A Systems Architecture-based Approach to Assess Candidate Upgrades to Complex Systems

by

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Submitted to the Engineering Systems Division
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

September 2012

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Submitted to the Department of Engineering Systems on August 31, 2012
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Abstract

The Compatibility Assessment Method (CAM), a new structured process for assessing compatibility between parent systems and child subsystems is proposed and applied to several cases where subsystems are being replaced in legacy systems. CAM is a screening process intended to be used by project managers who need to replace components of complex systems. The functional model-based process uses an extension of the Integrated Definition Modeling Language of IDEF0. The IDEF0 method is used for defining compatibility measures based on each of the four constituent arrows that show inputs, controls, outputs, and mechanisms (ICOM). In this extension, the control constituents are replaced with constraints. Each of the ICOM constituents is expanded with parameters which include metrics and values. The ICOMs with their parameters and metrics are then used to characterize two or more subsystems in a matrix format. The differences between these matrices are entered into the sparse "Delta Matrix" which shows analysts the differences between the systems. These differences can be assigned to the appropriate levels of technical expertise to be analyzed and to determine feasibility of the child subsystem in the parent system. The process is compared to current practices in government unmanned aircraft system program offices to determine the usefulness of adopting this compatibility assessment process.

This dissertation outlines the need for and development of the method for application by practitioners responsible for replacing subsystems on legacy systems. The development includes evaluations of the method and an experiment with cohorts of student system engineers to compare the output of the Compatibility Assessment Method to less-structured methods.

This research contributes additional insight into system architecting theory and proposes a structured method for practitioners to use to improve the processes to perform part replacement in legacy systems. While others have offered methods to measure aspects of system architecture, this proposed method moves beyond the extant literature with tools for practitioners.

Thesis Supervisor: Warren P. Seering

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Dedication

To Cathy, Cameron, and Lauren:

Make no little plans.

~ Daniel Burnham, Architect (1846-1912)

Acknowledgements

The journey of earning a doctorate degree is not made alone. Many people are involved in the foundations, motivation, and the process. I start by thanking my parents, Richard and Laurel, for instilling high values for education. I consulted many academics along the way: Elvin Isgrig, Bonita Campbell, General Al Henderson, and John Colombi. These mentors helped me to make the decision to advance my education.

Many friends told me that I would be a good teacher through the years. These friends planted the seeds that made me consider the opportunity when the Air Force offered. Ross McNutt opened a door by recommending that I be brought into the faculty pipeline.

Next, I want to thank the people who ***didn't*** tell me what getting a PhD is all about. First, I wouldn't have believed you if you told me. And, if I would have believed you, I wouldn't have taken this journey and I would have missed the joys of learning how to learn and conduct research.

I had an amazing research cohort – ***The Silo Five***. The original group included Robb Wirthlin, João Castro, Dan Livengood, Sid Rupani, and me in the Lean Product Development research group. We supported each other; challenged each other; entertained each other. We welcomed others into the group. Thank you, Claudia Wagner, for bringing me yogurt parfaits during general exams. Pedzi Makumbe, you were a great office mate and regularly challenged my thinking and direction – thank you! The rest of the Lean Aerospace Initiative and Engineering Systems Division provided great friendship and support. Elizabeth Milnes shined as a staff member who supported students in spite of their [my] crazy needs and requests.

My friends and colleagues at AFIT who encouraged me and helped with data analysis: John Colombi (yes, he's acknowledged twice!], Dave Jacques, Dave Fass, John Elshaw. Ryan Easton and Ross Johnston earn special thanks for learning CAM and applying it in their program offices.

The committee who helped shape my research: Olivier de Weck, Missy Cummings, Sheila Widnall.

The co-advising team – Warren Seering (Committee Chair) and Eric Rebentisch – demonstrated patience and guided me to improve my research skills. Their individual and team advising skills complemented each other. One of my recurring memorable meeting interactions was coming into the office with a stack of work that I had done over the last week. I knew I had a lot of work done, but it took Warren and Eric to help me make sense of it and put it in context. I hope that I can be as insightful and helpful to advisees in the future.

Finally, I would be remiss to not thank my wife and kids for their years of support, sharing the kitchen table while we all studied and did our homework, packing and moving to make the experience possible, and learning along with me whether you wanted to or not.

Thank you to everyone who let me stand on your shoulders to reach the new heights.

– David Long

Disclaimer

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

Chapter 1 – Introduction

Problem Statement

For the fiscal year 2013, the United States Air Force has received a budget of $4.4 billion to upgrade aircraft. The 2013 budget for new aircraft in the USAF is $8.2 billion (OMB, 2012). At the same time, the average age of an Air Force aircraft is 23 years and some of the airframes go well beyond 40 years (Defense Insider, 2011). As the aircraft continue to age, continued upgrades are expected. Improving insight into proposed subsystem compatibility for upgrades has large potential benefits.

Many organizations are faced with the challenges of refreshing their products during their products' life cycles. These upgrades are sometimes associated with cost overruns, schedule delays, safety considerations, and performance issues. The solutions that organizations employ to upgrade systems are oftentimes ad hoc, disjointed, and inefficient.

This research aims to gain insight into how new subsystems are incorporated into existing systems and then conduct an inductive study to determine if a better way of integrating components into legacy systems exists.

Motivation

The Government Accountability Office (GAO) has identified duplication of capabilities as one reason for excessive costs in acquisition (US Government Accountability Office, 2004). The Office of the Secretary of Defense (OSD) has directed the military departments to decrease costs. One way that OSD has identified to decrease costs is to increase subsystem commonality across systems. The system architecting community provides a lens to understand the issues associated with complex systems and their relationships to their subsystems. Research in this area will help understand the issues associated with system upgrades and potentially provide insights to practitioners to avoid the upgrade problems of the past. Finally, studying this problem may contribute to theory and practice of system architecting.

This thesis establishes the importance of learning about performing subsystem upgrades in legacy systems, reviews the extant literature regarding system architecting and how the tools of systems architecting have been applied, identifies areas which are under-represented in research, and then develops and expands the tools of the system architect for practitioner use.

Research Questions and Methodology

The research in this thesis was conducted to answer the following three questions:

- How can subsystem information embedded in system architectures be formally represented to allow more-structured processes for system upgrades?
- How can these representations be used to evaluate potential subsystem upgrades?
- Is there a more effective way to plan subsystem upgrades and is a proposed approach better?

The research methodology uses practitioner surveys, exploration of literature, a structured method using a set of pairwise case studies performed by Air Force project managers, and an experiment conducted on the process with a group of Air Force system engineers and the resulting exit interviews of the process users.

Thesis Overview

This thesis provides the motivation and background literature review to expand the body of system architecting knowledge and inform the inductive development of an architecting tool that can be used by practitioners to identify compatibility issues when they consider changes to complex systems. The research was initially informed by the researcher's experiences of system upgrade processes. The extant literature was reviewed to determine how systems architecture knowledge has been used to learn about systems. Contacts were made in military and commercial organizations that stated imperatives to replace current subsystems in legacy systems. The practitioners used ad hoc processes or hired outside organizations to perform analysis. The ad hoc processes were not repeatable and the contracted studies, while detailed and thorough, were slow and costly. They also left questions about the motivations and the assumptions used in the reports. A need for a process was identified and a search for system architecting solutions was performed. An inductive study beginning with IDEF0 was performed through several systems and a method emerged as an extension to current literature. This method was matured through a series of developmental experiments with practitioners. The method was tested in two program offices and then a representative study was developed for a larger systems engineering graduate student cohort that compared legacy methods with the proposed method of assessing compatibility of the new systems with the legacy subsystems. Conclusions and recommendations were made based on the studies conducted with members of the program office and the student cohort.

This thesis is organized in the following chapters:

Chapter 1 Introduction and thesis organization
Chapter 2 Review of the literature
Chapter 3 Development of Compatibility Assessment Method
Chapter 4 Application of Compatibility Assessment Method in program offices
Chapter 5 Testing Compatibility Assessment Method in an academic environment
Chapter 6 Conclusions and recommendations

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Chapter 2 – Literature review

In order to develop an understanding of systems and their associated subsystems, the organization of systems must be understood. Knowledge of system architecture and its related components provides a framework to inform understanding of complex systems. System architecture is the foundation that enables analysis of subsystem compatibility. An understanding of system architecture enables a structured method to study systems and their functions. This chapter reports the extant literature related to systems, product families, platforms, modularity, and architecture representations.

This review decomposes the extant literature about system architecture and explains the components of the system architecture taxonomy and how they relate to each other. In addition, a review of the models and measurements is conducted to determine the metrics that are available to measure characteristics of systems from an architecting perspective.

System architecture

The term "system architecture" does not have a single, accepted definition; rather, literature reveals many accepted definitions. Maier and Rechtin report the following: a unifying or coherent form or structure; the structure (in terms of components, connections and constraints) of a product, process, or element; the highest-level concepts of a system and its environment; the fundamental and unifying system structure defined in terms of system elements, interfaces, processes, constraints, and behaviors; and many others. An insightful definition is Maier's tongue-in-cheek rule of thumb: the set of information that defines a system's value, cost, and risk sufficiently for the purposes of the system's sponsor (Maier & Rechtin, 2000).

System architecture aids in the understanding of a complicated system. A system that has many layers and components may be easier to understand if system architecture principles have been followed. The architecture allows segregating the system into chunks that can be managed and understood by a single person. Since psychologist George A. Miller's research in human channel capacity (Miller, 1956), a range of five to nine items is considered a manageable number of chunks.

The purpose of system architecture is to maximize profit for a product line (Martin & Ishii, 2002). The architecture may be focused on a portfolio of products that aids in developing a platform, fostering reuse, and increasing commonality. It may also be used to manage generational change to meet future needs with a single system.

When developing system architecture, five key decisions must be made: setting the boundary, deciding the degree of modularity, locating functions, designing interfaces, and maintaining flexibility (Smith & Reinertsen, 1998). The degree of modularity must be decided because it impacts how an organization will design and support a system.

Product Architecture

Architecture is the structure that results as a product of art and science to meet the user's purpose (Maier & Rechtin, 2000), and at the same time it can be the arrangement of functional elements into physical chunks (Karl T. Ulrich & Eppinger, 2004). Product architecture is the set of technical decisions for product layout, modules, and interactions between modules (Gulati & Eppinger, 1996). Another view shows the three elements of product architecture as a set of functions, functions to module mappings, and interface specifications (Baldwin & Clark, 2000). Good architecting practices dictate that the function and interfaces be established before building the product. Engineering design practices now focus on identifying customer needs and mapping those needs to functional descriptions. This "function before form" methodology resolves the disconnects between customer needs and design concepts (Otto & Wood, 2001). Product architectures can display either modularity or integrality (Karl T. Ulrich & Eppinger, 2004). A modular architecture would have chunks, or collections of elements, that would individually embody a single function. In a modular architecture, the interactions between the chunks are fundamental to the primary functions of the product; integral architecture differs in that it has a single chunk that implements many functional elements and the interactions between the chunks are not well defined. Studies of organizations have been performed and when architecture of a product is compared to the organization that designed or managed it, the structures can have many similarities (Gulati & Eppinger, 1996).

Platforms

Another aspect of System Architecture is platforms. The concept of platforms emerges from systems architecture and applies to modularity. A platform encompasses the design and components shared by a set of products (M. H. Meyer & Utterback, 1993) and includes a set of subsystems and interfaces that can be leveraged to produce a stream of derivative products (Marc H. Meyer & Lehnerd, 1997; Muffatto & Roveda, 2000; Robertson & Ulrich, 1998). Platforms are developed when chunks of a system are reused for a product line. The pieces of the system that are common become a physical platform. As with much of the literature about product development and system architecture, other platform definitions exist, too. One example is that the Air Force uses the term "platform" to identify an aircraft system. For example, an F-16 fighter, a C-17 transport, and an MQ-1 unmanned aircraft system are all referred to as platforms.

The use of platforms is associated with rapid next-generation development (Martin & Ishii, 2002) to avoid developing entirely new products when customers' needs or new markets are identified (Marc H. Meyer & Lehnerd, 1997). Platforms that are used in product families are also recognized as a cost-reduction strategy. Economic order sizes may be increased when components or subassemblies are shared across a number of platforms (M. H. Meyer & Utterback, 1993; Sundgren, 1999).

Platforms and Parent-Child Relationships

The parent-child relationship in architecture can relate to two different situations. The first, and classic, reference is the component relationship to the next higher assembly. This child to parent relationship is seen in hierarchical system breakdown diagrams. The parent component is shown with exploded views that depict the children related to the higher component.

The second depiction of a parent-child relationship is more abstract. The parent can be identified as a collection of components, and each member of the collection can be considered a child. However, a platform emerges when the majority of the child components remain constant and a single child component is removed from the larger assembly of children and replaced (Colombi, 2010).

Product Families

Product families are groups of products sharing an architecture that is based on reusing components to develop a common platform and plan variability in order to differentiate products. Successful product families manage the common aspects of the systems by hiding them from the user and allowing the user to interact with the variables that differentiate the product.

A product family can also be a set of similar products that are derived from a common platform and yet possess specific features/functionality to meet particular customer requirements (Marc H. Meyer & Lehnerd, 1997). Yet another definition for product family is a group of related products that share common characteristics (e.g. features, components, modules, or subsystems), and the key to designing a successful product family is the product platform around which the family is developed (McGrath, 2001).

The concepts of product platforms, product modularity, and product families are inextricably linked to each other. Gonzalez-Zugasti and Otto provide a crisp set of definitions: A product platform is the set of components and subsystems shared across multiple products; a modular platform allows for swapping modules to configure multiple products in a family. They also write that platform design outperformed individual design when discounts from sharing are applied. While they write about individual capacity constraints that put limits on their compatibility within a product family, they model this problem mathematically but reveal no insights into how to determine compatibility (Javier P. Gonzalez-Zugasti, 2000). Similarly, when modeling product families for mass customization, other researchers focus on functional requirements decomposition and the organization of product building blocks(Jiao *et al.*, 1998), but offer no discussion of processes for determining module compatibility.

A product platform can satisfy a variety of markets if it is used to develop a product family, which is a group of related products derived from a product platform (T. Simpson, 2003). (T. W. Simpson, 2004) identified two types of product platform-based families: Module, the most common, in which one or more functional modules are added, changed or removed from a platform to create variants; or Stretched, in which one or more levers is used to change the dimensions of a platform to create the variants. Boeing employs stretching when it varies an aircraft by changing the length of the fuselage (Sabbagh, 1996).

Cross-functional product development teams are essential to developing a successful platform. Many companies have aligned organizations to maximize the benefits of cross-organizational information sharing. The benefits yield component reduction, common architectures and a deep research pool for innovation (T. W. Simpson *et al.*, 2006).

When a platform is expected to have a long lifetime and multiple product generations (military UASs and other acquisitions would likely fall into this category), a key challenge is designing the platform to be able to navigate the unexpected changes with the original design (T. W. Simpson et al., 2006).

Another benefit of employing a platform management process is the ability to navigate through the product development process faster than re-accomplishing the process for each product. The product development process comprises six parts: planning, concept development, system-level design, detail design, testing and refinement, and production ramp-up (Karl T. Ulrich & Eppinger, 2004). Toyota has been able to decrease its time to market by shortening the product development process, and has consistently executed the process of bringing a new body with a carrier for chassis and powertrain from styling freeze to the start of production in just 15 months. Some of Toyota's vehicles require only 12 months, while most competitors require 24 to 30 months to complete the same task (Liker & Morgan, 2006). This type of process management could shorten UAS development times, too.

Platforms can be viewed through either a wide or constricted aperture. Volkswagen (VW) chooses to share floor groups, drive systems, running gear and parts behind the dash for Seat, Skoda, Audi and VW brands (Wilhelm, 1997). Chrysler overused their K-car platform and was accused of "falling asleep with a finger stuck on the K key" because all their platforms looked alike (Lutz, 1999). Metrics have been developed to measure platforms in both fine-grained and coarse-grained ways. By calculating the number of times a platform is reused, platform efficiency and effectiveness can be measured. The finer-grained measurements include product differentiation, coupling index and others (T. W. Simpson, 2004).

Each member of a product family is known as a product variant or instance. While a product family is developed to meet the needs of a market segment, a variant addresses a specific subset of needs found in the customer market segment (Jiao *et al.*, 2007). Because all the product variants share common structures or technologies, they are identified as a family (Erens & Verhulst, 1997).

Platforms are developed by one of two approaches to product family design. First, the top-down (proactive) platform develops a family of products based on a product platform and its derivatives. The second approach is the bottom-up (reactive) platform method, in which individual products are redesigned to standardize and improve economy of scale (T. W. Simpson, 2004). Examples of successful proactive platform products include the Sony Walkman (Sanderson & Uzumeri, 1997) and the Apple iPod (Kim, 2006). Reactive platform successes have been reported across several industries, as exemplified by Lutron lighting controls (100+ products based on 15-20 components) (Pessina & Renner, 1998), Black & Decker electric motors for hand tools (Lehnerd, 1987), and John Deere's reduced variety in valves(Shirley, 1990).

Product family development and management can overcome the two major drawbacks associated with single product development: duplication of effort in marketing and development, and poor long-term consistency and focus. In spite of these drawbacks, much management effort addresses the development of a single product at a time (Marc H. Meyer & Lehnerd, 1997). In addition to forcing an increasingly competitive marketplace on companies by demanding larger varieties of products (J. P. Gonzalez-Zugasti & Otto, 2000), today's customers are not always satisfied with the mass-produced items that have been traditionally available as a one-size-fits-all solution; they seek customized products to fit their niche. This demand has been addressed through mass customization, a technique that allows individual customer satisfaction and the efficiencies of mass production (Pine, 1993).

Product families have been developed to achieve the economies of scale required for competitive prices and to allow product variety to service the customers' niches(M. H. Meyer & Utterback, 1993). A product family architecture exists only if systems have a common arrangement of elements, a common mapping between function and structure, and common interactions among components (Martin & Ishii, 2002). Many companies report adopting product family development processes to offer more variety to the market while keeping their economies of scale aligned with their manufacturing capacities(Robertson & Ulrich, 1998). Product family designs develop a common baseline, or platform, to capitalize on commonality while extending the use of the platform into a common product line structure (Jiao et al., 2007).

Two product family development strategies have emerged in the platform literature. First, an integral platform is characterized by a large portion of the product that will be shared with all the members of the product family. This integral portion will have individually-designed assemblies added to produce a variant. An example of this is a satellite system where the platform is the integral bulk of the system and few options are available. The second, more common, platform is the modular platform where the product is decomposed into several modules that can be individually stretched, combined, or changed to deliver a platform capability. In addition to the modules that comprise the platform, other modules may be added to the platform. These modules may be commodity items available from catalogs, special developments to provide a particular function for the system, or available and reused from earlier products (J. P. Gonzalez-Zugasti & Otto, 2000).

Because common definitions do not exist, different stakeholders often interpret product families with dissimilar lenses. The customer and marketing stakeholders may focus on a functional structure of the product family, and various functional features will be focal points for different customer/user groups (Agard & Kusiak, 2004). The engineering views of product families will likely focus on the product technology, components, and manufacturing processes(T. W. Simpson, 2004). In addition, the stakeholders of a military system will have many additional views of a product family. The system program office (SPO) is responsible for cost, schedule and performance of the system. The SPO will be interested in leveraging families in order to keep costs down and deliver the capability as soon as possible while mitigating program risk. An acquisition wing commander may manage several related systems -- which may or may not be families-- in a capability portfolio. This person may be interested in expanding the family role outside of an established product family and reusing acquisition processes or architectural chunks from one system to another. The Office of the Secretary of Defense (OSD) is chartered with oversight of many acquisition programs. OSD acts as a watchdog and drives requirements for commonality, based on the concept that commonality and reuse is directly linked to cost savings. The Air Staff acts as the corporate Air Force and makes top-level decisions about funding, IT integration, and capabilities integration. Each of these views could be quite different with respect to product families. Logisticians and maintainers have an interest in maximizing common parts to minimize the number of spares that need transport, and minimizing the amount of training that is needed to repair systems.

The prime contractor for military systems is generally contracted to develop, manufacture, support, sometimes repair/maintain, integrate, and manage upgrades over time. The Federal Acquisition Regulations (FARs) dictate many rules for profit and types of contracts. The contractor as a developer would prefer making investments to extend a single system into a product family to ensure a stream of income through many years. The contractor can also negotiate a cost-reduction sharing plan where a manufacturing product family view could lead to common manufacturing, material, and assembly product platform views. The prime contractor may hire a subcontractor to supply a component or develop a module that would integrate into the platform. The subcontractor's view of the product family will be the interfaces that directly affect their associated systems.

When delivering warfighter capability, the Joint Forces Commander (JFC) may see weapon systems as interchangeable modules in the overall warfighting architecture. The JFC may call for a capability to be assigned to a certain area, and then assign more capability modules to other areas of interest.

The challenge to designing a family of products is to balance commonality and distinctiveness. If the commonality is too high, the distinctiveness is lost, and individual performance is sub-optimal. If commonality is too low, manufacturing costs will likely increase because of the loss of economy of scale (Robertson & Ulrich, 1998). For profit-generating enterprises, product family is best obtained by minimizing the non-value added variations across the products within a family without limiting the customer's choices in each market segment. This results in making each product within a family distinct in ways customers notice and identical in ways that customers cannot see (Thevenot & Simpson, 2006).

Modularity

Modularity is the continuum describing the degree to which a system's components may be separated and recombined. In systems architecture, a module is a building block that can be grouped with other building blocks to form a variety of products (Salhieh & Kamrani, 1999). The module performs a discrete function and is a chunk of a product (K. T. Ulrich & Tung, 1991). A well-accepted definition of module is, "a unit whose structural elements are powerfully connected among themselves and relatively weakly connected to elements in other units" (Baldwin & Clark, 2000).

The key to developing modular designs is to group tightly coupled elements and separate the weakly bonded interfaces(Ethiraj & Levinthal, 2004). Other common definitions of module include (1) an independent chunk that is highly coupled within but only loosely coupled to the rest of the system (Hölttä-Otto & de Weck, 2006), and (2) a part of a system that has a one-to-one mapping from functional elements in the function structure to the physical components of the product (K. Ulrich, 1995).

When a system can be decomposed into subassemblies and components, the product is said to be modular. The converse, integrality, exists when a system cannot be decomposed into smaller chunks. The concept of modularity product architecture has gained traction as firms employ modularity to offer a larger variety of products at lower cost. But, while the concept of modularity has been applied more often in recent years, the science of modular design and the associated studies have lagged (Gershenson *et al.*, 2003).

Modularity may be the most important characteristic of a product's architecture. A modular architecture has two properties: first, chunks implement one or a few functional elements in their entirety; second, the interactions between chunks are well-defined and important to the primary function of the product (Karl T. Ulrich & Eppinger, 2004).

Modular design structures are very applicable when systems become large and have many interdependencies. The size and complexity of some systems makes integrated design efforts nearly impossible (Parnas, 1972), but modularity is a useful means of managing complexity. Modularity is a general set of design principles for managing the complexity of systems with many interfaces(Ethiraj & Levinthal, 2004). Modularity involves breaking the system into chunks that use standardized rules for interfaces (Langlois, 2002).

Literature shows that modular design structures have advantages over integrality-focused designs. Modular designs are important when flexibility and rapid changes outweigh the need for overall system performance and for reducing the associated design and development time for a system(Karl T. Ulrich & Eppinger, 2004). Modularity can foster product innovation within the component, or, by mixing and matching modules, it can allow parallelism in design and testing, multiplying design options by mixing and matching modules, and allowing customization (Baldwin & Clark, 2000). Other advantages include facilitating outsourcing, building alliances in a supply chain, reducing the scope of an organization's core competencies, and providing agility to adapt to new environmental conditions (Ethiraj & Levinthal, 2004). A product family that has modularity between the systems can bring quantity advantages to the overall system because of higher economic order quantities for parts(Baldwin & Clark, 2000). If the product family architecture is well-designed, well-defined modules that have simple interfaces can be easily reused in other products as long as the interface requirements are standard. Another advantage to developing the modules is that a complex architecture may be easier to understand in the smaller modular chunks (Ericsson & Erixon, 1999). Another benefit is the ability of modularity to reduce life-cycle costs by reducing the number of processes and reducing repetitive processes (Gershenson *et al.*, 1999).

Even though the general literature agrees that modularity has benefits, there has been no validation of these benefits on a large scale. Modules may have disadvantages such as the potential to over-design to incorporate a module into a system, or too many common modules may cause lost brand identity (K. T. Ulrich & Tung, 1991). Modular architectures cause reduced system performance in some applications and may facilitate reverse engineering of products by competitors (Mikkola & Gassmann, 2003). The amount of modularity that should be included in the system is another source of concern. Areas for further research include determining how long modularity benefits the system and when it may cause diminished returns (Gershenson et al., 2003).

Types of modularity. Modularity has been grouped in several ways that are orthogonal to each other. Gershenson has identified modularity with respect to the product lifecycle and focuses on modularity during design, manufacturing, service, and end of life (Gershenson et al., 2003). Another duo categorized modularity into design, manufacturing, and customer focus(Mattson & Magleby, 2001).

The more common views of the types of modularity focus on modularity's physical and relational aspects. The first grouping includes slot-modular, bus modular and sectional modular (Karl T. Ulrich & Eppinger, 2004). Mix-modular, a way to describe the interchangeability of Tinker Toys, was added next (Otto & Wood, 2001). Three more types -- component sharing, component swapping, and cut-to-fit -- were added to the modularity types (Stake, 2001).

Another viewpoint divides modularity into six types, all of which can be combined in a single complex system: component-sharing, component-swapping, fabricate-to-fit, mix modularity, bus modularity, and sectional modularity. These six types are defined as follows:

- Component sharing, also called commonality, involves using the same component across multiple products
- Component swapping creates variety by pairing different components with a basic product, creating as many varieties as there are components. An example of this type of modularity is the choice of several radios in a particular car model
- Fabricate-to-fit modularity assumes that one or more of the components is variable within practical limits. Aircraft fuselage is an example from the aerospace industry, which can be stretched to accommodate more passengers and create new models
- Mix modularity entails combining different components to create something new. Paint is a good example: yellow can be used to make both green and orange
- Bus modularity is comprised of a common structure that can attach a number of different components. Standard interfaces can be matched with any selection of components, which can be varied in both number and location on the bus. Again, an aircraft fuselage can function as a bus with standard interfaces, to which subsystems like avionics and propulsion can be attached
- Sectional modularity comprises a collection of components that can be configured in arbitrary ways, as long as they are connected at standard interfaces. Lego building blocks are the quintessential example of this type of modularity (Pine, 1993; Karl T. Ulrich & Eppinger, 2004).

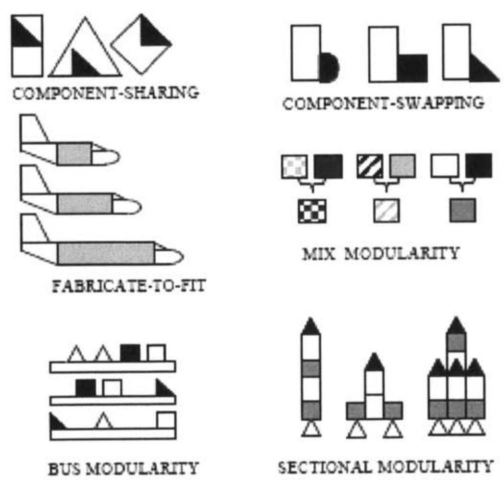


Figure 1 - Six types of Modularity (Nuffort, 2001)

The type of modularity that is the focus of replacing legacy components with new components is the Component-Swapping modularity. When a component is swapped from a parent system by removing it and replacing it with a new child, a component has been swapped. This is a model for upgrading complex systems that are characterized more by modularity than integrality.

In addition to the six types of modularity, there are six operands in modular systems that can be classified by how they are employed. The six operands are Splitting: breaking a system into two or more modules; Substituting: replacing a module with another module; Augmenting: adding a new module; Excluding: removing a module from a system; Inverting: making previously hidden information visible to the system; Porting: allowing a hidden module to function in more than one system(Baldwin & Clark, 2000).

Risks of modularity. The use of modularity is not without risks. While highly modular designs can speed product development processes, over-use of modularity may reduce the effectiveness of innovation processes and thwart development breakthroughs. In addition, modularity increases predictability and the chance that a competitor will develop similar products (Fleming & Sorenson, 2001).

A firm may use a modularity strategy and parse out for production modules that are not in their core competencies. This outsourcing allows the organization to focus on its area of competitive advantage (Venkatesan, 1992). This strategy failed with IBM and the development of the personal computer. IBM chose Intel and Microsoft to supply processors and operating systems for the PC. Customers soon became more interested in the Intel and Microsoft modules and began buying the hardware from any company that would assemble the components (Fine, 2000).

Modularity metrics. The purposes of measuring modularity include characterizing systems, benchmarking, and estimating costs of product families. While studies have been performed to gain insight into how systems are chunked into modules, humans have not been able to develop a process to decompose a system into modules that is repeatable across several groups of people (Guo & Gershenson, 2003). More success has been realized measuring modularity through a number of metrics. While several measures for modularity exist, the application of the metrics is nascent. The focus of the metrics is to quantify the degree of modularity for systems and subsystems.

Three types of system analysis are useful for modularity measures within a system: methods to find modules in existing architectures, a heuristic to determine the right number of modules in a system, and measurements of the modules and systems.

A simple type of modularity metric is ratios that can be determined by counting attributes of cells in a DSM. While the DSM is not required to use these metrics, the structure allows an organized way to manage the cells and interactions, and then formats the data in ways that allow easy porting into tools such as MatLab® or Excel®.

Table 1 – Methods of measuring modularity, the metric, and the purpose of the metric

Measuring Modularity			
Method	**Metric**	**Why?**	**Author**
Non-Zero Fraction	Count of non-zero elements in a matrix divided by the number of non-diagonal cells in the matrix	Returns density of a matrix	(Hölttä-Otto & de Weck, 2006)
Singular Value Modularity Index	$SMI = \frac{1}{N} \underset{\alpha}{\operatorname{argmin}} \sum_{i=1}^{N} \left\| \frac{\sigma_i}{\sigma_1} - e^{-[i-1]/\alpha} \right\|$	Integral systems have a faster connection decay rate than modular systems. Higher numbers of connections reveal more information about the system.	(Hölttä-Otto & de Weck, 2006)
Modularity Metric	#Modules/#Functions	Reports ratio of modules to functions that are used to perform the system functions	(Mattson, 2001)
Interface Reuse Metric	1-(#Interface types/#Interfaces)	Returns value that relates how often interface types are reused	(Mattson, 2001)
Vector Modularity Measure	VMM = [V, X, Y, Z] where: V = Degree of coupling X = Reusability Y = Reconfigurability Z = Extensibility	Several reasons exist for measuring modularity; this method captures measurements for four of the common modularity purposes and avoids loss of information in aggregate measures	(Oyama, et al., 2010)

The modularity metrics presented here focus on the analysis of a system. Other metrics focus on the modularity and commonality of chunks across a product line. The application of analysis across a product line would be applicable after extending the data set for this study to include more than one system. Overall, the use of modularity metrics is a nascent activity in the analysis of system architectures. While it is mathematically possible and oftentimes trivial to develop and calculate modularity metrics, the application of the metric lags in finding its usefulness. The Vector Modularity Measure (VMM) has recognized that measures of modularity can be used for different reasons (Oyama, et al., 2010). For example, the VMM could be used to focus on the reusability of a product based on one of its vectors. Design strategies that favor high degrees of coupling or system reconfigurability can be serviced by the VMM. Until large numbers of systems are evaluated by a common modularity metric, the "one size fits all" aspects of many of the measures will be of limited value.

Non-Zero Fraction (NZF): The Non-Zero Fraction measures the density of a matrix representing the interfaces between system elements. This metric helps characterize systems by the interface density (Hölttä-Otto & de Weck, 2006).

Singular Value Modularity Index (SMI): The Singular Value Modularity Index has been applied to systems and has determined that systems with characteristics of higher integrality have higher decay rates in this value(Hölttä-Otto & de Weck, 2006).

Modularity Metric (MM): The Modularity Metric reports the ratios of modules to functions found in a system (Mattson, 2001). This ratio is easy enough to find, but it has little value to system designers, other than knowing the module-to-function ratio.

Interface Reuse Metric: The Interface Reuse Metric reports how often a system interface is reused within an architectural boundary (Mattson, 2001).

Vector Modularity Measure: A method to assess product modularity using a vector approach. Modularity has several fundamental benefits agreed upon by industry, including reusability, flexibility, reconfigurability and extensibility. Current modularity measures focus on interfaces within or between modules in provide/depend relationships. This new method assesses module interfaces and captures and addresses each of the recognized modularity benefits in a four-dimensional vector format. Components of the modularity measure include terms for degree of coupling, reusability, and flexibility. Flexibility is assessed in terms of reconfigurability and extensibility (Stryker, 2010).

Compatibility

When determining if a proposed subsystem is a feasible replacement for another subsystem in a larger system, the decision is partially based on the technical aspects of compatibility between the systems. Compatibility is the capability of being used with or connected to other devices or components without modification.

Compatibility can be experienced through many consumer goods. Products that are usually systems which cannot be used individually, but are often purchased separately, are examples. One typical product includes cameras where a camera body, lens(es), flash memory cards, and processing are all required, but may be acquired from varied companies. Another example product is computer systems—the processor, storage systems, displays, and software are acquired individually, but cannot be used individually. In either of these examples of the camera or computer system, the compatibility between components in the systems allows the consumer an increased range of choices. If compatibility is assured, a consumer can choose components from separate sources. If compatibility does not exist, consumers would be able to buy a system from only a single supplier (Matutes & Regibeau, 1988).

While the Department of Defense has numerous published standards and handbooks that inform practitioners of the need to ensure compatibility, no standard definition of "compatibility" or "compatible" emerges. The best definition can be distilled from definition "c" in the entry for "standardization" in Joint Publication 1-02, Department of Defense Dictionary of Military and Associated Terms.

> **standardization** — The process by which the Department of Defense achieves the closest practicable cooperation among the Services and Department of Defense agencies for the most efficient use of research, development, and production resources, and agrees to adopt on the broadest possible basis the use of: a. common or compatible operational, administrative, and logistic procedures; b. common or compatible technical procedures and criteria; c. common, compatible, or interchangeable supplies, components, weapons, or equipment; and d. common or compatible tactical doctrine with corresponding organizational compatibility. (JP 1-02, 2012)

This definition is supported by "designed to work with another device or system without modification; *especially*: being a computer designed to operate in the same manner and use the same software as another computer" (http://www.merriam-webster.com. Retrieved Aug 12, 2012).

In this definition of standardization, compatible appears to mean the binary case of 100% compatibility or not compatible (0% compatibility). However, in practice, adjustments can be made to systems, and resulting capabilities can be adjusted to resolve incompatibility concerns. This continuum of compatibility drove the exploration for future work to better understand the continuum. The thesis presents a four-category continuum for incompatibility with the proposed category ranges: {severe, major, minor, none}. While this concept has been presented as an extension to CAM, continued research is necessary to understand the applications and calibrate the ranges with workable definitions.

Commonality

Commonality is a measure of how similar one system or subsystem is to another. Identical systems would be 100% common and completely different systems would be 0% common. A range of commonality has been developed, as have several commonality measures with varying degrees of usefulness. Commonality may be applied to function or physical aspects of a system. Many indices have been proposed to measure the degree of commonality within a product family by analyzing a combination of parameters. The indices are often used as surrogates to estimate manufacturing cost savings within a product family (Thevenot & Simpson, 2006).

Commonality Metrics. Literature has identified three areas of commonality: unique, cousins, and common (Boas, 2008). A description of each of these areas follows and is then extended to include commodity at one terminus in the continuum of commonality.

Uniqueness. Physical uniqueness occurs when two or more systems, subsystems, components, or elements are not at all similar to each other. Functionality can be unique when decomposed functions do not contain the same subfunctions.

Cousinality. Cousinality is the middle ground between common and unique and occurs when a subsystem is similar but not exactly the same as another subsystem. Cousin components can be very close to 100% common or very close to 0% common. One source of cousins is a part or subsystem that gets modified to allow it to be used in a slightly different than intended application (Boas, 2008).

Common. A common item may be designed and developed for an industry, a company, product line, or alternatively be available as a standard item.

Table 2 - Descriptions and examples for the continuum of commonality

If functions are common and systems	Then systems are	Examples
Are completely different	Unique	Function: transport goods Systems: Truck Aircraft
Share characteristics	Cousin	Function: Gain air superiority Systems: Joint Strike Fighter – Navy Joint Strike Fighter – Air Force
Can be interchanged	Common	Function: provide traction Systems: Bridgestone P175/70R15 Goodyear P175/70R15

Much literature has been written about the benefits of commonality. Common parts yield higher quantities for production, decreased investments in product development, economies of scale for logistics concerns, investments in quality, performance, and manufacturing processes, and more. In addition to the economic benefits of scale that result from commonality, a byproduct of commonality is interoperability (Ford, 2008).

Within the Department of Defense, commonality has been directed to establish a business case for developing a revolutionary capability. One example of directed commonality is the Joint Tactical Radio System, or JTRS (pronounced "jitters"). The direction by the Office of the Secretary of Defense (OSD) executed this tactic to further the development of the Joint Tactical Radio System (JTRS). The purpose of JTRS was to "Develop and produce a family of interoperable, affordable software-defined radios at moderate risk which provide secure, wireless networking communications capabilities for joint forces." The transformational efforts of DoD's architecture depend on the information infrastructure called the Global Information Grid (GIG). Without a capability like JTRS, the GIG's transformational networking would halt at the command center level, unable to extend to the actual mobile warfighters. JTRS is critical to serving as the last tactical mile, connecting the warfighter on the ground to the networking capabilities that are delivered through the GIG. Under the newly revised requirements, budget, and schedule established for the program, JTRS will provide the mobile, ad hoc networking capability that is essential to realizing DoD's transformational goals. The JTRS program is an example of a socio-political impetus behind the case for commonality instead of the availability of improved technology leading the drive.

System Architecture Modeling

There are many types of system architecture representations. The different representations have different purposes and several may be used to communicate the architecture to different stakeholders. The simplest representation is a hierarchical tree at the function or component level. This view decomposes the system into subsystems so the architecture can be visualized at several levels of abstraction (Hölttä-Otto, 2005). Functional structures show block diagrams of a product's functions and may include material, energy and information flows between the functional blocks (Pahl & Beitz, 2007). A schematic view can show physical relationships and interfaces (Martin & Ishii, 2002). The Integration Definition for Function Modeling (IDEF0)representation was originally for modeling processes, with functions being blocks that showed input, output, control and mechanism interactions (Mayer, 1992). The Design Structure Matrix (DSM) can be used for function or component architectures, and was originally developed for modeling organizations. The matrix has rows and columns that show the connections between the two (Steward, 1981). Object Process Methodology (OPM) represents objects and processes simultaneously and can be used for simulations (Dori, 2002). Unified Modeling Language (UML) was developed for software design and has been applied to non-software systems and has been applied to physical systems, too. UML's genesis was combining components of many architectural tools

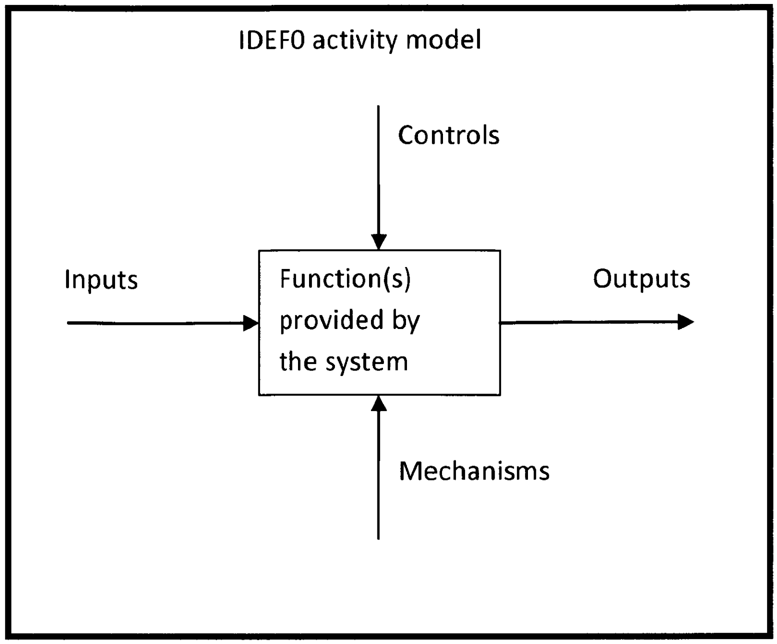


Figure 2 - IDEF0 Box and Arrow Graphics

and developing a standard language for documentation. UML is a complex, object-oriented architectural tool that uses use-cases for analysis and documentation (Maier & Rechtin, 2000). These representations allow architecture users to view architectures in many different architectural lenses. Each view has its importance, strengths, weaknesses and purposes. However, none of these models allows practitioners to resolve architectural issues relating to component replacement that may be required to upgrade a system.

Integration Definition for Functional Modeling

Integration Definition for Function Modeling, also known as IDEF0, is a function modeling method that is used in the fields of systems and software engineering. IDEF0 uses activities as the central building block of the model. The activity block is characterized by constituents that are depicted as arrows connecting to each side of the activity block. The four basic constituents are Inputs, Controls, Outputs and Mechanisms. These constituents are often abbreviated as "ICOMs."

The Federal Information Processing Standards (FIPS) Publication 183 outlines the standard for the IDEF0 modeling language. The objective is to baseline a standard that can be used consistently to model the functions of a system or enterprise. The IDEF0 language supports models which are applicable to a varied range of systems; provide rigor and precision; allow understanding through characteristics of being concise; focus on the functional, or conceptual, requirements instead of the physical or organizational constructs; and are sufficiently flexible to support systems through multiple phases of lifecycles (National Institute of Standards and Technology, 1993). For a full explanation of the IDEF0 model, please refer to FIPS 183.

Summary

The system architecting community has written extensively about the qualitative aspects of systems architecting. While no unified taxonomy has been adopted to describe systems, the language is translated from each author's viewpoints and terminology relatively easily. The literature does agree that function should precede form when developing an architecture. Starting with function perspective helps ensure that a physical solution is not selected prematurely or prior to understanding the functional requirements of the architecture.

A wide variety of metrics have been developed to measure system architectures. These metrics provide insight into systems. While many authors provide varied perspectives and used for system architecting, compatibility issues are not widely addressed in the architecture literature. For example, a system's modularity can be measured by counting modules, calculating ratios between modules and interfaces, and coupling. These provide characterization for systems, and as more systems are measured, improved insights to the meanings of these measurements are sure to follow. These insights may be important to researchers, however, practitioners who manipulate modules to replace subsystems gain little benefit from the architecture metrics currently available.

Chapter 3 – Exploratory research to determine the need and process for compatibility assessment

Determining the need

The original need for a structured, lightweight tool to screen for subsystem compatibility was encountered by the author while managing a countermeasure dispenser system (CMDS) upgrade on the F-16 aircraft (Appendix B, Case 4). The F-16 Air Force project manager received regular updates on the configuration of the CMDS as it was being developed. The updates were in form of interface control documents (ICDs) that were submitted as 100 to 200-page text documents. The government engineers and project manager reviewed the ICDs regularly, but did not discover the uncoordinated configuration change submitted by the CMDS developer. The seemingly small change, adding a single wire to an existing wire bundle from one component of the CMDS to another, drove the modification from a remove and replace in the field to a process that required an aircraft depot team to remove the F-16's engine, add the wire to an existing bundle, and change the military standard plugs on both ends of the cable run. The scope of the added work changed the maintenance action from a field operation to a depot modification. The Air Force aircraft project management team was at a disadvantage because of the difficulty in discovering the CMDS change and then determining the impact of the incompatible configuration change. A structured method for the project manager and engineer could have revealed the impacts and opened discussions with all stakeholders regarding the implications of the change.

Other incidents of incompatibility in upgrades of complex systems existing throughout the Air Force acquisition community reinforce the need for structured processes to screen for compatibility. The Joint Tactical Radio System (JTRS) Handheld, Manpack, and Small Form Fit (HMS) is developing a software-defined radio that includes a man-portable operational configuration. The previous manpack radio was 13 pounds and the requirements were set for the JTRS version to weigh only 9 pounds. The JTRS HMS failed its limited-user testing because of size, weight, and battery issues. The users had less mobility and had to carry more weight than previous radios. Because the interfaces with the human operator were not analyzed effectively, the radio managers allowed changes to the form-factor without understanding the human-machine compatibility impacts. By February 2011, the radio had been redesigned to meet its form-factor, size, weight, and power specifications (Sullivan 2011).

The Global Hawk RQ-4B was developed as an unmanned air vehicle that included upgrades to the original RQ-4A design. The RQ-4B version has three configurations to supply various sensor capabilities. The RQ-4B was expected to have substantial commonality with the RQ-4A variant. However, as the RQ-4B designs were completed and production ramped up, differences were much greater than anticipated. While the basic airframe design was stable, risk remained from late design changes to the sensor payloads (Sullivan 2011). These configuration changes could be monitored through a structured method that would allow insight into the extent of deltas required and where changes could be made with the least impact to the program.

Another upgrade program that was plagued with cost increases and schedule delays caused in part by incompatibilities was the Cheyenne Mountain Upgrade (CMU) program. Five separate subsystem acquisitions were begun. The complexities of managing the CMU program were realized and at the 6-year point, the schedule was delayed by 7 years and 40% over budget. Some of this was attributed to distributed management and was remedied by consolidating the management into a single program. During the testing of one of the warning systems, significant incompatibilities were discovered across CMU components. While the modules performed as expected individually, the interfaces between modules were incompatible. One example of an incompatibility was a data transmission that one module needed at a 30 frames per second rate. However, the processor in another module was able to process data at only 3 frames per second. This caused data to be delayed at an unacceptable rate or a loss of data (Attack Warning 1994). A structured tool to track interface characteristics may have averted data incompatibilities to be propagated across modules.

The US Air Force is not the only organization that has had these incompatibility problems. In 2005, an Israeli company won a $190 million contract for Turkey to purchase 10 Heron unmanned aircraft systems. The aircraft were scheduled to be delivered in 2007, but incompatibilities between Turkish-produced and Israeli-produced parts resulted in system performance test failures until February 2010. Because of the delays caused by the incompatibilities, Turkey received $18 million in price reductions. These incompatibilities may have been discovered earlier if the proposed components were systematically analyzed for deltas between the Israeli and Turkish systems.

Interviews with Air Force program office personnel and engineers and designers in industry revealed that both industry and the Air Force have needs for upgrading subsystems. The methods used for determining the compatibility of a proposed replacement system varied, but no one used a structured method to perform their analysis. Ad hoc methods were found when organizations performed the analysis internally. Additionally, the Air Force relied heavily on contracted studies. From these and other example cases, a need for a structured, lightweight screening tool to perform compatibility assessment emerged.

Exploring an existing model for a method

The IDEF0 functional activity model was the foundation for developing a method to assess compatibility between systems. The center block of the IDEF0 diagram represents the functions the system or subsystem of interest performs. The constituent arrows define the parameters that define the characteristics of the employed system. Originally, the basic constituent arrows were used to characterize the system, but the method revealed the need for more depth into the characteristics. This depth was accomplished by extending the basic IDEF0 to include the framework of parameters and metrics to each of the constituent arrows. For a full treatment of IDEF0, please refer to FIPS 183.

IDEF0 was used as a baseline for the model to assess upgrades for several reasons. First, IDEF0's foundations are in the functional domain. Analysts who remain in the functional domain as long as possible develop results with better understanding of the problem and the solution spaces. Second, the IDEF0 representation decomposes the functions into constraints that describe the system limitations. Finally, the IDEF0 is a simple construct with low overhead but still allows thorough analysis during elemental system reviews.

Having chosen the IDEF0 model as a candidate for describing systems, a series of potential research participants and associated systems was identified. Organizations were chosen on the basis of their need to assess compatibility. The associated systems had to be appropriately complex to ensure that the analysis was neither trivial nor too complex. Poor choices could have reduced access to programs and taken too long to perform to be able to improve the process several times during its development. The participants were sampled because they all were working to resolve their problems associated with how to replace a subsystem within a larger, complex system. After each engagement with a research participant the learning from the encounter was applied to an independent toy problem to test the recommended process changes. This method development included three research participant engagements. The inductive study began with a commercial lift truck manufacturer that was frustrated with their attempts of upgrading their systems with integrated control systems instead of the individual controls that are traditionally used in lift truck design. After the lift truck case study, a simpler problem that could be used for an easily understandable sample was created using a mouse and joystick on a personal computer. The next research engagement was with the B-52 program office engineers who were determining the feasibility of upgrading the aircraft with the Joint Precision Autonomous

Landing System (JPALS). After the B-52 case study, the research returned to a desktop study based on the historical event of integrating an upgraded countermeasure dispenser system (CMDS) onto the F-16 fighter. The researcher was the project manager for the CMDS upgrade and engaged with the corporate engineers and the program office engineers to ensure accuracy of the events. The final case study was revisiting the lift truck problem with the improved method to perform the study. After this case, the method was considered mature enough to continue with practitioner testing.

Developmental cases (three exploratory cases with practitioners and two example cases)

This section summarizes the case studies used to develop the Compatibility Assessment Method. The complete cases can be found in Appendix B – The developmental case studies that defined CAM. The following exploratory cases were performed in conjunction with practitioners who had a need to assess compatibility of a proposed replacement in a larger product. Between exploratory engagements with the research participants, the researcher developed additional cases to serve as examples and incorporate lessons learned from the exploratory cases. During the execution of these cases, the Compatibility Assessment Method (CAM) matured from a process that focused on IDEF0 modeling to its more mature state. Appendix E shows the development of CAM and includes a table of the significant improvements to the method that resulted from each case study.

Summary of Case 1: Lift Truck I (alpha test)

This is a summary of the full case study that can be found in Appendix B. This case was an attempt to use the IDEF0 function activity model to determine if an integrated control system could replace the current lift truck control system. This case presented the current and proposed lift truck models with respect to the Inputs, Controls, Outputs, and Mechanisms (ICOM) arrows of IDEF0. The models were drawn as a function and the arrows represented the ICOMs. The ICOM data current and proposed subsystems were transcribed into a table where the systems could be directly compared for deltas between the systems. The resulting Delta Matrix, the Proposed System Matrix minus the Current System Matrix, revealed categorical differences based on the IDEF0 arrow properties in the systems. Another application of the concept of a delta matrix is the System Overlap Matrix (SOM). The SOM was developed to analyze systems for commonality to determine opportunities for developing product platforms (Hoftstetter, 2010). Table 3 - Prior Delta Matrix References presents a summary comparison of the Delta DSM, the SOM, and the Delta ICOM Matrix.

