6**	**G 7**	**Agree w/Attr**	**Agree w/Def**	**Other Attr**
1	MDA SoS	SE	39	A	C	I	M	P	R	S	Yes	Yes	None
2	MDA-SoS	SE, T&E	35	P	R	C	I	S	M	A	Yes	Yes	Team Structure
3	SMC SoS	SE, MM	40	M	I	C	A	P	R	S	Yes. Need Mgt guidance.	Add Decision Making & Leadership	Same as Q6
4	FAA & MDA SoS	SE	34	I	C	A	P	M	R	S	No. Need Concept of Ops	No. Add Funding and Staffing	Same as Q6
5	Class SoS	Sec	16	R	A	M	P	S	I	C	Need clarification on Complexity & Interoperability	Yes	Stable Reqmts
6	XSats	PM, SME	13	R	M	I	P	S	A	C	Yes	Yes	None
7	Class SoS	SE, PM, SME	35	R	M	P	A	C	I	S	Yes	Yes	V&V Process
8	SMC SoS	Acq	3	R	M	S	A	C	P	I	Yes	Yes	None
9	Weather	Req, SME	20	M	R	P	A	D	S	I	Yes	Yes	None
10	Class SoS	SE, S&P	8	P	R	M	S	I	A	C	Yes	Yes	None
11	NASA, MDA SoS	SE	36	C	I	R	A	M	P	S	Add Reqmts, Architecture, & M&S	Same as Q5	Same as Q5
12	SMC SoS, Launch	SE, CM, Req	20	M	P	R	C	I	A	S	Yes	Yes	Reqmts Definition
13	AR	DE	16	A	C	R	I	P	M	S	Yes	Yes	None
14	SMC SoS	Acq	3	M	R	A	C	S	P	I	Yes	Yes	None
15	SMC SoS	SE, SI, Acq	21	A	R	M	S	C	I	P	Add Planning	Planning	Planning as separate Attribute
16	SMC SoS	SE, Acq, CM	11	M	P	R	A	C	I	S	Yes	Yes	None
17	MDA SoS	SE	4	R	S	P	A	M	I	C	Yes	Yes	Config Mgt
18	SMC SoS, MDA SoS	SE, Acq, SME	30	P	I	C	A	R	M	S	Yes	Yes	Capture "ilities"
19	SMC SoS	Acq	3	M	R	P	A	C	I	S	Yes	Yes	Clear Reqmts
20	SMC SoS	SE, Acq	20	A	I	R	S	P	M	C	Yes	Yes	Reqmts Definition

Q #	1 SoS	2 Exp	3 Ex	4 R 1	A 2	N 3	K 4	I 5	N 6	G 7	5 Agree w/Attr	6 Agree w/Def	7 Other Attr
21	Class SoS	SE	16	P	C	M	I	R	S	A	Yes	Ad d Config Mgt to Processes	None
22	Launch	SE, Acq, Ops	10	C	I	M	R	P	A	S	Need to Explain Schedule	Update Schedule Definition	Reqmts Definition
23	Class SoS	Acq, BM, SME	20	M	R	P	S	A	I	C	Yes	Yes	Technical Scope
24	XSats	SE, T&E	36	R	A	S	M	P	C	I	Yes	Yes	Concept of Operations
25	SMC SoS	Acq, BM, SME	14	C	I	R	M	A	S	P	Yes	Cybersecurity under Processes	Product Support
26	SMC SoS, Aircraft	SE, T&E	15	S	C	R	P	M	A	I	Yes	Yes	Reqmts Definition
27	SMC SoS	Acq, BM	8	P	M	A	S	R	C	I	Yes	Yes	Flexibility
28	SMC SoS	SE, PM	35	C	A	S	I	M	P	R	Yes	Yes	None
29	MDA SoS	PM, Acq, T&E	27	M	R	S	I	C	A	P	Yes	Yes	Cost & Schedule Risks
30	NASA	SE, PM	12	R	C	M	P	S	I	A	Yes	Yes	None
31	Class SoS	SE, Acq	13	M	R	P	A	S	C	I	Yes	Yes	None
32	SMC SoS	SE, Acq	25	C	A	S	M	P	R	I	Yes	Yes	None
33	Class SoS	SE, T&E	16	R	M	C	A	S	I	P	Yes	Yes	None
34	SMC SoS	SME	50	C	I	P	A	R	M	S	Yes	Yes	Reqmts Definition
35	Launch, SMC SoS	T&E	11	R	S	C	A	I	M	P	Yes	Yes	None
36	NASA, SMC SoS	SE, PM	25	C	P	A	I	M	R	S	Yes	Reqmts as part of Complexity	Reqmts could also be separated
37	Weather	Acq	9	M	R	C	P	S	A	I	Yes	Yes	Necessity
38	Launch	BM	18	M	R	S	A	P	C	I	Yes	Yes	Contracts Timeframe
39	SMC SoS	PM	12	M	S	I	P	C	A	R	Yes	Yes	Rate of Technology
40	ABL	DE	18	R	C	A	P	I	S	M	Yes	Yes	Transfer of Knowledge

Q #	1 SoS	2 Exp	3 Ex	4 R 1	A 2	N 3	K 4	I 5	N 6	G 7	5 Agree w/Attr	6 Agree w/Def	7 Other Attr
41	SBIRS	Acq	14	R	C	A	P	S	M	I	Yes	Yes	Training
42	Weather	Acq, BM	16	A	S	M	C	P	I	R	Yes	Yes	None
43	SMC SoS	SE, Ops, T&E	15	P	M	R	A	I	C	S	Yes	Yes	None
44	SMC SoS	SE	4	M	R	S	P	C	I	A	Yes	Yes	Reqmts Definition
45	Weather	SE, Acq	21	P	M	R	A	I	S	C	Add Overall Communication	Yes	Communication
46	MDA SoS	SE	35	M	P	R	S	C	I	A	Yes	Yes	Reqmts Definition
47	SMC SoS	Acq, PM	19	P	M	R	A	C	S	I	Add Strategic Planning	Yes	Strategic Planning
48	Weather	Acq	20	R	M	A	C	S	I	P	Yes	Yes	Identify Scope
49	Weather	SE	3	R	M	P	S	A	C	I	Yes	Yes	None
50	SMC SoS	SE, Risk	9	R	P	A	C	M	I	S	Yes	Yes	All Risks
51	SMC SoS	SE, Log, Acq	11	M	A	I	C	P	R	S	Add CONOPS	Yes	CONOPS
52	SMC SoS	Acq	17	R	S	M	P	A	C	I	Yes	Yes	Dependent Sys
53	SMC SoS	Acq, CM	30	P	M	R	S	A	I	C	Yes	Yes	Financial Impact
54	SMC SoS	SE, Acq	22	P	M	A	R	I	C	S	Yes	Yes	Clear Strategy
55	SMC SoS	Acq	14	C	P	M	I	R	S	A	Yes	Yes	None
56	Weather	SE, Acq	7	P	R	M	A	I	C	S	Add ICDs	Yes	ICDs
57	SMC SoS	Acq, Log	24	M	P	C	S	R	I	A	Yes	Yes	Design Interfaces
58	SMC SoS	Acq	9	M	R	P	S	A	C	I	Yes	Yes	Lead Integrator
59	Aircraft	SE	7	I	R	A	S	M	P	C	Yes	Yes	Security
60	SMC SoS	SE, SI	15	A	I	M	P	R	C	S	Yes	Yes	Include SME
61	NASA	SE, SI	37	I	C	M	A	P	R	S	Yes	Yes	None
62	SMC SoS	SE, Risk	4	M	R	P	A	S	C	I	Yes	Yes	None
63	NASA	SE, CM	7	S	R	C	A	M	I	P	Yes	Yes	None
64	XSats	SE, SI	11	S	A	R	M	I	C	P	Yes	Yes	None
65	NASA, Aircraft	SE, DE	39	R	S	P	A	I	C	M	Yes	Yes	None
66	XSats	SE, DE	18	A	R	P	C	I	M	S	Yes	Yes	Production, Safety

Q #	1 SoS	2 Exp	3 Ex	4 R 1	A 2	N 3	K 4	I 5	N 6	G 7	5 Agree w/Attr	6 Agree w/Def	7 Other Attr
67	NASA, Launch	SE, SI, SME	50	I	A	R	P	M	C	S	Modeling & Simulation (M&S)	M&S	Communication
68	NASA	SE, DE	20	R	P	I	S	A	C	M	Yes	Yes	Reqmts Definition
69	NASA, Navy	SE, CM, SI	36	R	I	C	S	A	M	P	Yes	Yes	None
70	Aircraft, Navy	SE	16	A	R	C	M	S	P	I	Yes	Include Facilities	None
71	Aircraft, MDA, SMC SoS	SE	19	I	A	C	R	M	P	S	Yes	Yes	None
72	SMC SoS	SE, DE, Acq	8	C	A	R	I	P	M	S	Yes	Establish culture under Management	None
73	SMC SoS	SE, Acq, SME	24	C	A	R	S	M	P	I	Clarity and Stability	Interface & Standards under Interop	Reqmts Stability
74	SMC SoS	Acq	10	A	C	M	S	P	I	R	Yes	Yes	Threat Assessment
75	Weather	Acq	22	A	C	I	M	P	R	S	Yes	Yes	Authority
76	XSats, NASA, Launch	SE, Acq	13	M	P	R	S	O	C	A	Politics	Yes	Leadership
77	SMC SoS	SE, Log, Ops, T&E	36	M	P	C	R	A	S	I	Yes	Yes	None
78	SMC SoS	Acq, BM	20	M	P	R	S	C	I	A	Yes	Yes	Decisive & Cohesive
79	SMC SoS	SE	3	M	P	C	A	R	S	I	Yes	Yes	None
80	SMC SoS	SE, PM	24	M	S	R	A	P	C	I	Yes	Yes	None
81	SMC SoS	SE	28	A	C	I	R	S	M	P	Yes	Yes	None
82	MDA SoS	SE	15	M	R	A	P	C	I	S	CONOPS	Yes	Reqmts Definition
83	SMC SoS	SE, Scq, SME	30	M	R	P	A	S	C	I	Yes	Yes	None
84	Launch	DE, SME	26	A	I	R	P	S	C	M	Yes	Yes	Cybersecurity
85	SMC SoS	SE, Sec	27	M	P	R	I	C	A	S	Yes	Yes	None
86	SMC SoS	SE, Acq, BM	14	M	C	I	A	S	R	P	Yes	Leadership	None
87	SMC SoS	SE	35	M	R	S	P	C	A	I	Safety, Risks	Yes	None
88	SMC SoS	SE, BM	8	A	M	S	C	P	R	I	Yes	Motivation	None