Table 3 - Prior Delta Matrix References

Delta Matrix Construct	Application	Author
Delta DSM	Describing the changes between an original system and a changed system based on infused technology. The Delta DSM then allows a cost estimate to be calculated.	Suh, de Weck, et al., 2009
System Overlap Matrix	Analyze systems to discover opportunities for increasing commonality and developing product platforms from the findings.	Hoftstetter, 2010
Delta ICOM Matrix	Identify the differences between proposed and baseline systems' inputs, outputs, constraints and mechanisms to highlight the scope of the integration effort the change will require.	Long ,2010

Several changes resulted from the first case study. First, the process of identifying the functions was formalized by documenting proposed and baseline system functions in a matrix that could be used to show the functional deltas between the systems. Second, to get quantitative comparisons of the systems, the ICOMs were expanded to include parameters that included a metric and a numerical value for calculations. Third, to make the matrix calculations easier for the research participant, a standardized matrix was developed to help eliminate miscalculations. Fourth, the level of abstraction of the analysis was determined to be important and care was required to ensure the abstraction level did not get changed during the process.

The research participant expressed that he perceived value in this structured method to determine the feasibility of a system upgrade.

Summary of Case 2: Mouse and Joystick Computer Input Devices

This is a summary of the full case study that can be found in Appendix B – The developmental case studies that defined CAM. The mouse and joystick computer input device case study was performed by the researcher to exercise the findings and recommendations from Case 1 and provide future research participants with a simple example that could be understood by practitioners without deep domain knowledge.

The mouse and joystick case study identified the functions of replacing a mouse device with an integrated joystick pointer as found on some laptop computers. The functions of the proposed and baseline subsystems were entered into the function Table matrix and the Deltas between the proposed and current functionalities were compared. Next, the ICOM Matrices were developed for the baseline two-button mouse and the proposed joystick pointer. From these matrices, the Delta Matrix was calculated with categorical and metric parameters that were compared qualitatively and value comparisons that were made quantitatively.

This case study revealed the importance of standardized forms and formats. These forms allowed moving the forms to align them to make the mathematical operations easier to manage. This case study did not have level of abstraction problems. The abstraction level was appropriate from its initial selection.

Summary of Case 3: Upgrading the B-52 with JPALS

This is a summary of the full case study that can be found in Appendix B – The developmental case studies that defined CAM. This case addressed the needs of an Air Force program office that was planning for an upgrade of the B-52 aircraft. The program office needed to learn about how the Precision Autonomous Landing System (JPALS) capability could be incorporated into the legacy aircraft. The project required keeping the current system capabilities and adding the JPALS functionality to the navigation suite. This would require adding some equipment and possibly removing equipment from the aircraft.

The case was executed by first presenting the program office an overview of system architectures and the mouse/joystick case study. A team of four people from the program office then engaged on the JPALS project with facilitation by the research leader. The team developed a functional decomposition of the B-52 with focus on the functions relating to the navigations systems that would be performed by the JPALS systems. The method performed is presented fully in Appendix B. The method included constructing the Function Table to compare the proposed and baseline system functionalities. The functions showed the proposed JPALS system performed all the functions the baseline system performed and added functionality. This was identified to be the intent of the JPALS upgrade and therefore the analysis continued. The continued analysis began by developing the modified IDEF0 models for controlling terminal guidance and zooming in to analyze the control systems. The original level of abstraction, at the level of terminal guidance for the B-52, was deemed too complex for the team. After attempting to address the entire terminal guidance problem, the team noticed that the navigation control systems addressed all the functionality and would be a tractable problem.

After the IDEF0 models were constructed, the data from the models were used to populate the system matrices. The system matrices were then compared to produce the Delta Matrix that allowed direct comparisons of the systems in a sparse matrix format. The resulting sparse Delta Matrix identified the integration challenges associated with changing the control systems from the current systems into the proposed JPALS configuration.

The method was embraced by the program office personnel who had the responsibility for determining the feasibility and a potential way ahead for upgrading the B-52 with the JPALS functionality. Some key findings that the method revealed included highlighting the integration issues of implementing the new system. They reported that they are too busy to fully understand the B-52 systems and they rely heavily on contractors to provide technical advice to propose the way ahead. This process could be seen as a structured method to allow government insight and decision making without relying on outside assistance. This process, while requiring additional development and standardization, could be seen as a helpful tool to help understand technical risk areas.

Summary of Case 4: Installing the ALE-47 on the F-16

This is a summary of the full case study that can be found in Appendix B – The developmental case studies that defined CAM. This case study reviewed the actions that were taken during a countermeasure dispenser system (CMDS) upgrade that was performed on the F-16 aircraft. This case study was built on collaboration among the Air Force F-16 program manager for CMDS integration, the Air Force program manager for the ALE-47, and the F-16's prime contractor engineer for electronic warfare.

The F-16 was originally fitted with the ALE-40 CMDS and was upgraded with the ALE-47, a form-fit-improved-function (FFIF) system. The upgraded system provided automatic dispense routines to deploy chaff and flares in a more effective and economic algorithm to counter missile threats. This case study uses the tools developed for this structured method in an inductive application.

This case began with construction of a function table to document the functions that the baseline system and the proposed systems would perform. After the Function Table was constructed and the functional deltas were identified, the modified IDEF0 function models were developed for the baseline and the proposed systems. These baseline and proposed IDEF0 models were translated into the baseline and proposed system matrices. The baseline and proposed system matrices were compared and the differences were entered into the Delta Matrix. The Delta Matrix identified the integration challenges for the ALE-47 retrofit project. The Delta Matrix was able to identify integration challenges that the program office did not discover until the installation schedule was impacted. The late identification of the integration problems precluded the ALE-47 from being incorporated on the F-16 production line.

The performance of this case study refined the instruction set and improved forms to collect, document, and report the results.

Summary of Case 5: Lift Truck II

This is a summary of the full case study that can be found in Appendix B – The developmental case studies that defined CAM. This case study revisited the problem of the lift truck in light of the new understanding of the importance of levels of abstraction, the new processes, the development of the parameters and metrics of the systems in the modified IDEF0 model, and the forms for collecting data. This case study engaged the original participant and incorporated several of his suggestions to mature the process.

This case study started by performing a functional decomposition on the lift truck control system. Function tables were built to compare the functionality between the baseline, uncoupled control systems and the proposed integrated control systems. The modified IDEF0 models were developed and the arrows and associated parameters and metrics were documented and entered into the baseline and proposed system matrices. With the baseline and proposed system matrices populated, the Delta Matrix was calculated. The Delta Matrix was usable at the selected level of abstraction. In addition to the areas of integration challenges that the Delta Matrix revealed, the Delta Matrix also revealed mode changes that needed to be considered for the operator of a lift truck with an integrated control system to operate the system effectively and safely.

Development history of the Compatibility Assessment Method

As the Compatibility Assessment Method evolved from its earliest instantiations, changes were made in the data collection processes and the characterizations of the integration challenges that emerged in the Delta Matrix populating.

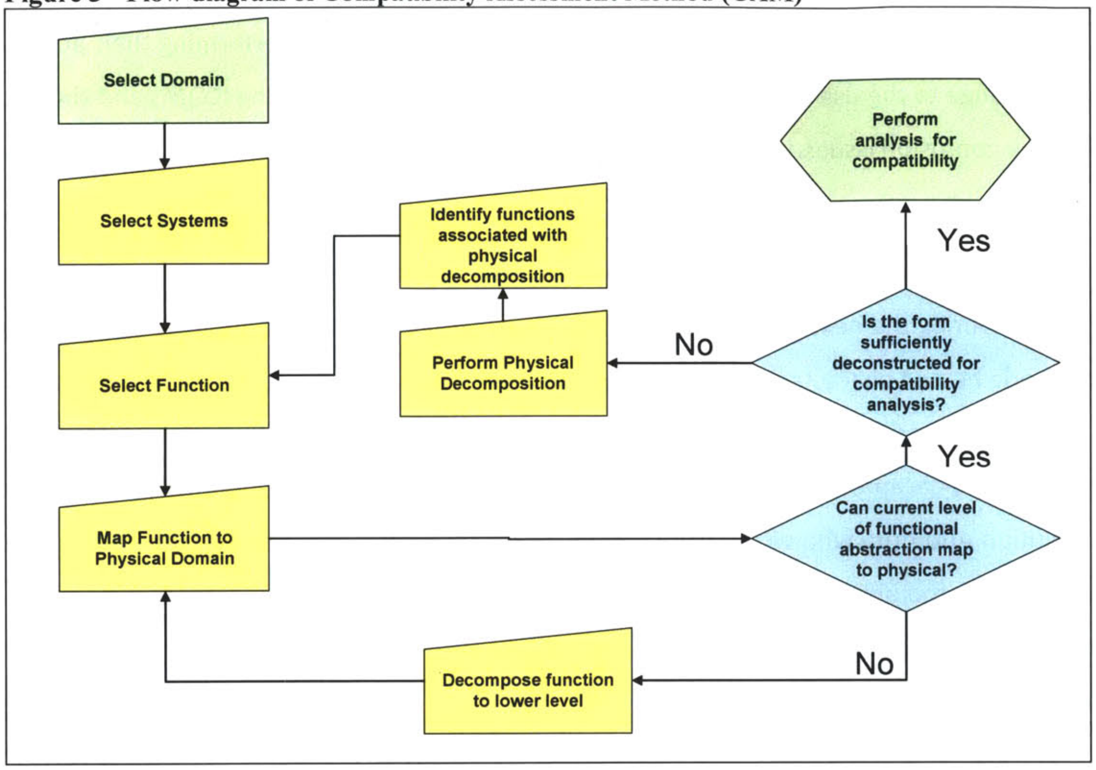
The initial compatibility assessment method was qualitative and used the constituent arrows from the IDEF0 methodology to assess the differences between a baseline and a proposed replacement system. The IDEF0 terminology became confusing to the practitioners because they confused the constituent term "Control" with the control system on which they were performing their analysis. This drove the change to the use of the term Constraint instead of Control for the ICOMs and this change resolved the confusion issues.

During the early exploratory studies, the need for parameters was identified. After the parameters were identified, they were decomposed into metrics and an associated value for each constituent. During the next case study, a desire for a Severity Code emerged. This project-manager supplied code helped characterize the extent of the differences discovered in the Delta Matrix. After the severity code was implemented, one program office wanted to know who could resolve the differences. This became a new entry column on the Delta Matrix, the Resolution Authority. Along with the Resolution Authority who would have the ability to change the requirements if a delta element was considered to be too high, the research participant wanted to collect the stakeholders who would be impacted by the decision to make a change. This would help include stakeholders when recommendations were made.

The last change was a program office recommendation for adding a cost estimate block to the Delta matrix. This block would trigger a cost estimate analysis for the changes between the subsystems and their impact on the larger system. This extension is considered beyond the scope of developing a method to evaluate compatibility.

The Compatibility Assessment Method

Figure 3 - Flow diagram of Compatibility Assessment Method (CAM)



Compatibility Assessment Method (CAM) Processes and Tools

The matured Compatibility Assessment Method (CAM) that resulted from the previous developmental case studies is presented here. Each of the improvements for change that was identified for adoption with the research participants is included in this method description. This procedure became the baseline method for the following cases performed in program offices by practitioners and by a systems engineering graduate student cohort. The process overview is depicted in Figure 3.

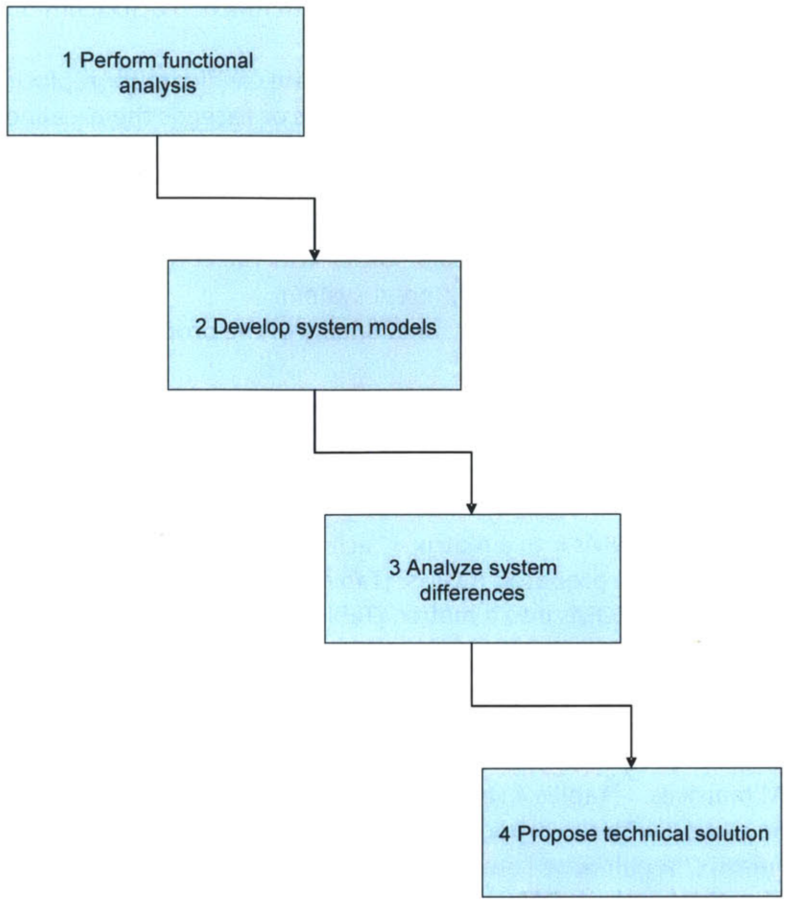


Figure 4 – Block diagram for CAM process at high level of abstraction

A more detailed text description of the method is presented here. Following this description, templates for the data collection and analysis are presented. These became the baseline tools to execute the method.

1. Perform functional decomposition. Decompose each subsystem to the basic functions needed to perform its requirements and the functions that provide additional value to the entire system.
2. Document functions of the baseline (current) system. Determine the key functions of the baseline system that must be met or exceeded by any proposed system to merit consideration for possible replacement. [Enter these functions into the Function Table, Column (2).]
3. Document functions of the proposed system. Determine the key functions of the proposed system along with any significant new functions that may be beneficial. [Enter these functions into the Function Table, Column (1).]
4. Compare baseline system functions with the proposed system functions. Find and document the differences between the baseline and proposed system functions. The basic functions of each system are entered into the function table and directly compared to one another by

subtracting the baseline functions from the challenger system functions. [Document the Deltas between the functions in the Function Table, Column (3).]

5. Determine if the proposed system functionality is an adequate candidate for replacing the baseline system. If the proposed system functionality meets or exceeds the baseline functionality and functional requirements, then the proposed system is functionally acceptable as a replacement. Functional acceptability is documented when either no deltas are found or the deltas contain functionality above the baseline. If the proposed system has equal or more functionality than the baseline, continue to Step 6. Otherwise, reject the proposed system and remain with the current system or propose a different system.
    a. If the user of the system accepts lesser functionality of the proposed subsystem, the lesser functionality may be accepted.
6. Develop activity models for baseline and proposed systems. Use the ICOM model to determine the Inputs, Constraints, Outputs, and Mechanisms (ICOM) for each system. The ICOMs are entered into a matrix with an associated metric and value to allow for a direct comparison of baseline and challenger ICOMs.
    a. Enter baseline system ICOMs into a matrix – Each ICOM will have an associated metric and value to compare the proposed ICOMs. [Table 4 (baseline)]
    b. Enter proposed system ICOMs into a matrix. [Table 4 (proposed)]
7. Determine the parameters (metric and value) for each system: The metric could be a unit such as pounds or inches with a number as the value or could be a yes/no question. "Does the system have this?" The metric would then be 1/0 (1 for yes, 0 for no) and the value either 1 or 0. The two systems can now be compared in a delta matrix. Enter the metric and value of each system into the ICOM matrices. [Tables 4 (baseline) and 4 (proposed)]
8. Compare the baseline system with the proposed system matrices: The two systems can now be compared in a delta matrix. A pair-wise comparison of the ICOMs can now be used to analyze commonalities or differences in the ICOMs and/or their values by subtracting the baseline ICOMs from the proposed ICOMs to create a delta ICOM matrix. Similar to the original functional comparison, the baseline system is subtracted from the challenger system. The baseline ICOMs are subtracted from the challenger ICOMs and a delta matrix is created leaving the differences between the two to be analyzed for significance. The difference will be negative if only the baseline system contains the ICOM or if it has a higher value. The difference will be positive if only the challenger system contains the ICOM or if it has a higher value. [Enter cell

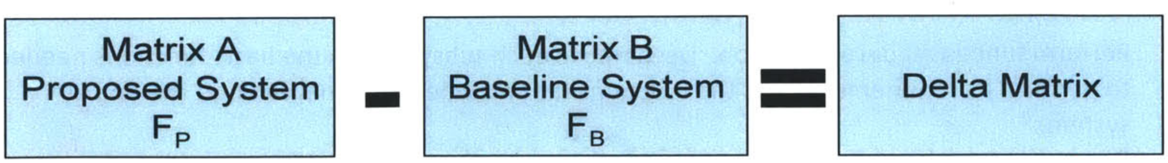


Figure 5– Block diagram of calculating Delta Matrix for CAM process

differences in Table 5.]

9. Evaluate deltas:

Find any differences and determine consequence, if any, of the deltas. If a delta is found the first step is to determine the significance of the baseline and proposed differences. Next, determine who is able to assess the deltas and make a recommendation on the acceptability of the delta.

Based on level of technical analysis needed and the tools available the following order should be used to make the decision:

1. Project/Program Manager (PM)
2. Staff Engineer
3. Prime Contractor or OEM
4. Other stakeholders (user, vendor, etc.)

A column was added on the right side of the delta matrix with a number (1-4) for level of decision needed for each delta found. The first level of decision making should be the PM. If the delta is relatively insignificant or the PM has the right tools, such as system specifications, Operational Requirements Document (ORD) technical data and standards, the PM can make the decision. As the delta becomes more significant or technically challenging, the staff, or program engineer(s) may need to become involved in the decision making process. If the deltas go beyond the scope of the staff engineers, then the prime contractor or OEM may need to get involved. Perhaps both systems meet the requirements, but provide different benefits or complications. In this case, the user may need to be consulted to determine what is best for them. [Enter Level of Decision in Table 5.]

10. Recommendation: Based on evaluation of deltas, determine if the proposed system is a viable candidate to replace the baseline system. After determining that the proposed system is functionally and technically a viable replacement, then ask the delta questions at the appropriated level (program manager, engineer, or prime contractor) and move on to the next step of acquiring a replacement system, or keeping the baseline as is.
11. OPTIONAL: Characterizations of Deltas [Table 6]: To better understand the characterizations of the deltas, an addition table was created to document the identified ICOMs, the Level of Decision, Severity Code, Resolution Authority, and a Cost Estimate of addressing the deltas. The cost estimation implementation was determined to be beyond the scope of this study and is left for the practitioner to implement using local costing procedures.

Sample Matrices

Table 4 – Sample function table for comparing functionality between proposed system and the baseline system

Function Table (SAMPLE)		
(1) Functions of Proposed System (F_P)	(2) Functions of Baseline System (F_B)	(3) Deltas between Systems ($F_P - F_B$)

Table 5 – Sample ICOM Matrix to capture the parameters for the baseline (or proposed) systems

Baseline or Proposed System ICOM Matrix (SAMPLE)											
Inputs (I)			Constraints (C)			Outputs (O)			Mechanisms (M)		
	Parameter(I)			Parameter (C)			Parameter (O)			Parameter (M)	
Input	Metric	Value	Constraints	Metric	Value	Output	Metric	Value	Mechanism	Metric	Value

Table 6 – Delta ICOM Matrix used to compare the differences between the Proposed and the Baseline ICOM matrices

Delta ICOM Matrix [calculations: Proposed Matrix - Baseline Matrix (SAMPLE)												
Inputs (I)			Constraints (C)			Outputs (O)			Mechanisms (M)			
	Parameter(I)			Parameter (C)			Parameter (O)			Parameter (M)		
Input	Metric	Value	Constraints	Metric	Value	Output	Metric	Value	Mechanism	Metric	Value	level of decision

Table 7 - Extensions to the Delta Matrix for Additional Characterizations

Characterizations of Deltas				
ICOMS	Level of Decision	Severity Code	Resolution Authority	Cost Estimate

Findings

Need for Process

Through interactions with managers who are responsible for making product upgrade decisions, a lack of an effective process to identify compatibility between current and proposed configurations was confirmed. While some organizations stated they had processes to perform upgrades, no documentation was found to show that a process existed. Several participants reported that processes were ad hoc and not formal or structured. One participant was frustrated by the lack of a structured process and expressed frustration with the slow speed and rework that was required when he tried to develop system upgrades. These insights led to developing and refining a structured method to determine if a proposed replacement would be compatible with a current system.

Method

During the exploratory research with potential process, participants explained that current methods they used were complex and required analyzing excessive amounts of data. The participants previously mined technical data on the systems and tried to capture the important interface and compatibility concerns. During the early stages of the exploratory research the participants were reporting insights on the systems that they attributed to the structured process and the resultant sparse matrix that was used to find and report the deltas between the current and proposed systems. Another participant appreciated the structured method because it could be interrupted and resumed at a later time without excessive rework. The promising results of the exploratory studies led to a continuation of the research and further development of the process.

Contributions

These case studies contributed to the knowledge about practitioners using systems architecture methods as a tool to help determine if a proposed candidate system is a feasible replacement for a current system. The program managers were able to use the maturing CAM process to gain insights to compatibility issues relating to system upgrades. When this high-level analysis was performed, deeper analysis and study could be avoided.

Summary

This chapter presented the maturing process that CAM followed through its exploratory interactions with potential practitioners who indicated a need for assessing compatibility when replacing or upgrading a subsystem. The lessons learned from each participant interaction were considered in the development of the CAM. Each iteration included updates to the process that were points of confusion for the participants or improvements to the data management processes. CAM was considered to be mature enough for practitioner use when the research participants were not recommending process changes and the method was remaining stable.

The final iteration of the exploratory process development was documented in this chapter as the Compatibility Assessment Method (CAM) that became the base method for additional studies.

Chapter 4 – Practitioners using CAM

The purpose of CAM is to have an effective screening method for Air Force project managers to determine if a proposed subsystem is a feasible replacement for a current subsystem. Until now, Air Force program managers have relied on slow and expensive contracted studies to perform feasibility analysis or ad hoc unstructured methods that were considered unreliable and non-repeatable.

The Compatibility Assessment Method (CAM) was developed through a series of interactions with potential users as described in the previous chapter. All potential users had a need to replace modules in their systems. No organization had a structured method to perform this type of analysis. All were interested in finding a method to find replacement subsystems for current systems. For the development of CAM, the researcher worked directly with potential users to advance the method. After CAM matured sufficiently for an independent user to employ CAM, a research project was undertaken that allowed project managers to use CAM independently of the developer.

This experiment was developed to test the ability of two project managers to execute CAM on a sample of subsystems. The results of the CAM method were then compared to results from legacy program office methods to determine the value of CAM to an Air Force program office. The value of CAM to the program managers was then documented by the researcher.

The research focus of this chapter is to (1) gain an understanding of the mechanics and metrics of practitioners using CAM and (2) learn about the value of CAM as compared with other methods for assessing the feasibility of using a proposed subsystem to replace a currently used subsystem or component.

Research Design

The research in this chapter, Practitioners Using CAM, was designed with two goals in mind. First, the CAM process was performed by potential practitioners who were representative of the potential future users of CAM. This was performed to learn if Air Force program managers possess the requisite skills to perform the analysis and determine the insights a practitioner could garner from the process. Second, the researcher collected users' experiences. This was done to determine the value created by use of the method. Practitioners' experiences and attitudes about use of previous methods were compared with those about use of CAM. This aspect of the research entailed comparing the value of the findings from CAM to the value of conducting similar studies with other methods.

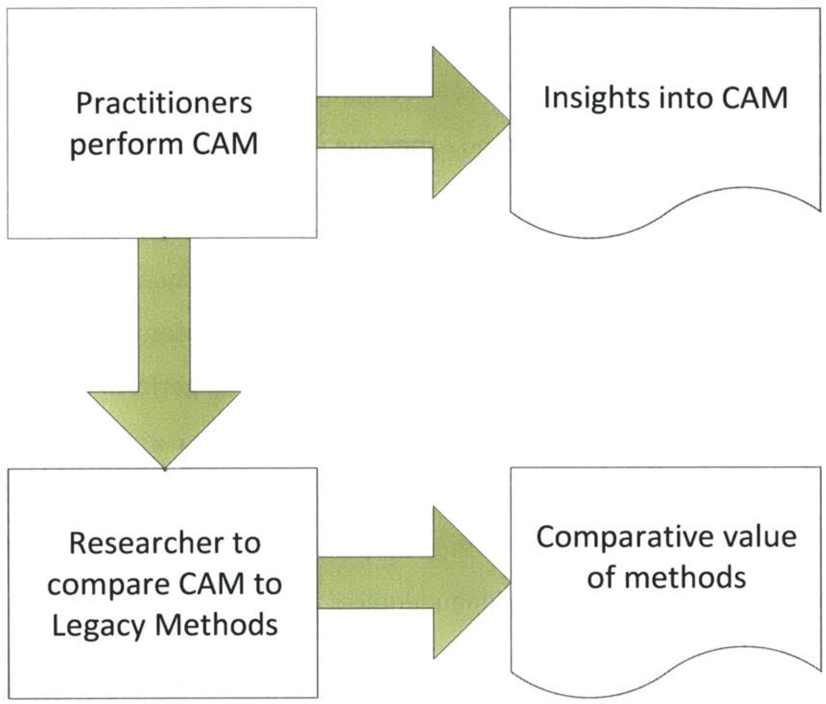


Figure 6 - Research flowchart for comparing CAM to results of Legacy Methods of determining subsystem compatibility

Research Constructs

To gain insight into the value of performing CAM as compared with the previous, unstructured methods of determining compatibility, constructs were developed to compare the users' attitudes and insight between the methods. The rationale for the selection of each of these constructs is explained below. The Research construct table was developed to map the construct to the variables that were to be measured and the method of data collection (Table 8).

Table 8 - Research constructs, the variable measured, and the method used to collect the variable data

Construct	Variable	Method of data collection		
		Interview	Document review	Physical observation
Government insight into the process	Knowledge of process	X		
	Knowledge of motivations of information provider	X		
	Knowledge of assumptions used in the process	X		
Confidence in decision	Repeatability (can process be performed again?)	X	X (if available)	
	Traceability (can the same outcome be expected if the people performed the analysis?)	X	X (if available)	
	Reproducibility (Would a different group of people get the same result?)	X	X (if available)	
Cost of making the decision	Was support contracted (Y/N)	X		
	What was the cost of the support?	X	X (if available)	
	Was travel involved?	X		
Time to make the decision	Man hours	X		X (if practical)
	Elapsed time	X		X (if practical)

Areas of insight from constructs

Government insight into the process

System upgrades are the result of many different variables. One of the variables regards the decision-making process. The government program office has several options in performing trade analyses. First, a government team could be assembled to perform the analysis. Second, an independent contractor could be hired to perform a study and make a recommendation. Third, the program office's prime contractor could be hired to study an upgrade issue and make a recommendation. If the government program office chooses the second or third method, transparency into the process may be lost. The contractor may not fully disclose the processes used to make the recommendations, reveal their motivations, or fully document the assumptions that are used in their processes. This work was conducted to determine if CAM provides the program office improved insight into the decisions being made.

Confidence in decision

When an analysis is performed to make a decision about replacing a subsystem in a program office, the results of the study may be accepted without knowing the process that was used to develop the recommendation. The assumptions that were used to make a recommendation can change results. Confidence in the recommendation can be linked to understanding the assumptions. Confidence in the results can be improved by knowing that the process is documented to allow repeating the process, and by improving traceability so the same outcome could be expected if the same people performed the analysis again. Finally, the research was to inform process reproducibility. That is, determining if the same result would be expected if a different group of analysts performed the study.

Financial cost of making a decision

The cost of making a recommendation should be understood. While costs were not directly measurable for the control aspects of this study, some proxies were used. First, the use of contracted support was determined. Then, if available, the cost of the contracted support was collected. Another proxy for cost was the requirement for travel. Travel manifests itself in the cost of travel and the opportunity costs for performing other tasks while in travel status.

Time required of making a decision

Contracted studies can require time to establish and award a contract followed by the time to collect the data, analyze, and generate a report. CAM doesn't require a contract or formal report generation if it is performed as an in-house screening tool. The elapsed time to complete studies and CAM and the actual man-hours were collected as comparisons.

Program manager to identify control projects

Because of the lengthy time required and lack of existing documentation regarding previous processes of assessing compatibility, program managers were asked to identify projects they had worked on that were similar in complexity and scope to the projects the project managers used for their analysis. The manager was asked about the projects and data was collected when possible.

Semi-structured interview

To compare the value of the CAM to the value of legacy methods, a semi-structured interview was performed with the project managers. In addition to the response to a series of questions, qualitative findings and quotations from potential users were captured.

Execution Plan

This phase of the research employed two Air Force project managers from separate program offices as research participants to perform CAM on multiple subsystems on two separate aircraft. Previously, the CAM method had been executed only by the researcher who worked directly with the participants by leading them through the process, collecting the data, and documenting the findings. This exercise removed the researcher from the process to remove developer-induced bias from the method. The two Air Force project managers were trained to use CAM. The managers executed the process independent of the researcher and reported results of executing the process on subsystems for their aircraft.

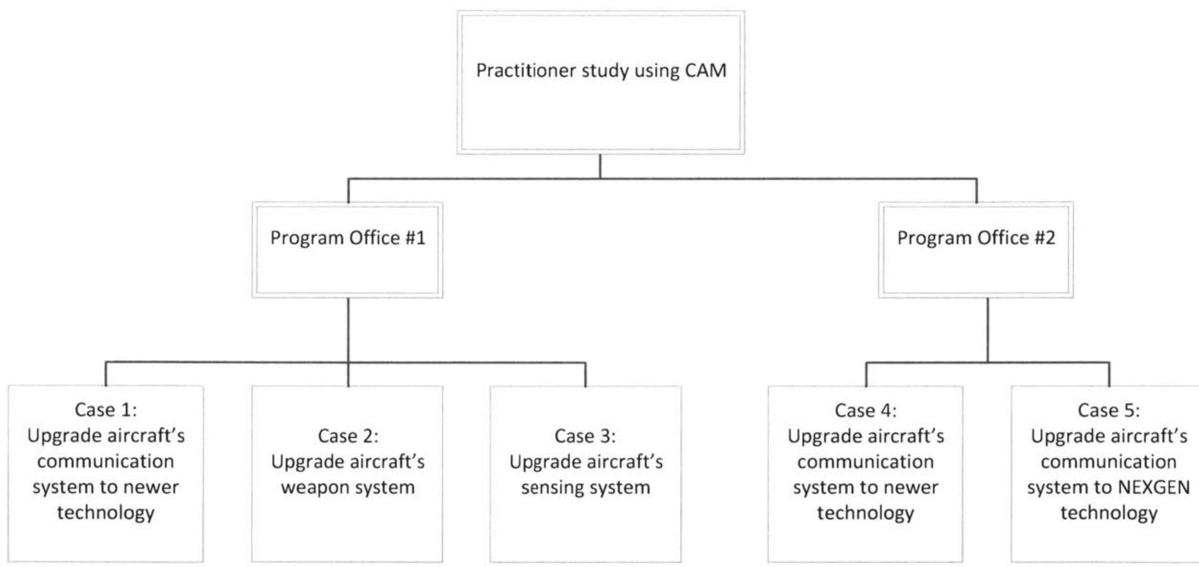


Figure 7 - Architecture of the five case studies that were performed by practicing project and program managers for this research study.

Participants and Cases – Program office #1

The first Air Force program office managed an aging aircraft that needed to upgrade sensor, communication, and weapon systems.

Figure 8 - Participants and their roles in Program Office #1

The participants in this exercise were a project manager, subject matter experts, and a senior program manager. The project manager for this program office was a senior Air Force captain with acquisition experience in multiple program offices. He had recently completed his coursework for a masters degree in Research and Development Management at the Air Force Institute of Technology. His coursework included system development and system architecting classes. In preparation for performing CAM independent of the developer, he read descriptions of CAM and independently replicated two completed CAM case studies.

The subject matter experts were subsystem managers and engineers in the program office. They had technical and management responsibilities for the subsystems being analyzed using CAM. They provided insight into the technical accuracy of the analysis that the project manager performed.

The senior program manager was an Air Force lieutenant colonel who was selected because of his years of acquisition experience and his current responsibility of overseeing multiple projects, including the projects that CAM was used to investigate. The senior program manager was given an overview of CAM and asked to evaluate the results based on the CAM processes. He was also requested to provide control cases to compare the results of CAM against legacy methods that he had used during his acquisition experience.

The first case study performed was to upgrade an external sensor system on the aircraft. An improved electro-optical sensor was being considered with upgraded video resolution. The project manager researched the systems and performed the compatibility analysis method to determine the feasibility of the proposed upgrade.

The second case study performed for the first program office was to upgrade radio communication systems. The current system was obsolete and production was being terminated by the radio manufacturer. The proposed system was scheduled to remain in production for many more years and provide additional functionality through advanced radio waveforms and operating modes.

The third case study performed for the first program office was to upgrade an external weapon system. The proposed weapon system would provide increased operational capability and be common with more aircraft systems. The project manager analyzed the feasibility of integrating the proposed weapon system onto the aircraft.

For the first program office, the project manager performed CAM on the three systems. Upon completion of the analysis on three cases, the project manager presented the results of his analysis to his supervisor. The program manager was asked to provide comparison cases from his experiences as a project manager. These comparison cases were used as control cases to compare the results of the CAM processes with the unstructured processes that were currently used.

Participants and Cases – Program office #2

The second Air Force program office managed an aging aircraft that needed to upgrade communication systems. The participant in this experiment was a single project manager who had responsibility for the management of the communication suite on an Air Force aircraft. Because analysis for the communication system upgrades had already been started by the program office, the entire CAM process was not necessary to be performed. In this situation, the process was entered at step 4 of the CAM process to evaluate the compatibility because the system to be replaced had already been identified. Additionally, two potential replacement systems were selected for additional analysis. This allowed the researcher to gain insight about the structure of potential systems to be done in future work.

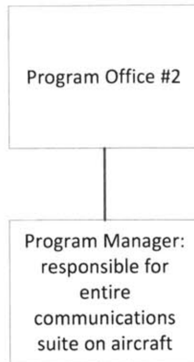


Figure 9 - Participant and roles in Program Office #2

This participant was a senior Air Force captain who had recently graduated from the AFIT masters graduate program in R&D Management. His coursework was identical to the coursework of the first program manager.

The first case study performed by the program manager on the aircraft in program office #2 was to replace a current radio system with a newer radio system. The current radio system was scheduled for retirement because it was going out of production and the program office needed a plan to replace the radio system. In this case, the proposed radio system was a newer model in the same product generation by the same radio system producer.

The second case study performed by the program manager on the aircraft in program office #2 was to replace a current radio system with a newer radio system. The proposed radio system in this case was considered to be the next generation of radio systems by the manufacturer. The next generation system added several new waveforms and improved security over the other alternatives.

In the second program office, the program manager performed CAM on two competing radio/communication system upgrades. In the first case, the program manager compared the baseline radio with the proposed radio. In the second case, the program manager compared the baseline radio with the next generation radio offering.

Upon completion of the CAM analysis for the two cases on the second aircraft, the program manager compared the CAM results with the results of a contracted study for upgrading the radio/communication systems on the aircraft.

Analysis Plan

The analysis included making measurements to learn the value of CAM to practitioners. This value was determined in two ways. For the first program office, the value was determined by comparing the treatment process (CAM) with legacy methods. The second program office used the results of CAM and compared the findings with the contracted study.

This research was developed to provide insights into the value of using CAM in several areas; government insight, confidence in recommendation, cost of making the decision, and time to make the decision. The research design uses a two-by-two matrix to compare the control (legacy methods) with the treatment (CAM) processes and compare baseline systems with the proposed systems (Table 9). While the process provides qualitative and quantitative information regarding the CAM findings, the reporting from the legacy methods relies on interviews with practitioners who previously performed similar work.

Table 9 - Construct for comparisons between treatments and controls for pairwise analysis of CAM and Legacy methods

	Baseline System Analysis	**Proposed System Analysis**
CAM (Treatment)	Baseline System	Proposed System
Legacy methods (Control)	Baseline System Historical Data	Proposed System Historical Data

Data Collection – CAM execution and evaluation

This portion of the research includes the execution of the CAM on five case studies and then compares the metrics and results that were found by CAM with the metrics and results that were found by legacy methods.

The execution of CAM engaged two Air Force project managers, each was associated with a separate aircraft program office.

The sampling plan for the first set of studies was to select several subsystems from the same aircraft. The selection of the aircraft was made because of the access to the program and the association of the program manager with the aircraft being studied. The subsystems that were sampled were based on contemporary issues of the program office. The sample included comparison of pairwise cases for sensor systems, radio systems, and missile systems.

The project manager first learned the CAM process by reviewing papers and learning the process by performing cases on other systems. CAM's developer was available for assisting and consulting for the learning phase of the project manager. The project manager then selected the pairwise cases and they were approved by the lead researcher. After the selection of the cases, the project manager performed the CAM process without oversight from the lead researcher.

After the project manager performed CAM, the lead researcher used the findings of the CAM process to present the results to a senior program manager in the aircraft system program office. Through a survey and a semi-structured interview, the senior program manager was asked to provide examples of similar complexity upgrade projects and provide value insights for CAM in a program office.

The second set of studies was performed by a program manager who was responsible for a system replacement on another aircraft. This program manager was interested in the CAM process to validate the findings of a contracted study that recommended a course of action for the program office. This project manager became familiar with CAM through reviewing the process as it was conducted on previous systems. The matrices that were developed to execute CAM were provided to the project manager. In addition, the first project manager and the CAM developer were available to resolve questions about the process.

Table 10 - Case studies with paired comparison performed by project managers in representative program office environment

	Case 1	Case 2	Case 3	Case 4	Case 5
Control Method Cases	DMS on Space Systems	Arc-fault Circuit Breaker Mod	Ground Weather Radar Mod	Contractor Study of Aircraft Radio Systems	Contractor Study of Aircraft Radio Systems
Treatment Method Cases	Aircraft Sensors A & C	Aircraft Radio Systems X & Y	Aircraft Missile Systems P & Q	Aircraft Radio Systems W & Z	Aircraft Radio Systems, Next Generation W & Y
Program Manager (and aircraft)	1	1	1	2	2

CAM Execution

The following five pairwise cases were conducted by program managers using CAM (the treatment method). The findings collected and analyzed through CAM are included in this section. The identities of systems and subsystems have been obscured when necessary for reporting purposes. Three of the five pairwise cases were performed by a project manager in one program office and the remaining two cases were performed by another project manager in a different program office.

Three Pairwise Case Studies (Treatments) Performed by Project Manager/Student Researcher

1. Sensor systems A & C (Reference: Appendix B – The developmental case studies that defined CAM)
2. Communication (Radio) systems X & Y
3. Missile systems P & Q (Reference: Appendix B – The developmental case studies that defined CAM)

Two Pairwise Case Studies (Treatments) Performed by Project Manager

4. Communications systems W & Z
5. Communication systems W & Y

This chapter reports only Case 2 in detail for brevity. The additional cases (Sensor systems, Weapon systems, and Radio systems on the second aircraft) are found in Appendix C.

Case Study 2: Communication Systems X & Y

Scenario:

The data and analysis using CAM in this scenario are the data and results of a graduate research thesis (Easton, 2010).

The program office is considering a block upgrade for its aircraft. Many subsystems have been in use for years and may not be taking advantage of the newest state of the art technology. The current radio system receiver/transmitter used on the aircraft, Comm X continues to meet all the requirements, but is no longer being manufactured per the manufacturer's 2009 announcement, and may need to be replaced in the near future. The manufacturer has many different versions of the radio with the latest technology in new variants that could be suitable replacements.

Current System (Baseline):

The aircraft VHF/UHF radio voice communication system includes the Comm X transceiver. The Comm X can operate in single channel mode supporting standard military AM/FM modes, or in frequency hopping mode supporting HAVEQUICK I/II and SINCGARS waveforms. The radio combines a stand-alone AM receiver capable of monitoring emergency guard channel transmissions, along with its main receiver for simultaneous monitoring of multiple mode frequencies. Secure voice communication is made possible by adding a communications encryption device. The secure voice system can be used with either the digital LOS data link mode (C-band DL) or with the SATCOM mode (Ku-band DL). (Rockwell Collins, 2008)

Comm X has a frequency band of 30 to 400 megahertz (MHz) with power controlled by the flight crew via the graphical user interface (GUI). The various frequency bands each provide a specific application necessary for a successful mission.

- 30-88 MHz – Tactical/Close Air Support
- 108-118 MHz – Navigation
- 118-136 MHz – Air Traffic Control
- 136-156 MHz – Land Mobile
- 156-174 MHz – Maritime
- 225-400 MHz – Mil/NATO, CASS/DICASS command
- 243-270 MHz – Long Haul Communications
- 121.5/243 MHz – Guard Channels
  (Rockwell Collins, 2008)

Current system functions include scan mode, where preset channels 22-25 are constantly scanned for activity and are ready for transmission, HAVEQUICK and SINCGARS. HAVE QUICK is a frequency hopping mode in the UHF 225-400 MHz band with both training and combat mode. Two HAVE QUICK radios must have identical Time of Day (TOD), Word of Day (WOD) and net number to communicate. SINCGARS, Single Channel Ground and Airborne Radio System, is a digital frequency hopping system, operating in the 30-88 MHz band, that works in plain voice or encrypted voice with the KY-100 encryption device. For two SINCGARS radios to talk, they must have identical time, hopset/net number/TRANSEC, and optional lockouts.

The key functions of the baseline system that must be met or exceeded by any other proposed system to warrant consideration for possible replacement include standard voice communication, secure voice (in DLOS and SATCOM), scan operation, emergency guard operation, anti-jam function, HAVE QUICK I/II and SINCGARS.

Possible proposed replacements for the currently used baseline system:

The manufacturer produces a family of military grade radios with anti-jam, two-way voice and Data Communication links for tactical aircraft. These radios operate in either normal or secure mode via LOS or SATCOM links. Each system provides specific functionality needed to meet user requirements. All radios operate via the MIL-STD 1553B data bus and can provide non-COMSEC functions - LOS and VHF/UHF capability, HAVEQUICK I/II, and SINCGARS ECCM waveforms. Some radios also include embedded COMSEC products. (Rockwell Collins, 2008)

Comm Y is the latest version of the family of Receiver-Transmitters (RT). This model incorporates all the features of its predecessors including the embedded COMSEC products with additional capabilities including:

- Frequency range extension to cover 30-941 MHz
- MIL-STD-188-220D and MIL-STD-2045-47001D networking and data transfer
- Enhanced SINCGARS Improvement Program (SINCGARS ESIP)
- Second-generation Anti-Jam Tactical UHF Radio for NATO (SATURN)
- Joint Precision Approach Landing System (JPALS)
- External Ethernet data connectivity via dedicated interface
- LPC-10 and MELP vocoders
- Growth for evolving capabilities, including MUOS (Mobile User Objective System), integrated waveform (IW) for UHF SATCOM, APCO 25, Intelligence Broadcast System (IBS), and Automated Identification System (AIS)

("Rockwell Collins to Develop Next-Generation an/Arc-210 Aircraft Radios", 2009)

Table 11 - The function table for the radio receiver/transmitter that compares the functions provided by the proposed and the baseline system so that the functional deltas can be calculated and analyzed

Function Table (Radio Receiver/Transmitter)		
(1) Functions of Proposed System (F_P)	(2) Functions of Baseline System (F_B)	(3) Deltas between Systems ($F_P - F_B$)
Comm Y	Comm X	
Standard Voice Communications	Standard Voice Communications	
Secure Voice Communications (Embedded)	Secure Voice Communications	Embedded Comsec functionality
Digital LOS Mode	Digital LOS Mode	
SATCOM Mode	SATCOM Mode	
Scan Operation	Scan Operation	
Emergency Guard Operation	Emergency Guard Operation	
Anti-Jam Function	Anti-Jam Function	
HAVE QUICK I/II	HAVE QUICK I/II	
SINCGARS (ESIP)	SINCGARS	ESIP (Enhanced SINCGARS Improvement Program)
Homeland Defense Channels		Homeland Defense Channels
Public Safety Bands		Public Safety Bands

Comm Y was chosen as the proposed system to replace Comm X because it met all of the functional requirements while adding new capabilities embedded into the system.

The basic functions of each system were entered into the function table (Table 11) and directly compared. The baseline system functions were subtracted from the proposed system and the deltas found between the two systems were all neutral or positive toward the proposed system with added capability. It was determined that Comm Y is functionally compatible and more detailed ICOM analysis is warranted to determine if Comm Y could be a good fit to replace Comm X in a future upgrade.

ICOM analysis:

After determining that the proposed system functionally supports the aircraft, the radio system was decomposed into its Inputs, Constraints, Outputs, and Mechanisms (ICOMs) to determine if the system is a good functional and physical fit. This ICOM breakdown is compared to the baseline system ICOMs to find commonality and differences between the systems.

The baseline system was decomposed into ICOMs first to determine key data points to compare each system.

Table 12 - Baseline system ICOM matrix

Baseline System ICOM Matrix [Comm X]											
Inputs (I)			Constraints (C)			Outputs (O)			Mechanisms (M)		
	Parameter(I)			Parameter (C)			Parameter (O)			Parameter (M)	
Input	Metric	Value	Constraints	Metric	Value	Output	Metric	Value	Mechanism	Metric	Value
Power	VDC	28									
Transmit	W	150									
Receive	W	25									
			Size	Width (in)	5						
				Height (in)	5.6						
				Depth (in)	9.9						
			Weight	lbs	12.2						
			Operating Temp	C	(-54 to 71)						
			Operating Alt	ft	70,000						
			Tuning Incrmts	MHz	2.5						
			Data Rate	BPS	80,000						
						2-way comm	Frequency Rnge	30-400MHz			
						CAS (30-88)	1/0	1			
						NAV (108-118)	1/0	1			
						ATC (118-136)	1/0	1			
						Land Mob (136-5	1/0	1			
						Maritime (156-17	1/0	1			
						Mil/Nato(225-400	1/0	1			
						Em Gd channels					
						121.5, 243	1/0	1			
						HAVEQuickI/II	1/0	1			
						SINCGARS	1/0	1			
						Secure Voice					
						DLOS/SatCom	1/0	1			
									Secure Voice Encryption device		
									KY-100	1/0	1
									Data Ports		
									1553B	1/0	1
									User interface		
									Arc 210 GUI	1/0	1

The proposed system was then decomposed into ICOMs to determine deltas in key data points of each system.

Table 13 - Proposed ICOM Matrix, Comm Y

Proposed System ICOM Matrix [Comm Y]											
Inputs (I)			Constraints (C)			Outputs (O)			Mechanisms (M)		
	Parameter(I)			Parameter (C)			Parameter (O)			Parameter (M)	
Input	Metric	Value	Constraints	Metric	Value	Output	Metric	Value	Mechanism	Metric	Value
Power	VDC	28									
Transmit	W	150									
Receive	W	25									
			Size	Width (in)	5						
				Height (in)	5.6						
				Depth (in)	9.9						
			Weight	lbs	12.2						
			Operating Temp	C	(-54 to 71)						
			Operating Alt	ft	70,000						
			Tuning Incrmts	MHz	1.25						
			Data Rate	BPS	80,000						
			Configuration Modification								
				1/0	1						
						2-way comm	Frequency Rnge	30-941MHz			
						CAS (30-88)	1/0	1			
						NAV (108-118)	1/0	1			
						ATC (118-136)	1/0	1			
						Land Mob (136-5	1/0	1			
						Maritime (156-17	1/0	1			
						Mil/Nato(225-400	1/0	1			
						Homeland Defense					
						(225-520)	1/0	1			
						Public Safety Bands					
						(806-941)	1/0	1			
						Em Gd channels					
						121.5, 243	1/0	1			
						HAVEQuickI/II	1/0	1			
						SINCGARS	1/0	1			
						Secure Voice					
						DLOS/SatCom	1/0	1			
						DAMA Satcom	1/0	1			
						COMSEC Fnctior	1/0	1			
						SATURN	1/0	1			
									Secure Voice Encryption device		
									Data Ports		
									1553B	1/0	1
									Ethernet	1/0	1
									User interface		
									Arc 210 GUI	1/0	???

The ICOMs were then entered into a matrix with an associated metric and value to allow for a comparison of baseline and proposed ICOMs. The inputs and constraints consisted of the usual size, weight, "how much power is required?" questions. The metrics are consistent with these measurements – inches, pounds, or MHz. The metrics for the outputs of the system leans more towards yes/no (1/0) questions. Either the system produced the output or it does not. Similar yes/no questions exist for mechanisms. Either an outside mechanism is used to run the system or it is not.

The two systems can now be analyzed through pair-wise comparisons. The baseline ICOMs are subtracted from the challenger ICOMs and a delta matrix is created to show the differences between the two to be analyzed for significance.

Table 14 - Delta ICOM Matrix , Comm Y vs. Comm X

Delta ICOM Matrix [calculations: Proposed Matrix(Comm Y) - Baseline Matrix(Comm X)]												
Inputs (I)			Constraints (C)			Outputs (O)			Mechanisms (M)			
	Parameter(I)			Parameter (C)			Parameter (O)			Parameter (M)		Level of
Input	Metric	Value	Constraints	Metric	Value	Output	Metric	Value	Mechanism	Metric	Value	Decision
Power	VDC	0										
Transmit	W	0										
Receive	W	0										
			Size	Width (in)	0							
				Height (in)	0							
				Depth (in)	0							
			Weight	lbs	0							
			Operating Temp	C	0							
			Operating Alt	ft	0							
			Tuning Incrmts	MHz	-1.25							1, user
			Data Rate	BPS	0							
			Configuration Modification									
				1/0	1							2,3
						2-way comm	Frequency Rnge	400-941MHz				
						CAS (30-88)	1/0	0				
						NAV (108-118)	1/0	0				
						ATC (118-136)	1/0	0				
						Land Mob (136-5	1/0	0				
						Maritime (156-17	1/0	0				
						Mil/Nato(225-400	1/0	0				
						Homeland Defense						
						(225-520)	1/0	1				1, user
						Public Safety Bands						
						(806-941)	1/0	1				1, user
						Em Gd channels						
						121.5, 243	1/0	0				
						HAVEQuickI/II	1/0	0				
						SINCGARS	1/0	0				
						Secure Voice						
						DLOS/SatCom	1/0	0				
						DAMA Satcom	1/0	1				1, user
						COMSEC Fnctior	1/0	1				2, 3
						SATURN	1/0	1				1, user
									Secure Voice Encryption device			
									KY-100	1/0	-1	1
									Data Ports			
									1553B	1/0	0	
									Ethernet	1/0	1	1, user
									User interface			
									Arc 210 GUI	1/0	???	2,3

Comm X vs. Comm Y ICOM Discussion:

Inputs: No deltas exist in the inputs. Both systems require 28 VDC of electrical input power, and both systems use 150 Watts of power to transmit and 25 Watts of power to receive.

Constraints: The size and weight are exactly the same for Comm X and Comm Y, as are the operating temperature, altitude and data rate constraints. The constraint deltas occur in the tuning increments and the wiring requirements. Comm Y can tune the radio in smaller increments – 1.25 kHz compared to 2.5 kHz for Comm X. No special wiring is required for the Comm X, but special wiring and shielding is required for the embedded COMSEC equipment. According to the Air Force Program Office, other modifications will be needed as well such as a different control head for the operator. (Aircraft Program Office, 2010)

Outputs: Both Comm X and Y cover radio band frequencies 30 to 400 MHz. Comm Y extends this basic coverage from 400 to 941 MHz, adding military/homeland defense channels, UHF 225-512 MHz, and public safety bands, UHF 806-824, 851-869, 869-902, 935-941 MHz. The Comm Y radio adds capabilities such as Demand Assigned Multiple Access (DAMA) satellite communications, Second-generation Anti-jam Tactical UHF Radio for NATO (SATURN), Enhanced SINCGARS Improvement Program (ESIP) and embedded COMSEC capabilities.

Mechanisms: The MIL-STD 1553 data bus is the primary data port used by both systems. The Comm Y adds the Ethernet data port capability. Comm X uses the KY-100 communications encryption device for secure voice communication and adds a Control window GUI to use the associated controls. For Comm Y, secure voice communication and encryption devices are embedded into the system. It is unknown through the literature if a GUI is needed for the Comm Y security functions. The engineers, either system or contractors should be able to answer this question.

Delta Evaluation:

Inputs: No deltas occurred in the inputs, so no evaluation is necessary.

Constraints: The constraints offer two deltas that may require more investigation. The first difference in tuning increments is an advantage for the challenger system, but how much of an advantage is the question. The user should be consulted to determine if they want or need tighter tuning increments and how much this difference would mean to them.

The second delta in constraints is physical modifications required for the system to work. The baseline system works as is and requires no modifications. The proposed system requires additional wiring for shielding and terminating considerations. ("Rockwell Collins to Develop Next-Generation an/Arc-210 Aircraft Radios", 2009) The aircraft program office also expressed concerns about the need for integrating a new control head for the operator. These delta questions would require engineering expertise starting at the program level to determine the significance of the special wiring or how difficult the control head change would be. The aircraft prime contractor may also need to be consulted if they would be the ones making these changes to the system.

Outputs: Output deltas all favor the proposed system, the Comm Y, which produces the same outputs as Comm X plus additional capabilities. Greater frequency range allows for extra military/homeland defense channels and public safety bands. DAMA SATCOM, SATURN, and enhanced

SINCGARS are additional outputs that may not be required at this time, but will they be needed in the future? The user should be consulted to determine if these are necessary upgrades that will be used or if they are just nice to have. The embedded security features would be nice to have, but will they actually improve the system or will they just sit there and do nothing more than the current addition of the external security system? System engineers would answer the question of immediate impact on the system. The users or other stakeholders would be surveyed to determine the requirement for the proposed system's embedded security features.

Mechanisms: The 1553B data port would remain the same for either system. Comm Y adds an Ethernet port which may be needed for a future requirement. With the embedded security equipment, the need for a external security would no longer be necessary, eliminating extra equipment. The GUI requirements should be addressed through the system engineer.

Summary Analysis:

The Comm X radio system is no longer being manufactured and will need to be replaced in the near future. Comm Y would add to the capabilities of the current radio system, but the wiring, tuning increment interface, and shielding issues need to be resolved for physical integration and access to new tuning increments and frequencies that will require software integration.

Recommendation:

If these added capabilities are determined to be future requirements or necessities for future missions, then the aircraft program office should upgrade the radio system to the Comm Y. A business case analysis should be performed and evaluated against the value of the additional capabilities that Comm Y includes. If the additional capabilities are not required or future requirements are unclear, then the program office should take a closer look at the wiring requirements and find a system that will not impact the current wiring when it does need to be replaced.

CAM Evaluation

After the analyses were performed by the project manager in the first three cases and the project/program manager in the fourth and fifth cases, a semi-structured interview was performed. For the first three cases, the interview was conducted with the project manager's supervisor, a program manager and division chief, for the first aircraft. These were also asked of the program manager who performed the CAM analysis on the second aircraft. The following questions were discussed and the responses were scored. Responses included Yes/No, Likert scales, discussions about systems for comparison, and numeric values for time and costs related to estimates. The results were tabulated and analyzed to find the strengths and weaknesses of the Capability Assessment Method. For the fourth and fifth cases, the manager was able to access a study that performed a technical analysis of the trades required to upgrade the communication systems on his aircraft. This study was obtained after the project manager's evaluation of the systems and the CAM process.

The outline that was used as a guideline for the semi-structured interview with the first aircraft's program manager and with the second aircraft's project/program manager can be found in Figure 22 .

The results from the interviews with the program managers were collected and organized as shown in Table 15 - Results of comparing Legacy and Compatibility Assessment Methods after CAM has been used in program offices.

Analysis and results

CAM Execution

Practitioners were able to use CAM to validate previous decisions. The project/program managers demonstrated the requisite skills to perform CAM with little instruction. The practitioners were able to contribute to the process and suggest improvements based on their needs and applications.

Practitioners were able to gain insights into systems that SMEs were not expecting. Mature insights were gained with readily available information. System engineers were surprised by how much information was readily available from open source information. Engineers in program offices believed that system information was held more closely and not easily available. SMEs were shown the results produced by the project manager and the recommendations were discussed. The SMEs agreed with the findings that were found by the project manager and the data available by official sources supported the recommendations.

Practitioners could enter the CAM process at different points in the acquisition cycle depending on the information that was already collected and the constraints placed on the solutions. With one program manager, CAM was the first time that the subsystem upgrade was analyzed. The practitioner conducted market research through open source literature reviews and technical reports from system producers to perform the analysis. In this case the practitioner needed to determine alternatives that were available before conducting the comparisons. In the case of the second program manager, a contractor analysis had been performed and the program manager used CAM to determine the feasibilities of the contractor recommendations and validate the contractor studies.

CAM practitioners required expert users and needed coaching or experience to use the models. The execution of the CAM process did require instruction from an experienced CAM user until the practitioner had competed at least two iterations of the process. An example proved to be valuable for the practitioners to use as a guide.

CAM Evaluation

The comparisons of the methods were evaluated by non-parametric analysis for the Likert data and parametric analysis for the cost and time data.

Analysis and qualitative results

To evaluate the Compatibility Assessment Method against previously employed methods of assessing compatibility, a set of survey questions was administered as part of semi-structured interviews. These questions were developed to learn about

(1) government insights;
(2) confidence in recommendation;
(3) cost of making the decision; and
(4) time to make the decision.

Each of these constructs was decomposed to gain insight into the managers' understanding of execution of the methods used to perform compatibility assessment and determine a value of using CAM instead of previous methods. The entire data set resulting from the manager interviews was presented in the next section Table 15.

After the CAM process had been executed, the researcher engaged with the division chief who supervised the program manager on System 1 and the program manager who was responsible for the communication suite on System 2. The engagement used Likert scales to evaluate the insight afforded the government personnel and the confidence in the recommendations. Costs were captured where possible, and the time to make a decision was recorded.

The [non-parametric] Mann-Whitney U test was used to analyze the Government Insight and Confidence in recommendation categories of data. The six variables were inspected for response distributions comparing CAM to Legacy methods, comparing distributions from program managers across programs, median responses across methods, and finally, the median responses from program managers across programs. A significant test statistic indicates the medians are non-equal or that the distributions are non-equal. The analysis was performed by SPSS and can be reviewed in Appendix C.

Table 15 - Results of comparing Legacy and Compatibility Assessment Methods after CAM has been used in program offices

Questions			Case 1	Case 2	Case 3	Case 4	Case 5	Mean: 5 systems	Std Dev: 5 Systems	Median: 5 Systems	Research Design Constructs
1											
	a										
2											
	a		**Legacy Methods**								**Government Insight**
		i	3	2	3	1	1			2	Process
		ii	4	4	4	2	2			4	Motivation
		iii	3	2	3	2	2			2	Assumptions
	b										**Confidence in recommendation**
		i	1	3	1	2	2			2	Repeatability
		ii	1	3	1	3	3			3	Traceability
		iii	1	3	1	2	2			2	Reproducability
	c										**Cost of making the decision**
		i	no	no	no	yes	yes				Contract support?
		ii	0	0.2	0	1.75	1.75	0.74	0.93		Support costs ($Million)
		iii	yes	yes	yes	yes	yes				Travel
	d										**Time to make decision**
		i	unknown	unknown	unknown	unknown	unknown				Man-hours
		ii	0.5	2	0.25	0.4	0.4	0.72	0.72		Years (Elapsed time)
3			**Compatibility Assessment Method (CAM)**								
4											
	a										**Government Insight**
		i	4	4	3	4	4			4	Process
		ii	4	4	3	3	3			3	Motivation
		iii	4	3	3	3	3			3	Assumptions
	b										**Confidence in recommendation**
		i	4	4	4	4	4			4	Repeatability
		ii	4	3	3	4	4			4	Traceability
		iii	4	4	3	3	3			3	Reproducability
	c										**Cost of making the decision**
		i	no	no	no	no	no				Contract support?
		ii	0	0	0	0	0	0.00	0.00		Support costs ($Million)
		iii	no	no	no	no	no				Travel
	d										**Time to make decision**
		i	2	3	4	3.5	2	2.90	0.89		Man-hours
		ii	2	4	4	2	1	2.60	1.34		Hours (Elapsed time)

Government Insight

This construct queried the managers to determine the extent of knowledge of the processes, the motivations of the person(s) who made recommendations, and knowledge of the assumptions that were used in framing the decision-making. These were collected on a 4-point Likert scale.

A paired-samples Mann-Whitney U Test was conducted to compare government decision-makers' **understanding of the processes** used to make a recommendation based on the use of Legacy methods and using the Compatibility Assessment Method. These results ($U=2$ ($U_2=1$), $p=0.05$, $N=10$) suggest that CAM provides a greater knowledge of the processes used to make a decision. The null hypothesis that the Legacy and CAM users have the same understanding is rejected. Specifically, when the CAM process is selected, the government program managers have a better understanding of the process used to make a recommendation for future subsystem upgrade acquisitions.

A paired-samples Mann-Whitney U Test was conducted to compare government decision-makers' understanding of the **motivations** of the entities performing the analysis used to make a recommendation based on the use of Legacy methods and using the Compatibility Assessment Method. The test found no significant difference between CAM and legacy methods regarding knowledge of the motivation of the entities performing the analysis to make a recommendation ($U=2$ ($U_2=12$), $p=0.05$, $N=10$).

A paired-samples Mann-Whitney U Test was conducted to compare government decision-makers' understanding of the **assumptions** that were used to make a recommendation based on the use of Legacy methods and using the Compatibility Assessment Method. These results suggest that CAM provides a greater knowledge of the assumptions used to make a recommendation. Specifically, when the CAM process is selected, the government program managers have a better understanding of the assumptions used to make a recommendation for future subsystem upgrade acquisitions ($U=2$ ($U_2=4$), $p=0.05$, $N=10$).

Confidence in recommendation

This construct measured the managers' confidence in the recommendation that was made by CAM or an alternate legacy method of making a determination. The confidence in the recommendation was determined through assessing the repeatability, traceability, and reproducibility of the decision.

This information was collected on a 4-point Likert scale that ranged from Very Unlikely (1) to Very Likely (4).

A paired-samples Mann-Whitney U Test was conducted to compare government decision-makers' confidence in the recommendation by measuring their confidence in the **repeatability** of the study that was performed based on the use of Legacy methods and using the Compatibility Assessment Method. These results suggest that program managers believe that CAM provides a result that would be more likely to be repeatable than the Legacy methods previously performed ($U=2$ ($U_2=0$), $p=0.05$, $N=10$). The null hypothesis that the Legacy and CAM users have the same confidence in repeatability is rejected. Specifically, when the CAM process is selected, the government program managers believe the analysis could be repeated for a recommendation about future subsystem upgrade acquisitions.

A paired-samples Mann-Whitney U Test was conducted to compare government decision-makers' confidence in the recommendation by measuring their confidence that the **same outcome** (**traceability**) could be expected if the same people performed the analysis that was performed based on the use of Legacy methods and using the Compatibility Assessment Method. These results suggest that program managers believe that CAM provides a result that would be more likely to be repeated than the Legacy methods when performed by the same analysis team. Specifically, when the CAM process is selected, the government program managers believe the results of the analysis could be repeated for a recommendation about future subsystem upgrade acquisitions if the same group of people performed the analysis ($U=2$ ($U_2=3$), $p=0.05$, $N=10$).

A paired-samples Mann-Whitney U Test was conducted to compare government decision-makers' **confidence** in the recommendation by measuring their confidence that the same outcome could be expected if a different, independent group performed the analysis that was performed based on the use of Legacy methods and using the Compatibility Assessment Method. These results suggest that program managers believe that CAM provides a result that would be more likely to be repeated than the Legacy methods when performed again by a different analysis team. Specifically, when the CAM process is selected, the government program managers believe the results of the analysis could be repeated for a recommendation about future subsystem upgrade acquisitions if a different group of people performed the analysis($U=2$ ($U_2=1.5$), $p=0.05$, $N=10$). The null hypothesis that the Legacy and CAM users have the same confidence in their results is rejected.

Parametric Analysis

The cost of making the decision and the time to make the decision can be analyzed by parametric methods.

Cost of making the decision

To assess the cost of making the decision about which subsystem to use, a construct for capturing the cost of making the decision was developed. The components of this construct included asking if contract support was used to make the decision or if the analysis was performed by internal personnel. If contract support was used and a cost could be captured, that number was collected. This metric could be collected easily if the analysis was performed by a contracted study. Another component of the cost was travel costs. While a travel cost was not calculated for each activity, the determination if travel was required or not was captured.

Table 16 – Cost of making a decision using Legacy and CAM

	Legacy Method	CAM
Contract Support i	Mixed	No
Support costs ii	M=1.75, SD=0.93, n=5 ($ Million)	M = 0 SD = 0 n=5 ($)
Travel iii	Yes	No

The costs for performing the Legacy Method were attributed to contractors hired to support the program study, direct costs of contracting the support to perform the study, and traveling to collect data. The contract support and travel were captured with Yes/No responses to provide a proxy for costs being allocated to that activity. For the contract support, the Legacy Method sometimes used contract support and other times the organizations performed the analysis with organic capability. In all LM cases, travel was performed to gather the data. The CAM executions required no contract support, other support costs, nor travel expense.

Time to make the decision

Manpower is a resource that has staffing and cost implications. This construct attempted to collect the number of man-hours that the evaluation required. Also, to learn about the responsiveness of a decision, the elapsed time to make a decision was collected.

Table 17 – Time to make a decision using Legacy methods and CAM

Time [CAM units]	Legacy Method	CAM
Man years [hours] i	Unknown	M=2.90 SD = 0.89 N=5 hours
Years [hours] elapsed ii	M=0.42 SD=0.72 years N=5	M= 2.6 SD= 1.3 hours N=5

The data were unavailable to document the hours expended for the LM project, but the hours to perform CAM in the experiment were measured at 2.9 (SD=0.89) hours. The elapsed times were captured. For the LM, the length of time was estimated by the division chief who had been the program manager for the control projects. For the CAM projects, the data was collected in accordance with the research plan. The LM times lack precision, however their scale is measured in years instead of hours.

Qualitative results

In addition to the qualitative measures collected through the semi-structured interviews, comments that the managers made during their method evaluation session were collected and archived. Some of these comments are reported here.

Table 18 - Quotes from CAM users and evaluators

Case	Quotes (position of person making quote)
1	• The sparse matrix format in the delta matrix lets us quickly see where the issues may arise. (System Engineer)
2	• This method [CAM] did not capture growth potential of systems and sustainability issues. (Division Chief)
3	• We will adopt this process and institutionalize it. (Division Chief) • This [CAM] gives us insight into what we've relied on contractors for. (Project Manager)
4	• [I] would like an operationalized version for Project Managers to use at their desks. (Project Manager) • To operationalize, [I] would like Excel spreadsheets and worksheets. (Project Manager)
5	• For program managers, the most important factors to include in the matrix are SWaP (Size, Weight and Power). (Project Manager)

Conclusions

Analysis of the post-data collection information provided the following insights:

The CAM provided improved insight into subsystem upgrades and the decision-makers had increased confidence into the results from CAM than the previously-used methods. The users indicated that CAM should not be used to make the final determinations, but that it provides a high-level assessment that can be performed by current acquisition staff members quickly and at a low cost. The participants were interested in the process because it provided answers to their compatibility questions in hours instead of months. The program office participants understood that detailed engineering studies would be required to make a course of action determination; however, CAM could be used to provide initial assessments which could preclude contracting for additional studies. By providing CAM as a tool to the program managers, quick assessments of compatibility of a proposed end-item replacement could be a time saver.

The research subjects found value in the method. One program office decided to institutionalize the method and the other program office asked for the templates for the data collection and analysis to allow them to further explore the applicability of CAM in their area.

This chapter documented how project managers in two Air Force program offices used CAM to analyze the feasibility of replacing a current subsystem on an aircraft with a proposed system. The program managers were able to execute the CAM process to determine the differences between the current and proposed systems. These differences were characterized by severity and the resolution authorities were identified.

When the processes of CAM and methods previously used to determine feasibility of a proposed replacement were compared, CAM execution did not provide the same depth of information, but did provide insight into the solution spaces. The proposed CAM process was deemed appropriate to be used as a screening tool to quickly determine if the proposed subsystem would be a viable replacement for the current system.

Chapter 5 – Students applying CAM in an academic environment

The final experiment in this research was developed to test the value of the Compatibility Assessment Method (CAM) with a larger sample of representative users in a controlled case study. The experiment was designed to allow the sample to be split into two cohorts. One cohort used their own unstructured processes to represent legacy methods of performing compatibility analysis, while the other group was tutored in CAM and directed to use that method to determine compatibility.

A stylized case study was developed for this research activity. The scenario mimicked a real-world scenario that several Air Force program offices are working to solve. The scenario given to the students reported that they were project managers for MQ-XX, a multi-role unmanned aircraft system, and they were responsible for the communication suite on the air vehicle. The currently installed radio system included the RT-1556, a transceiver from the AN/ARC-210 family of radios, which was becoming obsolete because the manufacturer was discontinuing it. The fictitious RT-5959 was proposed as a replacement for the RT-1556, and the students were asked to determine whether it was suitable for that purpose. The exercise was seeded with 12 known incompatibilities between the two systems. These incompatibilities ranged from easily discovered to more subtle. The subtle seedings helped determine the participants' ability to identify differences. The seeded incompatibilities were not intended to be an exhaustive list of all the incompatibilities in the system; rather, it was expected that participants would find different incompatibilities based on their experiences.

Table 19 - The 12 Seeded Incompatibilities for the student exercise

The 12 Seeded Incompatibilities	
1	Size
2	Power required
3	Operational Altitude
4	Operational Temperature Range
5	Weight
6	Frequency spacing
7	ARINC Data Bus
8	Additional frequency tuning range
9	Embedded cryptographic capability
10	Anti-jam capability
11	SATURN
12	DAMA SATCOM

Experimental design

The experiment was designed for graduate student systems engineers to perform CAM in comparing an actual system to a proposed system.

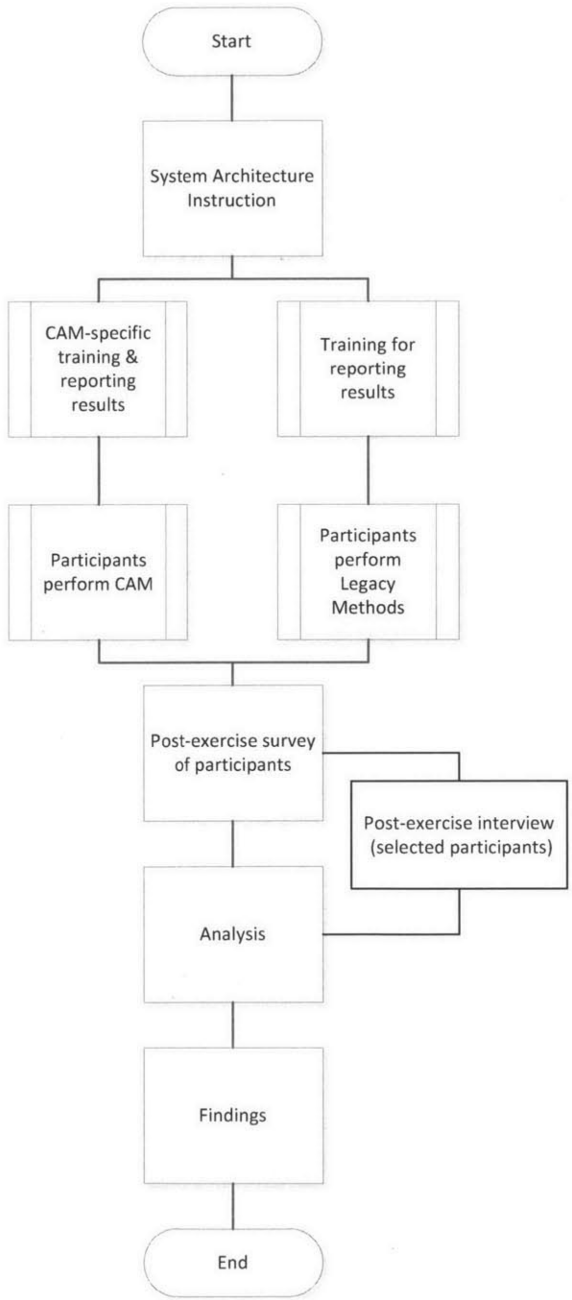


Figure 10 - Flow chart of participant activities and products for comparing CAM and Legacy methods of determining compatibility of subsystems

The participants in the study were graduate students studying systems engineering at the Air Force Institute of Technology (AFIT). There were 27 students in the research cohort who were randomly assigned to one of two groups. The control group performed an unstructured method that provided little direction in how to perform the analysis. The treatment group was given additional instruction regarding the Compatibility Assessment Method (CAM). Each of the students was to work independently and keep track of the amount of time they spent on the exercise.

The stylized case study (Appendix D) was based on replacing a radio system on a fictitious unmanned aircraft system, the MQ-XX. The participants were given a description of the mission and the system, the MQ-XX, to ensure context for the research. Next, the ARC-210 family of radio systems was described and open source information about the ARC-210 from the Rockwell-Collins website was provided. A report on the sales forecasts for the ARC-210 radios (Forecast International, 2009) was provided to the participants, but is not included here because of its proprietary nature (permission was received from Forecast International to use the data for research purposes, but not for direct publication). For the purposes of the stylized case study, participants were told that the ARC-210's RT-1556 transceiver was being discontinued. A new system, the RT-5959, was proposed as a replacement. The participants were to perform the following tasks:

1. Determine the critical and most important differences between the current ARC-210 RT-1556 transceiver radio and the proposed transceiver.
2. Identify the extent of each of the incompatibility issues.
3. Assign an incompatibility severity code to characterize the magnitude of the differences in compatibility.
4. Identify the appropriate personnel category(ies) to resolve the compatibility issues.
5. Provide an assessment if the proposed system can be used as a substitute for the MQ-XX's currently-installed ARC-210 radio.

Before the assignment was released to the student participants, the students were given two class periods of system architecture instruction. Additionally, tailored presentations were given separately to the control and treatment groups regarding their specific tasks. The control group was given an example problem that needed to be solved and a final report table to complete for the assignment. The treatment group was given a similar presentation, plus a demonstration of the CAM process. They were also given the blank matrix charts required for performing the steps of the process.

The participants were given the exercise on a Wednesday morning and were requested to return their work two days later, at which point they were given a questionnaire regarding their findings and analysis of the CAM and legacy processes.

The students were given the material in conjunction with a systems architecting class that was part of their core classroom requirements. Attendance at the presentations was 100 percent; in addition, the exercise was completed by all participants. Finally, every one of the students completed the post-exercise surveys, and some were selected for additional questions about the process. The student participants were not compensated for completing the work; however, the researcher did provide the cohorts with pizza and soft drinks for lunch at the culmination of the exercise.

Participant Profiles

The participants in the academic setting experiment were all volunteers who were not expecting any compensation. They received the overview of system architecting and evaluation as part of their academic classroom instruction. The introduction to the case study and the directions to use CAM were also part of the academic instruction period. The assigned compatibility assessment case study was equivalent to their weekly homework load for the course and was aligned with the block of instruction the primary instructor was planning for the week of the experiment.

Demographic information on the participants was self-reported through a 12-question survey that was administered with the consent forms prior to presenting lecture material. Participants were briefed on the alignment between the exercise and their current module of study. The primary course instructor introduced the researcher and provided a transition from the exercise to the next module of instruction.

All participants were enrolled in AFIT's Systems Engineering graduate program at the time. Of the 27 participants, 25 were master's students and 2 were doctoral students. All of the participants were Air Force officers except for one Army officer, two Navy officers, and one Air Force civilian. The ranks of the officers ranged from second lieutenant to major. The civilian was on the Laboratory Demonstration pay scale at the DR-2 level. All were full-time students, receiving their salaries and free tuition. The time of government service ranged from 2 months to 16 years. Acquisition experience ranged from none to 12 years. Of the 27 participants, 17 had acquisition professional development certification in one or more acquisition areas.

The participants had all graduated from high school and an undergraduate educational program, which are basic requirements for military officers and for the positions in which the civilians were currently serving. All of the students had technical undergraduate degrees in engineering or sciences. Their self-reported undergraduate grade point averages ranged from 2.4 to 3.5 on a 4-point scale.

The participants were compared across groups to test for biases based on self-reported years of government service experience (Figure 25), years of government acquisition experience (Figure 27), and undergraduate grade point averages (Figure 29). None of the differences was statistically different between the groups based on Mann-Wilcox U-tests and Independent Samples Median Tests (Table 72 - Hypothesis test summary for participant demographics).

Post-exercise surveys

When the participants returned the completed exercise, they were also asked to complete a survey about their findings. The questions asked them to self-report the amount of time spent on the task, whether their skills were adequate to perform the analysis, whether the proposed system was a candidate for replacing the baseline system, the ease of completing the exercise, and 11 Likert-scale questions about the analysis. These 11 questions were developed to learn about the participants' attitudes regarding the analysis they performed. While the program managers' interviews focused on the usefulness of the method, confidence in the findings, and the time and cost to perform the method, the student participation was focused on learning about a non-domain expert's ability to perform the analysis. The student participants were measured on the time they spent on the project and the number of incompatibilities they found. Finally, the student participants were asked about their perceived value of performing the analysis for a program office. The student participant and program manager participant data were not designed to be correlated. However, some inferences can be made by comparing data.

In addition to the post-exercise survey, four participants participated in a semi-structured interview to learn more about their findings and how they addressed their findings.

Results

The results of this effort were twofold: first, the findings from the participants were compared, and second, the participants' surveys provided an evaluation of the legacy and proposed methods.

The student participants' results are reported in this section. Some findings were expected and others were not predicted by the researchers. The cohort was divided into two groups, with 15 participants performing the Legacy method and 12 participants performing the Compatibility Assessment Method (CAM). The number of times an incompatibility was found for the cohort ranged from a maximum of 22 times for both size and power requirements down to a single instance of identifying each of 12 incompatibilities (Figure 11). One of the seeded incompatibilities was found only once; another, just twice. Because the participants were not primed with suggested incompatibilities to identify, the right tail of incompatibilities that was found only one or two times is not unexpected.

The Legacy method participants found an average of 7.47 incompatibilities with a standard deviation of 2.17 and variance of 4.70. The CAM participants found an average of 4.83 incompatibilities with a standard deviation of 1.59 and variance of 2.52 (Table 20). The Legacy participants found a greater number of incompatibilities and had a higher variance than the CAM participants reported.

The Legacy method participants found more of the incompatibilities than the CAM users identified. The Legacy group also had a higher number of participants who found unique incompatibilities: that is, incompatibilities found by only a single participant. This happened 12 times in the Legacy method, and none for the CAM users.

When performing the unequal variance t-test to compare the incompatibilities found between the Legacy and CAM methods, the data resulted in the average number of incompatibilities for Legacy: m=7.47(4.70) sd=2.17 and CAM: 4.83(2.52) sd=1.59. The differences between the average number of incompatibilities (Table 20) is statistically significant (t=2.06, p=0.0012, N=27). The Legacy methods yielded more incompatibilities than CAM.

After analyzing the results of the methods and the findings, the data regarding attitudes toward the method, the time spent performing the method, and other user-oriented concerns from the participants were analyzed. The post-exercise survey captured many aspects of the process.

Figure 11 - Number of times that each incompatibility was found by participants

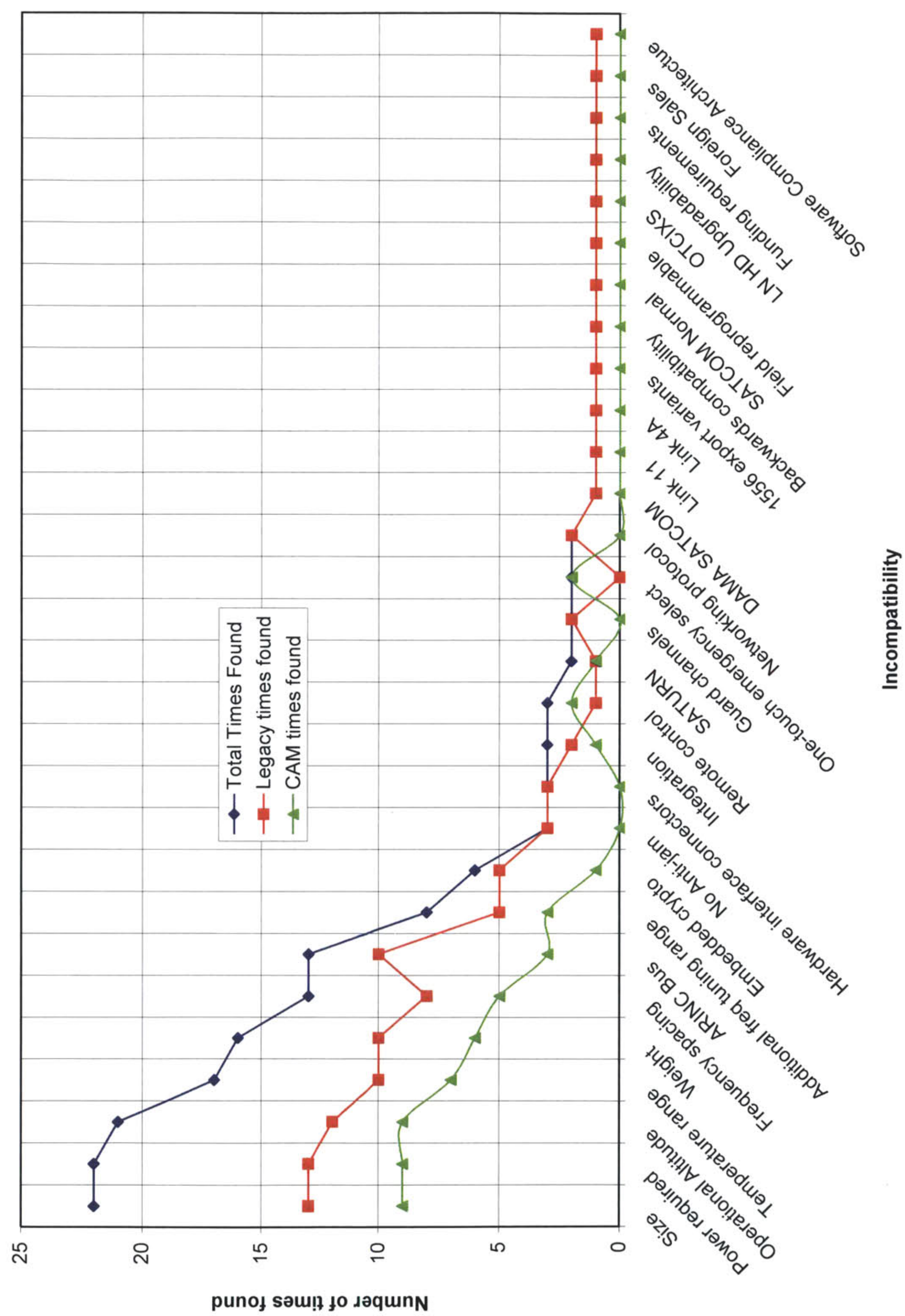


Table 20 - Comparisons between student findings using CAM and Legacy Methods

Participant	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15			16	17	18	19	20	21	22	23	24	25	26	27	
Incompatibilities found	Legacy																	CAM												Total Times Found
Size	x	x	x		x	x	x	x	x	x	x		x	x	x			x	x		x		x	x	x	x	x		x	22
more power required	x	x			x	x	x	x	x	x	x	x	x	x	x			x	x	x	x		x	x	x		x		x	22
Operational Altitude	x	x			x	x	x	x	x	x		x	x	x	x			x	x	x	x		x	x	x		x		x	21
Temperature range	x	x			x		x	x	x	x			x	x	x			x	x		x		x	x	x		x			17
Weight	x	x			x		x	x	x	x			x	x	x			x	x				x	x	x	x				16
Freq spacing	x	x	x	x			x		x		x	x							x			x				x	x		x	13
ARINC Bus	x	x	x	x				x	x	x	x	x			x											x	x	x		13
Additional freq tuning range					x	x	x		x		x								x						x		x			8
Embedded crypto				x		x			x		x		x									x								6
No Anti-jam				x			x				x																			3
Hardware interface connectors					x	x	x																							3
integration						x		x														x								3
Remote control											x											x			x					3
SATURN				x																								x		2
Guard channels		x		x																										2
One-touch emergency select																						x						x		2
Networking protocol									x			x																		2
DAMA SATCOM	x																													1
Link 11	x																													1
Link 4A	x																													1
1556 export variants	x																													1
Backwards compatibility			x																											1
SATCOM Normal				x																										1
Field reprogrammable				x																										1
OTCIXS				x																										1
LN HD Upgradability				x																										1
Funding requirements						x																								1
Foreign Sales						x																								1
Software Compliance Architectue						x																								1
																control	treatment													170
																15	12													
																Total	Total													
Number of incompatibilities	11	8	4	10	7	10	9	7	10	6	8	5	6	5	6	112	58	5	7	2	4	5	5	5	7	4	7	3	4	

Green box indicates the 12 differences that were designed into the experiment

Yellow box indicates significant differences [not proven statistically]

average	7.47	4.83
St Dev	2.17	1.59
Variance	4.70	2.52
Median	7.00	5.00
Table	able, df=25, p .05, t=2.0	
P-value	p=	0.0012

The first item of interest collected regarding the process was how long the participant spent on the exercise. The hours spent on the task ranged from 1 hour to 3.5 hours. The average time for all participants was 2.26 hours (with averages of 2.41 and 2.14 hours for CAM and LEM, respectively). The t-test applied to the differences in the average times was 0.38 which is not statistically significant ($t=0.90$, $p=0.38$, $N=27$) (Table 69). Specifically, there was no significant difference between the time the students used to complete the analysis in CAM or using Legacy methods.

The next question asked the participants whether they had the appropriate skills to perform the analysis. About half of the participants responded positively (6/12 CAM; 8/15 LEM), and the differences in response patterns between the two groups were not statistically significant. The most common reason given for not having the required skills was a lack of knowledge of the unmanned aircraft system domain and the radio communication domain. Better knowledge in this area would have improved understanding about some of the terminology associated with the communication systems; however, as the participants demonstrated, they were able to complete the experiment without a full understanding of the domain ($X^2(1)=0.0297$, $p <.05$).

Participants were not shown the alternative method performed until after the exercise and the post-exercise surveys were completed. When respondents were asked if they would use the same method again if given a choice, 5/12 of the CAM users and 9/15 of the LEM users were satisfied with the method they were assigned and would use it again. The CAM users did not want to repeat the same methodology because they reported the process took too much time and had too much overhead for the analysis they performed. The method satisfaction differences were not significant ($X^2(1)=0.54$, $p <.05$).

The next section asked participants to rank each of 11 areas (Table 21) on a 1-5 Likert scale ranging from Strongly Disagree to Strongly Agree (Table 22). Statement A results showed that CAM users were more likely to believe their analysis would be the same if another person performed the analysis ($U=59.5(49)$, $p>.01$, $n=27$).

Table 21 - The statements administered post-experiment to determine method preference

Statement	These are the statements used in columns A-K in the data above.
A	The results would be the same if performed by another individual.
B	I would get the same results if I repeated the method with the same information.
C	Performing this analysis was easy.
D	I have the appropriate skills to evaluate a sub-system to determine if it can be used as a replacement for a sub-system currently in use.
E	I have confidence that my assessment of compatibility is accurate.
F	Other system engineering students would get value from participating in this experiment.
G	I believe that my analysis would be valuable to the MQ-XX program office.
H	I believe the MQ-XX program office could make a decision on the RT-5959, based on my analysis.
I	CAM Users: I would recommend program offices adopt CAM as a standard practice.
J	CAM Users: CAM was a useful tool.
K	I would prefer a better-defined process to perform compatibility assessments.

Table 22 - Likert-scale responses for the post-experiment analysis

These are the response choices for the statements above	
Rate the statement using the following scale:	
	(1) Strongly disagree
	(2) Disagree
	(3) Neither agree nor disagree
	(4) Agree
	(5) Strongly agree

Student Participation Hypotheses

The null hypotheses for the Student Participant Exercise were that the test variable would be the same for CAM and Legacy methods. The null hypotheses also tested non-parametrically for medians and distributions across the paired methodologies. SPSS was used for the Mann-Whitney U-test for the distribution analysis and the Independent Samples Median Test for determining differences between the medians. The statistical reports and related charts can be found in Appendix H.

The questions in Table 21 were posed as hypotheses and tested to determine if significant differences between the responses between the two groups existed. At $\alpha = 0.10$ significance levels, 8 of the 11 hypotheses were found to be not statistically significant. While each of the hypotheses is presented here, only the significant results will be addressed in the text. For the complete data set, refer to Appendix H.

Ease of method H_o: The participant-reported ease of completing the exercise was the same between the CAM and Legacy method participants.

Confidence in value H_o: The participant-reported confidence in the value of the exercise output was the same between the CAM and Legacy method participants.

A H_o: The participant-reported confidence that another person would get the same results if using the same method was the same between the CAM and Legacy method participants.

B H_o: The participant-reported confidence that he or she would get the same results if using the same method was the same between the CAM and Legacy method participants.

C H_o: The participant-reported assessment of the ease of the exercise was the same between the CAM and Legacy method participants.

D H_o: The participant-reported confidence in having the proper skills to perform the analysis was the same between the CAM and Legacy method participants.

E H_o: The participant-reported confidence in result accuracy was the same between the CAM and Legacy method participants.

F H_o: The participant-reported other students would get value from performing the exercise was the same between the CAM and Legacy method participants.

G H_o: The participant-reported confidence that the result would be of value to the program office was the same between the CAM and Legacy method participants.

H H_o: The participant-reported belief that a program office could make a decision based on the analysis was the same between the CAM and Legacy method participants.

K H_o: The participant-reported desire for a better-defined process to perform compatibility assessments was the same between the CAM and Legacy method participants.

Table 23 - References to Statistic Results from SPSS analysis

Null Hypothesis Reference (hypothesis, test, line from table)	Decision a = 0.10	Table Reference	Supporting Graphic
A, Distribution, 13	Reject	Table 73	Figure 36
A, Median, 14	Reject	Table 73	Figure 37
B, Distribution, 15	Retain	Table 73	Figure 38
B, Median, 16	Retain	Table 73	Figure 39
C, Distribution, 17	Retain	Table 73	Figure 40
C, Median, 18	Retain	Table 73	Figure 41
D, Distribution, 19	Retain	Table 73	Figure 42
D, Median, 20	Retain	Table 73	Figure 43
E, Distribution, 21	Retain	Table 73	Figure 44
E, Median, 22	Retain	Table 73	Figure 45
F, Distribution, 23	Retain	Table 73	Figure 46
F, Median, 24	Retain	Table 73	Figure 47
G, Distribution, 25	Retain	Table 74	Figure 48
G, Median, 26	Retain	Table 74	Figure 49
H, Distribution, 27	Retain	Table 74	Figure 50
H, Median, 28	Reject	Table 74	Figure 51
K, Distribution, 33	Reject	Table 74	Figure 52
K, Median, 34	Retain	Table 74	Figure 53

Of the 18 null hypotheses (9 for median analysis and 9 for distribution analysis) related to the participant survey data, only four of the hypotheses could be rejected. The remaining null hypotheses should be retained. For brevity, only the reject decision data is presented here. For a complete analysis, refer to the tables and figures and shown in Table 23 - References to Statistic Results from SPSS analysis.

As depicted in Table 23, the null hypothesis that the distributions and medians were the same could be rejected four times. The rejections for null hypothesis "A" suggests the distributions and medians for participant responses regarding that other people would find the same incompatibilities if they used the same method are not the same. Table 23 shows the distributions of responses are higher and more consistent for the CAM users than the Legacy method users. The CAM users (*Mdn* = 4) were significantly more confident that the same answer would be found by someone using CAM than the participants using alternate methods (*Mdn* = 3), $U = 50.5$, $z = -2.02$, $p < .1$, $r = -.423$ (medium effect size).

For the null hypothesis "H" on line 28 of Table 23, that the medians are the same for the program office being able to make a decision based on the participants' analysis, the null hypothesis can be rejected. The CAM users (*Mdn* = 3) were significantly more confident that their analysis would be valuable to the program office than the participants using alternate methods (*Mdn* = 2), $U = 64.5$, $z = -1.298$, $p < .1$, $r = -.389$ (medium effect size). In addition to the median analysis, the distributions were analyzed to learn about the similarities of the data dispersions of the results. The dispersion can be studied via statistical analysis and by visual inspection.

The final comparison measured the differences in the numbers of incompatibilities found using each method (Table 78, Null Hypothesis K). The stylized case study exercise was developed and seeded with 12 specific differences between the RT-1556 and the RT-5959. For this portion of the exercise, the participants used free text on the data reporting table to describe in their own words the compatibility that was being reported. With the lists from each respondent, the researcher coded into categories the participant-supplied descriptions of the compatibility issues. This allowed for grouping the repeated reported compatibilities into categories, the differences of which were analyzed and reported. Participants' reports ranged from a low of 2 incompatibilities found, up to a high of 14. The CAM participants found an average of 5.25 incompatibilities, while the LEM practitioners reported 8.47. The t-test showed significant differences between the reporting of the CAM and LEM users in this category ($t=-2.85$, $p=0.01$, $N=27$).

A paired-samples Welch's t-test was conducted to compare the number of incompatibilities found by participants based on the use of Legacy methods and using the Compatibility Assessment Method. There was a significant difference in the scores for Legacy ($M=8.47$ incompatibilities found, $SD=3.56$) and CAM ($M=5.25$ incompatibilities found, $SD=2.26$) conditions; $t(24)=-2.85$, $p = 0.01$. These results suggest that CAM users find fewer incompatibilities before stopping their analysis than Legacy method users find.

Summary

The Compatibility Assessment Method (CAM) is intended to be a screening tool for program offices to analyze the feasibility of a proposed upgrade system, but this tool is not expected to be the final answer when used at this high level. The results of this academic-environment experiment gave mixed results for the value of CAM in a surrogate program office environment. While no universal findings can be reported with the limited sample size and participants in the study, some trends can be reported.

Time: CAM took slightly longer for the students to perform the analysis. The difference between the two methods was on the scale of hours with is categorically better than the months and years of the real-world performance. This finding was supported by the students' reports that CAM was too complex, and directed the use of too much overhead in the form of matrices for the relative simplicity of the system they analyzed.

Ease: CAM was slightly harder for the students to perform than LEM. This finding is related to the amount of time that the process required.

Confidence: No significant differences were reported by the student groups. The confidence they had in their results was independent of the methodology that was used.

Repeatability: CAM users reported their results would be the same if someone else repeated the assignment. LEM users did not report the same confidence that others would draw the same conclusions that they found.

Confidence in skills: CAM users reported more confidence in their skills to perform the tasks required for compatibility screening between two subsystems. LEM users had less confidence in their skills to perform the task; this could be the result of a structured method that led users through a complete process for the CAM users.

Method preferences: LEM users reported they would have preferred to use a more structured method. They generally wanted more instruction and a method to follow to get to a conclusion.

Incompatibilities found: This finding is a candidate for additional research. LEM users found significantly more incompatibilities than the CAM users; the reason behind this is unknown. One conjecture is that the CAM users were better able to determine the severity of the differences, and when they found a difference they deemed to be a show-stopper, they may have stopped. Several people from each group did report they thought they found all of the differences between the systems. No participant found all the seeded differences.

After the participants completed the experiment, they were asked if they felt that the results would be the same if another practitioner performed the analysis. The CAM participants had a higher confidence that the process would be repeatable. The null hypothesis that the means are the same was rejected.

The second question addressed the ability of the participant to attain the same results with the same information presented. Both groups of participants reported they would be very likely to be able to get the same results if they repeated the exercise.

Similar to the results of the Likert survey regarding the repeatability, the participants' reports had no statistical difference in their feeling that the analysis was "easy".

When the participants were asked if they had the appropriate skills to perform the task, the CAM participants reported slightly higher confidence in their skills than the Legacy cohort, but the difference was not statistically significant.

When asked to report their confidence of the accuracy of their assessments, the Legacy group reported a higher average accuracy than the CAM group, however, in neither case was a significant difference found.

To help determine if the exercise was of value to students in a systems engineering master's degree program, the participants were asked to rate the value of the experiment as a class assignment for future classes. Neither of the cohorts had a significant difference in recommending adopting this type of experiment into the curriculum.

Neither cohort showed a strong belief that their work would be beneficial to a program office that would be performing this type of analysis. In discussions with the participants, most felt they did not have the domain knowledge necessary to benefit a program office. Participants expressed that they were not comfortable in either the domains of the air vehicle or the radio communications systems.

Neither of the groups believed the information they provided would be decision-quality information that could be used for making a decision. However, at the same time these participants were using CAM, a program office was adopting its use for subsystem upgrade project managers.

When four of the student participants were interviewed about their participation, they presented information that potentially biased the findings. First, when asked about how they developed stopping rules, some indicated they stopped when they felt they had "enough" incompatibilities to show the compatibility issues prevented component substitution. Other comments indicated this was addressed as "another homework assignment" and that assignments usually took about 3 hours so they budgeted about 3 hours to perform the tasks.

Future student research

While some of the student participant results were unexpected and could not be resolved, more insight could be gleaned by repeating studies with student participants. Some of those suggestions follow:

- The sample cohort could be expanded to a larger sample size.

- Sample students from other services and academic institutions.
- Consider measuring the time to find a complete set of incompatibilities using control and treatment methods.
- Determine what types of compatibilities CAM is biased to discover.
- Increase the complexity of the problem and have student participants perform a new problem.

Conclusions

The experiment in this chapter was designed to gain additional insights into the execution of the CAM process and compare the outcomes with the output of unstructured, legacy methods of determining compatibility. A stylized case study for upgrading radio systems on an aircraft was developed and seeded with incompatibilities for the exercise. The case study was used as a common task for the pair of methods. The participant cohort was comprised of system engineers and their ability to perform the method supported the usability of the CAM methodology by potential program office practitioners. Upon completion of the experiment, the students were given a survey to capture quantitative and qualitative aspects of finding incompatibilities using the pair of methods.

The participants identified a range from 2 to 16 incompatibilities. Even though there were no statistical differences between the groups with respect to experience, longevity, and grade point averages, the cohort that used the unstructured method found more incompatibilities than the CAM cohort and also spent less time on the assignment. In addition to the quantitative data collected, participants also completed a 5-response Likert-scale survey to capture their qualitative impressions of their work. Of the 11 statements the participants were asked to rate, three of them received significant statistical differences between the methods. CAM users were more likely to agree that the results would be the same if another individual performed the experiment. When asked if the participants agreed with the statement that a program office could make a decision on their recommendation, the CAM participants responded more agreeable than the others. Finally, when asked about their agreement with desiring a better-defined process, the Legacy cohort wanted more structure than the CAM participants. The CAM participants commented that the method they used carried too much overhead for how simple the stylized case study was.

Overall, the student cohort exercise offered a demonstration that the skills required in a program office to perform subsystem upgrades on and aircraft exist in the system engineering graduate students. This conclusion indicates that CAM would be within the abilities of assigned program managers and engineers who would be assigned to program offices after their education at AFIT.

The participants who used the legacy, unstructured method found more incompatibilities than those who used the structured method, CAM. Because they did not identify and report unique incompatibilities, the CAM users were more consistent in their findings. The CAM users were less likely to discover incompatibilities that were hidden. The CAM group missed incompatibilities that were not space, weight, and power centric. They failed to identify embedded incompatibilities such as human interfaces and software issues.

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Chapter 6 – Conclusions and future work

On the path to developing the Compatibility Assessment Method (CAM) that uses an architectural approach to analyzing differences between currently employed components and proposed alternatives, this research characterized and generalized unmanned aircraft systems architectures and developed a proposed common taxonomy for functions that unmanned aircraft systems perform. Next, potential practitioners were engaged to determine the extent of Air Force program managers' skill sets that could be applied to assessing the differences between systems. Through a series of exploratory interactions with research participants in program offices and design functions, the CAM process emerged. CAM was next tested by practitioners in program offices with favorable results. Further attempts to identify the value of CAM by using a cohort of graduate students yielded mixed results with some of the students preferring the structure of CAM while others found unstructured methods to be faster to perform.

This research was originally conceived to develop a method to identify candidate subsystems that could be used to increase commonality across systems. The need for increasing commonality was discovered through corporate policy to increase commonality, improving the logistics tails of systems by decreasing the number of unique end items to support, and gain price decreases through increased economic order quantities. Through the course of the research, the concept of commonality was discovered to be too restrictive for the use of the method that was developed. By expanding the scope of the method application, additional uses for the method were identified. Without the constraint of focusing on increasing commonality, potential systems that could be analyzed were expanded.