Responses for Questions 8-18:

<u>*Question 8:*</u> This question asked about including Security as either part of Processes attribute or that it should be a separate attribute based on the participants' experience. Security can capture systems security, cybersecurity, administrative security, and physical security. They are all very important to the operations of the SoS and during integration. However, the overwhelming response (over 65%) was to include Security under the Processes attribute. There were 14% of responses that claimed it should be separated from the Processes attributes but most claimed that it would not be its own attribute. There were also 14% of the responses that Security can be captured under the Requirements attribute, and 7% of the responses were undecided. Based on the responses, Security will be captured under the Processes attribute.

<u>*Question 9:*</u> The responses to Question 9 varied tremendously based on the participants' experience on what their organizations have done to address major integration issues and challenges. The common responses were: 1) established a strong systems engineering process; 2) gathered resources to fund additional meetings for experience workforce and SMEs; 3) implementation of Tiger Team to get timely responses; 4) established risk management processes; 4) clearly communicated requirements and goals; and 5) emphasized the involvement of management.

<u>*Question 10 and 11:*</u> The focus of these questions was to understand if they heard about IRL before reading it on this survey (Question 10) and if it would be useful based on what they know about it now (Question 11). About half (54%) said they have not heard about IRL. One of the primary reasons could be that TRL is only used in DoD

Acquisitions. However, about 90% of them believe that it would be useful to improve systems integration based on introduction summary of the survey.

<u>Question 12:</u> There were 86% of the participants who responded to this question and their responses on benefiting from knowing IRL levels early in the process are summarized into three major areas that could help with the program and the system: 1) Improve risk management throughout the program; 2) Planning for resources ahead of time to support those risk areas; and 3) Identify critical path in schedule by better understanding the complexity and timeframe of efforts and events. The major benefit would be to help with decisions affecting areas of integration concerns and risks.

<u>Questions 13 and 14:</u> These two questions are related to understand how schedule delays could impact integration readiness. The response was overwhelming in that schedule delays would directly impact cost and resources. There were some agreement that IRL could improve through time by better understanding of the system maturity and more opportunities to do extra analyses; however, schedule would still negatively impact the resources. There were responses that provided time can help mitigate some integration risks with additional time to work through them, but time may also add scope and effort that could increase cost.

<u>Question 15:</u> This question asked about overarching risk areas throughout the SoS integration process. The responses to this question provided additional information on what needs to be considered while defining the Integration Attributes. The responses helped validate the need for the Attributes to be clearly defined and be able to capture those responses into their definitions. There were 90% of the participants' who provided a response to this questions, which were all captured under the following risk areas: 1)

Interface and compatibility issues; 2) Definition of clear requirements; 3) Coordination and communication between stakeholders; 4) Complexity of software and hardware development; 4) Low production of systems to do tests and comparisons; 5) Prioritization for limited resource; 6) Manage schedule and expectations; 7) Conducting Test and Verification processes; 8) Cost overruns and resource planning; and 9) Technical maturity of supporting systems.

Question 16: This question further expanded the previous question and allowed the participants to provide examples on the cause(s) of the integration failures that they have experienced. The responses are very similar to Question 15 with the same amount of participants who responded (90%), and most have also referenced Question 15 as their response to this question. The responses to the causes of integration failures include: 1) Miscommunication and lack of proper coordination between management and stakeholders; 2) Inadequate (or lack of) test and verification processes; 3) Requirements creep throughout the process; 4) Implementation of weak systems engineering process; 5) Mismanaging complexity; 6) Lack of personnel experience; 7) Lack of proper documentation; and 8) Lack of clear, concise, and realistic requirements.

Question 17: This question provided the participants an opportunity to identify and recommend areas to improve systems integration based on their experience, and 85% of them responded. Their responses to this question included: 1) Establish realistic and stable requirements and schedule; 2) Apply lessons learned from prior SoS integration processes; 3) Must have the right expertise and experience working on the SoS integration; 4) Implement effective and efficient communication processes; 5) Using mature and well understood technologies; and 6) Establish strong systems engineering processes.

Question 18: This question allowed the participants to provide the timeline to work through their integration issues. Only 75% of the participants provided a response to this question. Depending on the type of issue they experienced, the timeline to resolve the issues took between 6 months to 15 years. This provided another reason why understanding integration issues early can help mitigate some of the schedule risks throughout the program.

Initial Assessment of the Survey Results:

All the results from the survey were evaluated to understand the impacts of system integration. The results were insightful and provided validation of the usefulness of the attributes as well as help frame their definitions. All the answers helped establish the definition for each attribute, which can be very effective during the enhanced IRL assessment process. The survey analysis provided the breakdown of the attributes and how they are distributed during the IRL enhanced assessment process.

There were a total of 18 questions in the survey where some questions were for clarification of their responses to prior questions. The survey participants were a very experienced group, which had an average of 19.4 years of experience in their respective field.

Of the 88 participants, only seven said they were not in complete agreement with the attributes; however, their concerns were all addressed throughout the research process and through the updated definition for each attribute. The concerns were: exclusion of management guidance (addressed under Management); exclusion of concept of operations, which is developed as part of the scope of integration (also a Management task); exclusion of Model & Simulations (M&S) tools (addressed under Processes); exclusion of overall planning (addressed under Management); exclusion of requirements (which is outside of the focus of this research, but addressed in Problem Focus); and exclusion of risk areas (technical risks were addressed in Complexity and overall program risks are the output of the systems integration assessment framework). Most of the survey participants agreed that given the right supporting tools, an enhanced IRL assessment would be useful.

5.5 Survey Analysis

All 88 participants ranked the seven attributes in order and are summarized in Table 5-4. The ranking of the attributes are distributed by having the #1 ranked attribute equal to 7/7 (1.0). Values for the subsequent ranking: #2 is 6/7 (or 0.857), #3 is 5/7 or (0.714), #4 is 4/7 (or 0.571), #5 is 3/7 (or 0.429), #6 is 2/7 (or 0.286), and #7 is 1/7 (or 0.143).

Table 5-4: Summary of Survey Results – Ranking Attributes

#	Exp (Yrs)	Avail	Compl	Interop	Mgmt	Proc	Resour	Sched
1	39	1.000	0.857	0.714	0.571	0.429	0.286	0.143
2	35	0.143	0.714	0.571	0.286	1.000	0.857	0.429
3	40	0.571	0.714	0.857	1.000	0.429	0.286	0.143
4	34	0.714	0.857	1.000	0.429	0.571	0.286	0.143
5	16	0.857	0.143	0.286	0.714	0.571	1.000	0.429
6	13	0.286	0.143	0.714	0.857	0.571	1.000	0.429
7	35	0.571	0.429	0.286	0.857	0.714	1.000	0.143
8	3	0.571	0.429	0.143	0.857	0.286	1.000	0.714
9	20	0.571	0.429	0.143	1.000	0.714	0.857	0.286
10	8	0.286	0.143	0.429	0.714	1.000	0.857	0.571
11	36	0.571	1.000	0.857	0.429	0.286	0.714	0.143
12	20	0.286	0.571	0.429	1.000	0.857	0.714	0.143
13	16	1.000	0.857	0.571	0.286	0.429	0.714	0.143
14	3	0.714	0.571	0.143	1.000	0.286	0.857	0.429
15	21	1.000	0.429	0.286	0.714	0.143	0.857	0.571
16	11	0.571	0.429	0.286	1.000	0.857	0.714	0.143
17	4	0.571	0.143	0.286	0.429	0.714	1.000	0.857
18	30	0.571	0.714	0.857	0.286	1.000	0.429	0.143
19	3	0.571	0.430	0.287	1.000	0.713	0.857	0.143
20	20	1.000	0.143	0.857	0.286	0.429	0.714	0.571
21	16	0.143	0.857	0.571	0.714	1.000	0.429	0.286
22	10	0.286	1.000	0.857	0.714	0.429	0.571	0.143
23	20	0.429	0.143	0.286	1.000	0.714	0.857	0.571
24	36	0.857	0.286	0.143	0.571	0.429	1.000	0.714
25	14	0.429	1.000	0.857	0.571	0.143	0.714	0.286
26	15	0.286	0.857	0.143	0.429	0.571	0.714	1.000
27	8	0.714	0.286	0.143	0.857	1.000	0.429	0.571
28	35	0.857	1.000	0.571	0.429	0.286	0.143	0.714
29	27	0.286	0.429	0.571	1.000	0.143	0.857	0.714
30	12	0.143	0.857	0.286	0.714	0.571	1.000	0.429
31	13	0.571	0.286	0.143	1.000	0.714	0.857	0.429
32	25	0.857	1.000	0.143	0.571	0.429	0.286	0.714
33	16	0.571	0.714	0.286	0.857	0.143	1.000	0.429
34	50	0.571	1.000	0.857	0.286	0.714	0.429	0.143
35	11	0.571	0.714	0.429	0.286	0.143	1.000	0.857
36	25	0.714	1.000	0.571	0.429	0.857	0.286	0.143
37	9	0.286	0.714	0.143	1.000	0.571	0.857	0.429
38	18	0.571	0.286	0.143	1.000	0.429	0.857	0.714
39	12	0.286	0.429	0.714	1.000	0.571	0.143	0.857
40	18	0.714	0.857	0.429	0.143	0.571	1.000	0.286
41	14	0.714	0.857	0.143	0.286	0.571	1.000	0.429
42	16	1.000	0.571	0.286	0.714	0.429	0.143	0.857
43	15	0.571	0.286	0.429	0.857	1.000	0.714	0.143
44	4	0.143	0.429	0.286	1.000	0.571	0.857	0.714