The final instantiation of the research was designed to develop and test a process to assess compatibility issues related to replacing a current, or baseline, component with a proposed replacement component. The research was successful in developing a method, the Compatibility Assessment Method (CAM), which extended the functional activity modeling of IDEF0 to assess compatibility between subsystems. The domain of the research was selected as unmanned aircraft systems (UASs) because of their rapidly-increasing numbers and investments by the Department of Defense in the systems and their capabilities. Several major UAS programs were developed under rapid acquisition schemas with the emphasis on fielding systems and not the systems engineering that would develop an integrated plan for multiple system development. As some of the systems are now being upgraded, the opportunity for increasing commonality across systems is now available. This increase in commonality can be affected through policy and the use of methods to assess the compatibility issues associate with subsystem replacement. The research developed a process that was successful in analyzing potential replacement components in several scenarios.

Review of the research steps that were taken

The research that resulted in the operationalized Compatibility Assessment Method (CAM) to determine the feasibility of replacing a child subsystem on a parent system, started with a variation of action research that went to practitioners in Air Force program offices and industry that had needs to upgrade subsystems in their larger, complex systems. None of the practitioners knew of an efficient, structured method of assessing the compatibility of a proposed system change. This research sought to determine if the information captured in systems architecture representations would provide insight into compatibility issues.

The organizations with identified needs for performing upgrades were engaged in exploratory case studies. These cases began by using the IDEF0 taxonomy to describe the functions of systems. Through the course of performing these exploratory cases, the IDEF0 method was expanded and extended into a process that was named the Compatibility Assessment Method (CAM). CAM presented practitioners a set of tools and a process to capture the characterization of systems by comparing the respective Inputs, Constraints, Outputs, and Mechanisms (ICOMs). With the ICOMs documented, the differences between a current and a proposed system could be calculated. After CAM became stable in its configuration and method, government program managers were engaged to perform CAM on a sample of actual applications. Their results were evaluated and compared to control cases provided by the participants' organizations. The process was deemed to be of value to program offices that were performing subsystem upgrades on their larger systems.

After the practitioner participant study was complete, a sample of graduate systems engineering students participated in a project that compared the method of CAM with the unstructured methods that could be expected to be performed without other guidance. The results of this study were inconclusive regarding the efficiencies of the method. However, the participant cohort who used the proposed CAM method found lower average numbers of incompatibilities per participant than unstructured methods. The reason for the differences in means was not able to be determined. To resolve the difference in performance between the practitioners and the students, an extended study of practitioners is recommended to determine if more program offices would embrace the method as warmly as the two offices that participated in the experiment.

The engagement with the program offices confirmed a need for managers to be able to perform high-level assessments to determine compatibility when a replacement system is proposed. Using CAM in a program office assessment averts study contracts that are costly in terms of personnel workload, offers results that do not have unknown motivations, and are completed in hours instead of months.

Answers to research questions

The research questions posed at the beginning of this thesis have now been answered:

- How can subsystem information embedded in system architectures be formally represented?

The subsystem information embedded in system architectures can be formally represented by extending and modifying the IDEF0 taxonomy from FIPS 183. The functions can be described by the arrows of ICOMs, which can be represented in a compatibility assessment matrix. The CAM matrix representation provided a method to describe systems based on their functions and their ICOM arrows.

- How can these representations be used to evaluate potential subsystem upgrades?

The CAM matrix representations can be used to evaluate potential upgrades by performing operations on the CAM matrices. The operations include developing a Delta Matrix that shows the extent of the differences between the proposed and baseline systems. The Delta ICOM matrix calculations provided a mechanism to display the differences between systems and highlight the areas of significant integration concerns.

- Is there a more effective way to plan subsystem upgrades and is a proposed approach better?

Yes, a more effective way has been shown to plan subsystem upgrades, which also appears to be a better approach. Practitioners were able to use CAM to determine the compatibility feasibility associated with an upgrade quickly and with low overhead. The result was that practitioners were able to identify the difficult integrations associated with an upgrade. However, the CAM tool should not be the final decision-maker. Current use of CAM should be limited to being a screening tool and the current levels of abstraction. Additional study should be undertaken before using CAM in other applications and abstractions.

Comparisons

The research performed to determine if a screening tool could be developed and then determining its value was conducted with practitioner project managers and a student cohort of systems engineering students. These separate groups allowed several axes of comparison between the methods and the participants.

Project managers

When project and program managers used the proposed Compatibility Assessment Method (CAM), they indicated that the structured method improved insights into the systems they manage. They were able to discover information they needed about their systems to inform system acquisition decisions. They were able to use the method to report findings to their decision-makers. The CAM results, which were developed as a screening tool for project managers, did not get to the detail that contracted study contracts reported. The project managers focused on size, weight, and power (SWaP) concerns. Because the project managers normally focus on cost, schedule, and system performance of the upgrades they manage, there should be little surprise that they performed CAM at a high level of abstraction that precluded the level of detail that a contracted study including a detailed engineering analysis engaged.

Students

The students who participated in the experiment to compare the radio systems had varied backgrounds. Those without experience in system acquisition doubted their ability to perform a useful recommendation. Another aspect of their participation was the bias induced through their lens of being students—this project may have been performed as a homework assignment instead of an acquisition project. This could have provided stopping biases based on the amount of time they spent on the project. Also not captured was the heuristics they used to determine when they were "done" with the exercise. With the students using the structured CAM method finding significantly fewer incompatibilities than the students using the unstructured, legacy methods, the participants created an uncommunicated stopping rule. Why the stopping rule was implemented after fewer finds for CAM than legacy is unknown. The student CAM participants did express concern, however, that the CAM process required too much overhead for a task that was simple enough to complete without a method.

Project managers to students

Some commonalities emerge when the results of the project managers and the student participants are compared. Both the student participants and the project managers put focus on the

SWaP compatibility issues. This could be expected because they are the easiest parameters for visualization and development of quantitative comparisons.

The time spent on CAM was similar between the students and the project managers. However, the project managers were able to experience a learning curve effect where their subsequent iterations were shorter durations than the earlier trials. The students did not have the repetition to experience learning curve effects.

One significant difference between the project manager and the student groups was their commitment to the need for a method. The project managers could immediately embrace the need for a structured process they could perform in a matter of hours to screen the viability of a replacement system. The students spent about 3 hours on the project and were ready to be done with just another homework assignment. The project managers looked to CAM as a useful tool and the students wanted a grade on the assignment. The students did not have the immediate compelling need to perform compatibility assessments outside of academia—in fact, some of the students had never been professionally employed outside of time of being students. Project managers sought CAM as a solution to their on-going workload. The CAM solution gave them a structured process to perform a previously ill-defined process with little trust in the outcome.

Problems encountered during the research

Many of the problems of the method were addressed during the method development phase of the research. As research participants used the method they identified shortcomings and recommended improvements. These shortcomings were addressed by expanding the scope of CAM to include the elements of stakeholder analysis, severity codes for identified incompatibilities, and the additional research that developed CAM Cost to augment the model with a cost analysis capability.

One problem that appeared was the selection of constraints for the model. If inappropriate constraints were selected, the differences between the systems may not have been identified and the incompatibilities may not have been captured in a meaningful way. The selection of constraints gravitated toward size, weight, and power [SWaP] issues which were identified by the two program managers as being the primary concerns when making form-fit-function replacement decisions. While practitioners identified the SWaP constraints during experiment participation, the selection of SWaP constraints was not formalized. This formalization could emerge through continued application of CAM. Currently, the limited domain of unmanned aircraft systems precludes the elimination of other categories of constraints. Future research in domains outside of aviation could lead to other constraints.

Because of limited availability of practitioners in program offices to participate in the application of CAM, a student cohort was used as a research sample. This sample allowed comparing CAM to unstructured analysis methods, but without the deep domain knowledge and urgency of an immediate problem to solve. The selection of a student cohort as participants in a comparison between CAM and unstructured methods revealed unexpected findings. This could be resolved by engaging a larger practitioner cohort. The challenge of finding the larger cohort is the access to programs and the program managers' availability.

Application to practitioners

The results of the action research based experiments reveal that there exists a need for a structured analysis method to analyze compatibility of proposed components into a parent system. CAM does not delve into the compatibility issues at the same depth as a contracted, multi-man-year study. However, practitioners' responses suggest that the structured nature of CAM provides value as a screening tool that can be performed by existing program office staff in a short period of time. While all technical aspects of the replacements are not explored through CAM at the program manager level, the gross differences are captured in a useful manner. While the applications were performed at a high level of abstraction, CAM could be explored at a lower level of the system architectures to extract the finer technical details.

The employment of CAM instead of ad hoc, unstructured legacy methods of evaluating alternative replacement subsystems, gives the practitioners a structured, repeatable process that reveals insights to compatibility issues in hours for very low cost instead of months or years of expensive study contracts. While CAM applied at the highest levels provides a screening tool that could inform managers of insurmountable incompatibilities, if the problems are decomposed to lower levels, detailed insights may provide the deep information needed to transition CAM from a screening tool to a total analysis system.

Potential future research

In addition to the recommended research to improve the characterization and selection of constraints and operationalizing CAM with an improved instruction set, research should be performed to use the functional activity modeling as a basis for metrics that could be used to measure compatibility. These metrics could be scalars that could combine several aspects of compatibility in a single number. However, when multiple dimensional measures are combined, the resulting number is difficult to interpret. For this reason, a vector representation may be the better reporting tool for compatibility. Each component of the vector could be aligned with individual stakeholder's concerns. For example, a vector could include a value for changes to the parent system required, electrical component incompatibilities, component size differences, and capability deltas. Each of these vector components addresses concerns of a different component of stakeholders. The concept of vector components to report architecture characteristics guides system architect research away from finding a single number to describe architectures. The research could be expanded by determining the important aspects of architectures and developing metrics for these aspects. With multiple measures developed and reported in a vector format, system designers can develop trade-offs for implementing compatibility in system design.

The value proposition of CAM does have a sweet spot in the ECP process. By expanding the acronym ECP to Engineering Change Proposal we can see that the ECP is driven by change and CAM is a tool to assess the compatibility of the objects in the change. In addition to CAM being used as a tool during ECPs, further research could be conducted to learn how CAM works at higher levels of abstraction. One question to answer would be "Can CAM be used to analyze the addition of a new system into the warfighting enterprise?" This case could be seen when a new aircraft is proposed. CAM could then be used to understand the external systems diagram and all the related interfaces of the proposed system as compared to current capabilities.

The entire acquisition system is displayed on the Integrated Defense Acquisition, Technology, & Logistics Life Cycle Management Framework chart (DAU 2005) (Figure 13) and there are many points where CAM could be applied. The subsystem upgrade capabilities of CAM are found at the right side of the chart which is later in the acquisition life cycle. Fielded systems and fielded systems undergoing upgrades are on the chart's right. Other points of entry include Analysis of Alternatives (AOAs) where several systems or subsystems are compared for potential acquisitions. Potential points of inserting the CAM process are circled in red. Because the potential points are characterized by differing levels of conceptual abstraction, they should be addressed through controlled experiments before adopting the process at these points by a practitioner.

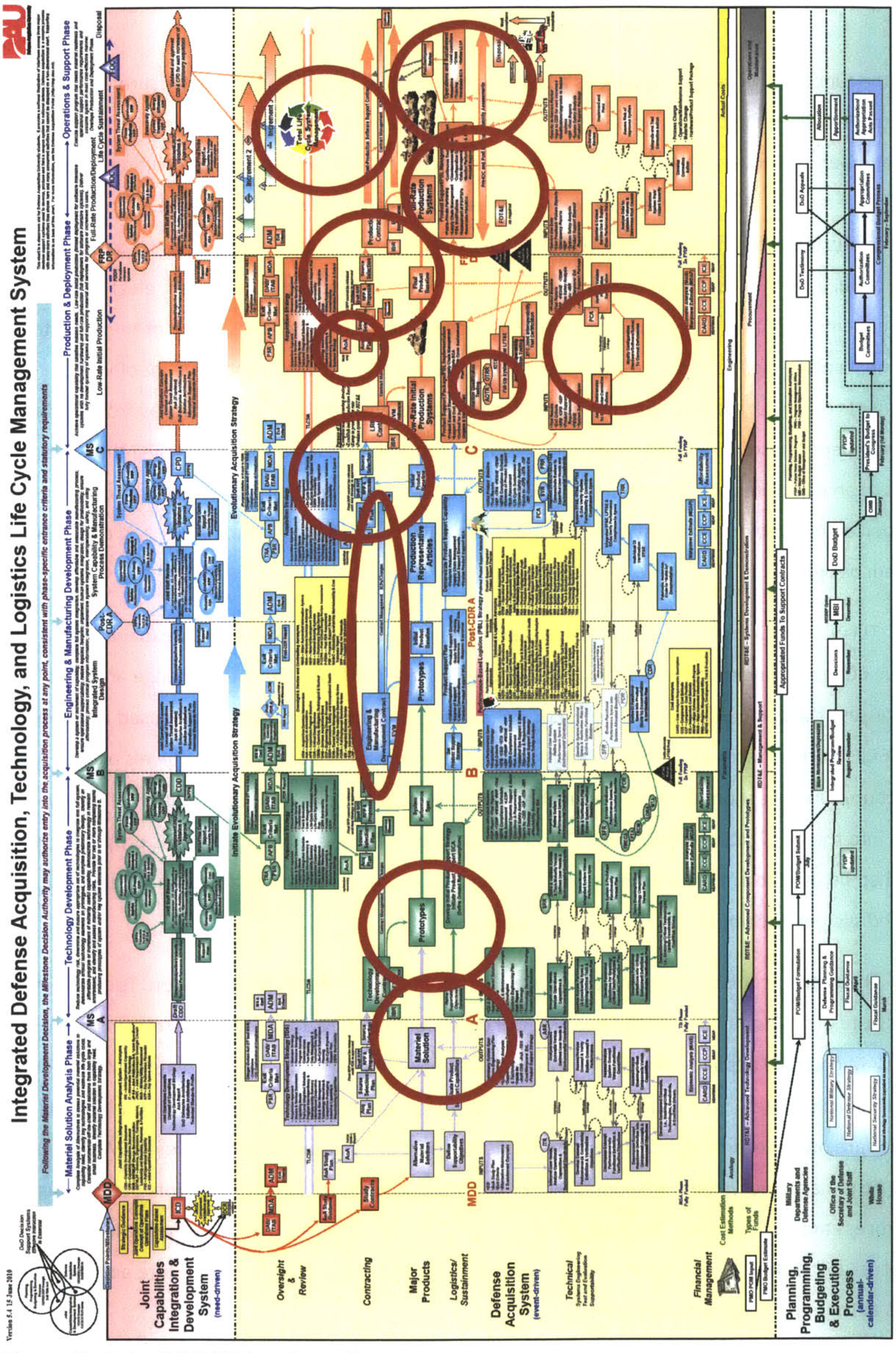

Figure 13 - Potential CAM insertion points

To make CAM more effective, the method should be operationalized and tested with several more program offices. The updates to operationalize CAM would include improved formatted data collection tools and matrices and cookbook-style directions that are clear for the practitioner.

Future development of CAM should help improve the instruction set for employing CAM so that an expert user would not be required for method execution. This improved instruction set would be constructed through management students performing acquisition research. These students would likely be identified for program management positions in their post-academic assignments in the Air Force.

One aspect of the original concept of CAM that did not exist and was not explored as part of this research was the addition of a cost element that could be associated with the differences between the current subsystem and the proposed subsystem integration and operation. Program managers in the exploratory and the development processes identified a need for a cost aspect. This cost view was explored in an independent research thesis by a cost analysis graduate student. The resulting "CAM Cost" model showed promise and should be explored on a variety of systems.

Another potential use for system architecture models similar to CAM has appeared. The Air Force uses Modular Open Systems Architecture (MOSA) as a design constraint for systems. Program managers have a tool that allows assessment of a system to determine the degree of MOSA implementation in a program. However, the program managers are finding that the systems are not as "open" as the specifications require. Systems are found to have embedded proprietary interfaces which undermine the intent of MOSA. Program managers need a tool to assess the implementation of MOSA throughout a system. An extension of IDEF0 based on the functional decompositions, mapping to form, and reconstituting the functions to a chunk may give program managers insight into the instantiations of MOSA. The arcs and information developed for CAM could possibly be used with MOSA in mind. The sparse matrix could be constructed and each of the arcs could be evaluated for openness.

Other models have been developed for system architecture manipulation and understanding. Some of these models could be extended to include CAM as a module to add additional capability or insights. OPM is an executable modeling language that allows architectural simulations. The power of OPM lays in its ability to model complex processes that take into account many agents and operands. At the highest levels, OPM is an executable model that models dynamic processes while CAM is a static model that captures the inputs, outputs, and non-functional attributes of a system that performs a function. However, CAM can be extended to complement OPM on a lower level. One of the lower levels of OPM includes a "STATE" attribute of the systems represented in OPM. While the OPM state representations allow for categorical states, discrete variables, and numerical ranges for continuous variables, CAM representations of systems that perform functions could be used to more completely describe the state of the system.

Research Contributions

The research that was performed in the development and execution of CAM provided several contributions to the communities of system architecting and program management practitioners. The contributions both extend knowledge of systems architecting and provide practitioners a new set of tools to screen subsystems for compatibility and feasibility of subsystem substitution. Contributions of this research apply to both the theory and the application of system architecture models to address compatibility issues related to subsystem replacement.

- The determination that because of their varied educational and experiential opportunities, all Department of Defense program managers will be able to perform technical analyses with different levels of competency.
- The IDEF0 taxonomy that is formalized in FIPS 183 continues to be useful and can be extended for additional uses beyond the currently-practiced applications.
- The CAM capability is offered to any community that has a need to compare systems for compatibility for application in a larger parent system.
- Performing functional decompositions until low levels of functionality were revealed allows mapping from functions to form. In these cases, the functions did not always map cleanly from one function to one module. However, the mappings could be adjusted by moving up and down the continuums of functions and modules to find direct mappings. The physical modules that were identified could reside in chunks or subsystems. This was found as the baseline for identifying the compatibility for subsystem substitution.
- After appropriate functional decompositions and reconstitutions to correctly identify the functions that mapped to the form, the information captured in the IDEF0 extensions enabled determinations of compatibility between the implementation of similar function sets.
- For applications to program managers in the Air Force, we now know that the program managers can perform compatibility assessments in a matter of hours instead of relying on lengthy and costly contracted or internal studies.
- We also now understand that the extensions of IDEF0 beyond the configurations proposed in FIPS 183 can be applied in multiple communities. CAM, the IDEF0 extension, was demonstrated on multiple complex systems in industry and military systems.

The research project concluded with a contribution of a system architecture based functional activity model, CAM, that has demonstrated potential worth to program office operations. Because organizations outside of Air Force program offices have needs to evaluate integration differences between current and proposed subsystems, CAM should be operationalized and provided to military and commercial organizations to provide a structured method to the task of assessing compatibility between subsystems.

Summary

A method for using the information contained within system architecting models has been proposed as a new process to evaluate compatibility of a proposed replacement subsystem with the existing system. The need for this capability, proposed here as CAM, has been discovered in industry and Air Force program offices as both segments strive to upgrade capability on existing product lines. The upgraded capability is the result of replacing modules that bring in updated or expanded functionality. The Compatibility Assessment Method (CAM) unleashes the information captured in system architecture models and organizes the inherent information to identify areas of incompatibility. CAM was informed by exploratory studies with potential users, used by practitioners in potential deployment scenarios, and then tested in an academic setting against unstructured methods by student participants who are potential future users of CAM.

Each of the areas of studies revealed favorable results. The exploratory research showed a need for a method to assess compatibility and helped shape the extensions of the base IDEF0 model. The practitioners were able to learn about compatibility of proposed systems in a matter of hours instead of the months and years they were to expect. The method was deemed valuable to program office operations and was embraced by senior program managers who directed institutionalizing CAM in their offices. Finally, the student cohort was able to perform CAM from open source research and identify areas of incompatibility based on the information provided in a stylized case study.

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Appendices

Appendix A – Discovering physical architectures of UAS

This appendix is organized in three sections. The first section describes UASs and explores their physical architectures. The second section recognizes that a common taxonomy does not exist for UASs and describes a method that was used to develop a proposed functional taxonomy. The third section reports the attempts to determine the capabilities of Air Force program managers and their abilities to perform system analysis on UASs.

What is a UAS?

The Department of Defense defines an Unmanned Aircraft System, or UAS, as a powered, aerial vehicle that does not carry any human operator, uses aerodynamic forces to provide vehicle lift, can fly autonomously or be piloted remotely, can be expendable or recoverable, and can carry a lethal or non-lethal payload. Ballistic or semi-ballistic vehicles, cruise missiles, and artillery projectiles are not considered unmanned aerial vehicles (Chairman of the Joint Chiefs of Staff, 2001). Removing the pilot from the air vehicle saves personnel costs, prevents injury or capture, facilitates upgraded digital communications and allows designs for smaller radar signatures. While pilots will be in cockpits for many years to come, for many missions, unmanned aircraft will be the superior weapon (Barbato, 2000).

While electro-optic, infrared, and synthetic aperture radar sensors have been the primary payloads for UASs in the DOD so far, many other mission areas are open to UASs. Many other payloads have been demonstrated in proof of concept demonstrations that include command and control, force protection, signals intelligence, combat search and rescue, theater air missile defense, meteorology and oceanography, counter narcotics, and others. UASs are brought into missions for several reasons. A primary focus is to remove the human operator from aircraft cockpits for dull, dirty, and dangerous missions. Another focus is that UASs are considered expendable vehicles because of their traditionally relatively low cost (Office of the Secretary of Defense (Advanced Technology and Logistics), 2005). The Air Force Small UAS Roadmap shows UASs as low-cost force multipliers that expand the battle space and multiplies a small team's area of influence (Hasagawa, 2005) that have proven successes in observing, tracking, targeting, and striking their targets ("Unmanned Aerial Vehicles: Major Management Issues Facing Dod's Development and Fielding Efforts;" 2004).

Military UASs are designed for use to provide surveillance, relay communications, attack a target, or transport cargo. In addition, commercial uses of UASs include surveillance, transportation, and applying chemicals to crops. Future uses of UASs are limited only by physics and developers' imaginations. Currently, UASs are used primarily for missions with low complexity and low likelihood of threats encounter. In contrast, manned aircraft are used in roles with high mission complexity and a large range of the likelihood of encountering a threat. As UASs increase in their capabilities, they are expected to take on missions with more complexity and in higher threat environments (Pinney, 2003). While some might believe that UASs are cheaper to operate than manned platforms, reports indicate that when a manned and unmanned platform with similar capabilities are compared, the unmanned vehicle is often more expensive to operate because of the additional costs of satellite communications to operate remotely (Kopp, 2006).

A UAS interacts in many operational battlespace architectures. The UAS has interfaces with communications, bandwidth, information, data collection, global information grid, software compliance, air space, operational, and many other elements of warfighting. Each of these domains has its own stakeholders, associated rules, and expectations. However, the capability provided by UASs is increasing in importance in the warfighting architectures. In that sense, the UAS is a module in the warfighting system. One of the goals for UASs is to develop a standard architecture for them that includes weapons interfaces (Office of the Secretary of Defense (Advanced Technology and Logistics), 2005).

Many classification structures for UAS have been proposed, adopted, and then abandoned for other ways classifying UASs. Some classifications refer to system attributes such as airspeed, weight, or operating altitude. The Joint Unmanned Aircraft System Center of Excellence (JUAS COE) categorizes systems as Tactical, Operational, or Strategic depending on their mission, payloads, weight, and endurance. When aligned by the FAA regulations, another categorization system emerges: Cat I, Cat II, and Cat III. These categories are based on the FAA regulations that govern their operation, airspace use, and airspeed. Another common ontology is High Altitude Long Endurance (HALE), Medium altitude Long Endurance (MALE), Micro, Mini, and Vertical Take Off and Landing (VTOL).

Research Methods and Analysis

To learn about unmanned aircraft systems, a study procedure was developed and exercised on multiple systems. The process included selecting an appropriate system for analysis, determining the physical architecture of the system, and then generalizing the physical architectures for the systems studied. After the architecture was generalized and documented for the sample of 12 UASs, a deeper exploration of the Global Hawk system was performed to learn about its architecture, system operations, functionality, and stakeholders. Here is the 12-step overview of the top-level procedure followed in this research:

1. Selected potential study system
2. Developed schematic architecture representations for 12 systems
3. Generalized the architecture for many systems
4. Selected a single system (Global Hawk) for initial in-depth study
5. Temporal operational system representation was developed and compared to the DoDAF functional decompositions
6. Developed function to function DSM
7. Populated binary DSM with information flows in the GH system
8. Developed DSM architecture representations at multiple abstraction levels
9. Calculated modularity metrics and compared results
10. Mapped the form of the Global Hawk system to its functions
11. Performed stakeholder identification, mapped stakeholders to functions, and analyzed distribution of stakeholders
12. Developed Automation Levels of Control DSM to characterize the information flows between functions

The first step was to select an initial study system to study to gain an understanding of Unmanned Aircraft System architectures. The architectures will be analyzed to learn additional insights about the UASs and architectures.

The analysis process began by collecting data on a single UAS: Global Hawk. The Global Hawk was used to develop study methods, exercise processes, and learn about the output of various analysis tools. Following the methods used on the Global Hawk, additional study systems will be included that will allow the possibility of finding trends and generalizing results to addition systems.

Within the domain of UASs, the research process started with a study of architectures, analyzing the architectures with a focus on properties of modularity, and then early application of modularity to systems automation. Future research is planned to look at finding and analyzing UAS automation modules in systems and managing modules of automation to improve the results of the acquisition process for UAS.

Preliminary research

An initial cluster sampling of UAS systems was taken from the DoD UAS Roadmap. Systems were selected based on the availability of data in the roadmap. Within that sampling frame, UASs were selected from multiple services and multiple DoD UAS categories. Unmanned airships, including aerostats and blimps, were not included in the sample. Systems were selected in a way to ensure major, small, and special operations systems were surveyed. After selecting 12 systems for further analysis, a physical architecture was developed for each of the systems based on the roadmap and open source data.

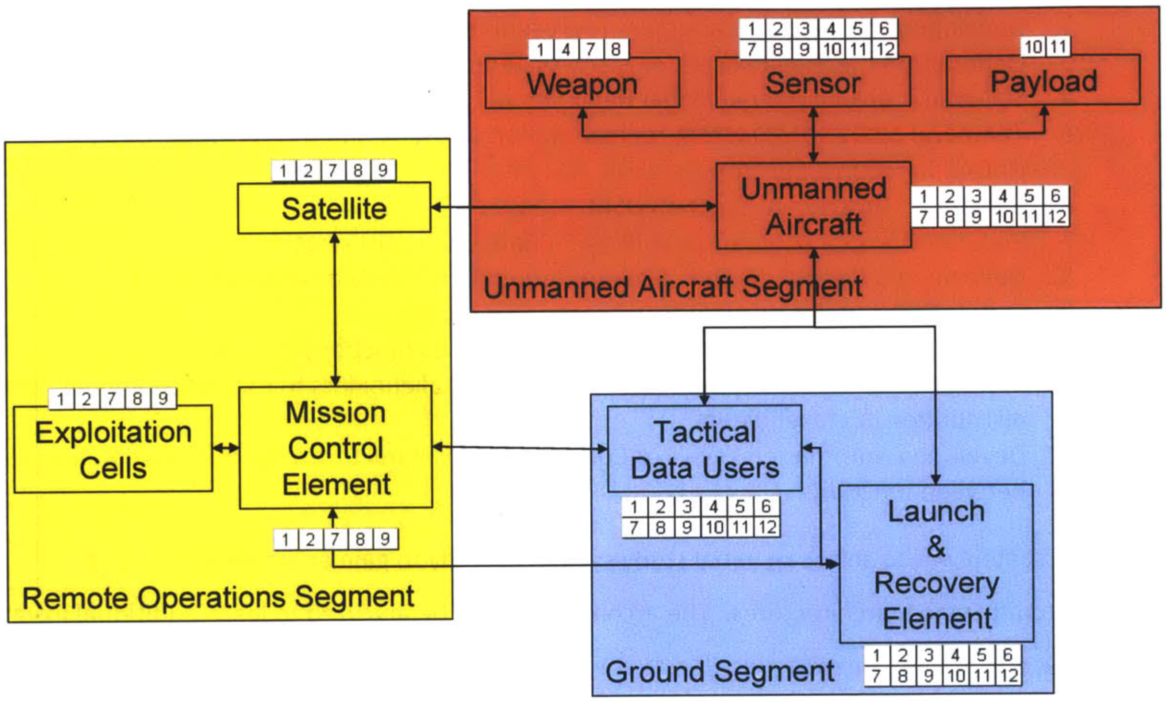


Figure 14 - Generalized UAS Architecture: Showing Remote operations segment, Ground Segment, Unmanned Aircraft Segment

The architectures of the 12 systems were compared to find common functionality and form. The sampling of the twelve systems spanned sizes, functions, and manufacturer. The twelve systems included the (1) Predator, (2) Global Hawk, (3) FPASS, (4) Pioneer, (5) Shadow 200, (6) Fire Scout, (7) Reaper, (8) JUCAS, (9) I-GNAT, (10) Neptune, (11) XPV-1 Tern, and (12) Mako.

Table 24 - Sample of 12 UAS for Architecture Study

Sample of 12 Unmanned Aircraft Systems for Architecture Study			
Information / **UAV**	**User** / **Mission**	**Manufacturer**	**Size/Weight/Speed**
1 Predator	**US Air Force Reconnaissance, Strike**	**General Atomics**	**48.7 ft, 1130 pounds, 70-90 kts**
2 Global Hawk	**US Air Force, Navy, NASA Reconnaissance**	**Northrop Grumman**	**116 ft, 8490 pounds, 351 kts**
3 Desert Hawk	**US Air Force Reconnaissance**	**Lockheed Martin**	**21cm, 3.5 kg, 40-80 Kmph**
4 Pioneer	**Navy, Marine Corps, Army Reconnaissance**	**AAI Corporation**	**5.2m, 450 pounds, 110 kts**
5 Shadow 200	**Army, Marine Corps Reconnaissance**	**AAI Corporation**	**4.3m, 186 pounds, 90 kts**
6 Fire Scout (Helicopter)	**Navy, Army Reconnaissance, targeting**	**Northrop Grumman**	**27.5 ft (rotor), 2073 pounds, 115 kts**
7 Reaper	**Air Force, Customs and Border Patrol**	**General Atomics**	**66 feet, 4900 pounds, 150-170 kts**
8 JUCAS	**US Air Force, Navy Strike**	**TBD, in Development**	**Unspecified**
9 I-GNAT	**Turkish Air Force Reconnaissance**	**General Atomics**	**35 ft, 560 pounds, 120 kts**
10 Neptune	**US Navy Maritime reconnaissance**	**DRS**	**7 ft, 80 pounds, 100mph**
11 XPV-1 Tern	**Navy, Special Operations Command Multiple uses**	**H-Cubed Corp, BAI Aerosystems**	**11.33 ft, 130 lbs, 78 mph**
12 XPV-2 Mako	**Special Operations Command Multiple uses**	**Navmar Applied Sciences Corp**	**12.75 ft, 140 lbs, 70 kts**
			(Office of the Secretary of Defense, 2007)

The table of UASs shows that there is a wide range of sizes, weights, and operational speeds that are related to the design. While all the services use UASs, they are primarily used for reconnaissance capabilities. That reconnaissance capability varies greatly from the largest, long endurance capabilities of a Global Hawk's strategic applications to the smaller platforms that are used tactically such as a Desert Hawk or Neptune. While many small companies provide UAS capability, several larger defense companies have entered the market with complex UASs and variants to service multiple customers and needs.

To perform the analysis, each of the twelve systems was decomposed into its physical components and sub-components. Then, the components and sub-components were compared to find common segments across systems. The architectures were then overlaid on each other to develop a high-level generalized UAS architecture for additional study.

Findings from Physical Decompositions

The results of the physical decompositions are shown in Figure 14. After each of the 12 individual systems was decomposed into its physical segments the task of finding common physical modules began. Each system had several components that were used for operating the system. The comparisons revealed nine unique physical elements that were organized into three building blocks, called chunks (K. T. Ulrich & Eppinger, 2008). The nine components were mapped into three chunks as shown in Figure 14. In this sample, all UASs were found to have at least two of the chunks: Ground Segment and Unmanned Aircraft Segment. The mission and the capabilities the systems provided were indicators of the existence of the Remote Operations Segment chunk. When a UAS was designed to be operated tactically for tactical data requirements, the system did not contain any of the elements in the remote operations segment chunks. Likewise, depending on the role of the UAS, the aircraft segment could vary to include or exclude any of the weapon, sensor, or payload elements.

Table 25 - UAS Physical Architecture Elements

Unmanned aircraft segment	Ground segment	Remote operations segment
Air vehicle	Launch and recovery element	Mission control element
Weapon	Tactical data users	Exploitation cells
Sensor		Satellite
Payload		

Segment descriptions.

Through the decomposition of the physical systems in the sample of unmanned aircraft systems, the subsystems were aligned into three chunks, or segments. The descriptions of these segments as informed by the decompositions follows.

Unmanned aircraft segment. This unmanned aircraft segment of the unmanned aircraft system is the portion that flies. This segment is often referred to as the unmanned aircraft vehicle, or UAV. The UAV contains all the required supporting equipment to operate the mission including radios, propulsion, aircraft structure, power sources and more. The UAV can be decomposed into the aircraft subsystems and the subsystems that are required to perform the system mission: the weapon system that delivers a strike capability such as a Hellfire or other weapon subsystem; the sensor package that collects data based on its technology such as chemical, optical, radiologic, biological, radio frequency, or other types of data; and the payload which may include cargo to be delivered, chemicals for agrarian applications, repeaters for extending communications, and other functional payload systems.

Ground segment. The ground segment was identified as the chunk where the UAV is controlled and operated. In addition, tactical data users, data users who receive information directly from the air vehicle are categorized in this segment. This ground segment is located near the operation of the air vehicle. Sometimes, the operator associated with the ground segment is also the tactical data user. In other systems, the data user can be separate from the operator controlling the UAV. In some systems that have geographically separated ground segments and remote operations segments, the control may be transferred away from the launch and recovery chunk to the remote operations cell which may be thousands of miles away.

Remote operations segment. The remote operations segment is an optional chunk of the physical UAS architecture. The remote operations segment can have mission control personnel who fly the UAV and personnel to perform data analysis. To facilitate control of the UAV from across long distances, a network connection is required to allow transfer of control from the operational ground segment to the remote operations cell. Supporting infrastructure is required for remote operations. Often, the communications are linked through satellite relays to pass information and control information from the UAV and the ground control segment to the mission Control element.

Temporally Informed Physical Representations

Next, another exploratory research activity was conducted. Additional system information was collected. A temporal representation of the Global Hawk operations was developed using manned aircraft as a template to develop functional decomposition. Activities required for operating UAS were added to the aircraft model. When the list of operational tasks became available for Global Hawk operations, the lists were compared. The lists were found to be functionally comparable. However, the Department of Defense Architectural Framework (DoDAF) functions decomposed the system with more focus on delivering data while the aircraft model focused on the physical aspects of the operating the system. The officially documented Global Hawk processes became the following:

Table 26 - Functional Decomposition and DoDAF Functionality (SV-4)

Developed Functional Decomposition Task List (Temporal – Aircraft model)	**DoDAF Functionality Description (SV-4)**
Prepare for Flight *	**A1 – Plan Mission**
Plan Mission *	Load Mission Data
Pre-flight maintenance *	**A2 - Collect (data)**
Taxi & Takeoff *	Control Aircraft
Transition *	Control Communication Links
Transfer Control to Remote Operations Segment	Airspace Coordination with ATC
Travel to Area of Interest *	Execute Pre-planned Target Deck
Acquire and Relay Information *	Respond to Ad Hoc Tasking
Return to Base *	Re-plan mission for Target
Maintenance and Servicing *	Retask Aircraft
	Retask Sensor
Replan – as required *	Monitor/Report Dissemination Status
	Military Airspace Coordination
	Image QC and Sensor Calibration
	A3 - Post (data)
	Disseminate Data
* Functional tasks found in manned aircraft flight operations	Monitor and Report Dissemination Status

Then next task of analyzing the architectures of UASs was to explore the functions performed throughout a mission of an unmanned aircraft system. Because of the similarities to aircraft functions, a temporal model of the functionally decomposed task list for a mission was developed. Then, the function descriptions that were developed as part of the Department of Defense Architecture Framework (DoDAF), Systems Functionality Description (SV-4a) were compared to the aircraft-based temporal model. The SV-4a documents the system functional hierarchies, system functions, and the data flows between the hierarchies and the functions. The SV-4a entries are based on DoDAF analysis of a UAS. The IDEFO framework was used to develop the A1, A2, and A3 top –level functionalities. The indentations in Table 26 reflect the hierarchies of the functions.

The comparison of the temporal functions and the SV-4a functions show similar information, but organize the functions with a different perspective. When performing a functional analysis, a temporal view can be important to ensure all the steps in a process are performed. The temporal aspect is good to document in a procedure checklist for the operator to use while performing many tasks. The functional hierarchy, however, focuses on the tasks that need to be performed to complete a mission. The hierarchy employs a broader perspective to help ensure all the functions are accounted for in the design architecture.

The next analysis of the functional architecture was to develop a system function-to-function matrix Table 27 to show the relationships between the functions documented in the SV-4. The hierarchical nature of the SV-4 tasks allowed analysis at several levels of abstraction and revealed the interactions of the lower-level tasks to higher-level tasks.

Table 27 - Global Hawk System Function-to-Function Matrix

Task	Task ID	1	1.1	1.1.1	1.1.2	1.1.3	1.1.4	1.1.5	2	2.1	2.2	2.3	2.4	2.5	2.5.1	2.5.1.1	2.5.1.2	2.5.2	2.5.3	2.6	3	3.1	3.2
Mission Planning	**1**	x																					
Load mission data	1.1		x	1	1	1	1	1															
Receive tasking and ATO	1.1.1			x	1	1		1															
Update weather,threat, map	1.1.2			1	x	1	1																
Plan contingencies	1.1.3			1	1	x		1															
Phase collection to battle operations	1.1.4			1			x	1															
Create and publish plan	1.1.5		1	1				x															
Data Collecting	**2**								x														
Control aircraft	2.1									x	1	1	1	1	1	1			1				
Control communication links	2.2									1	x	1		1		1	1	1	1				
Coordinate airspace with air traffic controllers	2.3									1	1	x	1	1	1	1			1				
Execute pre-planned target deck	2.4									1	1	1	x					1	1				
Respond to ad hoc tasking	2.5									1	1	1		x	1	1	1	1	1				
Replan mission to target	2.5.1									1	1	1		1	x	1	1		1				
Retask aircraft	2.5.1.1									1	1	1		1	1	x	1		1				
Retask sensor	2.5.1.2										1			1	1		x			1			
Monitor/Report dissemination status	2.5.2										1		1	1	1			x					
Military airspace coordination	2.5.3									1	1	1	1	1	1	1			x				
Image quality control and sensor calibration	2.6										1		1	1	1		1	1		x			
Information Distributing	**3**																				x		
Disseminate data	3.1																					x	1
Monitor and report dissemination status	3.2																						x

From the Function-to-Function Matrix, the decision to focus on the "Collect" segment of the flight activities was made because the military value of the system is primarily delivered in the "Collect" phase of operations. The reduced matrix was populated with the function-to-function information flows required to operate. This information populated a Binary Design System Matrix (BDSM):

Table 28 - BDSM with information flows

Task	Task ID	2	2.1	2.2	2.3	2.4	2.5	2.5.1	2.5.1.1	2.5.1.2	2.5.2	2.5.3	2.6
Data Collecting	**2**	x											
Control Aircraft	2.1		x	1	1	1	1	1	1			1	
Control Communication Links	2.2		1	x	1		1		1	1	1	1	
Coordinate Airspace with ATC	2.3		1	1	x	1	1	1	1			1	
Execute Pre-planned Target Deck	2.4		1	1	1	x					1	1	
Respond to Ad Hoc Tasking	2.5		1	1	1		x	1	1	1	1	1	
Replan Mission to Target	2.5.1		1	1	1		1	x	1	1		1	
Retask Aircraft	2.5.1.1		1	1	1		1	1	x	1		1	
Retask Sensor	2.5.1.2			1			1	1		x			1
Monitor/Report Dissemination Status	2.5.2			1		1	1	1			x		
Military Airspace Coordination	2.5.3		1	1	1	1	1	1	1			x	
Image QC and Sensor Calibration	2.6			1		1	1	1		1	1		x

The DSMs in this document should be interpreted as follows:

Mark above the diagonal: Function in row feeds information forward to function in the marked column.

Mark below the diagonal: Function in row feeds information back to earlier tasks.

The functional decomposition provided in the DoDAF included four levels of decomposition. Analysis was performed on the data in multiple ways:

(1) with each function included from level 2 through 4 (Level 0 data: Mission Plan, Collect, and Disseminate were not included in analysis calculations);

(2) with lower level architecture elements removed from the matrix;

(3) with a separate analysis matrix for the replanning functions.

Visual inspections of the BDSM revealed several bus structures in the processes. A bus structure is characterized by interactions of many components with a specific component. On the DSM, bus structures appear as a row or column of interactions. The bus structures appeared with respect to the functions associated with controlling data links, coordinating airspace with military controllers and air traffic controllers, and finally, with the functions associated with replanning a mission in flight.

Next, the matrix was changed by first removing the level 2 and 3 architectural data from the representation and developing a Level 1 functional matrix and a Level 2/3 matrix that focused on the subset of replanning activities.

Table 29 – BDSM at constant level of abstraction (Level 1)

Task	Task ID	2	2.1	2.2	2.3	2.4	2.5	2.6
Data Collecting	**2**	x						
Control Aircraft	2.1		x	1	1	1	1	
Control Communication Links	2.2		1	x	1		1	
Coordinate Airspace with ATC	2.3		1	1	x	1	1	
Execute Pre-planned Target Deck	2.4		1	1	1	x		
Respond to Ad Hoc Tasking	2.5		1	1	1		x	
Image QC and Sensor Calibration	2.6			1		1	1	x

The Level 1 BDSM resulted in a fairly dense matrix. However, bus structures emerged from a visual inspection: control aircraft, coordinate airspace, and control communication links. The control communication bus shows that all functions within this bounded portion of the system interface with communication control. All aspects of the operations either require sending or receiving communications. Similarly, the control of the aircraft and airspace coordination have many of the links, but neither requires input nor output of the sensor quality control or calibration.

The next analysis involved the Replanning Task Matrix at Levels 2/3. The only bus that emerged from the replanning structure was at the top level of abstraction for replanning mission to target.

Table 30 - Replanning Task Matrix (Level 2/3)

	2.5.1	2.5.1.1	2.5.1.2	2.5.2	2.5.3
Replan Mission to Target	0	1	1	0	1
Retask Aircraft	1	0	1	0	1
Retask Sensor	1	0	0	0	0
Monitor/Report Dissemination Status	1	0	0	0	0
Military Airspace Coordination	1	1	0	0	0

Summary: UAS Physical Architectures

This section focused on understanding architectures of unmanned aircraft systems. The initial study sampled 12 UASs and documented their physical architectures based on open source literature. The architectures were compared and the physical components of the architectures were found to group into three distinct architectural chunks: the ground segment, the aircraft segment, and the remote operations segment which was not found on all the systems.

Next, the functional tasks were identified through temporal aspects and hierarchical views to compare the two functional differences. They were found to be complementary and each had its primary use: the temporal aspects were important for operating processes and the hierarchical representations were important to find the complete lists of tasks that were required to perform the mission. Some of these were hidden from the operator and did not appear in the temporal processes.

After the hierarchical functions were identified, they were entered into DSMs for additional analysis. The DSMs revealed that controlling communication links and replanning missions while in flight required inputs from most of the other functions within each functional segment.

Developing a functional taxonomy of UASs through functional decomposition

The use of taxonomies has recently emerged from the study of biology and classifying libraries (Graef, 2002). A review of the existing UASs revealed the domain was compartmentalized with various system users using varied terminology when describing unmanned systems. To understand the concerns of compatibility across systems, a common taxonomy and dictionary were required. Taxonomy is the "practice and science of classification" where kinds of things are arranged in a hierarchical structure. These hierarchical structures are known as parent-child relationships ("Webster's Online Dictionary." 2011; www.websters-online-dictionary.org, 2011).

The community of military UAS acquisition and requirements personnel has identified the need for common terminology and dictionaries that are not currently aligned across systems, contractors, or military departments. To resolve these discrepancies, several cross-organizational groups have been established to coordinate activities and terminology. By-products of the multi-organizational meetings include common lexicons, aligned architectures, and shared understandings of requirements and capabilities.

To develop a common taxonomy, first a domain was identified. While the focus of the method is remaining in the functional domain as long as possible, an early concession to that focus was made to bound the solution space by selecting a physical domain of unmanned aircraft systems (UASs), to ensure the study space would be sufficiently limited for the study. A cross-sectional study of several classes of UASs led us to limit the scope to US military UASs that have a high or medium altitude endurance role. The systems selected can be seen in Table 24.

Develop functional taxonomy

With the domain of unmanned aircraft systems selected, within the UAS domain a functional taxonomy was developed. The functional taxonomy was selected to ensure all functions were considered and that the physical instantiation, or form, of the system was considered only after the functions were identified. The practice of identifying function and then mapping the function to form is a widely-accepted process of developing system architecture (Crawley, 2006). Many of the functions representations were reviewed to select the functions that would comprise the top-level functions in the functional architecture for UASs. The multi-service Common Unmanned Control Segment (CUCS) Working Group, the Predator and Global Hawk system program offices, aircraft operations manuals, and UAS operator functions (Nehme *et al.*, 2007) for UASs were reviewed to scope the extent of functions included in the proposed functional taxonomy.

The role of this step in the method is multi-purpose. The first purpose begins by identifying the highest-level of functions that the domain of UASs performs. The intent is to identify the continuum of all functions of the domain. After these high-level functions (also known as capabilities or missions) are identified, the functions were decomposed into lower-level abstractions to better understand the complex, high-level functions. The second purpose behind developing the functional taxonomy was to build a common dictionary. A common dictionary is important when comparing functions across organizational and cultural boundaries so that terms of reference are universally understood.

The functional taxonomy was divided into two parts which were named following Lean conventions as Value-added and Support functions. The Value-added functions were defined as the elements that directly provide actionable information or interaction to the warfighter. These included the direct functions the system performs to execute missions. The Support functions are enabling roles the system must perform to operate. The warfighter does not interact directly with these functions. They could be considered "black boxes" (Otto & Wood, 2001) by the system beneficiary. The black box functions include preparing for flight, moving (and flying), powering the system, recovering the system and maintaining for the next mission, and the internal communications required to control the air vehicle, coordinating airspace and monitoring the health and status of the UAV and its sensors.

The functional taxonomy provides the framework to build into the functional decompositions. For this example the functional taxonomy we developed for UAS was used as shown in Table 26.

Perform Functional Decompositions

Functional decompositions are performed by engineers to both simplify the functions of the system and allow rapid development by employing parallel design processes. Simplifying complex functional systems deconstructed the complex functions of the system into smaller chunks that can be better understood and facilitate fully documenting the functionality and the interfaces. The decomposition process is often used to both simplify and allow parallel design processes(Pimmler & Eppinger, 1994). The decompositions were developed for UASs to use the functional decomposition to improve the understanding of the systems and allow comparison of the decomposed functions as an entry point into developing units of analysis at appropriate levels of abstraction.

The hierarchical decompositions developed for UASs begin with the UAS domain at the highest level. The next level is the set of high-level functions that UASs currently perform or that are being considered for future functionality. These ten high-level functions were aligned with one of two categories: mission functions and supporting functions. The mission functions are identified by providing the impetus for using UASs to solve the mission problem. For example, many UASs are used for sensing functions. The sensing product is the reason the system is acquired. The five functions in the mission functions include Sensing, Attacking, Protecting, Communicating, and Transporting.

The second category of UAS functions is the Supporting function roles. These are functions that are required to be performed by the UAS for it to fulfill its mission, but do not directly provide value in their execution. The five supporting functions were identified as Preparing, Moving, Powering, Recovering, and Communicating. Normally, when functions are decomposed, functions are not repeated in decomposition. However, in the case, Communicating appears in both the Mission and the Support function decompositions. The Communicating mission function includes performing the missions of broadcasting information to targeted recipients or relaying messages from one location to another. These are functions that could identify UASs as solutions for users' needs. The Supporting function Communicating refers to the communications that are required within the UAS. These are messages and information that provide the links for controlling the air vehicle, relaying voice communications to the airspace controllers, coordinating the use of airspace, and monitoring the health and status of the air vehicle.

While ten functions have been identified in this proposed universal taxonomy for UASs, these ten should not be considered all-inclusive. Future missions of UASs and changing system technologies will likely change or add additional functions over time. Similarly, all UASs will not perform all of the ten top level functions to support a mission. UASs generally perform only one or two of the Mission functions. Likewise, the design of a UAS levied complexity and the requirement for internal supporting functions.

The next level decomposes the high-level functions. The purpose of the functional decompositions is multi-faceted. First, the functions are decomposed to ensure all aspects of the system's functionality are documented. Next, the decomposed functions are mapped to the physical instantiations that perform the functions. The decomposed functions and the associated physical forms are identified as modules that will be used as units for replacement. This functional decomposition was continued one or more levels until the resultant decomposed function could be mapped directly to the physical component of the system that performs the decomposed function. An example of this decomposition and the mapping to a physical solution is presented next.

The functional decomposition for the sensing example began as analyzing the function of sensing visible light. The product from sensing the visible light would be seen as real time video. By entering into Figure 15, a functional decomposition can be identified as SENSING//IMAGING//VISIBLE.

The taxonomy was greatly influenced by the works in the areas of UASs and system architecture of Nehme on developing an operator functional taxonomy (Nehme et al., 2007). We used the operator functional taxonomy as a starting point when we developed the system functional taxonomy. The work on commonality in developing systems (Boas, 2008) influenced concepts on commonality, cousin, and unique parts. Boas's work was applied to drive commonality into existing systems instead of studying the time-series decay of commonality in product families.

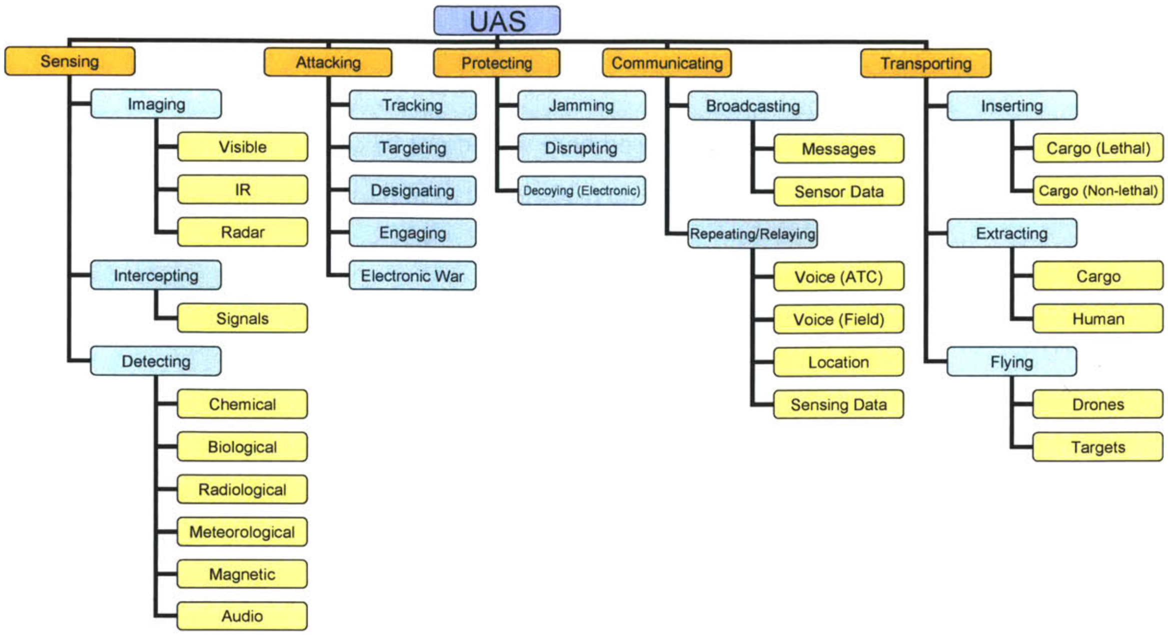


Figure 15 - UAS Mission functions

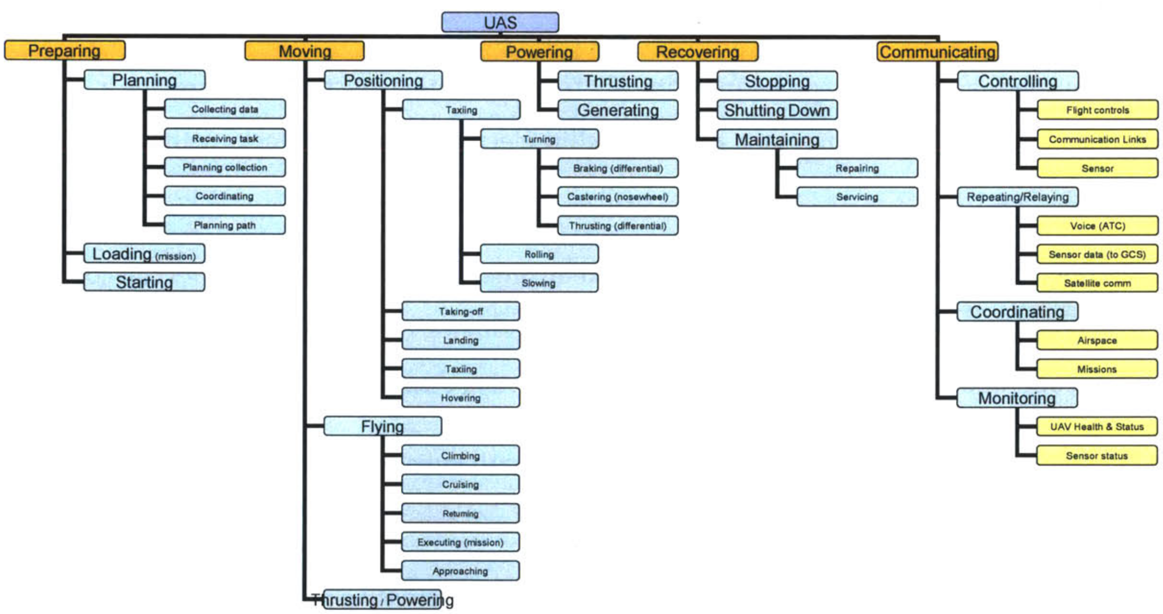


Figure 16- UAS Supporting functions

The functional taxonomy that was developed includes five high-level functions that are required to perform the warfighting capability and five supporting functions that are artifacts of the methods employed to perform the mission. In the vernacular of Lean, the Mission functions are "Value-added functions" and the Supporting functions are "Non-value adding work" that must be performed because of the current conditions (Murman, 2002). In this case, they must be performed because of the choice of using an unmanned aircraft constrained by current configurations, technology, and system requirements.

As with any taxonomy, the taxonomy proposed here should not be considered to be "the correct" taxonomy. This taxonomy may be adopted by users in full or in part and can be extended for applications. The common functional taxonomy is proposed as a baseline for architecture discussions about unmanned aircraft systems.

UAS Mission Functions

Sensing. One of the primary missions of UASs is reconnaissance. Reconnaissance is a mission that uses visual or other detection methods to obtain information about the adversary or topography of an area (Chairman of the Joint Chiefs of Staff, 2001). The sensing function encompasses imaging through the use of visual and invisible portions of the spectrum, intercepting signals, and detecting other phenomena such as radiation, chemicals, sound, and others.

Attacking. Another mission of some UASs is to destroy a target. This function was decomposed into the kill chain sub-functions of tracking an entity of interest, targeting functions, designating a target, engaging militarily with an adversary, and conducting electronic warfare attacks with energy weapons.

Protecting. A use of an unmanned system is to keep other items from harm. A UAS can conduct protecting functions that include jamming adversary radars, disrupting the ability to conduct offensive electronic attack operations, or decoying an enemy into redirecting assets away from high value targets.

Communicating. A UAS can broadcast information as with radio programming and relay functions that extend the range of communication devices.

Transporting. A transporting operation can be conducted by airlifting items for insertion or extraction from a military operational theater. Items can include supplies, emergency equipment, or potentially humans as passengers.

UAS Supporting Functions

Preparing. Preparing for a UAS mission includes mission planning, loading the planned mission information into the system, and readying the air vehicle for flight. This function is based on the temporal aspects of a UAS mission by including the activities that are required prior to conduction the Mission functions of the system's tasking.

Moving. One of an air vehicle's advantages, its ability to operate in different locations, requires a moving function. The air vehicle moves on the ground before its transition to flight. Ground operations decompose the sub-function of [ground] positioning into taxiing, taking-off, and landing flight activities. In addition, air vehicles that are in the form of helicopters may perform a hovering function.

Powering. Most UASs require power for their system operation. The powering function can be decomposed into two sub-functions: providing thrust to support flight operations and generating electrical power to operate devices that require electricity to operate and execute the UAS mission.

Recovering. After the air vehicle completes its mission and lands safely, it must be recovered to prepare for the next mission. The vehicle must be stopped safely, systems turned off, and maintenance may be required. These functions were identified as children of the recovering parent functions.

Communicating. The function for communication appears in both the Mission and the Supporting functions. When communicating is performed as part of the mission, it is found in the Mission functional decompositions. When the communication is performed within the UAS internal boundaries, it is mapped to the Supporting function roles. Controlling, repeating, coordinating, and monitoring were included in the supporting communicating function. The controlling function includes the signals that must be passed to the air vehicle to give the air vehicle operating instructions from the ground control segment of the UAS. As part of the support function, a UAS operator may require voice communications with air traffic controlling agencies. To communicate with the controllers, the air vehicle must relay the communications between the controllers and the system operators. The UAS must also facilitate coordinating the mission with outside agencies. In these cases, operators communicate with battle managers and data product users to convey their support needs. The operators can take this external information and replan or improve the support to the users. The fourth aspect of communicating is the monitoring function of the UAS. The UAS operator needs to understand the condition of the UAS systems and its current flight conditions and location. These informational needs are met with the air vehicle reporting health and status to the operator.

Results of Common functional Taxonomy Development

The development of the proposed taxonomy with common functions provided a common language for multi-agency discussions about UAS capabilities. While practitioners did not adopt the taxonomy fully, its presentation gave working groups a methodology they could follow to resolve their lexicon gaps. They were able to quickly understand the advantages of a common language and would work to efficiently resolve communication errors when they arose. One multi-national group that was observed for this research came to an impasse on a term of reference. The concept behind the term needed to be defined, but the naming convention could not be resolved. The group agreed to calling this contentious element a "giraffe" as a surrogate name until more of the taxonomy was developed and a better name emerged that all could agree to use.

The determination of the levels of decomposition was also a concern. Practitioners expressed concerns about spending an inordinate amount of time performing the decompositions. One team decided to perform the decomposition in stages. The functions would be decomposed into finer granularity only as the decompositions were required.

Determining the capabilities of practitioners

The premise of the Compatibility Assessment Method is that an Air Force project manager would be able to perform a comparison between two systems to determine if a proposed system would be a suitable alternative for the current, baseline system. This experiment was developed to examine the capabilities of project managers to determine if a project manager would have the requisite skills to perform the analysis.

The need for analyzing alternatives for replacing currently installed systems is widespread. Some conditions of needing to evaluate a proposed system include subsystem unsupportability. Unsupportability occurs when the logistics processes cannot keep the sub-sytems operational because of discontinued components or loss of a manufacturer.

The acquisition specialties include scientists, development engineers, acquisition managers, financial managers, and contracting officers. Each of these specialties has its unique duties and responsibilities, and specialty qualifications and education requirements. The acquisition manager education requirements range from the technical engineering and science backgrounds to the management-oriented business education. The candidate project manager must complete 24 semester hours in business, management, or quantitative methods courses.

Because of the varied backgrounds that allow initiation into the career field, an understanding of the capabilities of the project managers was desired to determine if CAM could be performed by the target practitioner.

The acquisition managers have project management responsibilities. The Department of Defense program managers typically have responsibility for cost, schedule, and technical performance of the systems they are charged with acquiring.

For entry into the acquisition manager career field, requirements include an undergraduate academic degree specialization in engineering, engineering science, engineering management, mathematics, analytical science, physical science, business, or management; or completion of a minimum of 24 semester credit hours of study from an accredited institution of higher education from among the disciplines of: accounting, business finance, law, contracts, purchasing, economics, industrial management, marketing, quantitative methods, and organization and management is mandatory. The program manager is required to have grounding in technical issues and/or the business management acumen to engage on technical and financial concerns.

An Air Force project manager has a job title of Acquisition Project Officer. The top-level task descriptions of an acquisition manager is to manage defense acquisition programs covering every aspect of the acquisition process, including integrating engineering, program control, test and deployment, configuration management, production and manufacturing, quality assurance, and logistics support. The acquisition officer will perform functions essential to acquisition programs involving major defense acquisition programs and other, usually smaller, systems or subsystems.

Other roles of the program manager include activities that support acquisition processes. In addition to project management responsibilities, the roles include managing acquisition processes, supporting the personnel with organizations to support the individual acquisition specialists' needs, and conducting the prescribed management and technical reviews to ensure value delivery to the government.

The project manager may be responsible for a program in any phase of development or acquisition in a system's lifecycle from the earliest concept development and requirements identification through engineering, production, deployment, upgrades and support, and system disposal or reuse.

In addition to understanding the acquisition processes of the DoD, a manager is expected to have knowledge of the systems that are to be managed. Mandatory knowledge required includes the DoD and Air Force system, subsystem, and equipment acquisition program management philosophy, policies, and procedures applicable through several phases of an acquisition life cycle; and program management procedures pertinent to development, procurement, production, logistics support, and techniques of employment for the system being acquired.

Beyond the undergraduate level of education required for entry into the career field, specialty training is required on the DoD acquisition system. The entry course into acquisition is the Fundamentals of Acquisition Management (ACQ 101).

Hypothesis

The premise for the commonality research is that an acquisition project officer has the requisite skills to use a screening process to determine if a proposed subsystem is a feasible replacement for a current, baseline system. This complex task can be decomposed into several sub-tasks that should be understood before developing and exercising a compatibility assessment tool.

Research Design

This research module was developed for two purposes. First, the exercise was designed to determine if research participants could find appropriate information in open-source forums to identify common subsystems across complex systems. Second, this research was designed to determine the capabilities of project managers in discovering opportunities for commonality across a sample of systems. This exercise was developed using a sample of large, unmanned aircraft systems as the research domain. The research also included a sample of capabilities that unmanned aircraft systems perform.

Research Participants

The research participants were selected from acquisition officers who were on casual assignment status at the Air Force Institute of Technology. Casual status is the period of time before the student officially begins the course of study or the time following completion of the graduation requirements before relocating to a follow-on assignment. These periods of casual status may last from a few days to about a month in a few situations. The students were assigned to participate in the research during the time they also had various administrative tasks to support the institute. The officers were not compensated for their participation in the assessment.

Research Questions

Can an Air Force acquisition officer find common subsystems implemented across multiple UASs?

Can common subsystems be found across UASs using open source data sources?

Research Methodology

The researcher developed this exercise with a sample of six UASs and four capabilities. The UASs included the Global Hawk, the Predator, Reaper, Fire Scout, Navy variant of Global Hawk (Broad Area Maritime Surveillance System, or BAMS), and the Army's Sky Warrior. The capabilities included the following: communications, engines, transponders, and navigation,

Results of practitioner assessments

After developing the method of comparing the systems, parts of the process were tested by potential practitioners of the process. The initial study requested three Air Force program managers ranging from 3 to 12 years of program management experience. The program managers were given the domain of UASs and a list of six specific systems to use as a sample to find existing commonality across the systems. The program managers were asked to develop a matrix mapping UASs to common functions and to identify the form that implemented those functions.

The first test subject had 12 years of acquisition experience, was able to develop and populate a matrix in two hours of research in a library. This test subject had an undergraduate and master's degree in engineering.

The second test subject with three years of experience accepted the task, returned a week later and asked, "What is a matrix?" After providing more structure to the second test subject, the task was continued. About a week later, a matrix was returned with about half of the information the first test subject compiled. This test subject had an undergraduate business degree and had been accepted into a masters program for research and development management.

The third test subject with 7 years of experience as an Air Force program manager, constructed a matrix similar to the first test subject's matrix. The third test subject also had an undergraduate business degree and had completed about half of the coursework for a research and development management masters degree.

The results from the three test subjects revealed the need for additional understanding of the capabilities of program managers before expecting the ability to compare systems using this method.

Conclusions for Architecture Discovery

After reviewing the results of the three test participants, a wide variation of capabilities was discovered between acquisition officers. None of the participants had specific, prior domain knowledge of the unmanned aircraft systems, nor of the capabilities performed by the unmanned systems. Although the officers had no domain knowledge, some were able to richly populate a matrix of the systems and found the common implementations of subsystems. The populating was performed using only open-source library sources available in many university libraries. This finding suggests that some acquisition officers may be able to find existing commonality in an assigned domain and others may not be able to discover commonalities.

Appendix B – The developmental case studies that defined CAM (Chapter 3)

Case Study 1: Lift Truck I (alpha test)

This engagement with a research participant was the initial test of the earliest version of The Compatibility Assessment Method (CAM) with a potential user of the process. The participant was a product designer for fork lifts. His company is trying to upgrade its offerings with upgraded operator controls. The upgraded controls were to integrate the current, uncoupled lift truck controls into an integrated multi-functional [control] device (MFD) to control the lift truck and its load. A goal would be to make the control systems common across segments (or more) of their product line.

The participant was first asked to read about the CAM process and, at the beginning of the meeting, an overview of the process was discussed to clarify the purpose and select boundaries for the problem the participant was interested in solving.

The IDEF0 activity model was used to baseline understanding of the process. The IDEF0 diagram was helpful to understand the system and the concept and keep the focus on the functional domain. The ICOM constituents of Inputs, Outputs, and Mechanisms were well-understood. Because of the focus of the logistics system, the term "Controls" was often confusing because the project focuses on the "controls" of a system. This began the departure from the strict application of IDEF0 and CAM began emerging. After the participant and researcher replaced the use of "control" with "constraint", for the constituent arrow coming into the top of the activity diagram, confusion lessened.

The goal of using CAM on this project was for the company to improve operator controls on an industrial lift truck and upgrade multiple function (steer, move, lift) controls into an integrated control module.

Method as performed

This application of the method was IDEF0-centric. This was the first attempt to use the IDEF0 functional activity model to describe a system with its respect to inputs, controls, outputs, and mechanisms. The method did the following:

- Performed functional decomposition on lift truck operations;
- Identified functional boundaries for systems of interest;
- Captured a system description in IDEF0 activity model.

From performing the method, insights were gained from the interactions with the participant. These insights were documented as lessons learned and led to changes in the model.

The participant began by identifying functions of the baseline system. There was difficulty keeping the level of abstraction constant and staying at the single functional level. The baseline function was identified as "control steering angle." However, functions were added because of poor definition of the system of interest. Sketching the existing system helped focus on a single level of abstraction. After several attempts of changing levels of abstraction, the tiller function of controlling steer angle became the baseline for the focus of the effort.

> Tiller ➔ a wheel mounted horizontally with a knob to facilitate turning. Tiller controls steering through a hydraulic valve, electric switch, or chain (mechanical) depending on the application.

Next, the functions of the integrated control system (ICS) were analyzed through the model. The ICS provided more functionality than the tiller. In addition to control steer angle, the ICS and the associated automation software controls traction and lifting functions and subfunctions.

> ICS ➔ Integrated Control System. An advanced operator interface that controls steering and forward motion on a lift truck.

> MFD ➔ Multi-functional [control] device. Operator interface on a lift truck to control the lifting functions.

In the practice of using the CAM process, a problem arose because the ICS has much more functionality than the tiller wheel. This may require expanding the boundaries of the tiller wheel to include the similar functionality of the ICS. The ICS could be generalized to the functionality of the existing tiller wheel plus the multi-functional [control] device (MFD).

At the system level, comparisons were made between the intended functionality of the ICS and the Tiller plus the MFD.

The system comparisons resulted in the system deltas of F_P - F_B = -MFD – Tiller + ICS.

F_P = Function of Proposed system

F_B = Function of Baseline system

After using the function table to compare the baseline and proposed functions, the IDEF0 pictograph was used to capture the ICOM information.

The ICOM diagram yielded:

Function: control steering
Inputs: Control force and vector

Controls (Constraints):
Physical
    Size
    Weight
    Location integration
Dynamic
    Adjust speed
    Ensure truck stability
    Input forces
Operator Ability and training
    Speed
 	
Outputs:
    Steer angle (turned wheels)
 	
Mechanisms
    Floor
    Truck architecture
    Rack configuration
    Pallet location
    Aisle width

Next, the proposed and baseline ICOM tables were completed. Categorical entries that were common between the proposed and baseline systems were circled.

The Delta (Proposed – Baseline) Matrix was filled out by comparing the non-common (non-circled) table entries, performing the difference calculations across the tables, and then entering the delta into corresponding cells in the constructed matrix.

Differences were found.

Inputs: Hand pressure With ICS, no pressure on the control provides a signal to stop the vehicle. This is a safety feature Controls: Dampening:
With the ICS, vibrations result in control inputs that need to be dampened [ignored] out of the system to allow smooth operation without jerking and undesired turns. Safety control

With the automation provided by the ICS, the vehicle dynamics need software control to ensure the vehicle cannot be operated in a situation that would allow tipping. The manually-operated tiller wheel system does not have this feature.

Methodology lessons learned

In this alpha test of using a functional activity model as a tool to determine compatibility between a baseline and proposed system, several key points were learned from interactions with the research participant. First, and possibly the most important, the analysis must be performed at an appropriate level of abstraction. Operating at too high a level of abstraction makes the process difficult and cumbersome with amounts of data to manage. Also, the level of abstraction needs be held constant. With the complexity of multiple functionalities implemented in the integrated control system, the participant was prone to slide up and down the level of abstraction that was being used for the analysis. This movement caused confusion and the constituent arrows did not align logically for the function of interest.

Second, more granularity is needed in the ICOM matrices. The initial design was focused on qualitative constituents. This became problematic for performing evaluations between systems. With only the qualitative comparisons, selections could not be made quantitatively. Because of the lack of quantitative information to base a decision, metrics and parameters were added to the model to quantify the qualitative measures.

Next, IDEF0 terminology of "controls" is confusing when working with control systems. Because of the nature of the problem this participant was attempting to solve, confusion existed both about the definition of the constituent "controls" and the goal of the project with the research participant was to resolve a system control design concern. Because the constituent arrows emerged as constraints to the system instead of function controls, a better terminology fit led to renaming the constituent arrow to "constraint."

Before, during, and after the Method analysis, the following concepts were captured:

[The process is] "complicated, but that might be the cost of the process."

Part of the difficulty of finding commonality is "artfully managing the team" of experts to stay engaged in the process. The effort would require the "right mix [of people] at the right time."

The most important aspect is to identify the motivation for the commonality case. Why should the project to increase commonality be undertaken? Which projects should be undertaken?

The operator is the most expensive part of the system. The operator accounts for 3-4 times more than the equipment. Making the operator more effective is important.

The process is simplified. "Several more layers of complexity exist in the real world."

During the experiment, the participant was asked, "How would this process be useful to your company?" The participant outlined the following suggestions for implementing

1. Two-hour presentation about why the process [and developing commonality] is important.
2. Succinctly communicate the core functionality of the process.
3. Several examples of running the process.
4. Show how to make the tradeoffs as to the System Value and what is important.
5. How to design the systems to increase commonality.
6. Why structured and not qualitative level/intuition

Finally, the subtraction function used to develop the differences, or delta matrices, between the systems, was confusing to the participant and required additional explanation to use the tools.

Methodology changes

The results of interactions with the first research participant informed several changes to the compatibility assessment method.

First, the initial understanding of the functions must be made richer. This can be addressed by spending additional effort on performing functional decomposition activities. The levels of abstraction for both the baseline and the proposed systems must be decomposed to the same level of abstraction to ensure a compatible comparison.

Next, to avoid the TTB process being the only heuristic that could be used for selecting a system, the model was improved by adding the ability to perform quantitative comparisons of differences. This is another departure from the IDEFO model. Each of the four constituent arrows was decomposed into Inputs and Parameters. This added metrics and parameters that could be used to quantify the previously qualitative measures of comparison.

Third, the research participant's confusion about the method of calculating the Delta Matrix was resolved by developing an improved instruction set for calculating the Delta Matrix.

The last update that resulted from this case study was a need for an example project. The purpose of a small example project would serve as guideposts to help practitioners understand the process and have a model to compare process outputs.

Conclusions

The real world application of the process is more complex than originally believed for the ICS vs. tiller steering control system. These issues could be resolved through additional work in the functional decomposition and boundary definitions that closely guard levels of abstraction.

Also, when considering replacing a manual system with an automated system, the complexity of the automation and the software controls add many levels of complexity to the system.

When considering a change from a federated system to an integrated system, boundary definition becomes paramount. When couplings result from integrating controls, the ability to separate functions becomes much more difficult because of the interactions and moved system boundaries.

When working with integrated control systems, the constraint constituents may number in the 20's. This becomes a management problem with the amount of data that must be collected, managed, analyzed, and stored.

Case study 2: Mouse / Joystick

After initial learning about assessing compatibility through working with the lift truck, the need for an example project was identified. The example project needed to be simple enough to not require deep domain knowledge and needed to be simple enough that the example could be shown quickly. The case of comparing a computer mouse with a laptop joystick control was developed.

Method performed

As an example project, this exercise was not completed with research participants nor an organizational expectation from the outcome. The method followed the processes used in the Lift Truck Alpha Method using IDEFO

- Identified functions performed by the systems and the differences between functionalities
- Constructed baseline and proposed IDEF0 diagrams
- Captured IDEF0 data in matrices
- Calculated deltas between baseline and proposed systems
- Analyzed the compatibility in difference areas

Table 31 - Function Table for Joystick vs Mouse for PC interface

Function Table EXAMPLE (Joystick/Mouse)		
(1) Functions of Proposed System (F_P)	(2) Functions of Baseline System (F_B)	(3) Deltas between Systems ($F_P - F_B$)
Translate hand movement into cursor movement	Translate hand movement into cursor movement	
Select items ["click on"]	Select items ["click on"]	
	Access advanced menus	- Access advanced menus
IBM Thinkpad joystick	2-button mouse	

Table 32 – ICOM Matrix developed to describe a two-button mouse as the baseline system for comparison

Baseline System ICOM Matrix for Two-button Mouse											
Inputs (I)			Constraints (C)			Outputs (O)			Mechanisms (M)		
	Parameter(I)			Parameter (C)			Parameter (O)			Parameter (M)	
Input	Metric	Value	Constraints	Metric	Value	Output	Metric	Value	Mechanism	Metric	Value
Hand	distance	inches									
Finger	force (click)	1/0									
	distance	.1 inch									
			Sensitivity	Distance per dis	ratio						
			Surface	reflectivity	1/0						
			Space	Area	square inches						
						Moved cursor	distance	tbd			
						Selected "clicked" item		1/0			
						Accessed "right	selected	1/0			
									Computer	USB	1/0
										Serial port	1/0
									Working surface	flatness	tbd

Table 33 – ICOM Matrix developed to describe the IBM Thinkpad Joystick as the proposed system for comparison

Proposed System ICOM Matrix for IBM Thinkpad Joystick											
Inputs (I)			Constraints (C)			Outputs (O)			Mechanisms (M)		
	Parameter(I)			Parameter (C)			Parameter (O)			Parameter (M)	
Input	Metric	Value	Constraints	Metric	Value	Output	Metric	Value	Mechanism	Metric	Value
finger	displacement	time									
		distance									
finger (press)	force										
			Sensitivity	distance							
				Time							
						Moved cursor					
						Selected "clicked" item					
									None (integral design)		

Table 34 – Delta ICOM Matrix calculated from the differences between the Joystick Matrix (proposed system) and the Mouse Matrix (baseline system)

Delta ICOM Matrix [calculations: Joystick Matrix - Mouse Matrix]											
Inputs (I)			Constraints (C)			Outputs (O)			Mechanisms (M)		
	Parameter(I)			Parameter (C)			Parameter (O)			Parameter (M)	
Input	Metric	Value	Constraints	Metric	Value	Output	Metric	Value	Mechanism	Metric	Value
Hand	distance	inches									
finger	displacement	time									
		distance									
			Sensitivity	distance							
				Time							
			Sensitivity	Distance per dis	ratio						
			Surface	reflectivity	1/0						
			Space	Area	square inches						
						Accessed "right	selected	1/0			
									None (integral design)		
									Computer	USB	1/0
										Serial port	1/0
									Working surface	flatness	tbd

Positive result (proposed system has, baseline system does not

Negative (baseline system has, proposed does not)

Blue - Yellow = Pink/Green delta matrix

Methodology lessons learned

- Alignment of the matrices on the paper is helpful
- The case study's level of abstraction worked cleanly
- The parameters and metric added to the process enabled quantifying previously qualitative data

Methodology changes

- Developed standardized forms for practitioners to use for data capture
- Include the mouse / joystick data as an example for practitioners to follow

Case Study 3: JPALS on B-52

The B-52 Stratofortress aircraft has been through many transformations in its operational life. The aircraft was originally designed as a high-altitude bomber. Through the years since its 1954 debut, the B-52 has been modified and upgraded to increase its capability. Some of its roles have included high and low altitude bombing, conventional and nuclear weapons delivery, close air support, and missile launching (US Air Force, 2010). The goal of this case study was to (1) analyze the compatibility between the current navigational systems and the proposed Joint Precision Automatic Landing System (JPALS) that is being considered for the B-52, and (2) mature the compatibility assessment process.

The research participants were systems engineers and program managers from the program office. The researcher facilitated the process. The case began with a presentation to the program office engineers and project managers. The presentation outlined the need for a process to assess the compatibility between current and potential upgraded systems. In addition, the presentation included

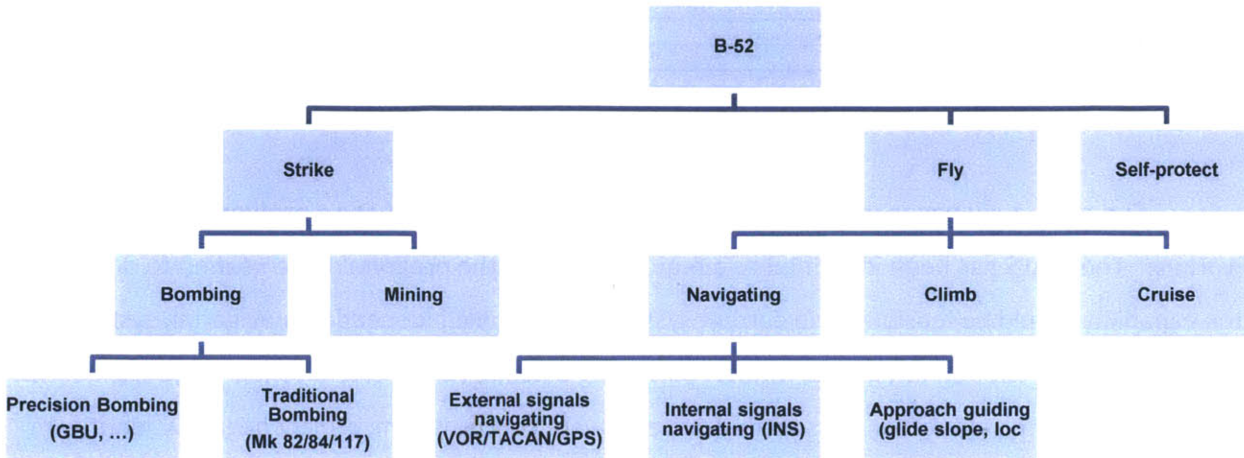


Figure 17 – Functional decomposition of B-52

the example problem that was developed to compare the computer mouse with the integrated joystick pointing device on laptop computers. After the presentation, the research participants began the method to determine the feasibility of a potential upgrade.

The participants agreed to the following activities and believed they would be valuable to the program office:

(1) Improve program office insight into replacement processes;
(2) Quickly identify the feasibility of a proposed system replacement solution;
(3) Identify the appropriate level of technical analysis for analyzing a replacement solution;
(4) Categorize the impact of the change on the system;
(5) Identify the stakeholders who have approval authority for the proposed change.

Method performed

1. Briefed participants about the process and its goals.
2. Identified candidate systems for action research project.
3. Performed functional decomposition for function of interest.
4. Identified stakeholders for candidate systems.
5. Documented activity model diagram for proposed and baseline systems.
6. Identified functions performed by the baseline system and the proposed systems, then and calculated the differences between the baseline and the proposed systems' functions.
7. Documented functions for the proposed and baseline systems in matrix format.
8. Calculated differences between proposed and baseline systems in matrix format.
9. Assigned impact code to the differences between the elements.
10. Identified resolution authority for differences between the baseline and proposed systems.

Table 35 - Function Table for the comparisons between the individual controls with the integrated controls including JPALS

Function Table		
(1) Functions of Proposed System (F_P)	(2) Functions of Baseline System (F_B)	(3) Deltas between Systems ($F_P - F_B$)
Select 40-channels of VOR/LOC frequencies	Select 20-channels of VOR/LOC frequesncies	20 channels
Select TACAN Channel	Select TACAN channel	NONE
Select JPALS frequency		Select JPALS Frequency

The case study began with the program office personnel identifying a problem they were working. The JPALS has been identified as a requirement and the program office needed to determine if the capability would be feasible. The current system has multiple independent navigation systems and the JPALS system adds an integrated Global Positioning Satellite (GPS) system. The available space and the interfaces to the aircraft and associated systems were concerns. The project began by identifying the functions these systems performed and decomposing the functions to ensure all associated

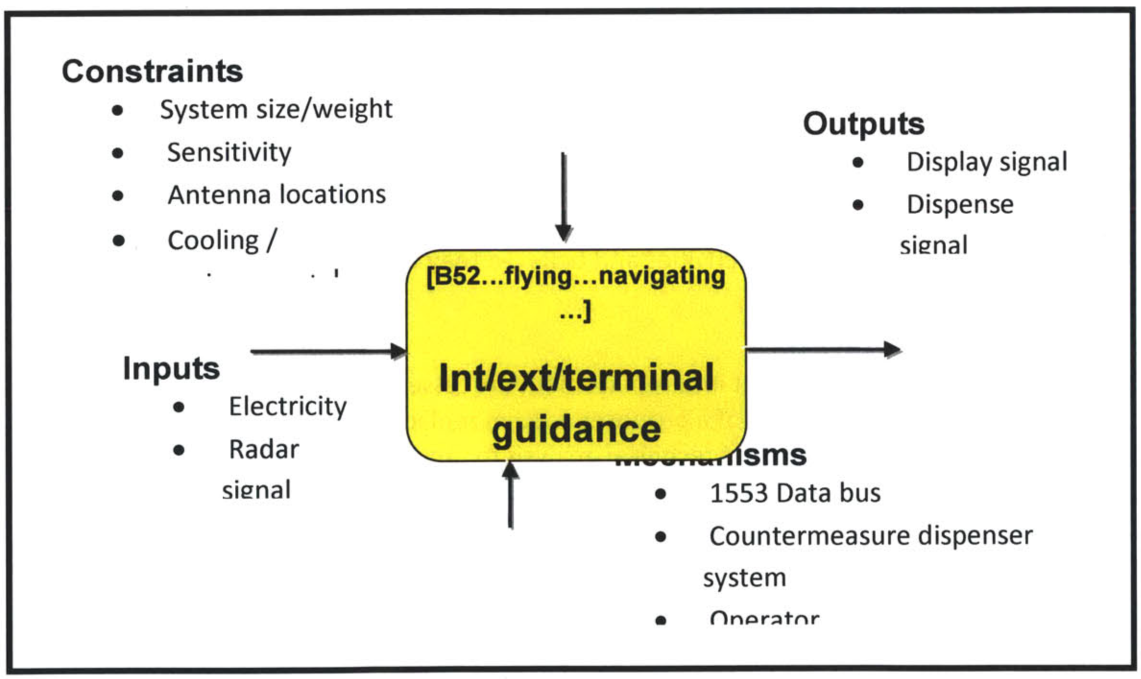


Figure 18 – Modified IDEF0 model for Controlling terminal guidance in the B-52

functions were identified. The functional decompositions became complicated with the interfaces with each of the multiple systems. This led the team to rescope the research effort to develop a project that could be performed within two days. After performing the system analysis and drawing system block diagrams, the participants recommended focusing on the integrated switch aspect of the system upgrade. The proposed switch was identified as a multi-functional, software-reprogrammable, electronic display with touch-screen controls. This would replace the mechanical navigation switches and add the JPALS control functionality. With this new boundary identified, the process was restarted.

Table 36– ICOM Matrix for Legacy Switches in B-52 Flightdeck (baseline system)

Baseline System ICOM Matrix (Legacy switches)											
Inputs (I)			Constraints (C)			Outputs (O)			Mechanisms (M)		
	Parameter(I)			Parameter (C)			Parameter (O)			Parameter (M)	
Input	Metric	Value	Constraints	Metric	Value	Output	Metric	Value	Mechanism	Metric	Value
ARN-14 Control Panel											
Energy	Power	28VDC									
			Size	Length							
				Width							
				Depth							
			Location								
			Power								
			Weight								
			Human Factors								
			MTBF	Hours							
						Signal	20-settings				
						Signal	Voltage out	[0, 28]			
						Signal	Volume setting				
									Human operator		
									Installation template		
TACAN Control Panel									VOR/ILS Transmitter		
Channel select									TACAN transmitter		
Mode select											
Test reply loop (signal)											
			Size	Length							
				Width							
				Depth							
			Location								
			Power								
			Weight								
			Human Factors								
			MTBF	Hours							
						Signal	40-settings				
						Signal	Mode select	[5 choices]			
						Signal	Volume setting				
						Signal	Test output				
						Signal	Test result				
									Human operator		
									Installation template		
									Volume select		
									mode select		
									Channel select		

Table 37 – ICOM Matrix for JPALS Switch in B-52 Flightdeck (proposed system)

Proposed System ICOM Matrix (JPALS Switch)											
Inputs (I)			Constraints (C)			Outputs (O)			Mechanisms (M)		
	Parameter(I)			Parameter (C)			Parameter (O)			Parameter (M)	
Input	Metric	Value	Constraint	Metric	Value	Output	Metric	Value	Mechanism	Metric	Value
VOR/LOC Chan	Power	28VDC									
TACAN Control Panel											
TACAN Channel select											
TACAN Mode select											
TACAN Test reply loop (signal)											
Signal from JPALS ground system (from coax)			Size	Length							
Signal from 1553/OAS, GPS/blended Nav signal				Width							
Ident function				Depth							
			Location								
are these switch or system ?			Power	GPS IU Power							
			Weight	Additional 3 card	+5 pounds						
			Human Factors								
			MTBF	Hours							
			Memory of existing soft switch								
			Number of buttons on soft switch (Group A)								
			Additional wiring to soft switch								
			Amount of info for display								
			Display radio frequency								
			Card slots (6 ava	JPALS		Signal	40-settings				
				TACAN		Signal	Voltage out	[0, 28]			
				VOR/LOC		Signal	Volume setting				
			Software develo	Integration	1	Signal	Mode select	[5 choices]			
			Hardware develo	cards	1	Signal	Volume setting				
						Signal	Test output				
						Signal	Test result				
						JPALS frequency select					
						Ground Station Identification					
						Display status					
						Signal to interface box					
						Signal to 429/1553 data bus		1/0			
						Fault data (BIT/IBIT) to OAS			JPALS Ground Station		
						JPALS "ident" signal			Human operator		
									Installation template		
									Volume select		
									mode select		
									Channel select		
									VOR/ILS Transmitter		
									TACAN transmitter		

Table 38 – Delta ICOM Matrix resulting from comparison of proposed JPALS switch and baseline Legacy Switches in B-52 Flightdeck

Delta ICOM Matrix [calculations: Proposed Matrix - Baseline Matrix)												Category of Delta	Delta resolution authority
Inputs (I)			Constraints (C)			Outputs (O)			Mechanisms (M)				
	Parameter(I)			Parameter (C)			Parameter (O)			Parameter (M)		None, Minor, Major, Severe	Program manager, engineering staff, Prime/OEM, User
Input	Metric	Value	Constraints	Metric	Value	Output	Metric	Value	Mechanism	Metric	Value		
Select JPALS frequency												Minor	Prime/OEM
			Weight	pounds	-5							Minor	EN staff
			Human factors	pages	increased							Minor	EN, USer
				Location	improved							Minor	EN, prime, user
			Card slots	JPALS								Minor	OEM
				TACAN								Minor	OEM
				VOR/LOC								Minor	OEM
			Processor throughput									Major	OEM
			Memory usage i	MB	increase TBD							Major	OEM
			Additional wiring	routing	1/0							Minor	EN, Prime
			Power usage	amps	expect decrease							Minor	EN
			Display	Radio frequency display requirements								Minor	EN
			Software develo	Integration	1							Major	Prime/OEM
			Hardware develo	cards	1							Major	OEM
						Signal (VOR/LO	channels	20				None	PM, EN
						JPALS frequency select						Minor	Prime, OEM
						JPALS Identification						Minor	EN, Prime, OEM
									JPALS Ground station			Major	Prime, OEM

After restarting, the functions of the as-is and to-be architectures and capabilities were documented. Additionally, the participants identified functions performed by the systems and the differences between functionalities. The IDEF0 diagrams were drawn for the baseline and proposed systems and the constituent arrow data was captured and entered into the baseline system and proposed system matrices. The matrices were compared and the Delta Matrix was calculated. Each of the differences identified in the Delta Matrix was analyzed and a severity code and responsible stakeholders were charted. Although beyond the scope of this research, the program office requested a placeholder be added to the method for performing cost analysis.

Findings for organization

As the participants worked through the model, the researcher captured insights the participants made throughout the case study effort. The findings were reviewed with the participants at the end of the exercise to ensure the process and exercise findings were accurately captured. The resulting findings:

- The proposed solution for combining the existing navigation switches into a single programmable switch that we developed for this action research project appears to be feasible.
- Software development, hardware development, and human interface issues are top concerns.
- The weight and power constraints are minimal. The new system seems to decrease the weight and power required.
- Elements that need to be explored more are requirements for displaying the radio frequency. Does the current radio frequency need to be displayed at all times? [Check with regulations and operators.]
- The addition of the additional 20 channels in the VOR/TACAN system appear to be relatively inexpensive to include in this modification.
- The only new external system for operating the JPALS seems to be the JPALS ground terminals.
- This process appears to work for the case of replacing a group of modules with a new system.

Comments by program office personnel

During the exercise, comments by the participants were captured to learn more about the process and areas for potential application and improvements. The participants' discoveries throughout the process added insight to their understanding of the JPALS integration problems. These discoveries were important enough that one of the participants left the room several times to report the progress and findings to the program director.

- We are too busy to spend the time to fully understand the systems on the B-52. We rely heavily on the prime contractor for technical advice and recommending the way ahead. This process gives us insight into the systems in a way that we can afford to take the time to use this process.
- Many of the steps in the process are currently performed ad hoc. The structure of this proposed process ensures the analysis is complete.
- We can see a logical way ahead for implementing JPALS after using this process.
- We need a way to perform cost estimates on the results.

- This process gives us improved insight into the JPALS installation process. Previous efforts on other projects required comparing paragraphs of system descriptions. The issues "pop out" and can be easily seen and addressed through the use of the diagrams and the delta matrix.
- This process should be used early in the process when exploring alternate concepts or systems.
- The process reveals the technical risk areas very clearly.
- The process facilitates communication about the system. The act of completing the matrices causes discussions of the ICOMs for the affected systems.
- This process will help us respond to the AFIMP 1067 [Air Force system modification] process.
- The resulting sparse matrix gives clear insight into issues.
- The process seems to work best with 2-3 people working on the project at a time. More people do not add value and fewer people don't help the discussions.
- This could be used to resolve diminishing manufacturing sources (DMS) issues.
- Process needs to be matured before we could adopt it

Program office could visually see the areas of change between the current configuration and the proposed configuration. Could visualize areas that had technical risk and required investments. Engineers wanted to use results to brief senior leaders/management

Method lessons learned

While working with the participants over a 2-day period, several opportunities were discovered for gaining insights into the methodology. These lessons learned about using the method are reported here.

First, as was discovered in earlier engagements, the level of abstraction for analysis remained important. The process takes discipline to identify and then remain at the appropriate level of abstraction. The level of abstraction directly controls the complexity of the problem. Selecting the unit of analysis may take more than one attempt. The participants initially selected multiple systems as the level of analysis and the method generated data at several levels. This data became difficult to manage and rework was required to ensure the constant level of analysis was kept. After the team came to the conclusion that the software switch should be the attempted unit of analysis, the process went smoother and more efficiently, and improved insight into the system analysis.

The participants quickly identified the process as valuable to the program office and asked that the model be extended for cost analysis. A placeholder was added to the analysis matrix to address costs in future research.

The delta matrix with its sparse format highlights issues that may have been otherwise missed with former methods of describing systems in text formats.

During the research activity, the group size varied over the two days. At the beginning, a group of about 8 participants began working the project. Over the course of the first day, participants who did not fully engage in the process excused themselves from the activity. At the end of the exercise, two or three subject matter experts were continuing to participate. At the end of the activity, the remaining participants offered that the participant level of 2-3 SMEs and a facilitator worked well. With the larger groups, there was more idle time which caused distractions and disruptions for others.

When the research began, the team was using large monitors to have the facilitator record the data. The practitioners found that they wanted to switch focus between multiple pages. They eventually chose paper forms over large screen monitors to document the systems.

The participants did not feel they could follow the process on their own. They stated that the method needs a facilitator.

Method changes

With the inputs of the participants, two changes were made to the method. First, a placeholder for cost analysis was added to the results matrix.

Second, the participants wanted paper forms as templates to help enter the data they collected. From this, standard blank forms were developed.

Case 4: Countermeasure dispensers

Background

The F-16 fighter aircraft was originally equipped with the ALE-40 countermeasure dispenser system (CMDS). The F-16 pilot received a threat notification from a radar warning receiver that relayed information about the type of threat and its location. The pilot then selected one of several pre-programmed countermeasure routines or a manual mode that triggered the ALE-40 to dispense chaff and flares to counter the incoming missile system.

As missile threats advanced, an improved version of the ALE-40 CMDS, the ALE-47, was proposed as a Form-Fit-Improved-Function (FFIF). Because the system was designed to be form and fit compatible with the ALE-40, the F-16 program office incorporated the ALE-47 into the F-16's electronic warfare suite of capability. The replacement was to be made in the field by flightline maintenance personnel. The potential for upgrading 3000 aircraft worldwide was seen as the potential retrofit market. In addition, the ALE-40 was planned to be included in the new F-16 production aircraft.

The AN/ALE-47 CMDS provides aircraft with a function of dispensing expendable countermeasures to defeat incoming missile threats. The ALE-47 is programmable, computer controlled capability for dispensing flares, chaff, non-programmable expendable jammers, and programmable jammers. The system receives inputs from on-board electronic warfare systems and automatically selects and deploys the appropriate countermeasures to defeat an identified threat. The purpose of the CMDS is to increase the survivability of many fighter, transport, tanker, helicopter, and surveillance aircraft across the continuum of threat environments. The AN/ALE-47 is an Acquisition Category (ACAT) III Joint program initiated to develop a common DoD CMDS to replace the AN/ALE-39 (U.S. Navy) and AN/ALE-40 (U.S. Air Force) (US Navy, 2002).

Goal of organization

This case study was developed to review the course of action that was executed by an Air Force aircraft acquisition office.

Methodology performed

After identifying the opportunity to use the ALE-40 to ALE-47 countermeasure dispenser system upgrade as a case to employ a tool to compare compatibility, the next step was to identify the functions performed by the ALE-40 andALE-47 systems. One of the program goals was to provide improved capabilities. The functions that emerged from these capabilities were areas to be considered for integration challenges.

Next, the ICOMs for baseline and proposed systems at system and subsystem levels were developed. These matrices were used to calculate the delta matrix to show the differences between the two systems. The delta matrix was analyzed and a category for each delta cell was assigned and the appropriate stakeholders were identified.

Table 39 - Function table comparing ALE-47 (proposed system) with ALE-40 (baseline system)

Function Table		
(1) Functions of Proposed System (F_P)	(2) Functions of Baseline System (F_B)	(3) Deltas between Systems ($F_P - F_B$)
Dispense chaff	Dispense chaff	
Dispense flares	Dispense flares	
Dispense pre-programmed routines	3 preprogrammed dispense routines	
Dispense chaff/flares manually	Dispense chaff/flares manually	
Dispense in automatic threat adaptive mode		Dispense in automatic threat adaptive mode
Dispense in semi-automatic		Dispense in semi-automatic
Dispense active expendables		Dispense active expendables

Table 40 - Baseline System ICOM Matrix for ALE-40

Baseline System ICOM Matrix											
Inputs (I)			Constraints (C)			Outputs (O)			Mechanisms (M)		
	Parameter(I)			Parameter (C)			Parameter (O)			Parameter (M)	
Input	Metric	Value	Constraints	Metric	Value	Output	Metric	Value	Mechanism	Metric	Value
Energy											
Operator	Select state	1									
		2									
		3									
	Slap switch	1									
			Power	Volts	28VDC						
				Amps	2 normal 7 when firing						
			Size	FF	1						
			Weight	pounds	62						
			Payload	chaff	0-60						
				flares	0-30						
				advanced	0						
						Dispense	Chaff	1, 2, 3			
							Flares	1, 2, 3			
							Manual	1			
									Maintenance	MLV	1
										Routines	1
										Aircraft integratio	1
										Programmer	1
									OFP		1

Table 41 - Proposed System ICOM Matrix for ALE-47

Proposed System ICOM Matrix											
Inputs (I)			Constraints (C)			Outputs (O)			Mechanisms (M)		
	Parameter(I)			Parameter (C)			Parameter (O)			Parameter (M)	
Input	Metric	Value	Constraint	Metric	Value	Output	Metric	Value	Mechanism	Metric	Value
Energy		1									
Operator	Select state	1									
		2									
		3									
		automatic									
		semi-automatic									
		Manual									
	Slap switch	1									
Signal	Threat	identification									
			Power	Volts	28VDC						
				Amps	2 normal 7 when firing						
			Size	form fit with prio	1						
			Weight	pounds	54						
			Payload	chaff	0-60						
				flares	0-30						
				advanced	0-60						
						Dispense	Chaff	optimized			
							Flares	optimized			
							Semi-automatic	optimized			
							Automatic	optimized			
							Manual	1			
									Maintenance	MLV	1
										Aircraft integratio	1
										Programmer	1
									Mission data		1
									OFP		1

Table 42 - Delta ICOM Matrix including Proposed and Baseline system ICOM Matrices

Delta ICOM Matrix [calculations: Proposed Matrix - Baseline Matrix)											
Inputs (I)			Constraints (C)			Outputs (O)			Mechanisms (M)		
	Parameter(I)			Parameter (C)			Parameter (O)			Parameter (M)	
Input	Metric	Value	Constraints	Metric	Value	Output	Metric	Value	Mechanism	Metric	Value
Energy		1									
Operator	Select state	1									
		2									
		3									
		automatic									
		semi-automatic									
		Manual									
	Slap switch	1									
Signal	Threat	identification									
			Power	Volts	28VDC						
				Amps	2 normal 7 when firing						
			Size	form fit with prior	1						
			Weight	pounds	54						
			Payload	chaff	0-60						
				flares	0-30						
				advanced	0-60						
						Dispense	Chaff	optimized			
							Flares	optimized			
							Semi-automatic	optimized			
							Automatic	optimized			
							Manual	1			
									Maintenance	MLV	1
										Aircraft integratio	1
										Programmer	1
									Mission data		1
									OFP		1
Energy											
Operator	Select state	1									
		2									
		3									
	Slap switch	1									
			Power	Volts	28VDC						
				Amps	2 normal 7 when firing						
			Size	FF	1						
			Weight	pounds	62						
			Payload	chaff	0-60						
				flares	0-30						
				advanced	0						
						Dispense	Chaff	1, 2, 3			
							Flares	1, 2, 3			
							Manual	1			
									Maintenance	MLV	1
										Routines	1
										Aircraft integratio	1
										Programmer	1
									OFP		1
Operator	state	Automatic									
		Semi-automatic									
Signal	Threat	identification									
			Weight	pounds	-8						
			Payload	advanced	0-60						
						Dispense	Chaff	optimized			
							Flares	optimized			
							Semi-automatic	optimized			
							Automatic	optimized			
									Maintenance	Counter routines	1
										Mission data	1

Methodology lessons learned

The ALE-47 upgrade encountered integration difficulties. This application was performed at two levels. At the higher, system level, the incompatibilities were minimal and expected. When the level of abstraction was changed to a lower level, which analyzed inside the boundaries of the ALE-47 system, the incompatibility that caused restructuring the Air Force's retrofit program was revealed.

The method appears to be sufficient for practitioner testing.