#	Exp (Yrs)	Avail	Compl	Interop	Mgmt	Proc	Resour	Sched
45	21	0.571	0.143	0.429	0.857	1.000	0.714	0.286
46	35	0.143	0.429	0.286	1.000	0.857	0.714	0.571
47	19	0.571	0.429	0.143	0.857	1.000	0.714	0.286
48	20	0.714	0.571	0.286	0.857	0.143	1.000	0.429
49	3	0.429	0.286	0.143	0.857	0.714	1.000	0.571
50	9	0.714	0.571	0.286	0.429	0.857	1.000	0.143
51	11	0.857	0.571	0.714	1.000	0.429	0.286	0.143
52	17	0.429	0.286	0.143	0.714	0.571	1.000	0.857
53	30	0.429	0.143	0.286	0.857	1.000	0.714	0.571
54	22	0.714	0.286	0.429	0.857	1.000	0.571	0.143
55	14	0.143	1.000	0.571	0.714	0.857	0.429	0.286
56	7	0.571	0.286	0.429	0.714	1.000	0.857	0.143
57	24	0.143	0.714	0.286	1.000	0.857	0.429	0.571
58	9	0.429	0.286	0.143	1.000	0.714	0.857	0.571
59	7	0.714	0.143	1.000	0.429	0.286	0.857	0.571
60	15	1.000	0.286	0.857	0.714	0.571	0.429	0.143
61	37	0.571	0.857	1.000	0.714	0.429	0.286	0.143
62	4	0.571	0.143	0.286	1.000	0.714	0.857	0.429
63	7	0.571	0.714	0.286	0.429	0.143	0.857	1.000
64	11	0.857	0.286	0.429	0.571	0.143	0.714	1.000
65	39	0.571	0.286	0.429	0.143	0.714	1.000	0.857
66	18	1.000	0.571	0.429	0.286	0.714	0.857	0.143
67	50	0.857	0.286	1.000	0.429	0.571	0.714	0.143
68	20	0.429	0.286	0.714	0.143	0.857	1.000	0.571
69	36	0.429	0.714	0.857	0.286	0.143	1.000	0.571
70	16	1.000	0.714	0.143	0.571	0.286	0.857	0.429
71	19	0.857	0.714	1.000	0.429	0.286	0.571	0.143
72	8	0.857	1.000	0.571	0.286	0.429	0.714	0.143
73	24	0.857	1.000	0.143	0.429	0.286	0.714	0.571
74	10	1.000	0.857	0.286	0.714	0.429	0.143	0.571
75	22	1.000	0.857	0.714	0.571	0.429	0.286	0.143
76	13	0.143	0.286	0.429	1.000	0.857	0.714	0.571
77	36	0.429	0.714	0.143	1.000	0.857	0.571	0.286
78	20	0.143	0.429	0.286	1.000	0.857	0.714	0.571
79	3	0.571	0.714	0.143	1.000	0.857	0.429	0.286
80	24	0.571	0.286	0.143	1.000	0.429	0.714	0.857
81	28	1.000	0.857	0.714	0.286	0.143	0.571	0.429
82	15	0.714	0.429	0.286	1.000	0.571	0.857	0.143
83	30	0.571	0.286	0.143	1.000	0.714	0.857	0.429
84	26	1.000	0.286	0.857	0.143	0.571	0.714	0.429
85	27	0.286	0.429	0.571	1.000	0.857	0.714	0.143
86	14	0.571	0.857	0.714	1.000	0.143	0.286	0.429
87	35	0.286	0.429	0.143	1.000	0.571	0.857	0.714
88	8	1.000	0.571	0.143	0.857	0.429	0.286	0.714

The results of the survey showed that almost all participants were in agreement with the derived attributes. Using the multivariable regression analysis, the Normal Probability Graph for all the attributes is shown Figure 5-2. Figure 5-2 illustrates how the seven attributes are distributed based on their ranking and Table 5-5 shows the resulting values for the ranked attributes. The Resources and Management attributes have the highest percentage values for 1.0 (#1 of 7), which is the reason for their high means. This is different from the data analysis where Interoperability, Processes, and Complexity had the highest means. In contrast, the graph shows that Schedule has the highest percentage values for 0.143 (#7 of 7), which is the reason for the lowest mean. In comparison to the data analysis, Schedule also had the lowest mean.

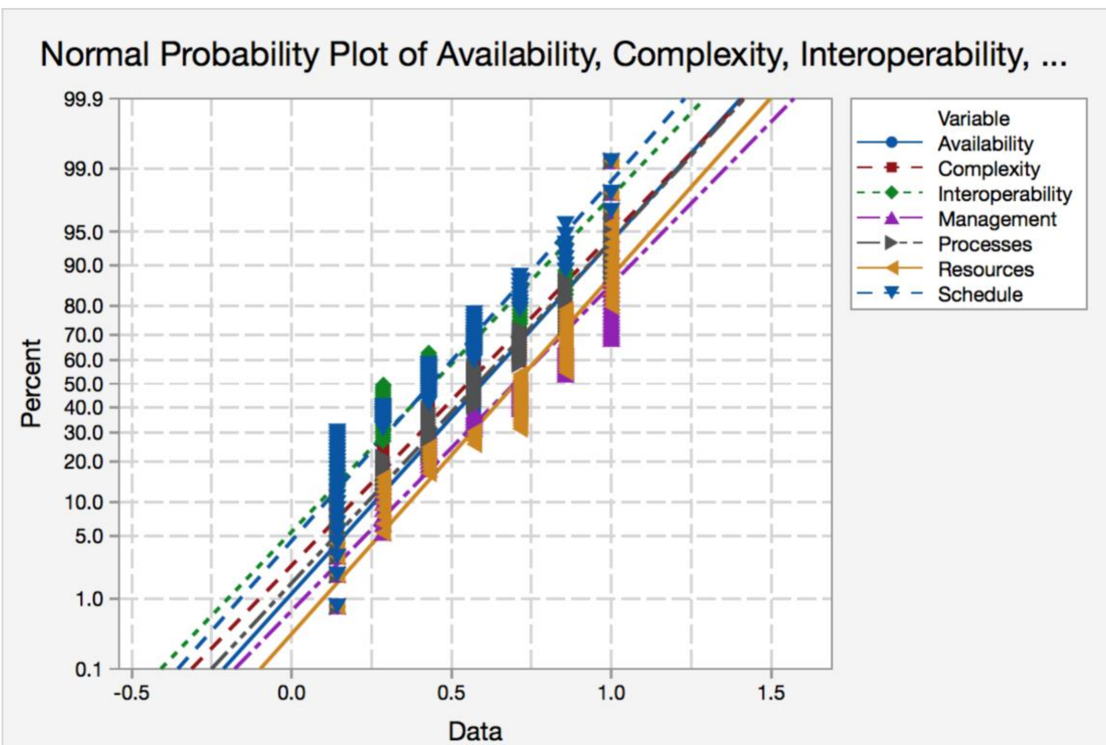

Figure 5-2: Normal Probability Graph of Attributes (Ranked Values from the Survey)

Summary Statistics					
Variable	**N**	**Mean**	**StDev**	**Minimum**	**Maximum**
Availability	88	0.596	0.262	0.143	1.000
Complexity	88	0.550	0.279	0.143	1.000
Interoperability	88	0.442	0.275	0.143	1.000
Management	88	0.696	0.283	0.143	1.000
Processes	88	0.583	0.270	0.143	1.000
Resources	88	0.700	0.258	0.143	1.000
Schedule	88	0.437	0.256	0.143	1.000

Table 5-5. Survey Results Summary Statistics

The analysis captured in Figure 5-2 and Table 5-5 can be useful, but it does not account for the Years of Experience of the survey participants. To calculate the weight of each attribute, the Years of Experience will be accounted for. The Years of Experience was collected where the values (from 3 years to 50 years) are a lot higher than the values of ranking the attributes (from 0.143 to 1.000). To reduce the skewness of the dependent variable (Years of Experience), the logarithm function will be used for the analysis.

According to Lattin J., Carroll, J., Green, P. (2002), "a dependent variable can be problematic when the values are a lot larger than the independent variable, and one way to deal with that is using the transformation of log function to reduce skewness." According to Benoit, K. (2011), "Logarithmic transformations are convenient means of transforming a highly skewed variable into one that is more approximately normal." The log function will help normalize the Years of Experience relative to the scores given to the attribute rankings. The log scale with base of 10 shows that 10 years of experience will be valued at 1.0 and 50 years of experience will not be 5 times more significant, but rather 1.699 times more (Log 50 = 1.699).