Findings for organization

No findings were made for the organization. This analysis was a postmortem application of the Compatibility Assessment Method to assess an outcome that was previously known.

Methodology changes

As the result of this case, no method changes were made. Changes were made to improve the forms used for data collection and refining the instruction set.

Case 5: Lift Truck II

This case study revisited the first participant after the compatibility assessment method had matured. Since the first engagement with this participant, the method had stabilized and tools had been developed to capture the data.

The organization has a future goal of developing an integrated "hands-on throttle and stick," or HOTAS, control system for a lift truck. This HOTAS is innovative because current lift truck operations are performed with a tiller wheel for steering, foot pedals for throttle and braking which is known as traction, and individual levers for the lifting operations.

The company knows that an integrated HOTAS has many barriers to implementation. These barriers include the technical integration components of the problem, but also include the social aspects of adopting a new operator concept, the safety issues and related regulatory concerns, and the increase capability of monitoring operations that the HOTAS enables. Because of the complexity of the entire HOTAS issue, the participant identified an interim goal of determining the feasibility of using a joystick controller to steer a lift truck instead of the current tiller system.

Methodology performed

Table 43 - Function Table comparing ICS with MFD/Tiller

Function Table: Integrated control system and MFD/Tiller		
(1) Functions of Proposed System (F_P)	(2) Functions of Baseline System (F_B)	(3) Deltas between Systems ($F_P - F_B$)
Control steer angle	Control steer angle	
Control traction		Control traction
Control lift		Control lift
Control lift sub-functions		
Integrated control system (ICS)	MFD/Tiller	- MFD - Tiller + ICS

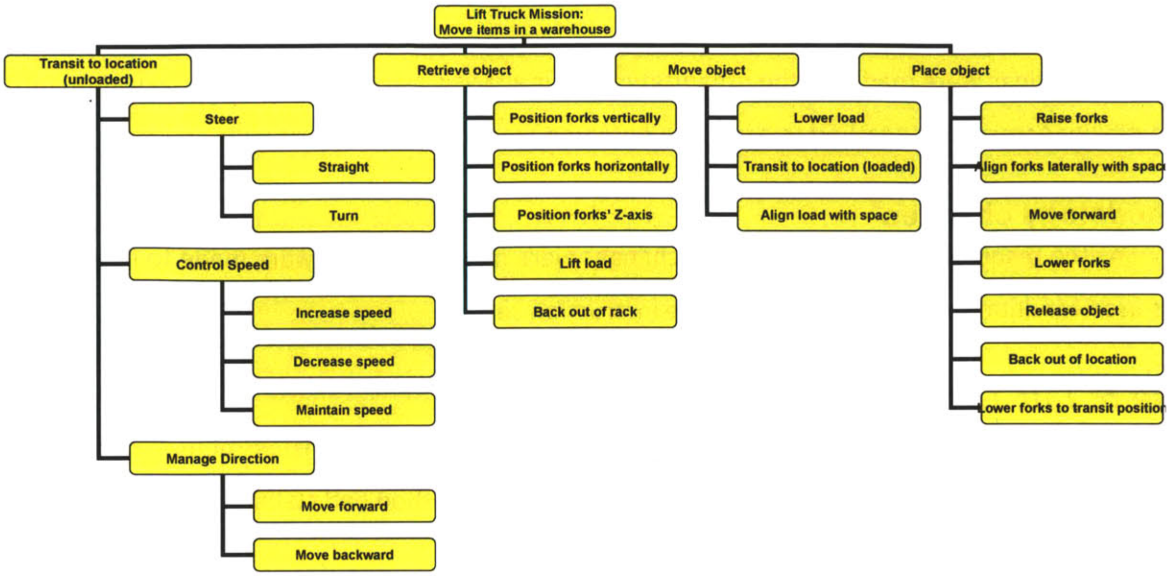


Figure 19 - Functional decomposition for lift trucks

First, a functional decomposition of lift truck activities was performed to identify steering functions. This led to developing the functional activity models for the steering functions. The functional activity models identified the constituent arrows that included the Inputs, Constraints, Outputs, and Mechanisms, or ICOMS, for the steering functions. These constituents were parameterized and assigned measurements when available for the as-is tiller steering and the to-be HOTAS steering architectures. With these baseline and proposed matrices, the Delta Matrix was calculated and the differences were evaluated.

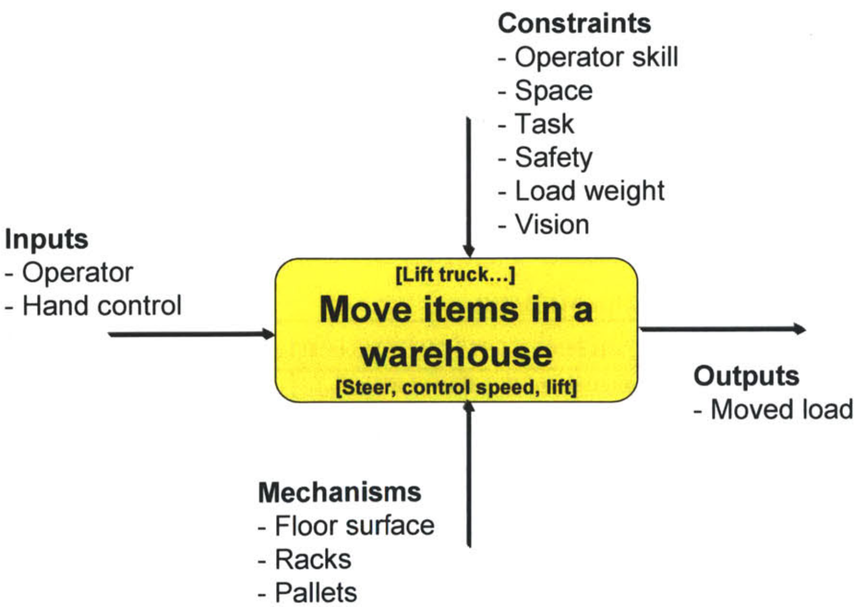


Figure 20 - Modified IDEF0 model for moving items in a warehouse (a function of a lift truck)

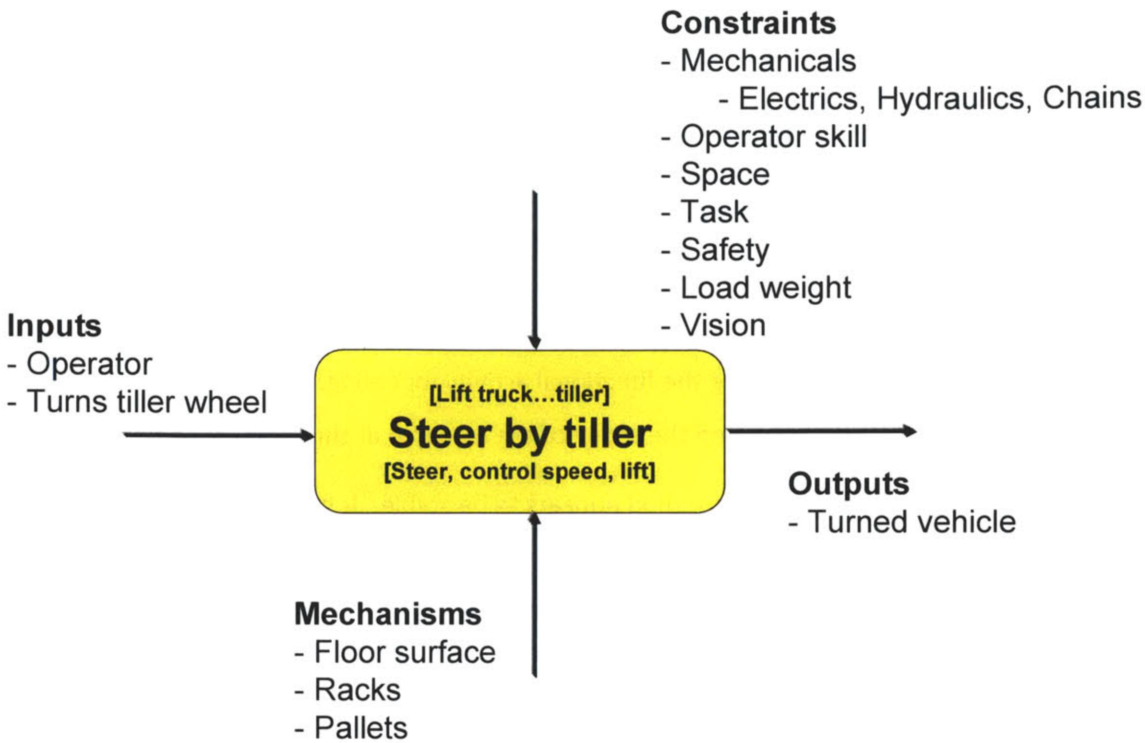


Figure 21 Modified IDEF0 model for steering a lift truck by tiller control

Findings for organization

During the analysis of the functional activity models and the associated ICOMs, the participant discovered that the functional models changed when the mode of operation changed. This insight revealed an additional complexity that needs to be addressed in some cases where multiple modes of operation exist. For a lift truck, modes change depending on the operation being performed. When a lift truck is traveling a long distance, the driver traditionally turns around and drives by looking to the rear of the vehicle. When the truck is positioning itself to pick up a load on a pallet, the driver needs fine positioning skills for fork placements and load positioning. This operation is performed with the operator in a forward-facing position. Next, the load is removed from its position, normally from a rack, and then the lift truck is driven backwards. The load may be lowered while in motion, which is called "blending." Because each of these operation modes requires different functionality of the system, each of the operational modes of the lift truck must be integrated to ensure proper system behavior and safety.

Methodology lessons learned

The method decomposed the functions of the lift truck operation and identified that when operation modes change, the functions change. This insight was identified by the research participant as important to the understanding of the safety and operational considerations that must be better understood before implementing an integrated control system.

Methodology changes

This case study resulted in no changes to the method. Additional insights were learned about addressing modes of operation when considering the functional activity modeling. The study of the effects of target system mode changes are beyond the scope of the research at this time.

Upon completion of this case study, the method appears to be stable. It has been used on several different systems and has matured from a qualitative assessment tool into a tool that allows both qualitative and quantitative analysis of a proposed replacement system. The method appears to be sufficiently mature for practitioner testing in a realistic applied environment.

Appendix C – Case studies performed by practitioners (Chapter 4)

Case Study 1: Sensor Systems A & C

Scenario:

The data and analysis using CAM in this scenario are the data and results of a graduate research thesis (Easton, 2010). In an effort to combine Air Force Predator and Army programs, a 2008 Acquisition Decision Memorandum (ADM) from the Deputy Secretary of Defense directed the Air Force and Army programs to resolve hardware differences in the Electro-Optical/Infrared (EO/IR) Sensor Ball components. The Air Force program office is considering the Army-developed Sensor C for its next block upgrade for its aircraft. Sensor A continues to meet requirements and does not need to be replaced, but due to the direction for common components, a choice may need to be made between the Air Force's Sensor A and the Army's Sensor C.

Current System (Baseline):

Sensor A provides electro-optical/infrared (EO/IR) and laser sensor capabilities for long ranged surveillance, target acquisition, tracking, rangefinding and laser designation for the Hellfire missile. The Sensor A is comprised of a turret mounted under the aircraft fuselage and an electronics assembly. The turret contains an Infrared (IR) sensor, two daylight TV (DTV) cameras, one Low Light TV (LLTV) camera, a laser Rangefinder/Designator (LRD), and a Laser Target Marker (LTM).

The key functions of the baseline system that must be met or exceeded by any other proposed system to merit consideration for possible replacement include long range surveillance and target acquisition.

Specific functions of surveillance include:

- IR detection and video
- DTV video/imaging - S-Video output
- LLTV video/imaging
- Image fusion processing - combining IR images with DTV or LLTV to create a single video

Specific functions of target acquisition include:

- Guiding the Laser guided munitions

- giving target range - measuring time between outgoing and incoming laser pulses from LRD
- tagging the target - illuminating with laser pulses

Possible proposed system to baseline system:

Sensor C is currently in use on the Army aircraft. Sensor C provides a day/night imaging sensor and laser designator for reconnaissance, intelligence, surveillance, target acquisition, and target designation. The sensor ball payload detects and recognizes operationally-meaningful targets at survivable standoff ranges, determines range-to-target, auto tracks and designates targets for precision-guided standoff weapons, provides target-location coordinates, and displays continuous high-resolution imagery to the battlefield commander. Sensor C shall, according to a draft of system specifications consist of a thermal imager, a visible imager, a laser designator, and an eye-safe laser rangefinder, a laser pointer, and a laser spot tracker all packaged within a stabilized gimbal. (System Specifications for Sensor C, 2007) According to company's Sensor C manager, the 18 inch sensor ball builds upon the Sensor A by "adding a laser spot tracker, electro-optical counter-countermeasures, and internal bore sighting." (Colluci, 2007) Sensor C, with self-configuring software, also adds the ability to automatically recognize which aircraft it is installed on.

The basic functions of the two systems were entered into the function table and directly compared by subtracting the baseline (Sensor A) from the proposed system (Sensor C). The analysis shows that the common functions are the same for both systems and that the Sensor C contains additional functionality. With the added features of Sensor C, Sensor C is a viable candidate to replace Sensor A. More detailed analysis through ICOM decomposition is warranted to determine if Sensor C could be a good fit to replace Sensor A in a future upgrade. (Table 44)

Table 44 - Function Table (IR Detection Set)

Function Table (IR Detection Set)		
(1) Functions of Proposed System (F_P)	(2) Functions of Baseline System (F_B)	(3) Deltas between Systems ($F_P - F_B$)
Sensor C	Sensor A	
IR Detection	IR Detection	
Daylight TV (DTV)	Daylight TV (DTV)	
Low Light TV (LLTV)	Low Light TV (LLTV)	
Image Fusion Processing	Image Fusion Processing	
Laser Guidance	Laser Guidance	
laser spot tracking	laser spot tracking	
internal bore sighting	boresighting	internal bore sighting
Electro-optical counter-countermeasures (EOCCM)		Electro-optical counter-countermeasures
Auto aircraft recognition		Auto aircraft recognition
		*Added Functionality. Do ICOM Decomposition

ICOM analysis:

After determining that the proposed system functionally supports the aircraft, the next step is to deconstruct the system into its Inputs, Constraints, Outputs, and Mechanisms (ICOMs) to determine if the system is a good fit both functionally and physically. This ICOM breakdown is compared to the baseline system ICOMs to find commonality and differences between the systems.

The baseline system was decomposed into ICOMs (Table 45) first to determine key data points to compare each system. Some of the key data points from the original comparison (Sensor A vs. Sensor C) were revised for a better comparison with Sensor C. For example, video resolution was added to the outputs and boresight enhancement was added to mechanisms.

Table 45 - Baseline ICOM Matrix, Sensor A

Baseline System ICOM Matrix (Sensor A)											
Inputs (I)			Constraints (C)			Outputs (O)			Mechanisms (M)		
	Parameter(I)			Parameter (C)			Parameter (O)			Parameter (M)	
Input	Metric	Value	Constraints	Metric	Value	Output	Metric	Value	Mechanism	Metric	Value
Power (Nom)	VDC	28									
Power(Peak)	VDC	28									
			Size	Diameter (in)	17.5						
				Height (in)	18.7						
			Weight	lbs	151						
			Operating Tem	C	(-54 to 55)						
			Operating Alt	ft	50,000						
			Operating Alt (LRD)		30,000						
						IR-Video	FOV	UW to UN			
							Zoom	2x, 4x			
						DTV-Video	FOV	UW to UN			
							Zoom	2x, 4x			
						LLTV -Video	FOV	Med to UN			
							Zoom	2x, 4x			
						Video Resolution Potential					
							Pixels	1080			
						Merged Images	1/0	1			
						target range	1/0	1			
						Illuminate targe	1/0	1			
						tag target	1/0	1			
									Control Interface		
									1553B	1/0	1
									Boresight Enhancement		
										1/0	1

The proposed system was then decomposed into ICOMs (Table 46) to determine deltas in key data points of each system.

Table 46 - Proposed ICOM Matrix, Sensor C

Proposed System ICOM Matrix (Sensor C)											
Inputs (I)			Constraints (C)			Outputs (O)			Mechanisms (M)		
	Parameter(I)			Parameter (C)			Parameter (O)			Parameter (M)	
Input	Metric	Value	Constraint	Metric	Value	Output	Metric	Value	Mechanism	Metric	Value
Power (Nom)	VDC	28									
Power(Peak)	VDC	28									
			Size	Diameter (in)	18						
				Height (in)	18						
			Weight	lbs	155						
			Operating Tem	C	(-61 - 55)						
			Operating Alt	ft	25,000						
			Operating Alt (LRD)		25,000						
						IR-Video	FOV	W to UN			
							Zoom	2x, 4x			
						DTV-Video	FOV	W to UN			
							Zoom	2x, 4x			
						LLTV -Video	FOV	Med to UN			
							Zoom	2x, 4x			
						Video Resolution Potential					
							Pixels	720			
						Merged Images	1/0	1			
						target range	1/0	1			
						Illuminate targe	1/0	1			
						tag target	1/0	1			
						Internal BE	1/0	1			
						EOCCM	1/0	1			
						A/C rec	1/0	1			
									Control Interface		
									1553B	1/0	1

The ICOMs were then entered into a matrix with an associated metric and value to allow for a comparison of baseline and proposed ICOMs. The key metrics for this the Sensor A/Sensor C comparison are in the outputs where the video Field of View and resolution, or the additional features could be determining factors in which system better meets the needs of the aircraft and the DoD.

The two systems can now be analyzed through pair-wise comparisons. (Table 47) The baseline ICOMs are subtracted from the proposed ICOMs and a delta matrix is created to show the differences between the two to be analyzed for significance.

Table 47 - Delta ICOM Matrix, Sensor C vs Sensor A

Delta ICOM Matrix [calculations: Proposed Matrix(System C) - Baseline Matrix(System A)]												
Inputs (I)			Constraints (C)			Outputs (O)			Mechanisms (M)			
	Parameter(I)			Parameter (C)			Parameter (O)			Parameter (M)		
Input	Metric	Value	Constraints	Metric	Value	Output	Metric	Value	Mechanism	Metric	Value	level of decision
Power (nom)	VDC	0										
Power (Peak)	VDC	0										
			Size	Diameter (in)	0							
				Height (in)	0							
			Weight		4							1
			Operating Temp		7C							1
			Operating Alt		(25,000)							1,user
			Operating Alt (LRD)		(5,000)							1,user
						IR-Video	FOV	(UW)				1,user
							Zoom	0				
						DTV	FOV	(UW)				1,user
							Zoom	0				
						LLTV	FOV	0				
							Zoom	0				
						Video Resolution Potential						
							Pixels	(360)				1,user
						Merged Images	1/0	0				
						Target Range	1/0	0				
						Illuminate Targ	1/0	0				
						Tag Target	1/0	0				
						Internal BE	1/0	1				1,
						EOCCM	1/0	1				1,user
						A/C Rec	1/0	1				1,2,user
									Control Interface			
									1553B	1/0	0	
									Boresight Enhancement (BE)			
										1/0	(1)	1

Sensor A vs. Sensor C ICOM Discussion:

Inputs: Both systems require 28 VDC of electrical input power. No other data was found in the open literature for the Sensor C. This is assumed to be a non issue because the Sensor C is currently replacing the Sensor A on the Army's aircraft.

Constraints: The sizes of the two systems are approximately the same. Exact data was not found for Sensor C, only that it was an 18 inch turret that has a requirement of less than 155 pounds combined weight of both the turret and electronics units compared to 151 pounds for the baseline Sensor A. A slight, difference (-55 C for Sensor A compared to -61 C for Sensor C) was found in the operating temperature specs. The operating altitude is also different for the two systems with the Sensor A able to operate at 50,000 ft and a max LRD altitude of 30,000 ft compared to 25,000 ft for the Sensor C.

Outputs: Video outputs for both systems included IR, DTV, LLTV, and image fusion, and both had up to 4X zoom capabilities. Some differences occurred in the field of vision (FOV) range for each of these outputs. The Sensor A IR and DTV FOV ranged from Ultrawide (UW), 34o x 45o, to Ultranarrow (UN), .6o x .8o. The MX-10 has a range from Wide (W), 15o x 20o, to UN. Both systems were able to give target range, illuminate and tag the targets with a laser pulse system. The Sensor A has an architecture that can handle an upgrade to process video and track targets in 1080p. The Sensor C, according the aircraft program office, with a more closed architecture, does not have the ability to expand its video processing and target tracking greater than 720p. Sensor C also adds internal boresight enhancement, EOCCM, and aircraft recognition software. This software can identify, verify, and load command and control profiles for specific platforms. (Colluci, 2007)

Mechanisms: Both used Mil Std 1553B data bus for its primary data control interface. Sensor A needs to add extra hardware, software and temperature calibration for a boresight enhancement system. Boresight enhancement is embedded in Sensor C.

Delta Evaluation:

Inputs: The inputs have no apparent deltas and with the lack of data found from open sources it is deemed that no further evaluation of inputs is necessary.

Constraints: The size constraints and the temperature constraints do not offer a significant difference. The delta in operating altitude of 50,000 ft for the Sensor A compared to 25,000 ft for the Sensor C would be a concern when the aircraft performs high altitude missions. The smaller difference, of 5,000 ft for LRD operating altitude should not pose a problem as the weapon systems will probably not be fired from above the 25,000 ft max offered by the Sensor C. The users may need to be consulted to verify operating altitudes of the aircraft.

Outputs: Some key deltas were found in the outputs for the Sensor A and Sensor C systems. The ultrawide FOV and the 1080p video processing and target tracking capability is clearly an advantage for the baseline Sensor A. The question remains as to whether or not these are requirement or just nice to have capabilities. If they are just nice to have, then the user needs to be consulted to determine how important this capability is to them. How much does it help when performing a mission? The additional outputs (internal boresighting, EOCCM, and aircraft recognition) of the Sensor C are a clear advantage, but like the FOV and video processing, these capabilities are not necessarily requirements but would be nice to have. For more detailed analysis program engineers could be consulted to determine the importance of internal boresighting capability compared to an added mechanism currently used for boresight enhancement. The users would be consulted on the need for EOCCM and the usefulness of aircraft recognition software.

Mechanisms: The primary control interface for both systems is the Mil-Std-1553B. No issues exist. The Sensor C alleviates the need for the added BE system.

Summary Analysis:

Basic functions are the same. The baseline system (Sensor A) offers advantages in field of view and future video processing capabilities. The proposed system (Sensor C) offers added internal capabilities with internal boresighting, EOCCM and aircraft recognition software.

Recommendation:

The recommendation is to first consult the users to find out how important each of these capabilities is to performing the mission. Then consult the engineers and maintainers to determine the effects on installing and maintaining the payloads with each of these configurations.

Case Study 3: Missile Systems P & Q

Scenario:

The data and analysis using CAM in this scenario are the data and results of a graduate research thesis (Easton, 2010).

The company has developed a new version of a missile. Missile P was designed specifically for the aircraft. It is essentially the same as the standard version of the missile but adds an expanded operating envelope. Missile Q is recommended by its developer as a significantly improved version of the similar missile being built for the Army. (Parsch, 2009)

Current System (Baseline):

Missile P is a precision guided fire and forget anti-armor missile consisting of five major sections including a seeker, warhead, guidance, propulsion, and control. Missile P's warhead is a tandem shaped charge High Explosive Anti-tank (HEAT), with external blast frag sleeve that targets all armored threats. The sleeve improves performance against light vehicles and urban threats. An alternate model, with its Metal augmented charge (MAC) and thermobaric warhead, produces a lower peaked, sustained pressure wave creating a series of reactions combining heat and pressure for more effective attacks against enclosed structures such as caves, bunkers, and hardened complexes. The guidance system for Missile P includes semi-active laser homing, digital autopilot, electro-optical countermeasures, and automatic target reacquisition. Propulsion and control are the same for all of this family's missiles. Solid propellant rocket fuel motor propels the missile to greater than Mach 1.0. The control unit contains actuators for the control fins forming the boat tail around the motor's exhaust. (http:www.scramble.nl, 2009)

Possible replacement to baseline system:

Missile Q is a multifunctional missile with the same basic functions of the previous family of missiles. Missile Q is fitted with a multi-purpose warhead that can destroy all the targets of previous missiles, to include armor and air defense systems, patrol boats, and enemy combatants in SUVs or caves. Missile Q addresses issues of reliability and maintainability, and DMS (diminishing manufacturing sources). It also has an added an inertial measurement unit allowing the missile to hit targets located behind the launch platform. ("Anti-Armor-Weapons-and-Missiles", 2011)

The basic functions of the two systems were entered into the function table and directly compared by subtracting the baseline (Missile P) from the proposed system (Missile Q). The analysis shows that the common functions are the same for both systems and that the Missile Q contains possible additional utility in that it can shoot any target with the one warhead. The basic functions are the same for both systems because the base function of the missile is still the same. Both shoot down intended targets. With the added flexibility features of the Missile Q, it is a viable candidate to replace the Missile P. More detailed analysis through ICOM decomposition is warranted to determine if Missile Q could be a good fit to replace Missile P in a future upgrade (Table 48). The key functions of the baseline system that must be met or exceeded by any other system to be considered for possible replacement.

Table 48 - Function Table (Missile)

Function Table (Missile)		
(1) Functions of Proposed System (F_P)	(2) Functions of Baseline System (F_B)	(3) Deltas between Systems ($F_P - F_B$)
Missile Q	Missile R	
Anti-armor	Anti-armor	
Air to Ground	Air to Ground	
Precision Strike	Precision Strike	
Operational Flexibility		Operational Flexibility

ICOM analysis:

After determining that the proposed system functionally supports the aircraft, the next step is to deconstruct the system into its Inputs, Constraints, Outputs, and Mechanisms (ICOMs) to determine if the system is a functional and physical fit. This ICOM breakdown is compared to the baseline system ICOMs to find commonality and differences between the systems.

The baseline system was decomposed into ICOMs (Table 49) first to determine key data points to compare each system.

Table 49 - Baseline ICOM Matrix, Missile P

Baseline System ICOM Matrix (Missile P)											
Inputs (I)			Constraints (C)			Outputs (O)			Mechanisms (M)		
	Parameter(I)			Parameter (C)			Parameter (O)			Parameter (M)	
Input	Metric	Value	Constraints	Metric	Value	Output	Metric	Value	Mechanism	Metric	Value
Guidance											
Semi-Active Laser											
	1/0	1									
Propulsion											
Solid Propellant											
	1/0	1									
			Size	Diamet (mm)	178						
				Length (m)	1.63						
				Wing Span (m)	0.33						
			Weight	lbs	106						
			Range	KM	9						
			Altitude	Ft	25,000						
			Speed	Mach	1.3						
						EOCM Resistance					
							1/0	1			
						Target Reacquisition					
							1/0	1			
						Air to Ground Targets					
						Tanks	1/0	1			
						Structures	1/0	1			
						Bunkers	1/0	1			
						Caves	1/0	1			
						Lt Vehicles	1/0	1			
						Urban Tgts	1/0	1			
									Fuse		
									Impact	1/0	1
									Warhead		
									Tandem Anti-armour		
										1/0	1
									MAC Thermobaric		
										1/0	1
									Launch Platform		
									UAV	1/0	1
									Laser Guidance		
									Sensor Ball	1/0	1

The proposed system was then decomposed into ICOMs (Table 50) to determine deltas in key data points of each system.

Table 50 - Proposed system ICOM Matrix (Missile Q)

Proposed System ICOM Matrix (Missile Q)											
Inputs (I)			Constraints (C)			Outputs (O)			Mechanisms (M)		
	Parameter(I)			Parameter (C)			Parameter (O)			Parameter (M)	
Input	Metric	Value	Constraints	Metric	Value	Output	Metric	Value	Mechanism	Metric	Value
Guidance											
Semi-Active Laser											
	1/0	1									
Inertial Measurment											
	1/0	1									
Propulsion											
Solid Propellant											
	1/0	1									
			Size	Diamet (mm)	178						
				Length (m)	1.63						
				Wing Span (m)	0.33						
			Weight	lbs	108.5						
			Range	KM	9						
			Altitude	Ft	25,000						
			Speed	Mach	1.3						
						EOCM Resistance					
							1/0	1			
						Target Reacquisition					
							1/0	1			
						Air to Ground Targets					
						Tanks	1/0	1			
						Structures	1/0	1			
						Bunkers	1/0	1			
						Caves	1/0	1			
						Lt vehicles	1/0	1			
						Urban Tgts	1/0	1			
									Fuse		
									Variable Delay		
										1/0	1
									Warhead		
									IBSF	1/0	1
									Launch Platform		
									Helo/UAV	1/0	1
									Laser Guidance		
									Sensor Ball	1/0	1

The ICOMs were then entered into a matrix with an associated metric and value to allow for a comparison of baseline and challenger ICOMs. The key metrics for this comparison occur in the inputs, outputs and mechanisms where additional strike capabilities could be determining factors in which system better meets the needs of the aircraft system and the DoD.

The two systems can now be analyzed through pair-wise comparisons. (Table 51) The baseline system ICOMs are subtracted from the proposed system ICOMs and a delta matrix is created to show the differences between the two and to be analyzed for significance.

Table 51 - Delta ICOM Matrix for Missile Q and Missile P

Delta ICOM Matrix [calculations: Proposed Matrix(Missile Q) - Baseline Matrix(Missile P)]												
Inputs (I)			Constraints (C)			Outputs (O)			Mechanisms (M)			
	Parameter(I)			Parameter (C)			Parameter (O)			Parameter (M)		
Input	Metric	Value	Constraints	Metric	Value	Output	Metric	Value	Mechanism	Metric	Value	level of decision
Guidance												
Semi-Active Laser												
	1/0	0										
Inertial Measurment												
	1/0	1										1,user
Propulsion												
Solid Propellant												
	1/0	0										
			Size	Diamet (mm)	0							
				Length (m)	0							
				Wing Span (m)	0							
			Weight	lbs	2.5							2
			Range	KM	0							
			Altitude	Ft	0							
			Speed	Mach	0							
						EOCM Resistance						
							1/0	0				
						Target Reacquisition						
							1/0	0				
						Air to Ground Targets						
						Tanks	1/0	0				
						Structures	1/0	0				
						Bunkers	1/0	0				
						Caves	1/0	0				
						Lt vehicles	1/0	0				
						Urban Tgts	1/0	0				
									Fuse			
									Variable Delay			
										1/0	1	1,,user
									Warhead			
									IBSF	1/0	1	1,user
									Launch Platform			
									Helo/UAV	1/0	0	
									Laser Guidance			
									Sensor Ball	1/0	0	

Missile P vs. Missile Q ICOM Discussion:

Inputs: Both missile systems use the same solid propellant propulsion and both have the same semi-active laser guidance. The Missile Q adds inertial measurement to its guidance system.

Constraints: The physical dimensions of the two systems are the same. The Missile Q is 2.5-4 pounds heavier.

Outputs: Both the systems have been hardened against electro-optical countermeasures and both have the capability to reacquire its target if lost. The deltas in the outputs occur in the target sets each is designed to attack. The Missile P target set includes armored threats on the ground such as tanks, bunkers and structures, light vehicles, caves and urban targets. The Missile Q target sets include everything from the previous versions and it provides the flexibility to take out any target from a single warhead.

Mechanisms: Both missiles can use an aircraft as a launch mechanism, and both need a laser guidance system for precision bombing such as the Sensor A or Sensor C. Deltas are in the Warheads and Fuses used for detonation. Missile P uses the Tandem shaped charge high explosive anti-tank (HEAT) warhead with an impact fuse. Missile Q uses an integrated blast frag sleeve (IBSF) warhead that combines the features of a shape-charged and a blast fragmentation warhead with a variable delay fuse. (Parsch, 2009)

Delta Evaluation:

Inputs: The inputs have one delta. With the added inertial measurement unit to its guidance system, the Missile Q has the ability to hit targets behind its launch platform, although the Missile P envelope is being expanded as well. This inertial measurement unit is still an advantage over the older versions, the only question is how important is this feature to the users.

Constraints: Constraints are generally the same in each missile. The difference in weight of 2.5-4 pounds caused by a heavier warhead appears to be insignificant, although a quick check with the program engineers may be appropriate just to verify that this will not cause any problems.

Outputs: No actual deltas were found in the outputs for the missile systems. Missile Q is capable of destroying all the same armored target sets as the Missile P and one of its variants combined with such targets as air defense systems, patrol boats, and enemy combatants in ground vehicles and caves ("Anti-Armor-Weapons-and-Missiles", 2011). The key difference is that Missile Q is an all in one missile that would not need to be changed out for different missions and intended target sets, as is the current practice with Missile P.

Mechanisms: The added operational flexibility is a result of the mechanism used. The multipurpose IBSF warhead gives a single missile an increased engagement envelope to cover all of the mentioned target sets with greater lethality. Missile Q also gives the extra benefit and greater flexibility with the option of a variable delay fuse that can be activated by the operator. (Parsch, 2009) With clear advantages to the newer missile, the users should be consulted to determine the utility of these extra capabilities.

Summary Analysis:

The current missiles operate in combination at accomplishing the mission. Technically there really is no advantage to keeping the current missiles over the improved Missile Q. Missile Q combines the previous missile capabilities, and adds to the effectiveness, efficiency, reliability and maintainability and flexibility. The question will become one of cost, logistics, and need. How much will it cost to buy and replace the existing inventory? To what extent does the user need this extra operational flexibility?

Recommendation:

A value judgment needs to be made on the cost of replacing the current inventory, if any, with the need for the added flexibility.

Program manager assessment

The program office program manager (PM) was asked the same questions as the SMEs, but from a different perspective. From a PM's perspective, he was asked to evaluate the case studies as if one of his Project Managers had brought him this information to help him make a decision on changing or upgrading any of the given subsystems. His past results analysis were from a broader perspective of decisions made and the processes used on different systems from his past experience as opposed to those specifically relating to the case studies.

Case Studies 4 & 5: Communication Systems on a second aircraft

The previous three pairwise case studies, including the one in Chapter 4 and the two found in this appendix were performed by a project manager using three types of systems, a sensor, communication, and weapon system, on a single aircraft. The following two pairwise cases involve a project manager who managed communication systems on another aircraft system. This communication systems project manager also had program management responsibilities for the communication system upgrades. Where the previous three evaluations engaged higher management levels, Case Studies 4 and 5 were performed and evaluated by the project manager because his scope of responsibility included making the recommendations for the system selection decisions.

The following two case studies are related. The program office was developing a strategy for an upgrade path for the communication system. The upgrade was required because the current communication system was becoming unsupportable. The manufacturer discontinued the production of the system and replacement sub-components were also going out of production. The program office considered two upgrade paths. The first path included upgrading to a newer model of the radio that was being discontinued. The second path upgraded the radio to the next generation of technology. The program manager needed to evaluate the options and choose an upgrade path.

For these cases, the pairwise control for comparison was not determined subjectively by a senior program manager. For these cases, a contractor study had been performed to make a recommendation on communication system upgrades. This contractor study was used as a control and the CAM evaluations were used as the treatments.

The program manager completed a reduced set of the CAM matrices for these evaluations because many the functionality differences between the current communication system and the proposed communication systems were well-understood by the program manager and his support team. The program manager focused on developing the ICOM matrices and the Delta matrices for these systems that were already identified to be of interest.

Case Study 4: Communication Systems W & Z

The first case performed by the program manager for this aircraft was comparing the current communication system (Comm W) that is going out of production with a proposed communication system (Comm Z) that is scheduled to be in production for several more years. The first step was to construct the Function Table (Table 52). The analysis showed that DAMA modem functionality and Link 4A data exchange functions were available in the new system that were not available in the current version.

The next step was to construct the Baseline System ICOM Matrix for Communication System W (Table 53). This matrix describes the baseline system that will be used in comparisons to both Comm Z and Comm Y, the next generation communication system. This table can be reused as often as necessary to perform pairwise comparisons to any proposed upgrade.

Table 52 - Function Table comparing Comm systems Z and W

Function Table		
(1) Functions of Proposed System (F_P)	**(2) Functions of Baseline System (F_B)**	**(3) Deltas between Systems ($F_P - F_B$)**
Comm Z	**Comm W**	
Voice communications	**Voice communications**	
COMSEC communciations	**COMSEC communciations**	
VMF(188-220C)	**VMF(188-220C)**	
Have Quick I/II	**Have Quick I/II**	
SINCGARS	**SINCGARS**	
AMLV	**AMLV**	
DAMA A/B		**DAMA A/B**
Link 4A		**Link 4A**

Table 53 - Baseline System ICOM Matrix (Comm W)

Baseline System ICOM Matrix (Comm W)											
Inputs (I)			Constraints (C)			Outputs (O)			Mechanisms (M)		
	Parameter(I)			Parameter (C)			Parameter (O)			Parameter (M)	
Input	Metric	Value	Constraints	Metric	Value	Output	Metric	Value	Mechanism	Metric	Value
Power	VDC	28									
Transmit	Watts	155									
Receive	Watts	45									
			Size	Width (in)	5						
				Height	5.6						
				Depth	9.85						
			Weight	pounds	12.2						
			Operating Temp	C	(-54 to 71)						
			Altitude	feet	70000						
			Tuning incremen	kHz	8.33						
						Voice Comm	Frequency	30-400 MHz			
						Have Quick I/II		Yes			
						SINCGARS		Yes			
						COMSEC		Yes			
						SATCOM	DAMA	Yes			
							DAMA A/B	No			
						Link 4A		No			
						JPALS		No			
						Programmable COMSEC		No	Encryption devic	Applique	Yes
						SATURN		No		Embedded	No
						ESIP		No	Retrofit Kit		Yes
						Ethernet link		No	TCTO Issued		No
									TO Changes		No
									Software Definable Radio		No

Following the development of the current system's iCOM matrix, the Proposed system ICOM Matrix (Table 54) was constructed to characterize the parameters of the proposed system, Comm Z. The manager selected the ICOM categories based on his bias that space, weight, and power (SWaP) would be the primary concerns for integration. He had experienced this in previous modification projects.

Next, the differences between the matrix developed for Comm W and Comm Z were identified and documented in the Delta ICOM Matrix (Table 55). In addition to the Delta Matrix, this program manager also included columns for Category of the Delta which is the assigned severity code for the difference, the Delta Resolution authority, and finally, the Stakeholders who would be affected by the delta that was discovered. For this project, none of these additional areas (Table 55) was pursued, but the data were collected.

Table 54 - Proposed System ICOM Matrix (Comm Z)

Proposed System ICOM Matrix (Comm Z)											
Inputs (I)			Constraints (C)			Outputs (O)			Mechanisms (M)		
	Parameter(I)			Parameter (C)			Parameter (O)			Parameter (M)	
Input	Metric	Value	Constraint	Metric	Value	Output	Metric	Value	Mechanism	Metric	Value
Power	VDC	28									
Transmit	Watts	121									
Receive	Watts	43									
			Size	Width (in)	5						
				Height	5.6						
				Depth	9.85						
			Weight	pounds	11						
			Operating Temp	C	(-54 to 71)						
			Altitude	feet	70000						
			Tuning incremer	kHz	8.33						
						Voice Comm	Frequency	30-512 MHz			
						Have Quick I/II		Yes			
						SINCGARS		Yes			
						COMSEC		Yes			
						SATCOM	DAMA	Yes			
							DAMA A/B	Yes			
						Link 4A		Yes			
						JPALS		No			
						Programmable COMSEC		No	Encryption devic	Applique	Yes
						SATURN		No		Embedded	No
						ESIP		No	Retrofit Kit		Yes
						Ethernet link		No	TCTO Issued		Yes
									TO Changes		Yes
									Software Definable Radio		No

Table 55 - Delta ICOM Matrix (Comm Z - Comm W) with Categories, Resolution Authorities, Stakeholders, and Cost Estimate entries

Delta ICOM Matrix [Calcualtions: Proposed Matrix - Baseline Matrix; Comm Z - Comm W]												Category of Delta	Delta resolution	Stakeholder	Cost estimate
Inputs (I)			Constraints (C)			Outputs (O)			Mechanisms (M)						
	Parameter(I)			Parameter (C)			Parameter (O)			Parameter (M)		Severe, Major,	PM, EN, Prime		
Input	Metric	Value	Constraints	Metric	Value	Output	Metric	Value	Mechanism	Metric	Value	Minor, None	and/or OEM		
Power	VDC														
Transmit	Watts	-34										Minor	EN		
Receive	Watts	-2										Minor	EN		
			Size	Width (in)											
				Height											
				Depth											
			Weight	pounds	-1.2							Minor	EN		
			Operating Temp	C											
			Altitude	feet											
			Tuning incremer	kHz											
						Voice Comm	Frequency	400 - 512 MHz				Minor	EN, Prime, OEM	Users, Logistics, Other Agencies	
						Have Quick I/II									
						SINCGARS									
						COMSEC									
						SATCOM	DAMA								
							DAMA A/B	Yes				Minor	EN, Prime, OEM		
						Link 4A		Yes				Minor	EN, Prime, OEM	Users	
						JPALS									
						Programmable COMSEC									
						SATURN									
						ESIP									
						Ethernet link									
									Encryption devic	Applique					
										Embedded					
									Retrofit Kit		Yes	Major	PM, EN, Prime, OEM	Maintenance, Users	
									TCTO Issued		Yes	Minor	PM, EN, Prime, OEM	Maintenance, Users	
									TO Changes		Yes	Minor	PM, EN, Prime, OEM	Maintenance, Users	
									Software Definable Radio			Minor	PM, EN, Prime, OEM	Maintenance, Users	

Table 56 - Delta ICOM Matrix (Comm Z - Comm W)

Delta ICOM Matrix [Calcualtions: Proposed Matrix - Baseline Matrix; Comm Z - Comm W]											
Inputs (I)			Constraints (C)			Outputs (O)			Mechanisms (M)		
	Parameter(I)			Parameter (C)			Parameter (O)			Parameter (M)	
Input	Metric	Value	Constraints	Metric	Value	Output	Metric	Value	Mechanism	Metric	Value
Power	VDC										
Transmit	Watts	-34									
Receive	Watts	-2									
			Size	Width (in)							
				Height							
				Depth							
			Weight	pounds	-1.2						
			Operating Temp	C							
			Altitude	feet							
			Tuning incremer	kHz							
						Voice Comm	Frequency	400 - 512 MHz			
						Have Quick I/II					
						SINCGARS					
						COMSEC					
						SATCOM	DAMA				
							DAMA A/B	Yes			
						Link 4A		Yes			
						JPALS					
						Programmable COMSEC					
						SATURN					
						ESIP					
						Ethernet link					
									Encryption devic	Applique	
										Embedded	
									Retrofit Kit		Yes
									TCTO Issued		Yes
									TO Changes		Yes
									Software Definable Radio		

Table 57 - Extensions to CAM

Category of Delta	Delta resolution	Stakeholder	Cost estimate
Severe, Major, Minor, None	PM, EN, Prime and/or OEM		
Minor	EN		
Minor	EN		
Minor	EN		
Minor	EN, Prime, OEM	Users, Logistics, Other Agencies	
Minor	EN, Prime, OEM		
Minor	EN, Prime, OEM	Users	
Major	PM, EN, Prime, OEM	Maintenance, Users	
Minor	PM, EN, Prime, OEM	Maintenance, Users	
Minor	PM, EN, Prime, OEM	Maintenance, Users	
Minor	PM, EN, Prime, OEM	Maintenance, Users	

Case Study 5: Communication Systems W & Y

The second case performed by the program manager for this aircraft was comparing the current communication system (Comm W) that is going out of production with a proposed communication system (Comm Y), the next generation of communication systems, that was scheduled to start production in 2010 (Rockwell Collins, 2008).

The function table (Table 58) comparing the current system (Comm W) with the proposed next generation system (Comm Y) revealed several additional functions. This data was collected from technical documents available from open source documents (*Jane's Avionics 2007-2008*, 2007; Rockwell Collins, 2008, "Rockwell Collins to Develop Next-Generation an/Arc-210 Aircraft Radios", 2009). By moving to the next generation in the product line, several changes in functionality are discovered. In addition to the functionality increases found by moving to a newer model, advanced capabilities and architectures need to be considered. The Joint Precision Autonomous Landing System (JPALS) that was the upgraded system in the B-52 case study, the Software Defined Radio architecture, and additional waveforms are available in the next generation model. Because the new generation system meets the current functions, the system analysis was continued with the ICOM development and analysis.

Table 58 - Function Table comparing Comm systems Y and W

Function Table		
(1) Functions of Proposed System (F_P)	(2) Functions of Baseline System (F_B)	(3) Deltas between Systems ($F_P - F_B$)
Voice communications	Voice communications	
COMSEC communciations	COMSEC communciations	
VMF(188-220C)	VMF(188-220C)	
Have Quick I/II	Have Quick I/II	
SINCGARS	SINCGARS	
AMLV	AMLV	
DAMA A/B		DAMA A/B
Link 4A		Link 4A
JPALS		JPALS
Software Defined Radio		Software Defined Radio
SATURN		SATURN
ESIP		ESIP

The Baseline System ICOM Matrix was reused from Case Study 4 (Table 53) and then the Proposed System ICOM Matrix was developed for Comm Y (Table 59).

The Delta ICOM Matrix (Table 60) indicates a decrease in the power used by Comm Y. The program manager was able to assign the severity code as Minor and would be able to adjudicate the resolution to the engineering staff working on his program. The physical aspects of the system were the same as the previous system—no deltas emerged. In the outputs of the system, the new functionalities' outputs were identified. In addition, the system has additional capability be being able to use frequencies 490-900 MHz. This allows communication with Homeland Security broadcasts. The manager stated this as a Minor severity, but that it would require several stakeholders to address the changes. Finally, in the Mechanism arc, a retrofit kit would need to be developed to integrate the changes into the aircraft, technical orders would be required for operators and maintainers, and support equipment would be required to program the software definable radio. One physical aspect in the mechanisms category is the embedded cryptological capability. In the previous versions of this system, the classified crypto was a removable appliqué. In this version, the crypto is embedded. This requires additional handling and shipping constraints. This was identified as a severe category of the Delta. This is documented in the Delta ICOM matrix (Table 61).

Table 59 - Proposed System ICOM Matrix (Comm Y)

Proposed System ICOM Matrix (Comm Y)											
Inputs (I)			Constraints (C)			Outputs (O)			Mechanisms (M)		
	Parameter(I)			Parameter (C)			Parameter (O)			Parameter (M)	
Input	Metric	Value	Constraint	Metric	Value	Output	Metric	Value	Mechanism	Metric	Value
Power	VDC	28									
Transmit	Watts	150									
Receive	Watts	25									
			Size	Width (in)	5						
				Height	5.6						
				Depth	9.85						
			Weight	pounds	12.2						
			Operating Temp	C	(-54 to 71)						
			Altitude	feet	70000						
			Tuning incremen	kHz	8.33						
						Voice Comm	Frequency	30-960 MHz			
						Have Quick I/II		Yes			
						SINCGARS		Yes			
						COMSEC		Yes			
						SATCOM	DAMA	Yes			
							DAMA A/B	Yes			
						Link 4A		Yes			
						JPALS		Yes			
						Programmable COMSEC		Yes	Encryption devic	Applique	No
						SATURN		Yes		Embedded	Yes
						ESIP		Yes	Retrofit Kit		Yes
						Ethernet link		Yes	TCTO Issued		Yes
									TO Changes		Yes
									Software Definable Radio		Yes

Table 60 - Delta ICOM Matrix (Comm Y - Comm W)

Delta ICOM Matrix [Calcualtions: Proposed (Comm Y) Matrix - Baseline (Comm W) Matrix]											
Inputs (I)			Constraints (C)			Outputs (O)			Mechanisms (M)		
	Parameter(I)			Parameter (C)			Parameter (O)			Parameter (M)	
Input	Metric	Value	Constraints	Metric	Value	Output	Metric	Value	Mechanism	Metric	Value
Power	VDC										
Transmit	Watts	-5									
Receive	Watts	-20									
			Size	Width (in)							
				Height							
				Depth							
			Weight	pounds							
			Operating Temp	C							
			Altitude	feet							
			Tuning incremen	kHz							
						Voice Comm	Frequency	400 - 960 MHz			
						Have Quick I/II					
						SINCGARS					
						COMSEC					
						SATCOM	DAMA				
							DAMA A/B	Yes			
						Link 4A		Yes			
						JPALS		Yes			
						Programmable COMSEC		Yes			
						SATURN		Yes			
						ESIP		Yes			
						Ethernet link		Yes			
									Encryption devic	Applique	No
										Embedded	Yes
									Retrofit Kit		Yes
									TCTO Issued		Yes
									TO Changes		Yes
									Software Definable Radio		Yes

Table 61 - Delta ICOM Matrix (Comm Y - Comm W) with Categories, Resolution Authorities, Stakeholders, and Cost Estimate entries

Delta ICOM Matrix [Calcualtions: Proposed (Comm Y) Matrix - Baseline (Comm W) Matrix]												Category of Delta	Delta resolution	Stakeholder	Cost estimate
Inputs (I)			Constraints (C)			Outputs (O)			Mechanisms (M)						
Input	Parameter(I)		Constraints	Parameter (C)		Output	Parameter (O)		Mechanism	Parameter (M)		Severe, Major, Minor, None	PM, EN, Prime and/or OEM		
	Metric	Value		Metric	Value		Metric	Value		Metric	Value				
Power	VDC														
Transmit	Watts	-5										Minor	EN		
Receive	Watts	-20										Minor	EN		
			Size	Width (in)											
				Height											
				Depth											
			Weight	pounds											
			Operating Temp	C											
			Altitude	feet											
			Tuning incremer	kHz											
						Voice Comm	Frequency	400 - 960 MHz				Minor	EN, Prime, OEM	Users, Logistics, Other Agencies	
						Have Quick I/II									
						SINCGARS									
						COMSEC									
						SATCOM	DAMA								
							DAMA A/B	Yes				Minor	EN, Prime, OEM		
						Link 4A		Yes				Minor	EN, Prime, OEM	Users	
						JPALS		Yes				Minor	EN, Prime, OEM	Users, ATC	
						Programmable COMSEC		Yes				Minor	EN, Prime, OEM	Security, Logistics, Users	
						SATURN		Yes				Minor	EN, Prime, OEM	Security, NATO, Users	
						ESIP		Yes				Minor	EN, Prime, OEM	Users	
						Ethernet link		Yes				Minor	EN, Prime, OEM	Users, TBD	
									Encryption devic	Applique	No	Severe	PM, EN, Prime, OEM	Security, Logistics	
										Embedded	Yes	Severe	PM, EN, Prime, OEM	Security, Logistics	
									Retrofit Kit		Yes	Major	PM, EN, Prime, OEM	Maintenance, Users	
									TCTO Issued		Yes	Minor	PM, EN, Prime, OEM	Maintenance, Users	
									TO Changes		Yes	Minor	PM, EN, Prime, OEM	Maintenance, Users	
									Software Definable Radio		Yes	Major	PM, EN, Prime, OEM	Maintenance, Users	

Findings from the contracted study

The contracted study was performed by the aircraft prime manufacturer in its role as a systems integrator. The contractor recommended updating the aircraft with Comm Z. The contractor recommended a retrofit kit to integrate Comm Z onto the aircraft and then follow up with ground and flight testing. During the analysis of Comm Z, a single radio was tested on a single frequency and it was discovered that it has better frequency separation than the baseline system, Comm W. The proposed system requires only 25 MHz frequency instead of 40 MHz. the contractor was given ground rules for the replacement that the current radio functionalities must be maintained, space, weight, power, and software could not be changed. These requirements precluded the selection of Comm Y, the next generation system.