The approach to use the logarithmic transformation seems to be more of a realistic comparison when distinguishing between the participants' years of experience relative to the values of their attributes' rankings, where 10 years of experience is a reasonable amount to acquire relevant experience in systems engineering and acquisitions. The 10 years of experience usually gives the systems engineers and acquisition professionals enough time to obtain beginning, intermediate, and advanced level certifications in DoD acquisitions while gaining relevant experience to be considered experts. Conversely, log 1 year of experience is 0 where their inputs would not be considered due to their lack of experience. Therefore, setting the logarithm with base 10 for the 10 years of experience is reasonable. Tables 5-6 shows the calculated values of Log Years of Experience multiplied to each ranking of the attributes in order to determine the weight of each attribute ranking relative to years of experience.

Table 5-6. Value of Attributes from Survey Results (Accounting for Log Years of Experience)

	Log Years	Log Years *Avai	Log Years *Comp	Log Years *Inter	Log Years *Mgt	Log Years *Proc	Log Years *Res	Log Years *Sch
1	1.591	1.591	1.364	1.136	0.909	0.682	0.455	0.227
2	1.544	0.221	1.103	0.882	0.441	1.544	1.323	0.662
3	1.602	0.915	1.144	1.373	1.602	0.687	0.458	0.229
4	1.531	1.094	1.313	1.531	0.656	0.875	0.438	0.219
5	1.204	1.032	0.172	0.344	0.860	0.688	1.204	0.516
6	1.114	0.318	0.159	0.796	0.955	0.637	1.114	0.477
7	1.544	0.882	0.662	0.441	1.323	1.103	1.544	0.221
8	0.477	0.273	0.204	0.068	0.409	0.136	0.477	0.341
9	1.301	0.743	0.558	0.186	1.301	0.929	1.115	0.372
10	0.903	0.258	0.129	0.387	0.645	0.903	0.774	0.516
11	1.556	0.889	1.556	1.334	0.667	0.445	1.112	0.222
12	1.301	0.372	0.743	0.558	1.301	1.115	0.929	0.186
13	1.204	1.204	1.032	0.688	0.344	0.516	0.860	0.172
14	0.477	0.341	0.273	0.068	0.477	0.136	0.409	0.204
15	1.322	1.322	0.567	0.378	0.944	0.189	1.133	0.756
16	1.041	0.595	0.446	0.298	1.041	0.893	0.744	0.149
17	0.602	0.344	0.086	0.172	0.258	0.430	0.602	0.516
18	1.477	0.844	1.055	1.266	0.422	1.477	0.633	0.211
19	0.477	0.272	0.205	0.137	0.477	0.340	0.409	0.068
20	1.301	1.301	0.186	1.115	0.372	0.558	0.929	0.743
21	1.204	0.172	1.032	0.688	0.860	1.204	0.516	0.344
22	1.000	0.286	1.000	0.857	0.714	0.429	0.571	0.143
23	1.301	0.558	0.186	0.372	1.301	0.929	1.115	0.743
24	1.556	1.334	0.445	0.222	0.889	0.667	1.556	1.111
25	1.146	0.491	1.146	0.982	0.655	0.164	0.819	0.327
26	1.176	0.336	1.008	0.168	0.504	0.672	0.840	1.176
27	0.903	0.645	0.259	0.129	0.774	0.903	0.387	0.516
28	1.544	1.323	1.544	0.882	0.662	0.441	0.221	1.103
29	1.431	0.409	0.613	0.818	1.431	0.204	1.227	1.022
30	1.079	0.154	0.925	0.308	0.771	0.617	1.079	0.463
31	1.114	0.637	0.318	0.159	1.114	0.796	0.955	0.477
32	1.398	1.198	1.398	0.200	0.799	0.599	0.399	0.999
33	1.204	0.688	0.860	0.344	1.032	0.172	1.204	0.516
34	1.699	0.971	1.699	1.456	0.485	1.214	0.728	0.243
35	1.041	0.595	0.744	0.447	0.298	0.149	1.041	0.893
36	1.398	0.999	1.398	0.798	0.600	1.198	0.399	0.200
37	0.954	0.273	0.682	0.136	0.954	0.545	0.818	0.409
38	1.255	0.717	0.359	0.179	1.255	0.538	1.076	0.897
39	1.079	0.309	0.463	0.771	1.079	0.616	0.154	0.925
40	1.255	0.897	1.076	0.539	0.179	0.717	1.255	0.358
41	1.146	0.818	0.982	0.164	0.328	0.654	1.146	0.492
42	1.204	1.204	0.688	0.344	0.860	0.517	0.172	1.032
43	1.176	0.672	0.336	0.505	1.008	1.176	0.840	0.168
44	0.602	0.086	0.258	0.172	0.602	0.344	0.516	0.430

	Log Years	Log Years *Avai	Log Years *Comp	Log Years *Inter	Log Years *Mgt	Log Years *Proc	Log Years *Res	Log Years *Sch
45	1.322	0.755	0.189	0.567	1.133	1.322	0.944	0.378
46	1.544	0.221	0.662	0.442	1.544	1.323	1.102	0.882
47	1.279	0.730	0.549	0.183	1.096	1.279	0.913	0.366
48	1.301	0.929	0.743	0.372	1.115	0.186	1.301	0.558
49	0.477	0.205	0.136	0.068	0.409	0.341	0.477	0.272
50	0.954	0.681	0.545	0.273	0.409	0.818	0.954	0.136
51	1.041	0.892	0.595	0.744	1.041	0.447	0.298	0.149
52	1.230	0.528	0.352	0.176	0.879	0.703	1.230	1.054
53	1.477	0.634	0.211	0.422	1.266	1.477	1.055	0.843
54	1.342	0.958	0.384	0.576	1.150	1.342	0.767	0.192
55	1.146	0.164	1.146	0.654	0.818	0.982	0.492	0.328
56	0.845	0.483	0.242	0.363	0.603	0.845	0.724	0.121
57	1.380	0.197	0.985	0.395	1.380	1.183	0.592	0.788
58	0.954	0.409	0.273	0.136	0.954	0.681	0.818	0.545
59	0.845	0.603	0.121	0.845	0.363	0.242	0.724	0.483
60	1.176	1.176	0.336	1.008	0.840	0.672	0.505	0.168
61	1.568	0.895	1.344	1.568	1.120	0.673	0.449	0.224
62	0.602	0.344	0.086	0.172	0.602	0.430	0.516	0.258
63	0.845	0.483	0.603	0.242	0.363	0.121	0.724	0.845
64	1.041	0.892	0.298	0.447	0.595	0.149	0.744	1.041
65	1.591	0.908	0.455	0.683	0.228	1.136	1.591	1.364
66	1.255	1.255	0.717	0.539	0.359	0.896	1.076	0.180
67	1.699	1.456	0.486	1.699	0.729	0.970	1.213	0.243
68	1.301	0.558	0.372	0.929	0.186	1.115	1.301	0.743
69	1.556	0.668	1.111	1.334	0.445	0.223	1.556	0.889
70	1.204	1.204	0.860	0.172	0.688	0.344	1.032	0.517
71	1.279	1.096	0.913	1.279	0.549	0.366	0.730	0.183
72	0.903	0.774	0.903	0.516	0.258	0.387	0.645	0.129
73	1.380	1.183	1.380	0.197	0.592	0.395	0.985	0.788
74	1.000	1.000	0.857	0.286	0.714	0.429	0.143	0.571
75	1.342	1.342	1.150	0.958	0.767	0.576	0.384	0.192
76	1.114	0.159	0.319	0.478	1.114	0.955	0.795	0.636
77	1.556	0.668	1.111	0.223	1.556	1.334	0.889	0.445
78	1.301	0.186	0.558	0.372	1.301	1.115	0.929	0.743
79	0.477	0.272	0.341	0.068	0.477	0.409	0.205	0.136
80	1.380	0.788	0.395	0.197	1.380	0.592	0.985	1.183
81	1.447	1.447	1.240	1.033	0.414	0.207	0.826	0.621
82	1.176	0.840	0.505	0.336	1.176	0.672	1.008	0.168
83	1.477	0.843	0.422	0.211	1.477	1.055	1.266	0.634
84	1.415	1.415	0.405	1.213	0.202	0.808	1.010	0.607
85	1.431	0.409	0.614	0.817	1.431	1.227	1.022	0.205
86	1.146	0.654	0.982	0.818	1.146	0.164	0.328	0.492
87	1.544	0.442	0.662	0.221	1.544	0.882	1.323	1.102
88	0.903	0.903	0.516	0.129	0.774	0.387	0.258	0.645

Figure 5-3 illustrates the values of the ranked attributes from the survey accounting for the Log Years of Experience of each participant. The resulting numbers for the regression analysis is covered in 5-7a & b. Accounting for the Log Years of Experience did not produce significant changes among the weights of each attribute relative to each other. Figure 5-3 still shows that the Resources and Management attributes still have the highest values in the graphs, while Schedule attribute has the lowest value. One of the reasons for the Resources and Management values is the thought that these two attributes are enablers of the other attributes. For example, Management needs to approve funding (Resources) in order to execute the integration activities. Because of the attention these two attributes get in program offices, they can also be resolved before being captured as issues in the DOT&E Annual Reports. The Schedule attribute has a low value for both the data and survey analyses because it is usually caused by one of the other attributes (i.e. a Complexity related issue caused the delay of the scheduled integration activities). However, schedule (planning and execution) is still critical to the success of SoS integration, and needs to be considered as a separate attribute.

Table 5-7a shows the resulting values of the means and standard deviations for each attribute, with the lowest to highest means is still the same order as when not taking the Years of Experience into account. The null hypothesis for this analysis is that data follow a normal distribution. According to the P-Values in Table 5-7b, only Resources is greater than 0.05, which shows the data follow a normal distribution.