An analysis of the connectors and pins showed that there were no changes required for the recommended upgrade. The contracted report also characterized the transmitter and receiver characteristics. The contractor compared the operational environment with the system specifications. No differences were discovered when performing comparisons.

The study also included developing engineering drawings for the installation, designing the modification kit required to install Comm Z, schedules for acquisition to testing to installation. In addition, the contractor identified the stakeholders. The solution recommended testing in laboratories, on the ground, and for slight test.

Findings from Case Studies 4 and 5

The analysis of the delta matrices in Case Studies 4 and 5 revealed that the compatibility between the baseline and the proposed systems would be straight-forward for the transition from Comm W to Comm Z. The systems are of the same generation in the product family and very few physical changes are made. Some additional capabilities are gained through the upgrade, but the compatibility is high.

When the analysis turned to upgrading the current system to the next generation system as a proposed system, the deltas between the systems increased and compatibility decreased. These findings supported the information that was developed through the contracted study. The differences between the contracted study and the CAM outputs were related to the level of abstraction that was reported. In the contracted study, a fine-grained, more detailed analysis was performed. Details that included individual wires and their signals were addressed. The communication systems were bench tested and analyzed for co-site interference which is well beyond the scope of CAM analysis. The contracted study noted that no changes in connectors and pins were required by the change from Comm W to Comm Z. This could have been performed through CAM analysis by zooming-in on the connectors, but this was not performed by the program manager. Operational, environmental, and electro-magnetic interference concerns were also tested by the contractor.

The contracted study identified that some assemblies would require to be changed, installation kits would need to be developed, and engineering change orders would be required. These items were also discovered through the use of the CAM process.

Table 62 - Mann-Whitney U Test for comparing distributions of the six variables leading to government insight when comparing CAM with Legacy methods of determining subsystem compatibilities

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of Process is the same across categories of L=0 C=1.	Independent-Samples Mann-Whitney U Test	.012	Reject the null hypothesis.
2	The distribution of Motivation is the same across categories of L=0 C=1.	Independent-Samples Mann-Whitney U Test	.910	Retain the null hypothesis.
3	The distribution of Assumptions is the same across categories of L=0 C=1.	Independent-Samples Mann-Whitney U Test	.042	Retain the null hypothesis.
4	The distribution of Repeatability is the same across categories of L=0 C=1.	Independent-Samples Mann-Whitney U Test	.005	Reject the null hypothesis.
5	The distribution of Traceability is the same across categories of L=0 C=1.	Independent-Samples Mann-Whitney U Test	.031	Retain the null hypothesis.
6	The distribution of Reproducability is the same across categories of L=0 C=1.	Independent-Samples Mann-Whitney U Test	.017	Reject the null hypothesis.

Asymptotic significances are displayed. The significance level is .05.

This non-parametric Independent Samples Mann-Whitney U Test compared the distributions of the Legacy and CAM processes. In each case the null hypothesis was that the distributions of the program managers' responses were the same in each area for CAM and Legacy methods. The null hypotheses were rejected three out of seven times in the areas of Process, Repeatability, and Reproducibility. Therefore the distributions varied between CAM and Legacy methods for Process, Repeatability, and Reproducibility variables. This suggests a difference between CAM and Legacy methods exists for the Process, Repeatability, and Reproducibility variables.

Table 63 - Non-parametric Independent Samples Mann-Whitney U-test comparing program manager responses across systems.

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of Process is the same across categories of S1=0 S2=1.	Independent-Samples Mann-Whitney U Test	.655	Retain the null hypothesis.
2	The distribution of Motivation is the same across categories of S1=0 S2=1.	Independent-Samples Mann-Whitney U Test	.011	Reject the null hypothesis.
3	The distribution of Assumptions is the same across categories of S1=0 S2=1.	Independent-Samples Mann-Whitney U Test	.223	Retain the null hypothesis.
4	The distribution of Repeatability is the same across categories of S1=0 S2=1.	Independent-Samples Mann-Whitney U Test	.819	Retain the null hypothesis.
5	The distribution of Traceability is the same across categories of S1=0 S2=1.	Independent-Samples Mann-Whitney U Test	.165	Retain the null hypothesis.
6	The distribution of Reproducability is the same across categories of S1=0 S2=1.	Independent-Samples Mann-Whitney U Test	.657	Retain the null hypothesis.

Asymptotic significances are displayed. The significance level is .05.

This non-parametric Independent Samples Mann-Whitney U Test compared the response variable from Likert data surveys across the program manager and system grouping distributions of the Legacy and CAM processes. In each case the null hypothesis was that the distributions of the program managers' responses was the same in each area system 1 and system 2. The null hypotheses were rejected only for the Motivation variable. Therefore the distributions varied between the systems and program manager for only the Motivation variable. This suggests a difference between the systems exists for the Motivation variable only.

Table 64 - Non-parametric Independent Samples Mann-Whitney U measuring the medians of the Likert data responses across methods

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The medians of Process are the same across categories of L=0 C=1.	Independent-Samples Median Test	.048[1,2]	Reject the null hypothesis.
2	The medians of Motivation are the same across categories of L=0 C=1.	Independent-Samples Median Test	1.000[1,2]	Retain the null hypothesis.
3	The medians of Assumptions are the same across categories of L=0 C=1.	Independent-Samples Median Test	1.000[1,2]	Retain the null hypothesis.
4	The medians of Repeatability are the same across categories of L=0 C=1.	Independent-Samples Median Test	.008[1,2]	Reject the null hypothesis.
5	The medians of Traceability are the same across categories of L=0 C=1.	Independent-Samples Median Test	.167[1,2]	Retain the null hypothesis.
6	The medians of Reproducability are the same across categories of L=0 C=1.	Independent-Samples Median Test	.444[1,2]	Retain the null hypothesis.

Asymptotic significances are displayed. The significance level is .05.

[1]Exact significance is displayed for this test.

[2]Fisher Exact Sig.

When non-parametric tests for Independent Samples median tests were conducted, the null hypothesis were that the medians were the same for the Legacy and CAM methods. In the areas of Process and Repeatability, the null hypotheses were rejected. This analysis suggests that the methods do not yield the same results across methods with respect to the Process and Repeatabillity.

Table 65 - Non-parametric Independent Samples Median Test to analyze the distribution of response variables across systems.

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The medians of Process are the same across categories of S1=0 S2=1.	Independent-Samples Median Test	1.000[1,2]	Retain the null hypothesis.
2	The medians of Motivation are the same across categories of S1=0 S2=1.	Independent-Samples Median Test	.048[1,2]	Reject the null hypothesis.
3	The medians of Assumptions are the same across categories of S1=0 S2=1.	Independent-Samples Median Test	1.000[1,2]	Retain the null hypothesis.
4	The medians of Repeatability are the same across categories of S1=0 S2=1.	Independent-Samples Median Test	1.000[1,2]	Retain the null hypothesis.
5	The medians of Traceability are the same across categories of S1=0 S2=1.	Independent-Samples Median Test	.500[1,2]	Retain the null hypothesis.
6	The medians of Reproducability are the same across categories of S1=0 S2=1.	Independent-Samples Median Test	.467[1,2]	Retain the null hypothesis.

Asymptotic significances are displayed. The significance level is .05.

[1]Exact significance is displayed for this test.

[2]Fisher Exact Sig.

When the medians of the Program Managers' responses were tested using the Independent Samples Median Test, the Null Hypothesis were that the median were the same for both the Legacy and the CAM methods. The Null Hypothesis could be rejected only in the area of government insight into the Motivation of the organization performing the analysis. The analysis suggests that across systems and program managers that Motivation varies.

Figure 22 - Semi-structured interview framework for discussions with program managers to evaluate CAM against Legacy Methods

Capability Assessment Method Study [semi-structured interview guidelines]

1. Present the systems that were the units of analysis for the proposed study.
    a. Ask the program managers to identify replacement activity with similar complexity that has been recently performed.

Legacy Method

2. Ask the program managers about the time to make the similarly-complex decision using the legacy method.
    a. Ask the program managers about government insight into the process ((1,2,3,4) [Very poor, poor, well, very well].
        i. Do you understand the process used to make the recommendation?
        ii. Do you understand the motivations of the person/organization who made the recommendation?
        iii. Do you have knowledge of the assumptions that were used in the process?
    b. Ask the program managers about the confidence in the decision (1,2,3,4) [Very unlikely, unlikely, likely, very likely].
        i. Is the process repeatable? (Can it be performed the same way again?)
        ii. Does the process have traceability? (Can the same outcome be expected if the people performed the analysis?)
        iii. Is the process reproducible? (Would a different group of people get the same result?)
    c. Ask the program managers about the cost of making the decision.
        i. Was contract support used? (Yes / No)
        ii. What was the cost of the support? (Value)
        iii. Was travel required to make the decision? (Yes / No)
    d. Ask the program managers about the amount of time used to make the decision.
        i. How many man-hours did it take to complete the data collection, analysis, and recommendation? (Value)
        ii. What was the elapsed time taken to complete the data collection, analysis, and recommendation? (Value)

Capability Assessment Method

3. Present the method and the process that the project manager used to make the technical recommendation. Show results from project manager's analysis of systems with a technical recommendation for a proposed replacement system.
4. Ask the program managers through a semi-structured interview about results and the process used (these answers can be collaborated between the project and program managers).
    a. Ask the program managers about government insight into the process ((1,2,3,4) [Very poor, poor, well, very well]).
        i. Do you understand the process used to make the recommendation?

   ii. Do you understand the motivations of the person/organization who made the recommendation?
   iii. Do you have knowledge of the assumptions that were used in the process?

b. Ask the program managers about the confidence in the decision. (1,2,3,4) [Very unlikely, Unlikely, Likely, Very likely].
   i. Is the process repeatable? (Can it be performed the same way again?)
   ii. Does the process have traceability? (Can the same outcome be expected if the same people performed the analysis?)
   iii. Is the process reproducible? (Would a different group of people get the same result?)
c. Ask the program manager about the cost of making the decision.
   i. Was contract support used? (Yes / No)
   ii. What was the cost of the support? (Value)
   iii. Was travel required to make the decision? (Yes / No)
d. Ask the program manager about the amount of time used to make the decision.
   i. How many man-hours did it take to complete the data collection, analysis, and recommendation? (Value)
   ii. What was the elapsed time taken to complete the data collection, analysis, and recommendation? (Value)

Repeat steps 1 through 4 for each case using the proposed method and the legacy methods.

The results from the interviews with the program managers were collected and organized as shown in Table 15 - Results of comparing Legacy and Compatibility Assessment Methods after CAM has been used in program offices.

Appendix D – Student experiment (Chapter 5)

Student experiment

This appendix contains the materials that were used to administer the pairwise experiment to the student participants. Included in this section are the consent releases, survey questions, semi-structured interview guidelines, collected data, and data analysis in graphical and table formats.

Consent Forms

CONSENT TO PARTICIPATE IN INTERVIEW

Finding Opportunities for Commonality in Complex Systems

You have been asked to participate in a research study conducted by David Long from *ESD* at the Massachusetts Institute of Technology (M.I.T.). The purpose of the study *is to learn about commonality.* The results of this study will be included in David Long's doctoral dissertation. You were selected as a possible participant in this study because *(of your experience in product development, acquisition, and/or unmanned systems).* You should read the information below, and ask questions about anything you do not understand, before deciding whether or not to participate.

• This interview is voluntary. You have the right not to answer any question, and to stop the interview at any time or for any reason. We expect that the interview will take about *TBD.*

• You will not be compensated for this interview.
• Unless you give us permission to use your name, title, and / or quote you in any publications that may result from this research, the information you tell us will be confidential.

• We would like to record this interview on audio cassette so that we can use it for reference while proceeding with this study. We will not record this interview without your permission. If you do grant permission for this conversation to be recorded on cassette, you have the right to revoke recording permission and/or end the interview at any time.

This project will be completed by *November 2012* All interview recordings will be stored in a secure work space until (*1 year*) after that date. Any tapes will then be destroyed.

I understand the procedures described above. My questions have been answered to my satisfaction, and I agree to participate in this study. I have been given a copy of this form.

(*Please check all that apply*)

[ ] I give permission for this interview to be recorded on audio cassette.

[ ] I give permission for the following information to be included in publications resulting from this study:

[ ] my name [ ] my title [ ] direct quotes from this interview

Name of Subject ______________________________

Signature of Subject ______________________________ Date ____________

Signature of Investigator ______________________________Date _________

Please contact *(David Long, dave13@mit.edu)* with any questions or concerns.
If you feel you have been treated unfairly, or you have questions regarding your rights as a research subject, you may contact the Chairman of the Committee on the Use of Humans as Experimental Subjects, M.I.T., Room E25-143b, 77 Massachusetts Ave, Cambridge, MA 02139, phone 1-617-253-6787.

Student Background Survey

Student Background Survey

1. Name (for control purposes only): ______________________________________
2. Rank/Grade: ________________________
3. Years of government service: _____________________
4. Years of acquisition experience: _________________
5. Primary AFSC (job series) / years: __________/___ secondary / years: ___________/ __
6. Education
    a. Undergraduate degree_______________ gpa:___________
    b. Projected masters degree________________
    c. Projected masters degree graduation: __________________
7. Acquisition professional development
    a. Stall 1:_______________________________________ Level:__________
    b. Stall 2:_______________________________________ Level:__________
    c. Stall 3:_______________________________________ Level:__________
8. Describe your prior acquisition experience:

Post-Exercise Survey

Post-Exercise Survey **Name** ______________________________

Which group were you for this analysis? (circle one) Group 1 (CAM) / Group 2 (LAM)

How did you determine if the proposed system [RT-5959] could be installed in the MQ-XX? [Did you follow the Group 1 process? If you deviated from the prescribed method, what did you do? If you didn't use the Group 1 process, how did you perform the analysis?]

What factors are important to consideration when selecting a replacement subsystem?

How much time did you spend on the analysis?

Start __________

End ____________

Elapsed________

What skills are needed to perform this analysis?

What educational background is required to perform this analysis?

Do you have all the skills to perform this analysis? (circle one answer)

Yes / No

What skills are you missing?

Is the information presented adequate to

1. Determine compatibility? Yes / No
   a. What is missing?
2. Determine areas of incompatibility? Yes / No
   a. What is missing?

Would you use the same method to perform the analysis again? Yes / No

Why or why not?

What could be improved with the method used?

Rate the difficulty in performing this analysis:

(1) Impossible
(2) Very difficult
(3) Difficult
(4) Neither difficult nor easy
(5) Easy
(6) Very easy

Please put your score here:

What confidence do you have in your results?

Rate the following statements using the following scale:

(1) Strongly disagree
(2) Disagree
(3) Neither agree nor disagree
(4) Agree
(5) Strongly agree

Table 66 - Survey questions for CAM Analysis

Score (1, 2, 3, 4, 5) Disagree => Agree		**Statements**
	A	The results would be the same if performed by another individual.
	B	I would get the same results if I repeated the method with the same information.
	C	Performing this analysis was easy.
	D	I have the appropriate skills to evaluate a subsystem to determine if it can be used as a replacement for a subsystem currently in use.
	E	I have confidence that my assessment of compatibility is accurate.
	F	Other system engineering students would get value from participating in this experiment
	G	I believe that my analysis would be valuable to the MQ-XX program office.
	H	I believe the MQ-XX program office could make a decision on the RT-5959 based on my analysis.
	I	**GROUP 1** Users: I would recommend program offices adopt the CAM METHOD as a standard practice.
	J	**GROUP 1** Users: CAM METHOD was a useful tool.
	K	I would prefer a better-defined process to perform compatibility assessments.

Where should the method you used be adopted as a process?

Can the RT-5959 replace the RT-1556 system that is currently installed in MQ-XX?

1. Yes
2. No
3. Under certain circumstances (please explain)

Do you have any other comments about the presentations, the materials presented, the exercise, or anything else you would like to share?

Follow-up questions

Follow-up questions

Name____________________ Date ____________ Circle: Group 1 / Group 2

1. How did you decide when you were "done"?

2. How did you decide what were the showstoppers?

3. Did you find "all" the deltas? Why or why not?

4. Additional insights about how you performed the task and how you determined what you found.

Compatibility Case Study:

Replacing the RT-1556 on the MQ-XX

Remotely piloted vehicle description:

The remotely piloted vehicle (RPV) MQ-XX is a medium to high altitude, long-range, long-endurance, multi-role unmanned aircraft system that performs a hunter-killer mission. The system as it is operated has an air vehicle, a ground system that has two components:

(1) a ground control system for launching and landing the air vehicle in direct line of sight with the air vehicle normally from within the theater of operations; and

(2) a ground control system that is capable of operating the air vehicle from half a world away through satellite link communications.

The air vehicle provides a data collection platform that uses a choice of sensors to gather information. In addition, after sensing potential adversaries, the MQ-XX can use its missiles to attack systems.

Radio communications system description:

The MQ-XX uses the Rockwell Collins ARC-210 family of radios for its communication needs. The ARC-210 provides jam-resistant two-way voice and data communication links and has many models and variants available for a wide range of applications. One component of the ARC-210 system is the transceiver "RT-1556" that is used on the MQ-XX. The RT-1556 is being retired from the ARC-210 product line and an alternative transceiver will need to be identified for fielded systems and to be installed on the MQ-XX (and other air vehicles) production lines.

The Problem:

The MQ-XX has a communication subsystem that is going out of production and will become unsupportable. The MQ-XX program office predicted this situation and made gap-filling end-of-life buy of the ARC-210 transceivers. However, the calculated requirement for transceivers was underestimated and now the end-of-life buy quantity is inadequate for projected MQ-XX operations. A new radio transceiver solution must be acquired.

One proposed solution to the problem is replacing Rockwell-Collins' ARC-210 transceiver RT-1556 with RadioCorp's™ transceiver RT-5959. RadioCorp™ advertises the RT-5959 as being compatible with applications that are currently using the RT-1556.

Often, the selection process is contracted to a support contractor who studies options and recommends a solution to the Air Force. This time the Air Force program management team is going to pre-screen replacement candidates to identify the extent of compatibility of using selected transceivers on the

MQ-XX. The first transceiver being evaluated is the RT-5959. You will use supplied specifications of the MQ-XX, Rockwell Collins' RT-1556, and RadioCorp's™ RT-5959. You will identify the compatibility issues associated with bringing the RadioCorp™ RT-5959 into the Air Force inventory and its use on the MQ-XX.

Your task:

1. Identify the critical and most important differences between the current ARC-210 RT-1556 transceiver radio and the proposed transceiver.
2. Describe the extent of each of the incompatibility issues.
3. Assign an incompatibility severity code to characterize the magnitude of the differences in compatibility.
4. Identify the appropriate personnel category(ies) to resolve the compatibility issues.
5. Provide your assessment if the proposed system can be used as a substitution for the currently installed ARC-210 radio that is installed on MQ-XX.

The class will be randomly divided into two sections. The first section will be given a presentation about methods and concepts for use in addressing the task. The second section will be given a presentation about a different set of methods and concepts. Then each member of each section will be asked to complete the task. You will be given reference materials regarding the RT-1556 and RT-5959 radio systems and information about the MQ-XX program. All the information you will need should be provided.

Members of both groups will work individually on the project. Please do not discuss the case, your methodology, or your findings with other students until after the exercise is complete. Please keep track of the time you spend on the project. After completing the task, each person will complete a short survey about the method used and we'll all discuss the outcomes.

Rockwell-Collins ARC-210 RT-1556

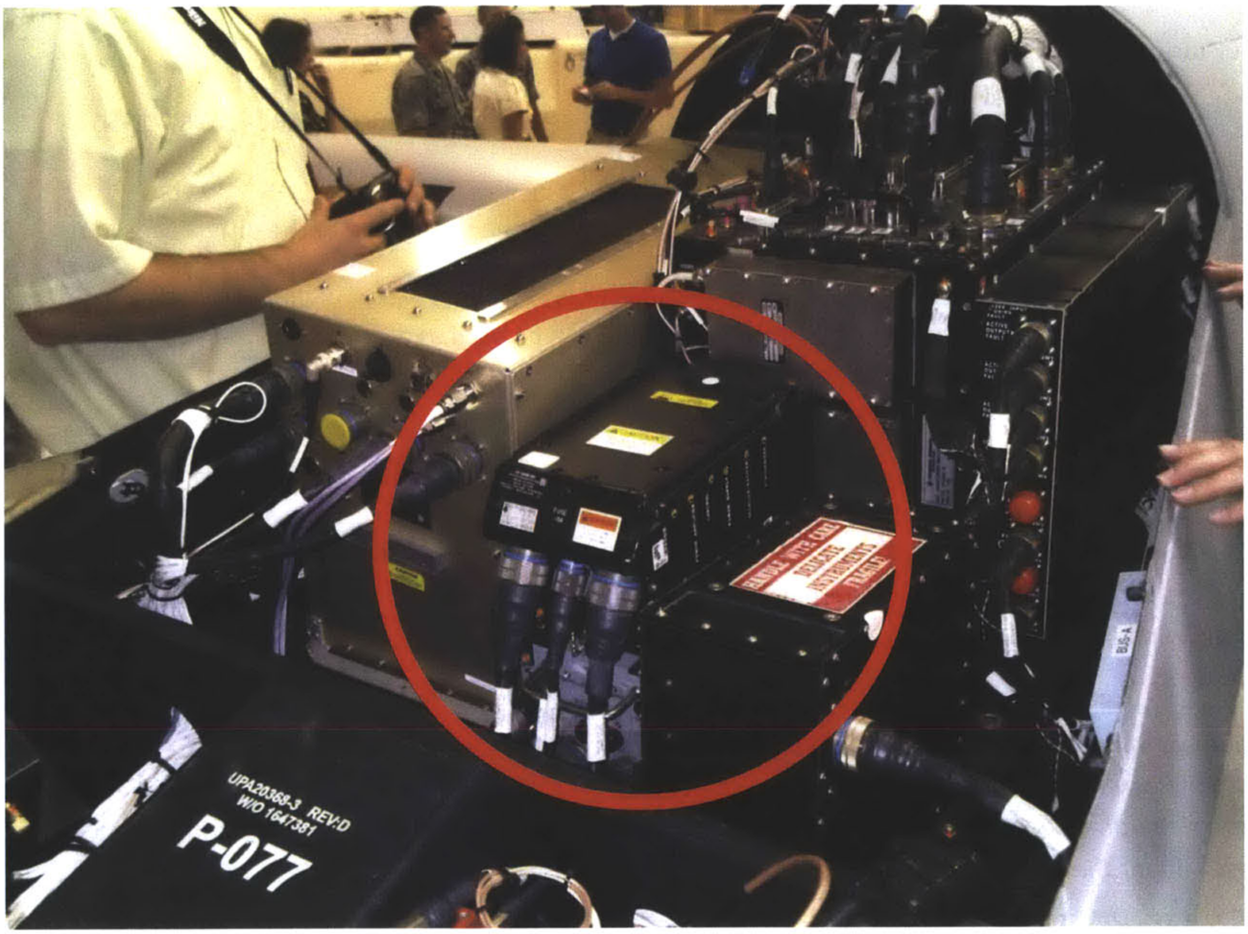


Figure 23- ARC-210 RT-1556 installed in MQ-XX

RadioCorp™ RT-5959: Specification Sheet

The RT-5959 is specifically designed with the Unmanned Aircraft System in mind. The system is lightweight and compact with low power requirements. The RT-5959 offers improvements in control systems, reliability, and tuning.

RT-5959 System Description:

The RT-5959 is a multimode communications system. The basic transceiver can be operated as a normal non-Electronic Counter Countermeasures (ECCM) type VHF/UHF radio system. Addition of various types of ECCM module subassemblies enables the RT-5959 Communications System to operate in SATCOM and jam-resistant modes. Several different types of ECCM module subassemblies are available. The RT-5959 transceiver is compatible with the U.S. Navy standard ECCM module subassembly provides the HAVE QUICK, HAVE QUICK II, SATURN, and the Single-channel Ground and Airborne Radio System (SINCGARS) waveforms.

The RT-5959 operates via the ARINC-429 data bus. Optionally, a remote control is available for manual operation of the transceiver system. Aviation red, Navy white, USAF white, or NVIS compatible (green) lighting is available, powered by 5 V ac or V dc, 28 V ac or V dc, or 115 V ac. A remote indicator and a family of broadband, electronically tunable antenna are available to enhance system performance. The standard 125-watt broadband high power amplifier (HPA) is also compatible for longer distance operations.

The RT-5959 is post-9/11 compliant and offers a frequency range of 30 to 512MHz and provides users static-free operations in UHF and VHF bands. The RT-5959 offers the popular "quick access" emergency feature that gives One-Button Push® to the VHF emergency frequency of 121.5 MHz. As with the previous generations of transceivers, the RT-5959 uses all digital design techniques, the most reliable surface mount technology that is available today, and the system can be upgrades because of its industry-leading modular construction. Physical modifications can now be made in the field and we've maintained the popular field software re-programmability!

Who do you need to communicate with? Our RT-5959 is compatible with Link 11 for those all-important inter-service communication needs. How often have you lost the cryptographic appliqué from your current generation transceivers? That hassle is all in the past. You'll kiss those pesky screw-in appliqués good-by when you upgrade to our embedded crypto version of the RT-5959 transceivers.

Don't forget the new, narrow-band transmission requirements that become FCC law in 2011. Your RT-5959 is ahead of the game and you can control your frequencies all the way down to 1 KHz increments with the super ARINC 429 data bus. Are you planning to fly in Europe? The ARINC 429 allows 1 kHz tuning which is significantly better than the Eurocontrol 8.33 kHz standard. The ARINC provides faster throughput than the MIL-STD-1553 data bus...we've eliminated the unnecessary redundancy checks on our data bus.

- State-of-the-art all digital design, surface mount technology, modular upgradeable construction
- Synthesizer speed and rapid radio response time handles any developed ECCM algorithm or LINK requirement
- Data rates up to 100,000 bits/second Line of Sight (LOS) with Bandwidth Efficient Advanced Modulation (BEAM) technology
- Compatible with Link 11, Link 4A, IDM
- Software re-programmable in the field (COMSEC RTs and their RCUs) via MLVS for rapid system integration and growth
- Industry standard ARINC 429 data Bus or remote control
- Built-in Test (BIT) to module level
- Channel Spacing: 25 kHz (30 - 512 MHz) and 8.33 kHz 118 - 137 MHz) and 12.5 kHz and 6.25 MHz (400 - 512 MHz)
- Tuning capability: 5 kHz with remote control, 1 kHz via 429 bus
- Frequency accuracy: 0.03 part per million
- Power output: AM: 10 to 15 watts FM: 15 to 23 watts (400 - 512 MHz FM: 5 watts)

The RadioCorp ™ RT-5959 is the most advanced Receiver-Transmitter available for UAVs today.

The RT-5959 has been designed to better meet warfighter needs and conform to Software Defined Radio (SDR) tenets and architectures. The RT-5959 provides the versatility is key to success on and above the battlefields of today and tomorrow. The RT-5959 outperforms today's industry standards for network and point-to-point requirements. What are YOUR data requirements? The RT-5959 seamlessly handles voice, imagery, and data communications.

Are YOU ready for operating at the next level? RadioCorp's ™ industry-leading technology adapts to the evolving transmission and security requirements. The RT-5959 is the first military airborne transceiver to provide an embedded, fully programmable INFOSEC capability in an open architecture SDR design. The embedded cryptographic subsystem (CSS) uses the National Security Agency (NSA) approved Janus multi-chip module (MCM). The CSS will provide secure communications using today's cryptographic algorithms (CAs) and will accommodate future growth for modern CAs. What does this mean to you? No more pesky crypto appliqués to ship separately or forget to install. The RT-5959 has a fully-integrated, embedded crypto capability.

The RT-5959 is a SDR radio whose software Multi-Waveform Architecture (MWA) provides the capability to port both legacy waveform code baselines and new waveforms that have been designed to be compliant with Software Communications Architecture (SCA). Our industry-leading MWA approach to supporting SCA waveforms is to use an optimized version of the components that make up an SCA execution environment. The RT-5959 incorporates similar form, fit, and improved functionality that currently resides in the currently fielded systems and maintains the same external I/O interface to the maximum extent possible. The RT-5959 will include new capabilities of

- MILSTD-188-220D capability for basic networking capability,
- Enhanced SINCGARS Improvement Program (ESIP),
- SATURN, and
- Increased frequency coverage of 30 - 961 MHz.

The guard receiver performance has been expanded to be tunable over the 30 - 512 MHz frequency range and allow for full duplex operations. Additionally, the RT-5959 hosts the Joint Precision Approach and Landing System (JPALS) airborne UHF data link functionality. RT-5959 provides a growth path for increased networking capability via UHF Follow-on (UFO) satellite communications (SATCOM) Integrated Waveform (IW), Mobile User Objective System (MUOS), Soldier Radio Waveform (SRW), and Integrated Broadcast system (IBS).

Table 67 - Physical characteristics of the RT-5959

Dimensions	Metric	US
Size	17.8 cm x 14.2 cm x 30.2 cm	7 in x 5.6 in x 11.9 in
Weight	7.35 kg	16.2 lbs

Table 68 - Survey responses from students performing CAM and Legacy methods

Method	Time	Skills needed	Compat ?	Incompat?	Same method?	Ease	Confidence (L/M/H 1/2/3)	A	B	C	D	E	F	G	H	I	J	K	Replace?	Number of Incompatibilities found
CAM	2.5	Yes	No	No	Yes	3	2	**4**	4	3	5	4	2	4	4	2	2	4	maybe	5
CAM	2.75	No	No	No	Yes	4	2	**4**	4	3	4	3	4	3	3	4	4	2	No	7
CAM	3.5	No	No	No	?	3	1	**1**	4	3	2	2	4	1	1	3	4	5	Yes	2
CAM	1.6	No	Yes	Yes	No	4	2	**4**	5	4	4	2	4	3	4	3	4	2	No	6
CAM	1.5	Yes	No	Yes	No	4	3	**4**	4	4	4	4	5	3	3	2	2	2	maybe	10
CAM	2.5	Yes	No	Yes	No	2	1	**3**	4	2	2	1	2	3	1	3	3	2	No	4
CAM	3	Yes	No	Yes	Yes	3	3	**5**	4	3	5	5	4	4	2	3	4	2	maybe	3
CAM	2.6	No	Yes	No	Yes	2	1	**4**	5	2	4	4	3	3	3	2	2	4	Yes	5
CAM	1	No	Yes	Yes	No	5	3	**4**	4	4	4	3	2	2	2	2	2	2	maybe	5
CAM	2	Yes	No	No	No	4	1	**4**	5	2	4	2	2	2	1	1	1	2	maybe	5
CAM	3.5	Yes	No	Yes	No	3	3	**3**	3	2	4	3	2	2	4	2	2	3	maybe	8
CAM	2.5	No	No	Yes	Yes	2	3	**2**	4	2	2	2	4	3	4	3	4	2	maybe	3
Legacy	1.5	No	No	Yes	No	3	3	**3**	4	2	4	3	4	4	2			4	maybe	16
Legacy	2.5	Yes	No	No	Yes	4	3	**4**	4	2	2	4	4	4	1			4	maybe	7
Legacy	1.5	Yes	No	Yes	Yes	6	3	**2**	4	5	5	5	4	4	4			4	maybe	11
Legacy	3.5	Yes	No	No	Yes	4	2	**3**	4	3	4	5	2	2	2			1	No	11
Legacy	2	No	No	No	Yes	3	1	**2**	4	2	3	2	4	2	2			5	maybe	4
Legacy	1.5	Yes	No	No	Yes	4	1	**2**	4	3	3	2	3	2	2			3	No	8
Legacy	1	No	Yes	Yes	No	3	2	**2**	4	3	2	2	4	4	2			4	No	6
Legacy	2	Yes	No	Yes	Yes	4	2	**4**	5	3	3	4	3	2	2			4	No	4
Legacy	2.5	No	No	Yes	No	3	3	**3**	4	2	4	4	5	4	4			4	No	8
Legacy	2.5	No	No	Yes	Yes	5	3	**2**	5	4	3	4	4	4	1			5	No	12
Legacy	3.5	Yes	No	Yes	Yes	4	1	**4**	5	2	2	3	4	3	2			5	maybe	7
Legacy	2	Yes	No	No	No	3	3	**4**	5	2	4	4	4	4	2			4	No	6
Legacy	1	Yes	No	No	No	3	2	**1**	4	2	3	1	3	1	1			5	maybe	14
Legacy	2	No	No	No	Yes	5	2	**3**	5	3	3	4	4	4	3			2	maybe	6
Legacy	3.1	No	No	No	No	2	1	**1**	2	1	1	1	3	2	1			4	maybe	7
12	2.41	6	3	7	5	3.25	2.08	3.50	4.17	2.83	3.67	2.92	3.17	2.75	2.67	2.50	2.83	2.67		5.25
	0.77					0.97	0.90	1.09	0.58	0.83	1.07	1.16	1.11	0.87	1.23	0.80	1.11	1.07		2.26
	0.59					0.93	0.81	1.18	0.33	0.70	1.15	1.36	1.24	0.75	1.52	0.64	1.24	1.15		5.11
15	2.14	8	1	7	9	3.73	2.13	2.67	4.20	2.60	3.07	3.20	3.67	3.07	2.07			3.87		8.47
	0.80					1.03	0.83	1.05	0.77	0.99	1.03	1.32	0.72	1.10	0.96			1.13		3.56
	0.64																			
	2.26					3.52	2.11	3.04	4.19	2.70	3.33	3.07	3.44	2.93	2.33			3.33		7.04
s (Excel	0.19					0.11	0.44	0.06	0.90	0.51	0.16	0.56	0.20	0.41	0.18			0.01		0.00441
	0.27					0.48	0.05	0.83	0.03	0.23	0.60	0.28	0.50	0.32	0.60			1.20		3.22
	0.30		t=2.06, df=25, p			0.28	0.26	0.31	0.17	0.24	0.31	0.34	0.32	0.25	0.36			0.31		0.65
	0.90					1.73	0.19	2.66	0.20	0.97	1.94	0.84	1.55	1.27	1.69			3.87		4.93

Statistical Tables for Student Participants

This appendix contains the statistical analysis for the student exercises that compared CAM with unstructured, legacy methods of determining compatibility.

The analysis was completed using SPSS 17. Non-parametric methods were used. The distribution of responses were analyzed with the Mann-Whitney U Test to determine if the distributions of responses were the same across both groups of participants. The Independent Samples Median Test was used to determine if the medians across the samples were the same across both groups of participants. For each of the 18 items, both analyses were conducted. The results of the analysis are reported in Chapter 5. This appendix reports the data in the following formats: histograms and boxplots for each set of data; histograms for the groups and continuous fields; descriptive statistics table; ANOVA analysis; and cross tabs to determine the relationships between the various statistics.

The distributions and medians were analyzed at $\alpha = 0.10$ significance for the null hypotheses. Each measure was analyzed in the student exercises. For two of the categories, data was collected only for the CAM exercise and therefore, the decision was reported as "Unable to Compute" and did not apply to the legacy methods.

Table 69 - Time (in hours) that participants self-reported to complete the exercise

Time to complete exercise (hours):

t-Test: Two-Sample Assuming Unequal Variances

	CAM	*Legacy*
Mean	2.41	2.14
Standard Deviation	0.77	0.80
Variance	0.59	0.64
Observations	12.00	15.00
Hypothesized Mean Difference	0.00	
df	24.00	
t Stat	0.90	
P(T<=t) two-tail	0.38	
t Critical two-tail	2.06	

Table 70 - Legend for data labels, data descriptions, and valid values for the entry

Data label	Data label description	Values
Govt service	Years of government service by respondent	Numerical (years)
Acq time	Years of government acquisition service by respondent	Numerical (years)
GPA	Undergraduate grade point average as reported by respondent	Numerical (on a 4-point scale)
Time	The amount of time to complete the exercise as reported by the respondent	Numerical (hours)
Ease	The ease of completing the exercise as reported by respondent	Likert scale (1-6)
Confidence	The confidence in the value of the product as reported by respondent	Categorical (High/Medium/Low)
A	The results would be the same if performed by another individual.	Likert scale (1-5)
B	I would get the same results if I repeated the method with the same information.	Likert scale (1-5)
C	Performing this analysis was easy.	Likert scale (1-5)
D	I have the appropriate skills to evaluate a subsystem to determine if it can be used as a replacement for a subsystem currently in use.	Likert scale (1-5)
E	I have confidence that my assessment of compatibility is accurate.	Likert scale (1-5)
F	Other system engineering students would get value from participating in this experiment	Likert scale (1-5)
G	I believe that my analysis would be valuable to the MQ-XX program office.	Likert scale (1-5)
H	I believe the MQ-XX program office could make a decision on the RT-5959 based on my analysis.	Likert scale (1-5)
I	CAM Users: I would recommend program offices adopt CAM as a standard practice.	Likert scale (1-5)
J	CAM Users: CAM was a useful tool.	Likert scale (1-5)
K	I would prefer a better-defined process to perform compatibility assessments.	Likert scale (1-5)
Number of Incompatibilities	The number of incompatibilities the respondent found while completing the exercise	Integer

Table 71 – Hypotheses Test Summaries for distributions and medians of student research participant responses (Part 1)

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of govt service is the same across categories of Method.	Independent-Samples Mann-Whitney U Test	.249	Retain the null hypothesis.
2	The medians of govt service are the same across categories of Method.	Independent-Samples Median Test	.449[1,2]	Retain the null hypothesis.
3	The distribution of acq time is the same across categories of Method.	Independent-Samples Mann-Whitney U Test	.530	Retain the null hypothesis.
4	The medians of acq time are the same across categories of Method.	Independent-Samples Median Test	.449[1,2]	Retain the null hypothesis.
5	The distribution of GPA is the same across categories of Method.	Independent-Samples Mann-Whitney U Test	.855	Retain the null hypothesis.
6	The medians of GPA are the same across categories of Method.	Independent-Samples Median Test	1.000[1,2]	Retain the null hypothesis.
7	The distribution of Time is the same across categories of Method.	Independent-Samples Mann-Whitney U Test	.277	Retain the null hypothesis.
8	The medians of Time are the same across categories of Method.	Independent-Samples Median Test	.398[1,2]	Retain the null hypothesis.
9	The distribution of Ease is the same across categories of Method.	Independent-Samples Mann-Whitney U Test	.271	Retain the null hypothesis.
10	The medians of Ease are the same across categories of Method.	Independent-Samples Median Test	.704[1,2]	Retain the null hypothesis.
11	The distribution of Confidence (L/M/H 1/2/3) is the same across categories of Method.	Independent-Samples Mann-Whitney U Test	.897	Retain the null hypothesis.
12	The medians of Confidence (L/M/H 1/2/3) are the same across categories of Method.	Independent-Samples Median Test	1.000[1,2]	Retain the null hypothesis.

Asymptotic significances are displayed. The significance level is .10.

[1]Exact significance is displayed for this test.

[2]Fisher Exact Sig.

Table 72 - Hypothesis test summary for participant demographics

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of govt service is the same across categories of Method.	Independent-Samples Mann-Whitney U Test	.249	Retain the null hypothesis.
2	The medians of govt service are the same across categories of Method.	Independent-Samples Median Test	.449[1,2]	Retain the null hypothesis.
3	The distribution of acq time is the same across categories of Method.	Independent-Samples Mann-Whitney U Test	.530	Retain the null hypothesis.
4	The medians of acq time are the same across categories of Method.	Independent-Samples Median Test	.449[1,2]	Retain the null hypothesis.
5	The distribution of GPA is the same across categories of Method.	Independent-Samples Mann-Whitney U Test	.855	Retain the null hypothesis.
6	The medians of GPA are the same across categories of Method.	Independent-Samples Median Test	1.000[1,2]	Retain the null hypothesis.
7	The distribution of Time is the same across categories of Method.	Independent-Samples Mann-Whitney U Test	.277	Retain the null hypothesis.
8	The medians of Time are the same across categories of Method.	Independent-Samples Median Test	.398[1,2]	Retain the null hypothesis.
9	The distribution of Ease is the same across categories of Method.	Independent-Samples Mann-Whitney U Test	.271	Retain the null hypothesis.
10	The medians of Ease are the same across categories of Method.	Independent-Samples Median Test	.704[1,2]	Retain the null hypothesis.
11	The distribution of Confidence (L/M/H 1/2/3) is the same across categories of Method.	Independent-Samples Mann-Whitney U Test	.897	Retain the null hypothesis.
12	The medians of Confidence (L/M/H 1/2/3) are the same across categories of Method.	Independent-Samples Median Test	1.000[1,2]	Retain the null hypothesis.

Asymptotic significances are displayed. The significance level is .10.

[1] Exact significance is displayed for this test.

[2] Fisher Exact Sig.

Table 73– Hypotheses Test Summaries for distributions and medians of student research participant responses (Part 2)

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
13	The distribution of A is the same across categories of Method.	Independent-Samples Mann-Whitney U Test	.043	Reject the null hypothesis.
14	The medians of A are the same across categories of Method.	Independent-Samples Median Test	.057[1,2]	Reject the null hypothesis.
15	The distribution of B is the same across categories of Method.	Independent-Samples Mann-Whitney U Test	.667	Retain the null hypothesis.
16	The medians of B are the same across categories of Method.	Independent-Samples Median Test	.696[1,2]	Retain the null hypothesis.
17	The distribution of C is the same across categories of Method.	Independent-Samples Mann-Whitney U Test	.433	Retain the null hypothesis.
18	The medians of C are the same across categories of Method.	Independent-Samples Median Test	.628[1,2]	Retain the null hypothesis.
19	The distribution of D is the same across categories of Method.	Independent-Samples Mann-Whitney U Test	.119	Retain the null hypothesis.
20	The medians of D are the same across categories of Method.	Independent-Samples Median Test	.569[1,2]	Retain the null hypothesis.
21	The distribution of E is the same across categories of Method.	Independent-Samples Mann-Whitney U Test	.512	Retain the null hypothesis.
22	The medians of E are the same across categories of Method.	Independent-Samples Median Test	.441[1,2]	Retain the null hypothesis.
23	The distribution of F is the same across categories of Method.	Independent-Samples Mann-Whitney U Test	.232	Retain the null hypothesis.
24	The medians of F are the same across categories of Method.	Independent-Samples Median Test	1.000[1,2]	Retain the null hypothesis.

Asymptotic significances are displayed. The significance level is .10.

[1]Exact significance is displayed for this test.

[2]Fisher Exact Sig.

Table 74– Hypotheses Test Summaries for distributions and medians of student research participant responses (Part 3)

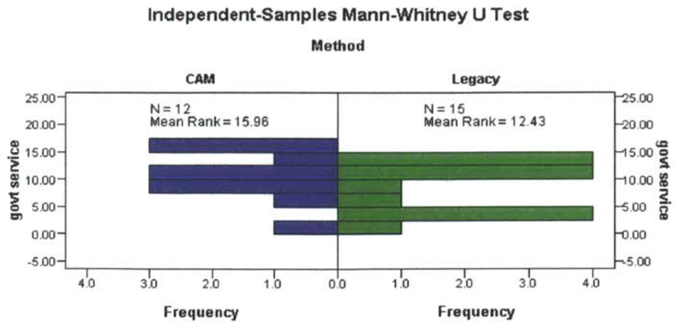
Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
25	The distribution of G is the same across categories of Method.	Independent-Samples Mann-Whitney U Test	.356	Retain the null hypothesis.
26	The medians of G are the same across categories of Method.	Independent-Samples Median Test	.107[1,2]	Retain the null hypothesis.
27	The distribution of H is the same across categories of Method.	Independent-Samples Mann-Whitney U Test	.194	Retain the null hypothesis.
28	The medians of H are the same across categories of Method.	Independent-Samples Median Test	.057[1,2]	Reject the null hypothesis.
29	The distribution of I is the same across categories of Method.	Independent-Samples Mann-Whitney U Test	.	Unable to compute.
30	The medians of I are the same across categories of Method.	Independent-Samples Median Test	.	Unable to compute.
31	The distribution of J is the same across categories of Method.	Independent-Samples Mann-Whitney U Test	.	Unable to compute.
32	The medians of J are the same across categories of Method.	Independent-Samples Median Test	.	Unable to compute.
33	The distribution of K is the same across categories of Method.	Independent-Samples Mann-Whitney U Test	.013	Reject the null hypothesis.
34	The medians of K are the same across categories of Method.	Independent-Samples Median Test	.342[1,2]	Retain the null hypothesis.
35	The distribution of Number of Incompatibilities found is the same across categories of Method.	Independent-Samples Mann-Whitney U Test	.011	Reject the null hypothesis.
36	The medians of Number of Incompatibilities found are the same across categories of Method.	Independent-Samples Median Test	.054[1,2]	Reject the null hypothesis.

Asymptotic significances are displayed. The significance level is .10.

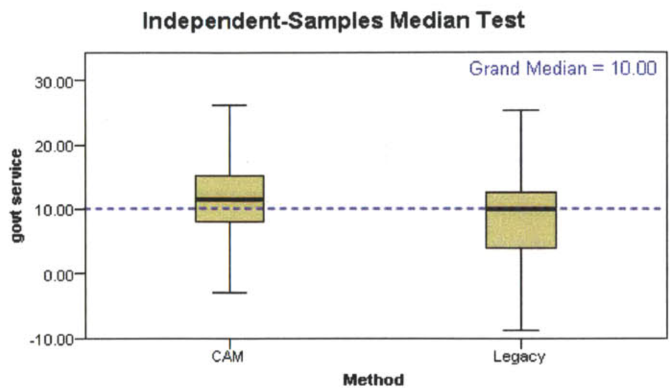
[1]Exact significance is displayed for this test.

[2]Fisher Exact Sig.