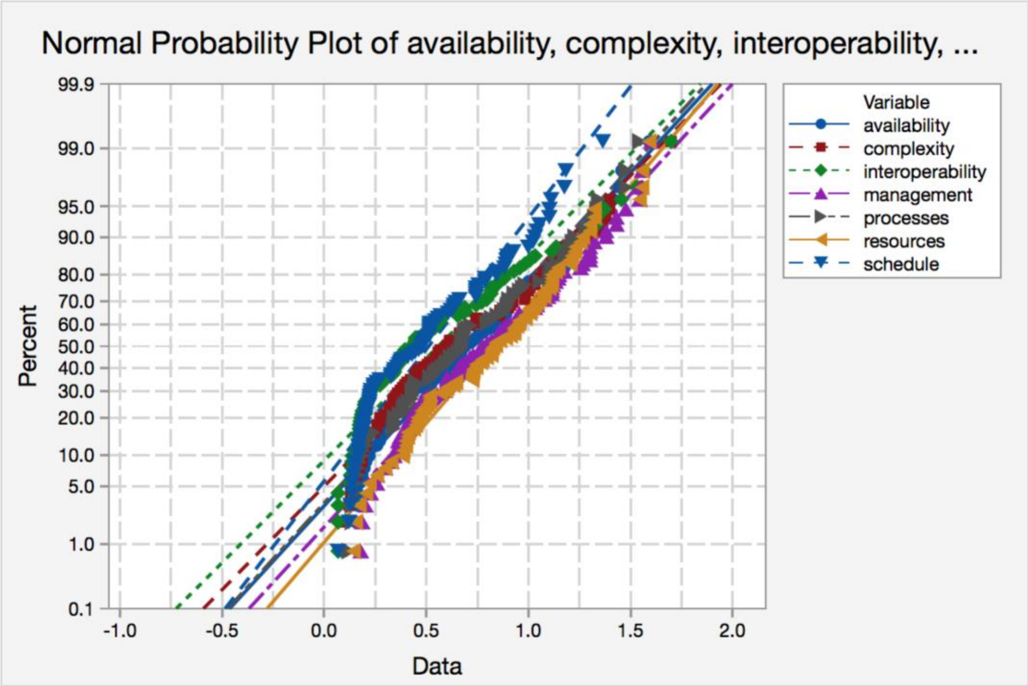

Figure 5-3: Normal Probability Graph for Survey Results (with Log Years of Experience)

Summary Statistics					
Variable	**N**	**Mean**	**StDev**	**Minimum**	**Maximum**
Availability	88	0.719	0.382	0.086	1.591
Complexity	88	0.676	0.410	0.086	1.699
Interoperability	88	0.559	0.415	0.068	1.699
Management	88	0.815	0.383	0.179	1.602
Processes	88	0.700	0.379	0.121	1.544
Resources	88	0.824	0.357	0.143	1.591
Schedule	88	0.512	0.323	0.068	1.364

Table 5-7a. Survey Results Mean & Standard Deviation w/ Log Years of Experience

Source	**P-Value**
Availability	0.0307
Complexity	<0.0050
Interoperability	<0.0050
Management	0.0431
Processes	0.0220
Resources	0.1927
Schedule	<0.0050

Table 5-7b. Survey Results Mean & Standard Deviation w/ Log Years of Experience

5.6 Comparison of Results

Using the results from the data analysis and survey analysis, the weights of the attributes were calculated. Figure 5-4 illustrates the process to derive the weight of each attribute. Both sets of data (data results and survey results) have different focus from one another: 1) the data collection focuses on the number of attributes identified in the 16 years of space systems integration; and 2) the survey results focuses on the ranking of the attributes with the given year of experience of the participants. However, the data derived from the two sets provide significant input to understanding how the attributes can be distributed during integration assessment.

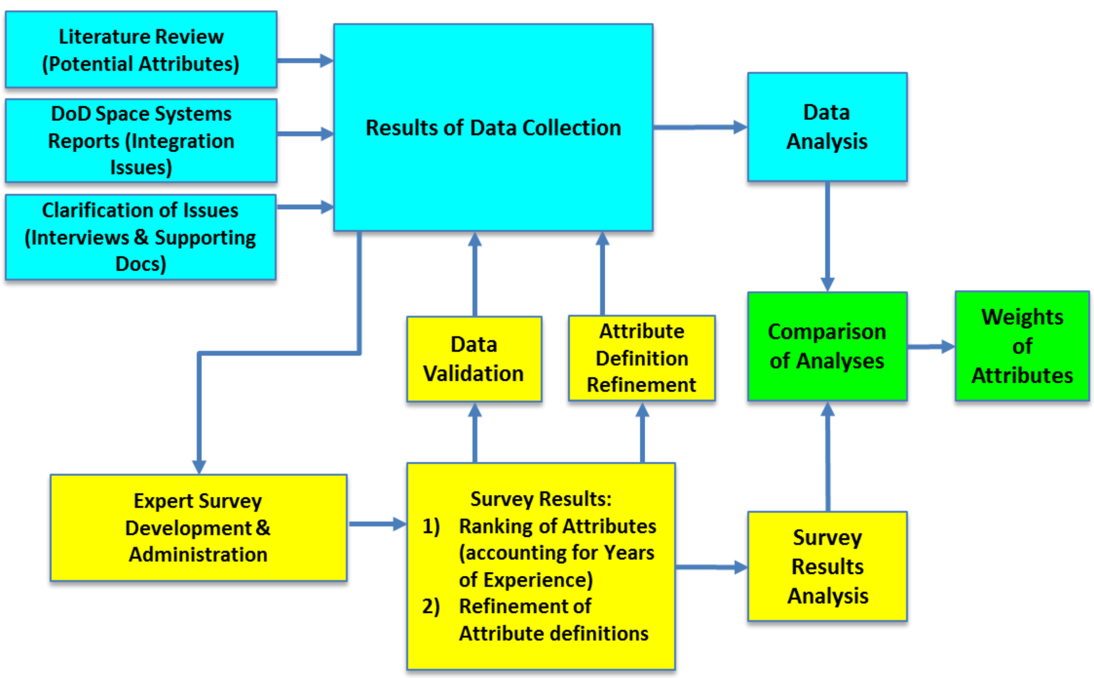

Figure 5-4. Research Framework to Derive Weights of Attributes

The data and survey analyses measure different values; therefore, the approach to compare the two is to evaluate the mean and standard deviation each attribute evaluated in each set. Each attribute is given a weighted percentage value relative to the other attributes (for each set). The weight of each attribute is calculated by comparing between the Data Mean & Standard Deviation and the Survey Mean & Standard Deviation analyses as shown in Table 5-8a and b.

Table 5-8a. Mean and Standard Deviation for Integration Data and Survey Results

Comparing Analyses	**Int Data, Mean**	**Int Data, Std Dev**	**Survey, Mean**	**Survey, Std Dev**
Availability	2.188	1.601	0.719	0.382
Complexity	3.188	3.656	0.676	0.410
Interoperability	4.000	2.921	0.559	0.415
Management	2.313	1.448	0.815	0.383
Processes	3.250	2.840	0.700	0.379
Resources	1.000	1.155	0.824	0.357
Schedule	1.000	1.033	0.512	0.323

Table 5-8b. Percentage of each Mean and Standard Deviation for Integration Data and Survey Results

Weight	**Int Data, Mean**	**Int Data, High**	**Int Data, Low**	**Survey, Mean**	**Survey, High**	**Survey, Low**
Availability	12.9%	12.0%	25.7%	15.0%	14.8%	15.6%
Complexity	18.8%	21.7%	-20.5%	14.1%	14.6%	12.3%
Interoperability	23.6%	21.9%	47.2%	11.6%	13.1%	6.7%
Management	13.7%	11.9%	37.8%	17.0%	16.1%	20.1%
Processes	19.2%	19.3%	17.9%	14.6%	14.5%	14.9%
Resources	5.9%	6.8%	-6.8%	17.2%	15.9%	21.7%
Schedule	5.9%	6.4%	-1.4%	10.7%	11.2%	8.8%

5.7 Weights of Attributes

Based on the percentage for each attribute, there are a lot of disconnects between the integration data analysis and the expert survey analysis on how the attributes should be weighted. The closest numbers for the Data and Survey are Availability at about 12.9-15% and Management at about 13.7-17%. Using the standard deviation, the High and Low for the means have also been calculated. The percentages for the High and Low values show significant variances. In this case, using the average of two means will provide a better estimate to use as the final weight of each attribute (Table 5-9).

Table 5-9. Derived Weight of Each Attribute

Avg Weight	**Mean Total**	**Final Weight**
Availability	27.9%	**13.9%**
Complexity	32.9%	**16.4%**
Interoperability	35.2%	**17.6%**
Management	30.7%	**15.4%**
Processes	33.8%	**16.9%**
Resources	23.1%	**11.5%**
Schedule	16.6%	**8.3%**

CHAPTER 6: CONCLUSION

6.1 Final Criteria of Attributes

One of the major goals throughout the research was to define each attribute (and understand the integration variables aligned to each attribute) so that they can be useful throughout the systems integration process. When they were initially introduced, some of the attributes could be interpreted similar to the other attributes based on how they were used. Despite the initial assumptions in Section 3.6 about the data collection clearly explaining each attribute, there were still some uncertainties on how each attribute would be defined.

Executing the research process by utilizing all the literature references, the collected data, and the survey, the results and analyses have proven that the criteria to define each attribute can be refined further. The data collection and analysis helped identify the attributes and the survey results and analysis helped refine the definitions of each attribute. Refining the criteria also helped to distinguish each attribute from one another. The final criteria to define each attribute are summarized in Table 6-1.

Table 6-1. Criteria for Each Attribute Using Derived Integration Variables

Integration Variables (Criteria to Major Attributes)	Major Attributes
Access high TRL supporting systems, subsystems, and components (i.e. COTS, operational ground systems, operational simulators)	Availability
Access overall expertise and supporting documentation to execute integration activities	
Access supporting hardware and software to execute integration activities (i.e. COTS, HW/SW reuse)	
Manage technical risks and low maturity of system design, development, and integration	Complexity
Determine complex interfaces between systems, subsystems, and components	
Manage low TRL supporting systems, subsystems, and components	
Understand compatibility and connectivity of systems, subsystems, and components; inputs into integrated systems produce desired outputs	Interoperability
Manage communications between systems, subsystems, and components; address semantic/syntactic issues	
Develop and document interface control documents	
Plan, develop, direct integration strategies and priorities	Management
Lead coordination, execution, and communication between stakeholder organizations	
Provide guidance and directives to integration activities	
Determine scope of integration activities and concepts of operations (CONOPS)	
Manage Requirement Changes (i.e. eliminate/minimize requirements creep)	
Manage support to integration activities and changes (i.e. supply chain)	
Develop and document Policies and Agreements with all stakeholders	
Document overall integration activity processes (i.e. overall communication and decision making processes)	Processes
Develop, document, and execute risks/mitigation processes	
Develop, document, and execute Configuration Management processes	
Develop, document, and execute information assurance and mission assurance processes	
Develop, document, and execute Standards, Procedures, and Algorithms	
Develop, document, and execute Model and Simulation activities	
Develop, document, and execute Test, Verification, and Validation processes	
Develop, document, and execute security and safety considerations	
Develop, document, and execute Training processes	
Develop, document, and execute Manufacturing and Assembly processes	
Allocate sufficient funding to support all integration activities	Resources
Provide trained personnel to support integration activities	
Provide the right tools and facilities to support integration activities	
Meet timeline goals (i.e. need dates, expected deliveries, milestones etc.)	Schedule
Understand Schedule impacts, parameters, and critical path	
Plan for schedule changes and impacts of delays	

6.2 Integration Assessment Framework Development

The integration requirements are addressed through an architectural framework, which according to Jain, R., Chandrasekaran, A., and Erol, O. (2010), "includes in both the physical and functional architectures of the system." With the final criteria providing clear definition of each attribute in Table 6-1 and with the weights of the attributes derived from the data and survey analyses (Section 5.7), an integration assessment framework was developed to help understand integration feasibility. When the models of a system are related through transformation, the collective frames can be referred to as a framework (Lin C *et al.,* 2009).

In architectural framework, understanding how the problem is framed is the most important step because it helps define the subsequent steps. Frameworks and standards define what should be modeled as opposed to which models should be used and how these models are related to each other (Zalewski A, Kijas S, 2013). According to Martin, J. (2008), "problem framing techniques have been found to be useful in avoiding rework and maximizing results." Architectural approaches include conveying options, change, and implications, as well as identifying easier traceability by providing agile documentation (Tyree J, Akerman A, 2005). The change based on initial IRL scores to enhanced IRL scores supports this approach. Architecture analysis includes key foundation that provides consistency, data completeness and transformation, lack of ambiguity, and flexibility to support iterative process (Ge B, Hipel K, Chen Y, 2014). Static Analysis is used in which, according to Ge, B. et al. (2013), helps leverage "static architectural models for analyzing and comparing the associations captured from the data elements."

The resulting systems integration assessment framework to facilitate SoS integration is illustrated in Figure 6-1.

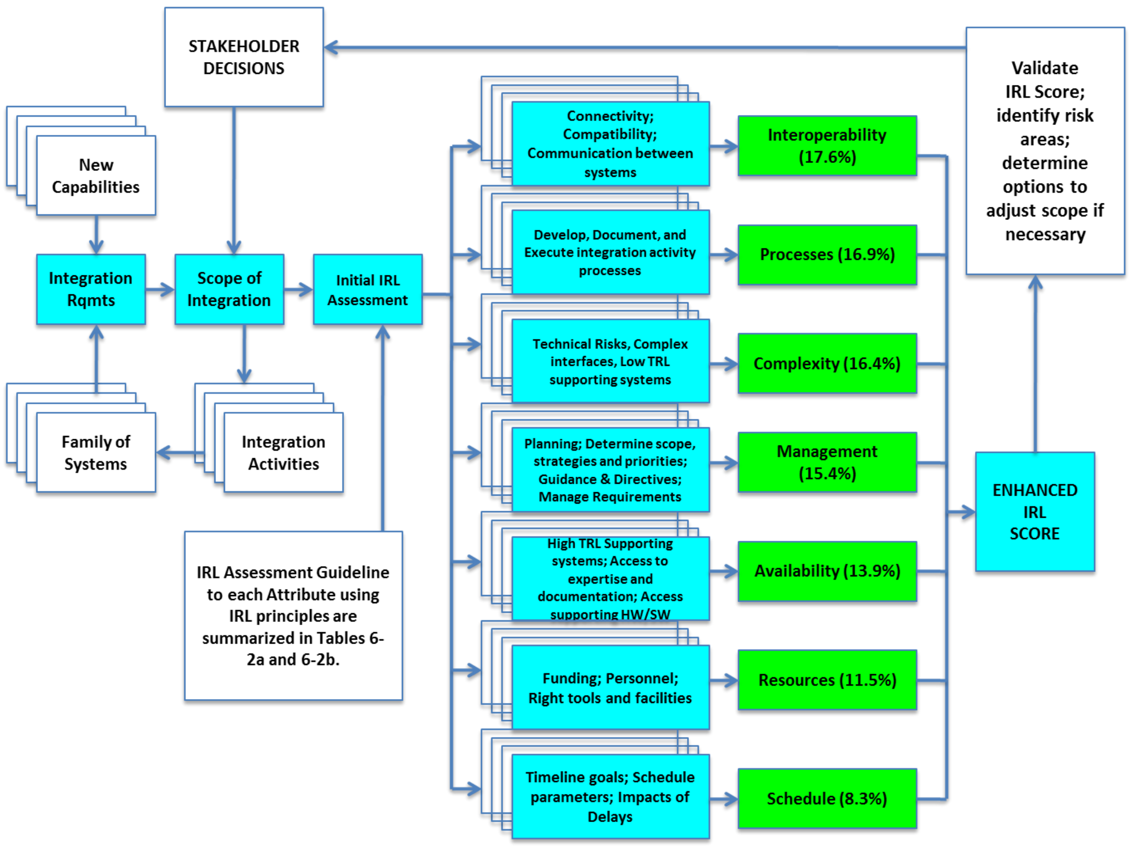

Figure 6-1. Systems Integration Assessment Framework

Framework Description

- New Capabilities: This block introduces the new capability (ies) into the SoS.
- Integration Requirements: This block is the development of Integration Requirements based on the New Capabilities
- Scope of Integration: This block identifies the scope of integration and defines the limitations of the integration process based on the requirements.
- Integration Activities: This block defines the integration activities based on the scope of integration that was determined
- Family of Systems: This block defines the potential impacts of the integration activities into the Family of Systems. Based on the criticality, it may impact the integration requirements and foster change.
- Initial IRL Assessment:
    - One of the initial steps of the framework is to determine the IRL value of the integration items supporting each attribute by using the current IRL principles and definitions as guidelines. Table 6-2a & b provides the guidance on how initial IRL for each attribute are defined using the IRL principles between systems as opposed to IRL principles between technologies.
    - Approaches to determine initial readiness level include: 1) Individual estimation by a SME; 2) Group discussion estimation through meeting or conference; and 3) Individual-group estimation where SMEs completes independent estimations and then discuss them with a group for a consensus decision (Tan W, Ramirez-Marquez J, Sauser B, 2011). Some

of the current techniques that can be used to formulate the estimate of initial readiness level assessment also include educated guess (not enough knowledge and not enough time), analogy (comparing prior work), and standards (developed within different organizations) (Tan W, Ramirez-Marquez J, Sauser B, 2011). Using the framework for systems integration will be an iterative process.

- Integration Variables: This sets of blocks explain the areas of focus during the systems integration assessment
- Attributes: This set of blocks include the defined integration attributes with their calculated weights toward the SoS integration
- Enhanced IRL Score: This block is the resulting IRL after each assessment
- Validate IRL Score: This block represents the validation of the enhanced IRL score and an opportunity to identify risk areas. It also an opportunity to determine options to adjust scope if necessary
- Stakeholder Decision: This block allows the Stakeholders to evaluate the validated score and make decisions to either move forward with the current process, make adjustments to risk areas, or make adjustments to the scope of integration

IRL Lvl	IRL Principles	IRL Availability	IRL Complexity	IRL Interoperability
1	Interface between systems have been identified	All currently available and unavailable supporting integration items (systems, subsystems, components, expertise, and documentation) are identified	Complexity and technical risks areas of design, development, and integration are identified	Interfaces and connectivity areas of systems, subsystems, and components items are identified
2	Interaction between systems have been specifically characterized	Available and unavailable items are characterized	Technical risk areas are characterized	Interaction between items are characterized
3	There is compatibility between systems	Initial plans to obtain unavailable items are compatible with overall strategy	Initial mitigation strategies are compatible to technical risk areas	Interoperability strategies are compatible with integration activities
4	Sufficient detail in quality and assurance between systems	Plans to obtain unavailable items provide sufficient details	Sufficient detail for mitigation strategies are defined	Interoperability strategies have sufficient details
5	Sufficient control between systems necessary to establish, manage & terminate integration	Plans are delivered and have sufficient control	Proposed mitigation strategies are delivered and have sufficient control	Proposed strategies are delivered and have sufficient control
6	Accept, translate, and structure information between systems	Proposed plans are accepted and executed	Mitigation strategies are accepted	Proposed strategies are accepted and executed
7	Integration between systems has been verified and validated	Plans are verified and validated	Mitigation strategies are verified and validated	Proposed strategies are verified and validated
8	Actual integration completed & mission qualified	All items are delivered and mission qualified	Mitigation strategies are mission qualified	Proposed strategies are mission qualified
9	Integrated systems are mission proven	All items are mission proven	Mitigation strategies are mission proven	Proposed strategies are mission proven

Table 6-2a. Guidelines to Initial IRL for each Attribute Using IRL Principles (Part I)

IRL Lvl	IRL Definition	IRL Management	IRL Processes	IRL Resources	IRL Schedule
1	Interface between systems have been identified	Strategies, scope, requirements, and priorities are identified	All integration activity processes are identified	All resources and funding risks to support integration are identified	Detailed integration schedule and schedule risks are identified
2	Interaction between systems have been specifically characterized	Key management decisions are characterized	Processes are characterized	All resources and funding risks are characterized	All schedule item and risks are characterized
3	There is compatibility between systems	Current strategies are compatible with Management decisions	Processes are documented and are compatible with management strategies	Initial mitigation strategies to funding risks are compatible with integration strategy	Initial mitigation strategies to schedule risks are compatible with integration strategy
4	Sufficient detail in quality and assurance between systems	Management strategies have sufficient detail in quality and assurance	Processes are sufficient detail in quality and assurance	Mitigation strategies have sufficient detail in quality and assurance	Mitigation strategies have sufficient detail in quality and assurance
5	Sufficient control between systems necessary to establish, manage & terminate integration	Management strategies are implemented with sufficient control	Processes are documented with sufficient control	Mitigation strategies are delivered with sufficient control	Mitigation strategies are delivered with sufficient control
6	Accept, translate, and structure information between systems	Management strategies, goals, and scope are accepted and executed	Processes are accepted and executed	Mitigation strategies for funding risks are accepted and executed	Mitigation strategies for schedule risks are accepted and executed
7	Integration between systems has been verified and validated	Management strategies are verified and validated	Processes are verified and validated	Mitigation strategies are verified and validated	Mitigation strategies are verified and validated
8	Actual integration completed & mission qualified	Management strategies are mission qualified	Processes are mission qualified	Mitigation strategies are mission qualified	Mitigation strategies are mission qualifed
9	Integrated systems are mission proven	Management strategies are mission proven	Processes are mission proven	Mitigation strategies are mission proven	Mitigation strategies are mission proven

Table 6-2b. Guidelines to Initial IRL for each Attribute Using IRL Principles (Part II)

6.3 Systems Integration Assessment Framework Application

The process of using the Systems Integration Assessment Framework is as follows:

1. SoS integration begins with the concept of integrating new capabilities into a family of systems or SoS.
2. Clear integration requirements are provided and approved by the stakeholders.
3. The Scope of Integration (i.e. cost, schedule, Concept of Operations etc.) is determined by the Stakeholders.
4. Based on the scope, the Integration Activities are identified and evaluated to determine if the activities impact the Family of Systems. The Integration Requirements, Scope of Integration, and/or Integration Activities may be adjusted if the Integration Activities negatively impacts the Family of Systems.
5. To begin understanding the overall feasibility of integration, the stakeholders and designated SMEs determine IRL score for the integration variables (or major areas of concern) under each attribute.
6. Using IRL principles (as described in Table 6-2a & b), the initial IRL value for each attribute is determined.

    - Each of the integration variable under each attribute are evaluated using the Guidelines in Table 6-2a & b; the lowest IRL value (as described in Table 6-2a & b) will be used as the attribute's IRL value. For example, the integration variables defined in the Availability attribute are supporting system's software and hardware, personnel, and documents. If software is IRL 6, hardware is IRL 5, personnel is IRL 4, and documents are IRL 6, then the Availability attribute's IRL value (IRLAvailability) is 4, which is lowest IRL value of the integration variables (Personnel). Like TRL evaluation, the IRL value cannot be higher than the lowest value of its constituents (Leete S *et al.*, 2015).

7. The derived weighted percentages are used to determine the enhanced IRL score for the SoS (IRLSoS). The resulting equation becomes:

$$IRLSoS = (IRLAvailability \times 0.139) + (IRLComplexity \times 0.164) + (IRLInteroperability \times 0.176) + (IRLManagement \times 0.154) + (IRLProcesses \times 0.169) + (IRLResources \times 0.115) + (IRLSchedule \times 0.083)$$

8. The Enhanced IRL score (IRLSoS) will be rounded down to lower whole number (i.e. IRLSoS = 4.5 will have the IRL score of 4). The IRL definition for each level in Table 6-2a & b will explain the IRL enhanced score, which provides the overall integration level at that point in time.
9. Stakeholders evaluate and validate the enhanced IRL score, identify risk areas, and determine options to adjust the integration variables under each attribute and/or adjust the scope of integration if necessary.
10. Determining integration feasibility is an iterative process and this framework allows the stakeholders to look at options to improve the areas of emphasis (low IRL levels) when new information is obtained.
11. Assessment of IRL can also be tied into major events and reviews throughout the development and deployment processes. It allows program managers to make adjustments to their program based on the results of the IRL assessment.

Application in DoD Acquisition Process

The System Integration Assessment Framework can be applied throughout the DoD Acquisition Process. The framework can be implemented after the new capabilities' system requirements are developed and Materiel Solution Analysis is completed (post-Milestone A of the DoD programs). An integration assessment can be conducted as part of the TRA process and as the system matures, it is likely that more relevant information is received and helps improve SoS integration. Therefore, continuous use of this framework would be beneficial for the program managers, which will help them understand and improve the lower IRL areas. Formal program reviews such as System Requirements Review, System Functional Review, Preliminary Design Review, and Critical Design Review would be optimal events to apply this framework and assess the feasibility of systems integration.

Framework Application Examples

To fully understand the application of the integration assessment framework tool, two fictional case examples are provided. The first example includes an experimental space sensor payload to be integrated into a communication satellite family of systems. The second example includes a new software capability to account for new business areas that needs to be integrated into the current operational software enterprise System of Systems.

CASE 1 Example: Experimental Payload integration into Operational Communication Satellite Family of Systems

1. Integration Requirements:
    a. Integrate an experimental payload (X1) into the next set of operational communication satellites (CS2) to measure capability (i.e. measure communication interference) and integrate entire satellite system into the already established operational communication satellite (OCS) family of systems
    b. Integration requirements architecture is illustrated in Figure 6-2:

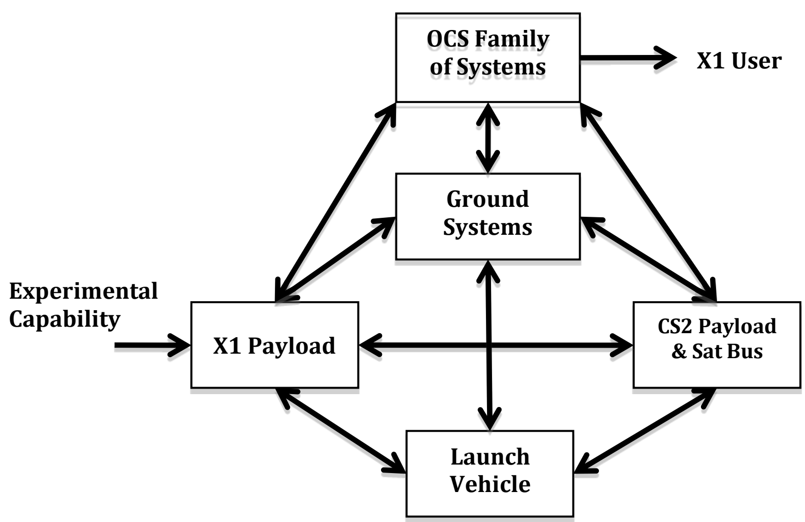

Figure 6-2. Case 1 Example: Integration of X1 payload into OCS Family of Systems

2. Scope of Integration:
    a. Integration cost is estimated at $30M
    b. Integration schedule is 24 months to make X1 operational
    c. Current integration scope does not include the CS2 integration with OCS integration. CS2 is the primary payload that shares the satellite bus with X1.

3. Integration Activities (as illustrated in Figure 6-2):
    a. Integrate X1 into: 1) CS2 Payload and Satellite Bus; 2) Ground Systems; 3) Launch Vehicle; and 4) OCS Family of Systems
    b. Stakeholders and SMEs determined the major integration variables under each attribute
4. Family of Systems: Defined integration activities do not negatively impact the OCS
5. Initial IRL Assessment (using Tables 6-2a and 6-2b as IRL level guidelines):
    a. Availability: IRL=8
        i. All supporting systems (software, hardware, documentation and expert personnel) have been identified, delivered, and mission qualified.
    b. Complexity: IRL=5 (lowest score from integration variables under Complexity)
        i. Complexity of design: Two major preliminary designs (X1 and CS2) are complete and mitigation strategies are accepted. IRL=6
        ii. Complexity of their integration to OCS: proposed strategies have been defined, delivered, and have sufficient control. IRL=5
    c. Interoperability: IRL=6 (lowest score from integration variables under Interoperability)
        i. X1 to CS2: Integration of size, weight, communication links, and power have been determined; strategies are accepted and executed. IRL=6
        ii. X1 to Ground Systems: proposed strategies are mission proven. IRL=9
        iii. X1 to Launch Vehicle: proposed strategies are mission proven. IRL=9

iv. X1 to OCS: strategies are accepted and executed. IRL=6

d. Management: IRL=6

   i. Management has provided strategies, goals, and scope that are accepted and executed.

e. Processes: IRL=3 (lowest score from integration variables under Processes)

   i. Documentation Processes: Interface Control Documents (ICDs) are documented and compatible with management strategies. IRL=3

   ii. Testing processes: Test Plans are in sufficient detail in quality and assurance. IRL=4

   iii. Development processes are all mission proven. IRL=9.

f. Resources: IRL=7

   i. There are enough resources to cover the estimated $30M estimate; personnel, facilities, and tools are verified and validated.

g. Schedule: IRL=3

   i. Current 24-month schedule may be a medium risk; compatible with integration strategy but does not have sufficient detail.

6. Enhanced IRL Score is equal to:

IRLSoS = (IRLAvailability x 0.139) + (IRLComplexity x 0.164) + (IRLInteroperability x 0.176) + (IRLManagement x 0.154) + (IRLProcesses x 0.169) + (IRLResources x 0.115) + (IRLSchedule x 0.083)

IRLSoS = (8 x 0.139) + (5 x 0.164) + (6 x 0.176) + (6 x 0.154) + (3 x 0.169) + (7 x 0.115) + (3 x 0.083) = 5.473

7. The calculated IRLSoS is 5.473. The IRLSoS is rounded to the lower whole number (IRL 5), which means there is sufficient control between systems necessary to establish, manage & terminate integration. If this is a DoD Acquisition Program, it would not pass the minimum IRL 6 to move into the Engineering & Manufacturing Development (EMD) Phase. Therefore, additional emphasis to the lower valued attributes needs to be addressed by the Stakeholders before another IRL assessment can be completed.
8. The current DoD Acquisition process requires a TRL value of 6 or more to be approved to enter into the EMD phase. Since the Complexity attribute includes the system design and technologies to achieve TRL value, addressing Complexity would be a primary responsibility in order to improve both the TRL and IRL values from Level 5.
9. Once the stakeholders agree on how to address the attributes' low IRL values and implement the strategies to improve them, the IRLSoS is calculated again. The goal is to have IRL 8 (actual integration completed & mission qualified) prior to operations.

CASE 2: The requirement is to integrate a new software capability to account for new business areas into the current operational enterprise software System of Systems.

1. Integration Requirements:

    a. Integrate the company's new business segment (NBS) software to account for newly acquired business areas into the company's current multi-segment operational enterprise software (OES) system of systems. The OES includes the customer segment, logistics management segment, employee segment, financial management segment, marketing segment, and partners segment.

    b. Integration requirements architecture is illustrated in Figure 6-3:

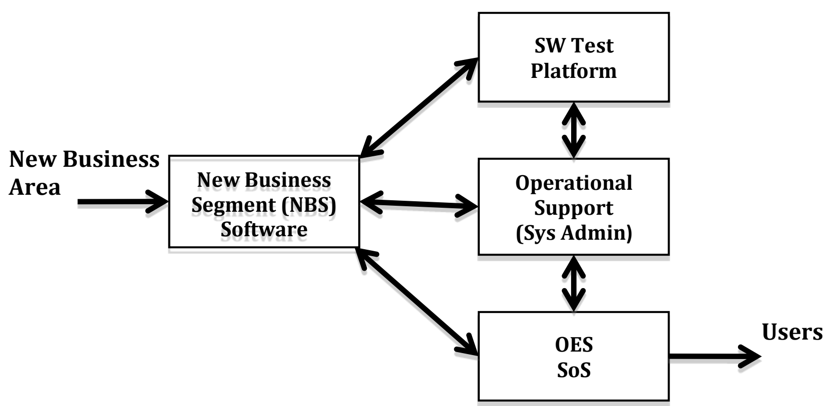

Figure 6-3. Case 2 Example: Integration of NBS into OES System of Systems

2. Scope of Integration:

    a. Integration Cost is estimated at $10M

    b. Integration schedule is 12 months to make NBS operational

3. Integration Activities (as illustrated in Figure 6-3):

    a. Integrate NBS to: 1) Software Test Platform; 2) Operational Support; and 3) OES SoS

b. Stakeholders and SMEs determined the major integration variables under each attribute

4. Family of Systems: Defined integration activities do not negatively impact the OES and its segments

5. Initial IRL Assessment (using Tables 6-2a and 6-2b as IRL level guidelines):

    a. Availability: IRL=2 (lowest score from major Availability areas)

        i. COTS software, hardware, and documentation are delivered and mission qualified. IRL=8

        ii. Expert personnel (specialized coders and testers) are unavailable but have been characterized. IRL=2

    b. Complexity: IRL=5 (lowest score from major Complexity areas)

        i. The design to the NBS software has sufficient detail for mitigation strategies are delivered and have sufficient control. IRL=5

        ii. Complexity of integrating to OES has mitigation strategies accepted. IRL=6

    c. Interoperability: IRL=4 (lowest score from major Interoperability areas)

        i. NBS to SW Test: New software to test has proposed strategies that are verified and validated. IRL=7

        ii. NBS to Ops Support: New software done before so proposed strategies is mission proven. IRL=9

        iii. NBS to OES: Interoperability strategies have sufficient details. IRL=4

    d. Management: IRL=6

        i. Management strategies are verified and validated. IRL=6

e. Processes: IRL=4 (lowest score from major Processes areas)

    i. Documentation Processes are mission proven. IRL=9

    ii. Test processes have sufficient detail in quality and assurance. IRL=4

    iii. Software development processes are mission proven. IRL=9.

f. Resources: IRL=6

    i. Mitigation for funding risks of $10M are accepted and executed.

g. Schedule: IRL=6

    i. Mitigation risks for schedule are accepted and executed.

6. Enhanced IRL Score is equal to:

   IRLSoS = (2 x 0.139) + (5 x 0.164) + (4 x 0.176) + (6 x 0.154) + (4 x 0.169) + (6 x 0.115) + (6 x 0.083) = 4.590

7. The current IRLSoS is 4.590. The IRLSoS is rounded to the lower whole number (IRL 4), which means that there is sufficient detail in quality and assurance between systems. Since this is a business SoS, it does not follow the DoD acquisition process. However, the assessment provides areas of emphasis to improve before completing another IRL assessment.
8. The goal is to have the actual integration completed and mission qualified (IRL 8) before it can be fully integrated into the OES SoS.
9. The advantage of this SoS is having a Software Test Platform to continue improving lower IRL areas and qualifies them before integrating into the OES SoS for operational use.

6.4 Discussion

Throughout the research process, there were several assumptions and challenges that helped shape the direction of the research. The initial approach to collect the desired data through interview of integration experts was not feasible and the approach to validate those data would not be clearly defined. Through refinement of the research process, the effort to research and collect DoD space systems integration data through documented reports have provided a more defined focus. The timeframe of the data collected from 1999 to 2014 provided significant insight to the behavior of the systems regarding systems integration. Extracting the integration variables and derived attributes from the data helped define the elements needed to understand and improve systems integration assessment. The method of gathering the data and using expert survey to validate the data helped improve the definition of the attributes and determine the weight of each attribute based on their importance to systems integration, which became the key elements in developing the integration assessment framework. The process to determine the final criteria for the attributes was very comprehensive, but it helped distinguish each attribute from one another.

Using the Minitab software analysis tool was very helpful when analyzing the data and the survey results. The software tool helped provide clarity on the relationships between data points. After completing the data analysis, the next significant step was validating the data with the right SMEs, which was critical to completing the research. Identifying the SMEs that have worked on the SoS data have been very helpful and their participation to the survey were very insightful to the overall criteria of each attribute.

As the research completed and the findings were summarized in a journal article for publication, the format to explain the process needed some improvement. All the information to complete the research were available; however, the feedback from systems engineering journal review panels, specifically the Defense Acquisition Research Journal review panel, helped provide guidance on summarizing the entire research. The application process of the integration assessment framework that was derived from defining the seven attributes is a useful systems engineering tool for program managers to determine integration feasibility. The Defense Acquisition Research Journal approved the research summary for publication in December 2016.

The result of the research produced seven systems integration attributes that are defined from derived criteria and are given different weights. Each attribute adds a dimension in evaluating SoS integration, and the resulting integration assessment framework tool provides an enhance IRL score that will help determine integration feasibility in planning and facilitating integration activities. The attributes were validated through the expert survey and the results proved that other attributes were more important than what it was initially defined.

The integration assessment framework tool can be used as many times as new information is provided, and adjusting the expectations and scope can help with understanding the feasibility of the IRL score. Calculating the enhanced IRL score is an iterative process with the thought that the IRL score could improve through time due to additional information and adjustments to each attribute. Although the current DoD process of deploying space system capabilities for operational use does not require assessment of integration maturity, the result of this research should help quantify the feasibility of integrating SoS using IRL principles.

6.5 Limitations and Future Work

Although several processes have been provided to assess TRL and IRL, there is still some subjectivity to these analyses. Every program has some uniqueness on how to integrate their systems, but the past data and past experience can help put some rigor in the analysis. IRL has effective principles if it complements other analyses to help with program manager decisions. Results can offer areas of emphasis as opposed to detailed solution. For IRL to be used effectively, high-level assumptions need to be clear up front and agreed to by stakeholders.

When grouped with other readiness metrics, IRL may have some applications in DoD research and development (Ross S, 2016), but IRL itself does not have the capacity to critically assess research and development effort. It also does not evaluate cost and schedule (Sauser B *et al.,* 2010). A more quantitative algorithm may be required for the assessment of IRL for complex systems. Without rigorous criteria, assessment for the determining IRL could lead to inaccurate analysis. Assessment of TRL and IRL sometimes can lead to oversimplification (Ramirez-Marquez J, Sauser B, 2009).

Although some of IRL may be subjective, there are several analyses using IRL principles that can be done to develop processes and help with program managers' decisions on SoS integration. Throughout DoD acquisitions and large complex programs, integration challenges will continue to persist and the need for additional analysis and tools to overcome those challenges are necessary.

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