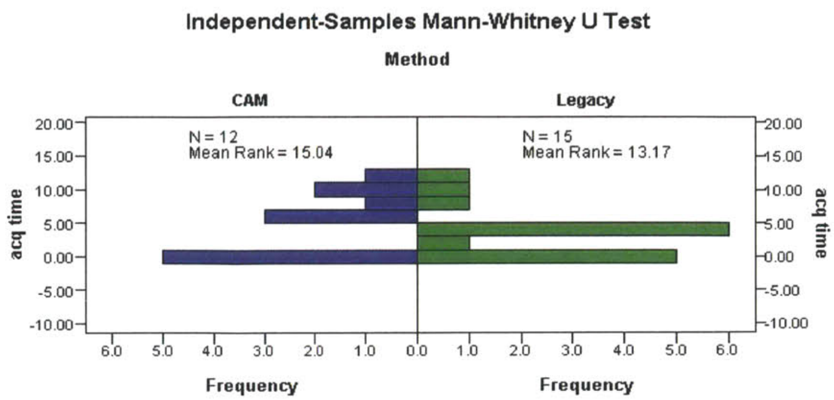
Total N	27
Mann-Whitney U	66.500
Wilcoxon W	186.500
Test Statistic	66.500
Standard Error	20.397
Standardized Test Statistic	-1.152
Asymptotic Sig. (2-sided test)	.249
Exact Sig. (2-sided test)	.256

Figure 24 – Distribution of years of government service by research participants



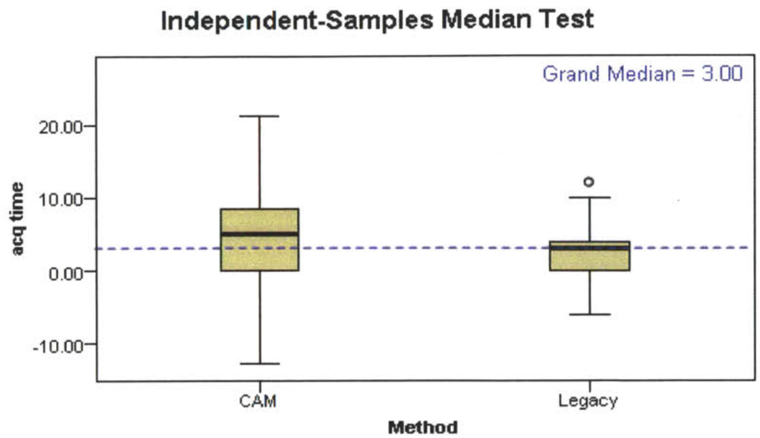
Total N	27
Median	10.000
Test Statistic	.898
Degrees of Freedom	1
Asymptotic Sig. (2-sided test)	.343
Fisher Exact Sig. (2-sided test)	.449

Figure 25 – Median test of years of government service by research participants



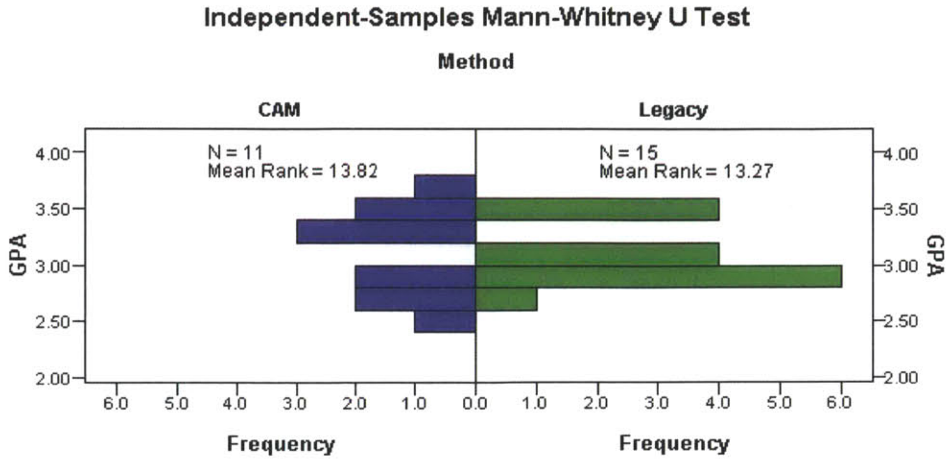
Total N	27
Mann-Whitney U	77.500
Wilcoxon W	197.500
Test Statistic	77.500
Standard Error	19.926
Standardized Test Statistic	-.627
Asymptotic Sig. (2-sided test)	.530
Exact Sig. (2-sided test)	.548

Figure 26 – Distribution and test statistics for years of acquisition experience (acq time) for research participants



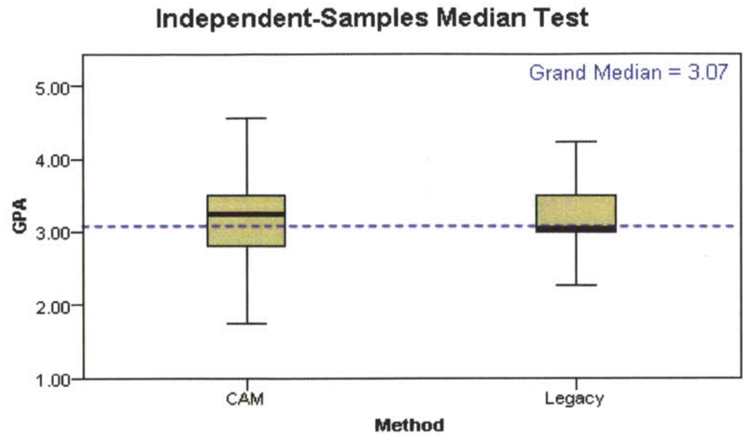
Total N	27
Median	3.000
Test Statistic	.898
Degrees of Freedom	1
Asymptotic Sig. (2-sided test)	.343
Fisher Exact Sig. (2-sided test)	.449

Figure 27 – Median test statistics for years of acquisition experience (acq time) for research participants



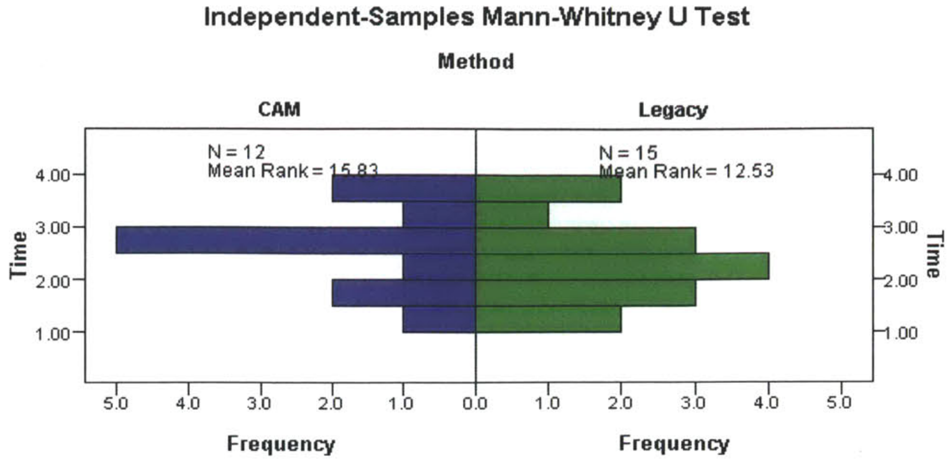
Total N	26
Mann-Whitney U	79.000
Wilcoxon W	199.000
Test Statistic	79.000
Standard Error	19.112
Standardized Test Statistic	-.183
Asymptotic Sig. (2-sided test)	.855
Exact Sig. (2-sided test)	.878

Figure 28 - Distribution and test statistics for undergraduate grade point average for research participants



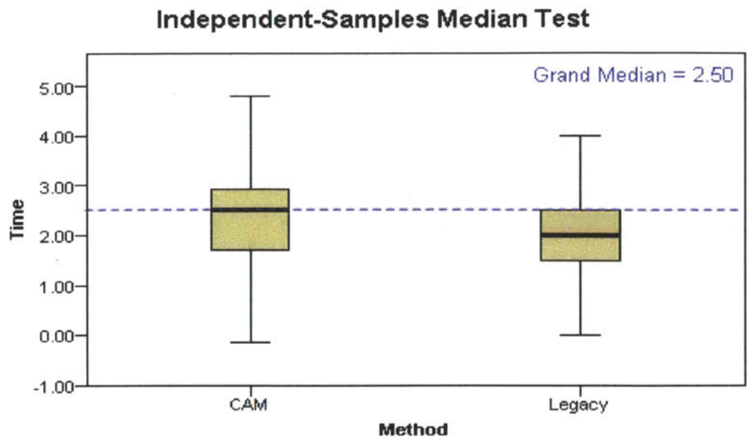
Total N	26
Median	3.070
Test Statistic	.158
Degrees of Freedom	1
Asymptotic Sig. (2-sided test)	.691
Fisher Exact Sig. (2-sided test)	1.000

Figure 29 – Median statistics for undergraduate grade point average for research participants



Total N	27
Mann-Whitney U	68.000
Wilcoxon W	188.000
Test Statistic	68.000
Standard Error	20.245
Standardized Test Statistic	-1.087
Asymptotic Sig. (2-sided test)	.277
Exact Sig. (2-sided test)	.300

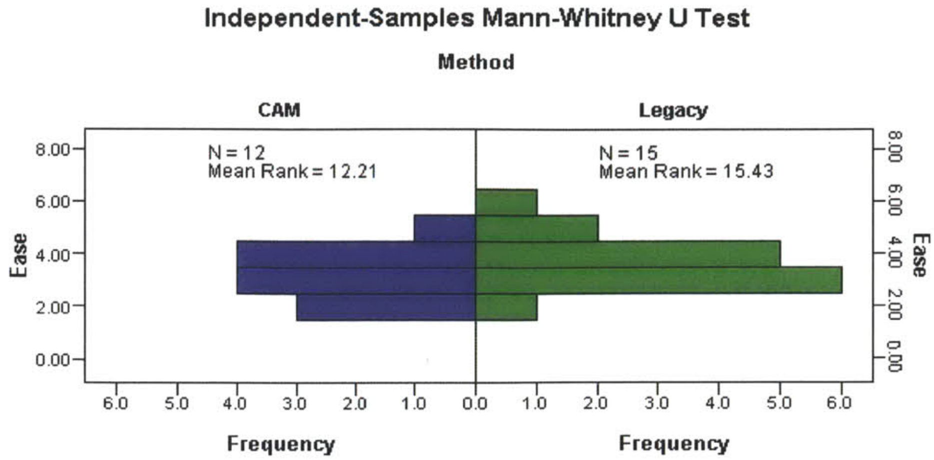
Figure 30- Distribution and test statistics for the length of time in hours that was required by participants to complete the compatibility assessment exercise



Total N	27
Median	2.500
Test Statistic	1.501
Degrees of Freedom	1
Asymptotic Sig. (2-sided test)	.221
Fisher Exact Sig. (2-sided test)	.398

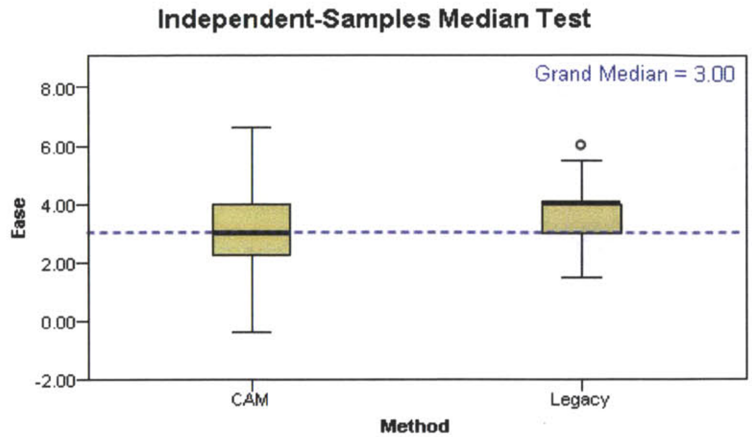
1. More than 20% of the cells have expected values less than five.

Figure 31 – Median test statistics for the length of time in hours that was required by participants to complete the compatibility assessment exercise



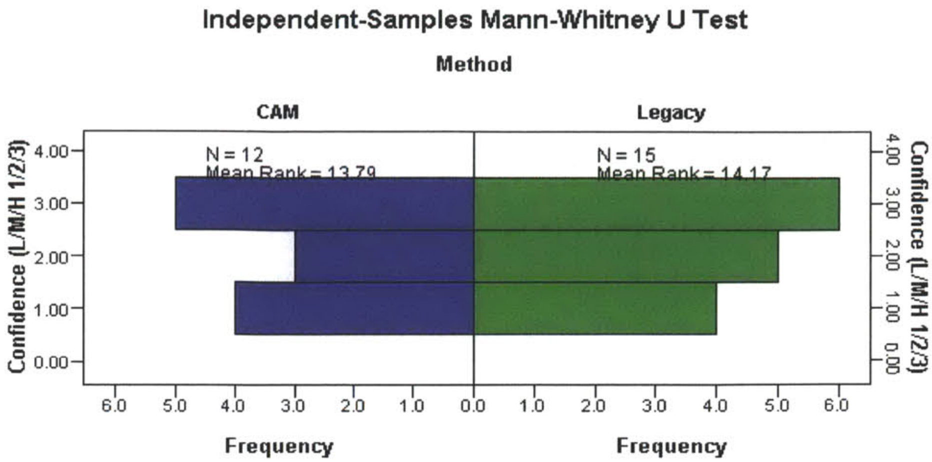
Total N	27
Mann-Whitney U	111.500
Wilcoxon W	231.500
Test Statistic	111.500
Standard Error	19.536
Standardized Test Statistic	1.101
Asymptotic Sig. (2-sided test)	.271
Exact Sig. (2-sided test)	.300

Figure 32 - Distribution and test statistics for the participant-reported ease to complete the compatibility assessment exercise



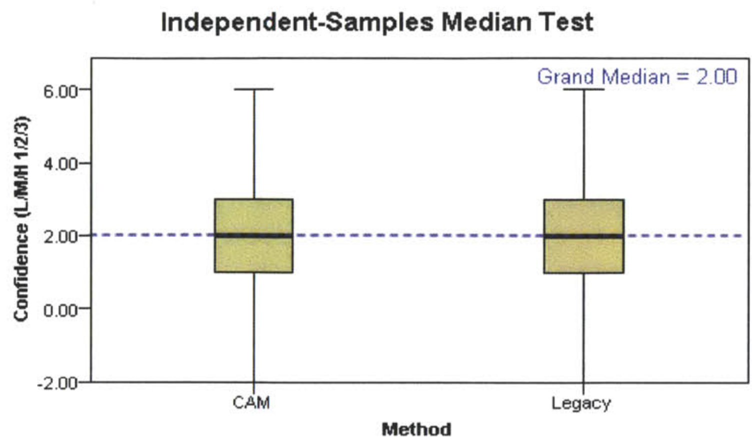
Total N	27
Median	3.000
Test Statistic	.363
Degrees of Freedom	1
Asymptotic Sig. (2-sided test)	.547
Fisher Exact Sig. (2-sided test)	.704

Figure 33 – Median test statistics for the participant-reported ease to complete the compatibility assessment exercise



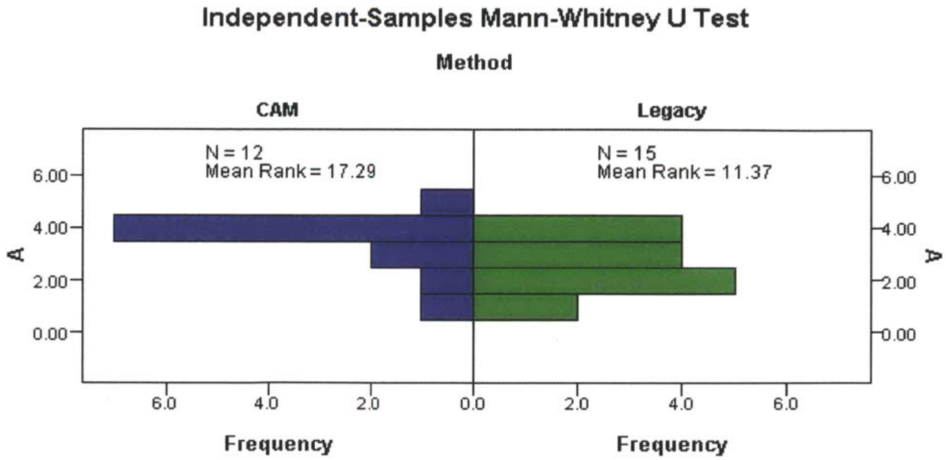
Total N	27
Mann-Whitney U	92.500
Wilcoxon W	212.500
Test Statistic	92.500
Standard Error	19.242
Standardized Test Statistic	.130
Asymptotic Sig. (2-sided test)	.897
Exact Sig. (2-sided test)	.905

Figure 34- Distribution and test statistics for the self-reported confidence of participants to complete the compatibility assessment accurately



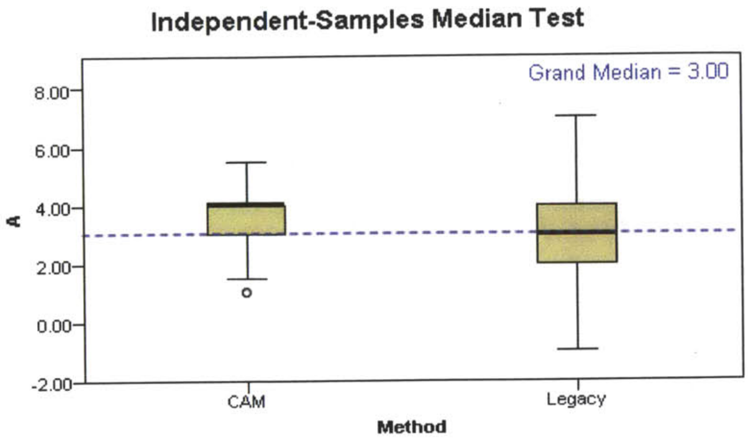
Total N	27
Median	2.000
Test Statistic	.008
Degrees of Freedom	1
Asymptotic Sig. (2-sided test)	.930
Fisher Exact Sig. (2-sided test)	1.000

Figure 35 – Median test statistics for the self-reported confidence of participants to complete the compatibility assessment accurately



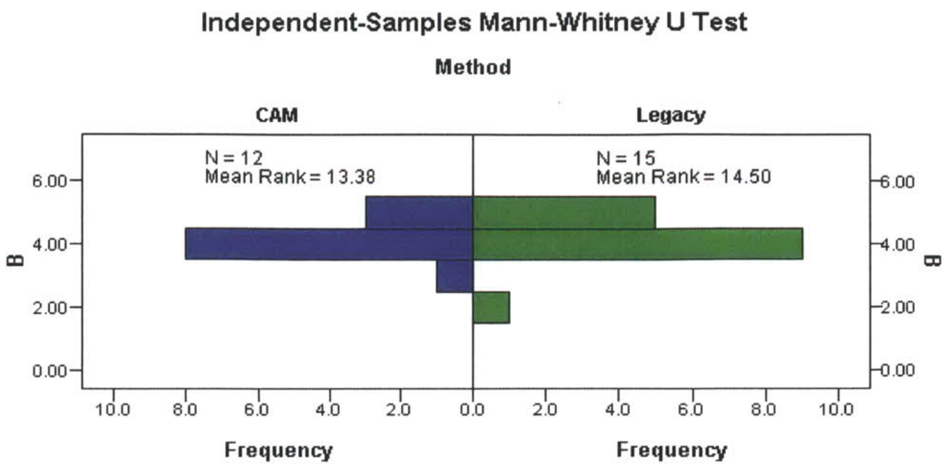
Total N	27
Mann-Whitney U	50.500
Wilcoxon W	170.500
Test Statistic	50.500
Standard Error	19.553
Standardized Test Statistic	-2.020
Asymptotic Sig. (2-sided test)	.043
Exact Sig. (2-sided test)	.053

Figure 36 - Distribution and test statistics for response to "The results would be the same if performed by another individual" (1-5 Likert Scale) in the post-exercise survey



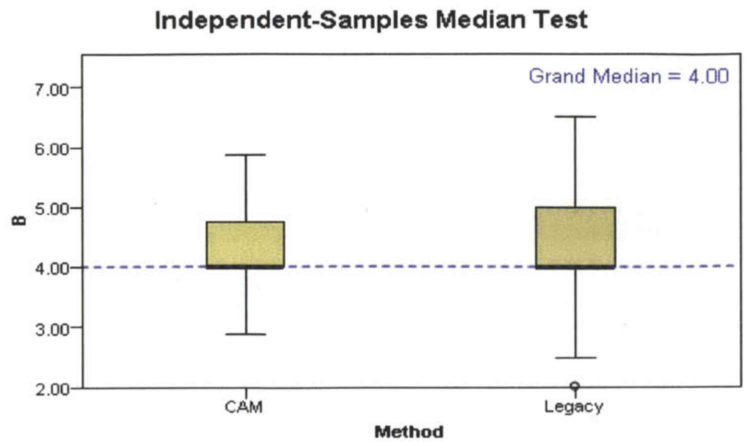
Total N	27
Median	3.000
Test Statistic	4.320
Degrees of Freedom	1
Asymptotic Sig. (2-sided test)	.038
Fisher Exact Sig. (2-sided test)	.057

Figure 37 – Median test statistics for response to "The results would be the same if performed by another individual" (1-5 Likert Scale) in the post-exercise survey



Total N	27
Mann-Whitney U	97.500
Wilcoxon W	217.500
Test Statistic	97.500
Standard Error	17.453
Standardized Test Statistic	.430
Asymptotic Sig. (2-sided test)	.667
Exact Sig. (2-sided test)	.719

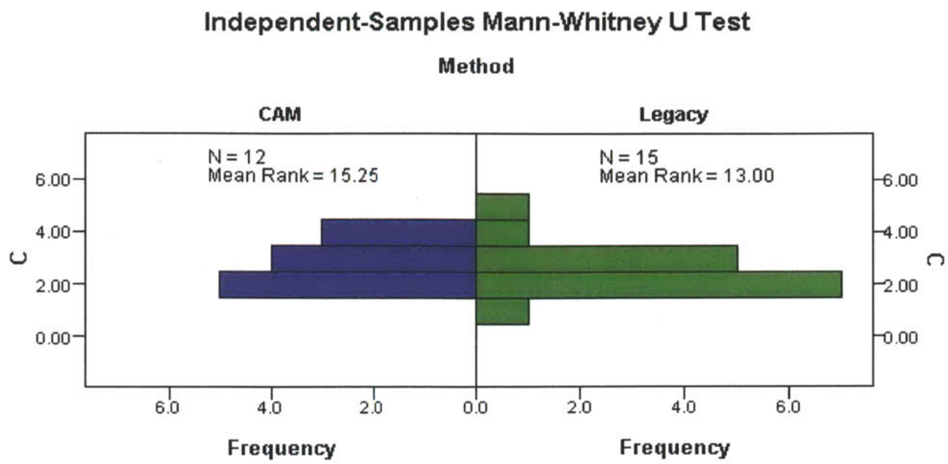
Figure 38- Distribution and test statistics for response to "I would get the same results if I repeated the method with the same information." (1-5 Likert Scale) in the post-exercise survey



Total N	27
Median	4.000
Test Statistic	.222
Degrees of Freedom	1
Asymptotic Sig. (2-sided test)	.637
Fisher Exact Sig. (2-sided test)	.696

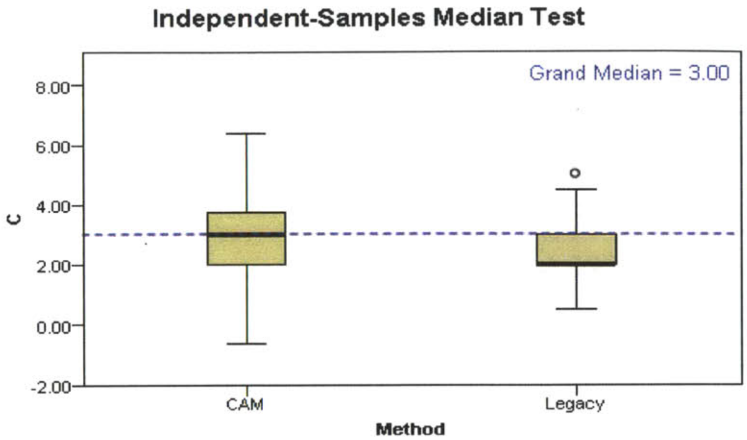
1. More than 20% of the cells have expected values less than five.

Figure 39 -- test statistics for response to "I would get the same results if I repeated the method with the same information." (1-5 Likert Scale) in the post-exercise survey



Total N	27
Mann-Whitney U	75.000
Wilcoxon W	195.000
Test Statistic	75.000
Standard Error	19.149
Standardized Test Statistic	-.783
Asymptotic Sig. (2-sided test)	.433
Exact Sig. (2-sided test)	.486

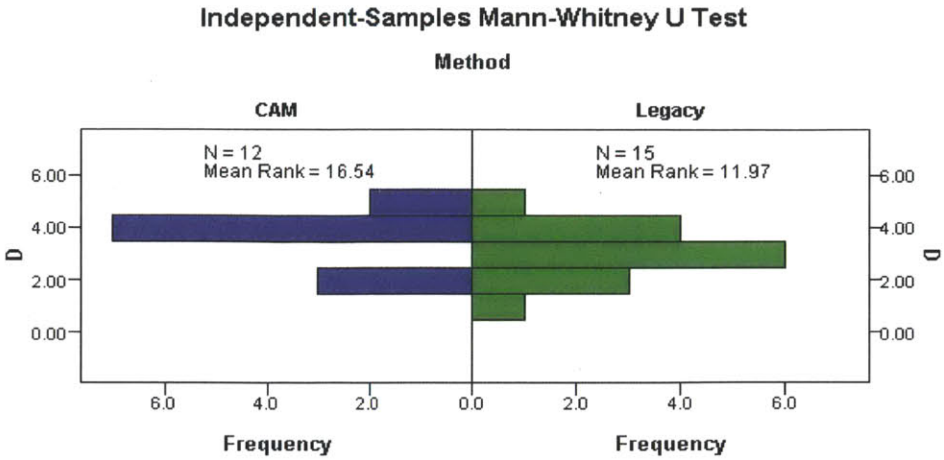
Figure 40- Distribution and test statistics for response to "Performing this analysis was easy." (1-5 Likert Scale) in the post-exercise survey



Total N	27
Median	3.000
Test Statistic	.601
Degrees of Freedom	1
Asymptotic Sig. (2-sided test)	.438
Fisher Exact Sig. (2-sided test)	.628

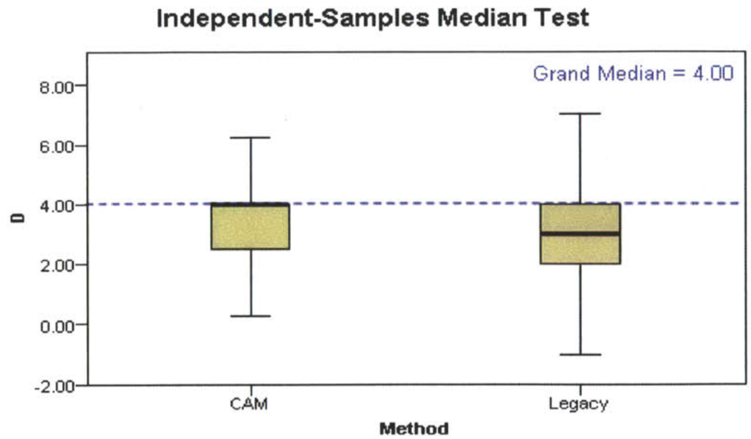
1. More than 20% of the cells have expected values less than five.

Figure 41 – Median test statistics for response to "Performing this analysis was easy." (1-5 Likert Scale) in the post-exercise survey



Total N	27
Mann-Whitney U	59.500
Wilcoxon W	179.500
Test Statistic	59.500
Standard Error	19.553
Standardized Test Statistic	-1.560
Asymptotic Sig. (2-sided test)	.119
Exact Sig. (2-sided test)	.139

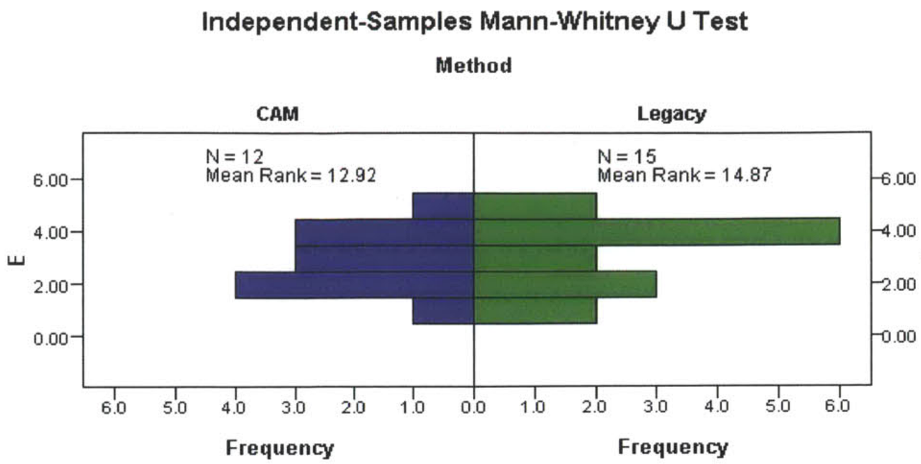
Figure 42- Distribution and test statistics for response to "I have the appropriate skills to evaluate a subsystem to determine if it can be used as a replacement for a subsystem currently in use." (1-5 Likert Scale) in the post-exercise survey



Total N	27
Median	4.000
Test Statistic	.675
Degrees of Freedom	1
Asymptotic Sig. (2-sided test)	.411
Fisher Exact Sig. (2-sided test)	.569

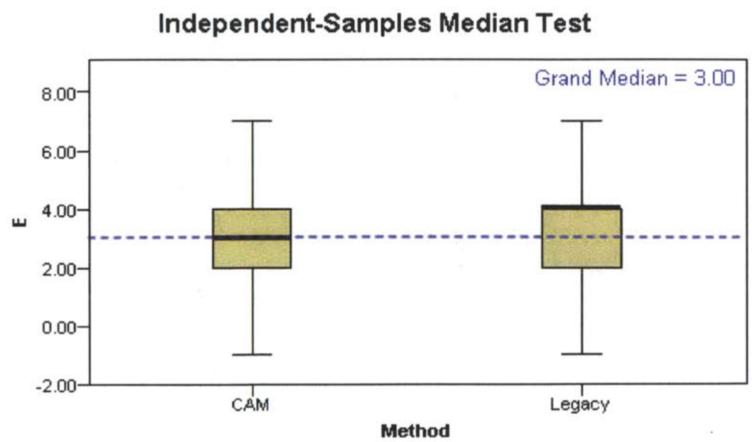
1. More than 20% of the cells have expected values less than five.

Figure 43 -- Median test statistics for response to "I have the appropriate skills to evaluate a subsystem to determine if it can be used as a replacement for a subsystem currently in use." (1-5 Likert Scale) in the post-exercise survey



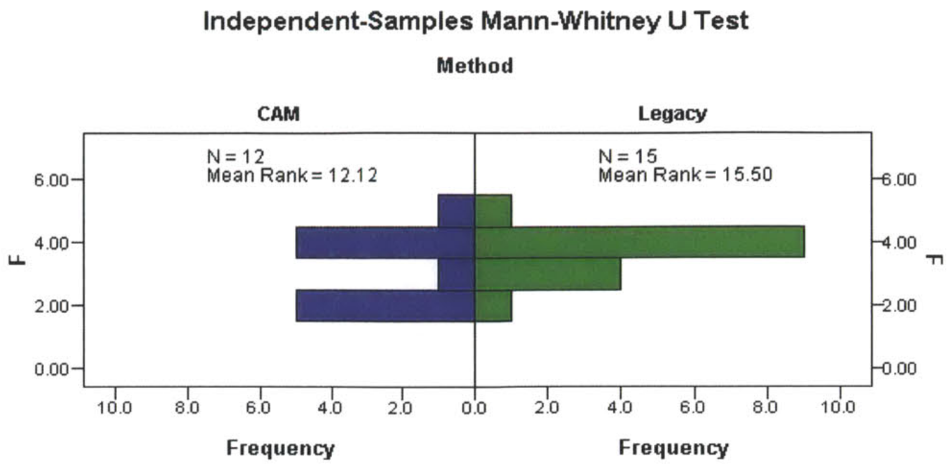
Total N	27
Mann-Whitney U	103.000
Wilcoxon W	223.000
Test Statistic	103.000
Standard Error	19.846
Standardized Test Statistic	.655
Asymptotic Sig. (2-sided test)	.512
Exact Sig. (2-sided test)	.548

Figure 44- Distribution and test statistics for response to "I have confidence that my assessment of compatibility is accurate." (1-5 Likert Scale) in the post-exercise survey



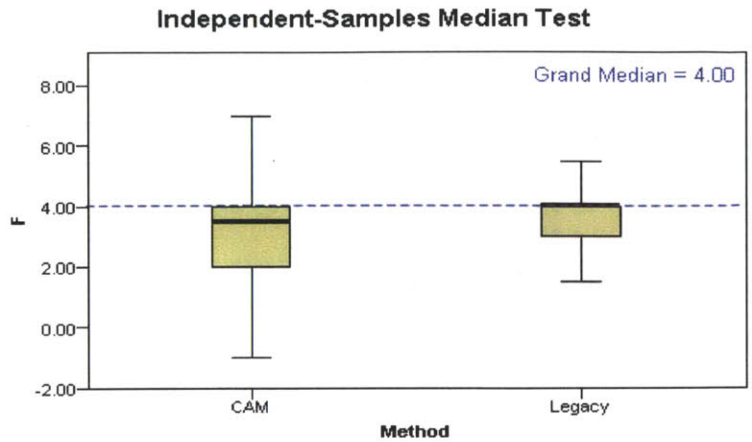
Total N	27
Median	3.000
Test Statistic	1.080
Degrees of Freedom	1
Asymptotic Sig. (2-sided test)	.299
Fisher Exact Sig. (2-sided test)	.441

Figure 45 – Median test statistics for response to "I have confidence that my assessment of compatibility is accurate." (1-5 Likert Scale) in the post-exercise survey



Total N	27
Mann-Whitney U	112.500
Wilcoxon W	232.500
Test Statistic	112.500
Standard Error	18.828
Standardized Test Statistic	1.195
Asymptotic Sig. (2-sided test)	.232
Exact Sig. (2-sided test)	.277

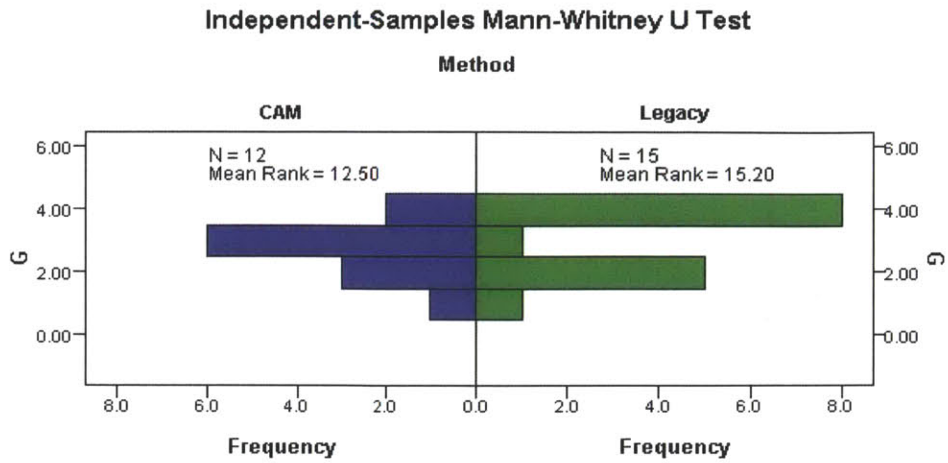
Figure 46- Distribution and test statistics for response to "Other system engineering students would get value from participating in this event." (1-5 Likert Scale) in the post-exercise survey



Total N	27
Median	4.000
Test Statistic	.027
Degrees of Freedom	1
Asymptotic Sig. (2-sided test)	.869
Fisher Exact Sig. (2-sided test)	1.000

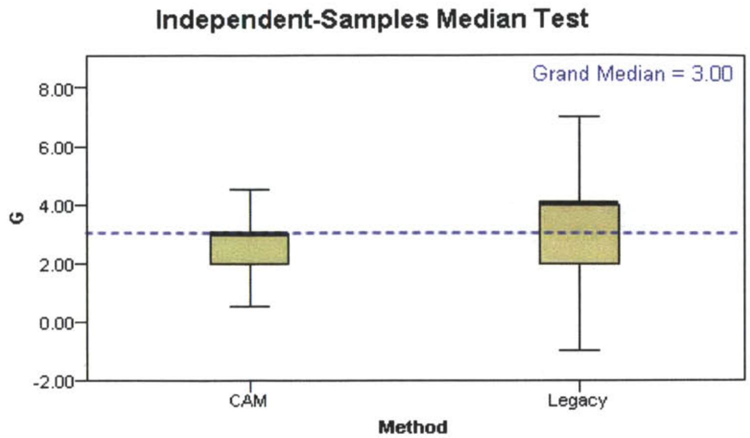
1. At least one cell has an expected value less than one.
2. More than 20% of the cells have expected values less than five.

Figure 47 – Median test statistics for response to "Other system engineering students would get value from participating in this event." (1-5 Likert Scale) in the post-exercise survey



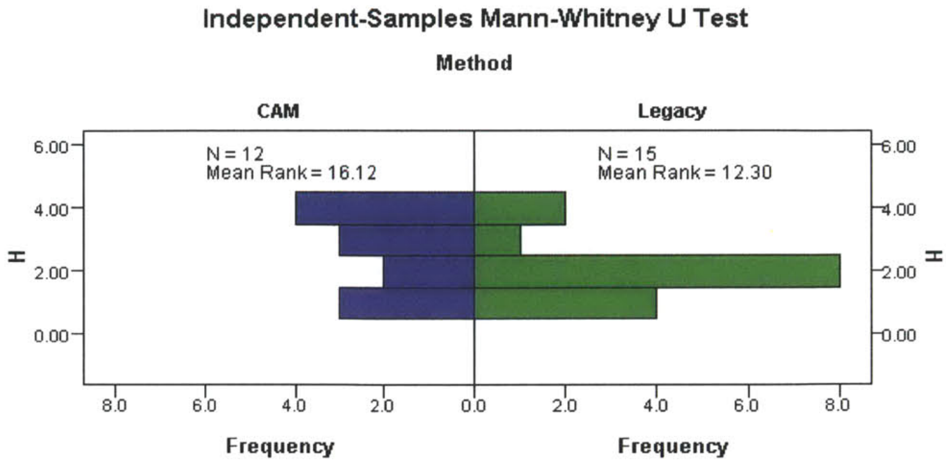
Total N	27
Mann-Whitney U	108.000
Wilcoxon W	228.000
Test Statistic	108.000
Standard Error	19.513
Standardized Test Statistic	.922
Asymptotic Sig. (2-sided test)	.356
Exact Sig. (2-sided test)	.399

Figure 48- Distribution and test statistics for response to "I believe that my analysis would be valuable to the MQ-XX program office." (1-5 Likert Scale) in the post-exercise survey



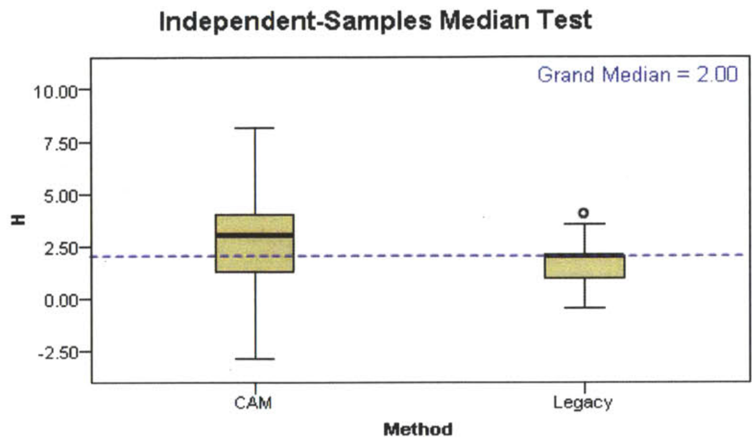
Total N	27
Median	3.000
Test Statistic	3.844
Degrees of Freedom	1
Asymptotic Sig. (2-sided test)	.050
Fisher Exact Sig. (2-sided test)	.107

Figure 49 -- test statistics for response to "I believe that my analysis would be valuable to the MQ-XX program office." (1-5 Likert Scale) in the post-exercise survey



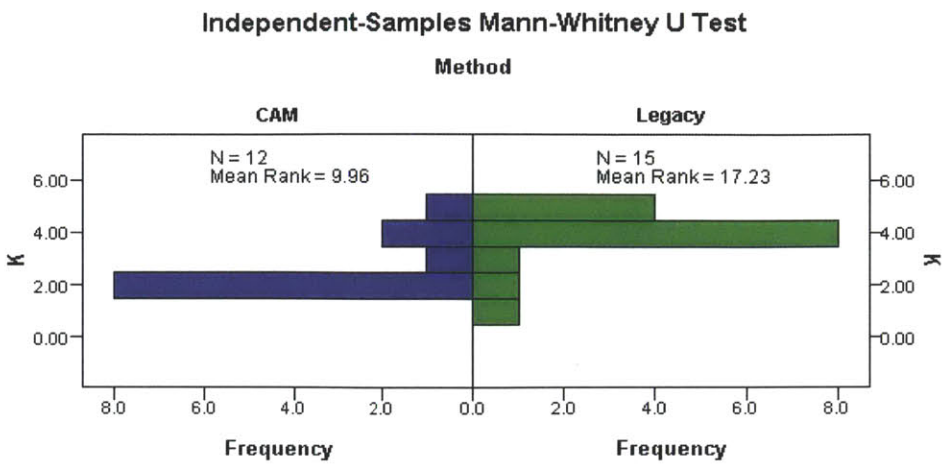
Total N	27
Mann-Whitney U	64.500
Wilcoxon W	184.500
Test Statistic	64.500
Standard Error	19.644
Standardized Test Statistic	-1.298
Asymptotic Sig. (2-sided test)	.194
Exact Sig. (2-sided test)	.217

Figure 50- Distribution and test statistics for response to "I believe the MQ-XX program office could make a decision on the RT-5959 based on my analysis." (1-5 Likert Scale) in the post-exercise survey



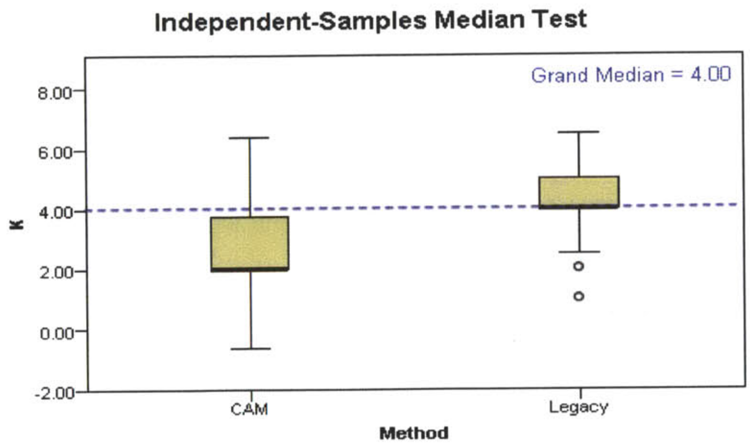
Total N	27
Median	2.000
Test Statistic	4.201
Degrees of Freedom	1
Asymptotic Sig. (2-sided test)	.040
Fisher Exact Sig. (2-sided test)	.057

Figure 51 – Median test statistics for response to "I believe the MQ-XX program office could make a decision on the RT-5959 based on my analysis." (1-5 Likert Scale) in the post-exercise survey



Total N	27
Mann-Whitney U	138.500
Wilcoxon W	258.500
Test Statistic	138.500
Standard Error	19.513
Standardized Test Statistic	2.485
Asymptotic Sig. (2-sided test)	.013
Exact Sig. (2-sided test)	.016

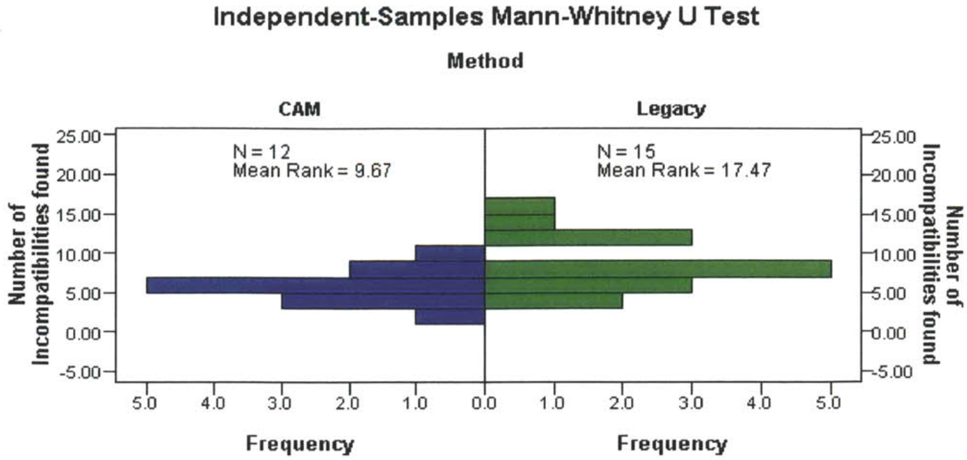
Figure 52- Distribution and test statistics for response to "I would prefer a better-defined process to perform compatibility assessments." (1-5 Likert Scale) in the post-exercise survey



Total N	27
Median	4.000
Test Statistic	1.485
Degrees of Freedom	1
Asymptotic Sig. (2-sided test)	.223
Fisher Exact Sig. (2-sided test)	.342

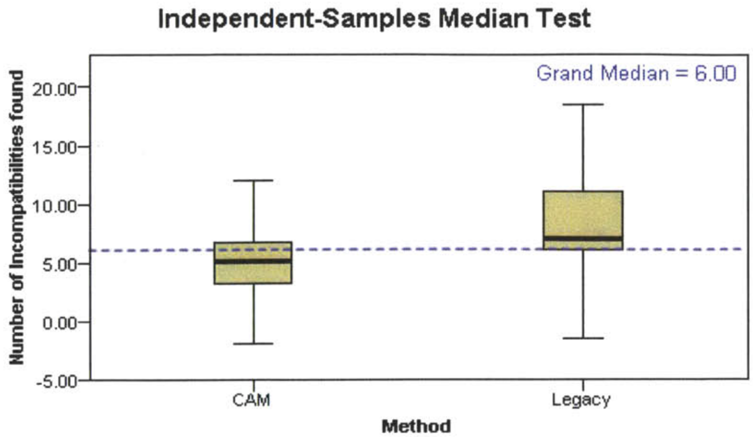
1. More than 20% of the cells have expected values less than five.

Figure 53 – Median test for response to "I would prefer a better-defined process to perform compatibility assessments." (1-5 Likert Scale) in the post-exercise survey



Total N	27
Mann-Whitney U	142.000
Wilcoxon W	262.000
Test Statistic	142.000
Standard Error	20.368
Standardized Test Statistic	2.553
Asymptotic Sig. (2-sided test)	.011
Exact Sig. (2-sided test)	.010

. **Figure 54- Distribution and test statistics for the number of incompatibilities that were found by participants in the compatibility assessment exercise.**



Total N	27
Median	6.000
Test Statistic	4.636
Degrees of Freedom	1
Asymptotic Sig. (2-sided test)	.031
Fisher Exact Sig. (2-sided test)	.054

Figure 55 – Median test for the number of incompatibilities that were found by participants in the compatibility assessment exercise.

The following graphs and tables show the categorized and continuous field information for the student-participant research.

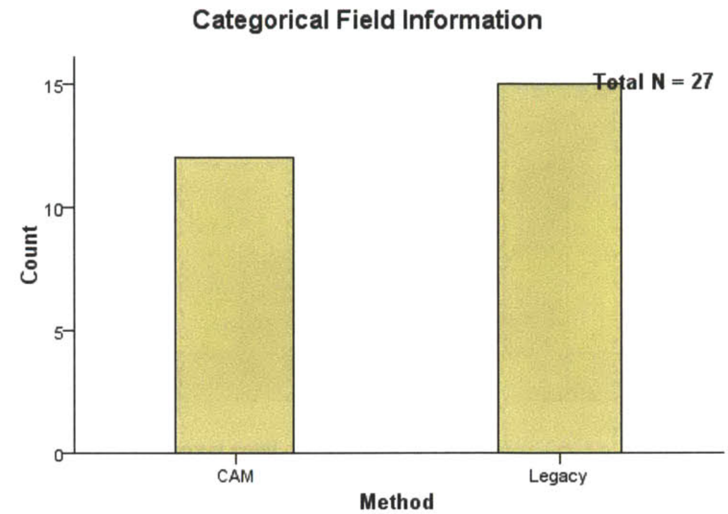


Figure 56 - Distribution of CAM and Legacy Method Users

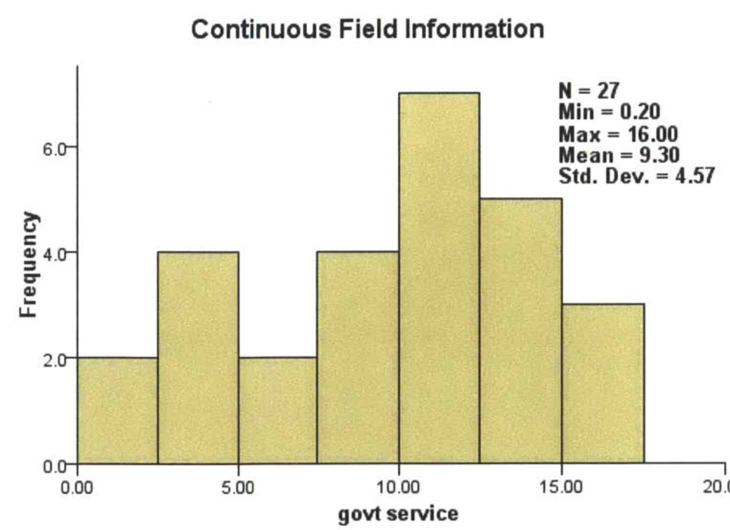


Figure 57 - Distribution of years of government service for participants

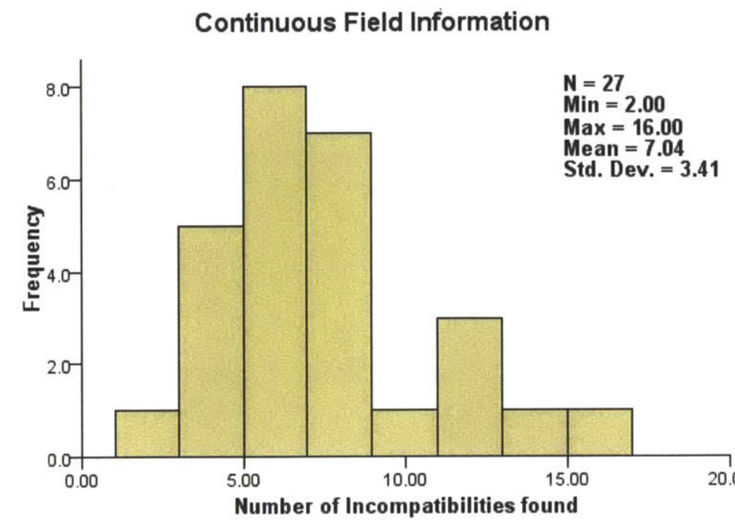


Figure 58 - Distribution of number of incompatibilities found by all participants

Mann-Whitney Test

Group 0 = CAM
Group 1 = Legacy

Ranks

Method	Group	N	Mean Rank	Sum of Ranks
govt service	0	15	12.43	186.50
	1	12	15.96	191.50
	Total	27		
acq time	0	15	13.17	197.50
	1	12	15.04	180.50
	Total	27		
GPA	0	15	13.27	199.00
	1	11	13.82	152.00
	Total	26		
Time	0	15	12.53	188.00
	1	12	15.83	190.00
	Total	27		
Ease	0	15	15.43	231.50
	1	12	12.21	146.50
	Total	27		
Confidence (L/M/H 1/2/3)	0	15	14.17	212.50
	1	12	13.79	165.50
	Total	27		
A	0	15	11.37	170.50
	1	12	17.29	207.50
	Total	27		
B	0	15	14.50	217.50
	1	12	13.38	160.50
	Total	27		
C	0	15	13.00	195.00
	1	12	15.25	183.00
	Total	27		
D	0	15	11.97	179.50
	1	12	16.54	198.50
	Total	27		
E	0	15	14.87	223.00
	1	12	12.92	155.00
	Total	27		
F	0	15	15.50	232.50
	1	12	12.13	145.50
	Total	27		
G	0	15	15.20	228.00
	1	12	12.50	150.00
	Total	27		
H	0	15	12.30	184.50
	1	12	16.13	193.50
	Total	27		
I	0	0[a]	.00	.00
	1	12	6.50	78.00
	Total	12		
J	0	0[a]	.00	.00
	1	12	6.50	78.00
	Total	12		
K	0	15	17.23	258.50
	1	12	9.96	119.50
	Total	27		
Number of	0	15	17.47	262.00
	1	12	9.67	116.00
	Total	27		

a. Mann-Whitney Test cannot be performed on empty groups.

Figure 59 - Mann-Whitney Rank-Sum Test Data for student participants

Test Statistics[b]

	govt service	acq time	GPA	Time	Ease	(L/M/H 1/2/3)	A	B	C	D	E	F	G	H	K	Incompatibiliti
Mann-Whitney U	66.500	77.500	79.000	68.000	68.500	87.500	50.500	82.500	75.000	59.500	77.000	67.500	72.000	64.500	41.500	38.000
Wilcoxon W	186.500	197.500	199.000	188.000	146.500	165.500	170.500	160.500	195.000	179.500	155.000	145.500	150.000	184.500	119.500	116.000
Z	-1.152	-.627	-.183	-1.087	-1.101	-.130	-2.020	-.430	-.783	-1.560	-.655	-1.195	-.922	-1.298	-2.485	-2.553
Asymp. Sig. (2-tailed)	.249	.530	.855	.277	.271	.897	.043	.667	.433	.119	.512	.232	.356	.194	.013	.011
Exact Sig. [2*(1-tailed Sig.)]	.256[a]	.548[a]	.878[a]	.300[a]	.300[a]	.905[a]	.053[a]	.719[a]	.486[a]	.139[a]	.548[a]	.277[a]	.399[a]	.217[a]	.016[a]	.010[a]

a. Not corrected for ties.

b. Grouping Variable: Method

Figure 60 - Test Statistics for the Mann-Whitney U test and the Wilcoxon W Test

Descriptive Statistics

	N	Range	Minimum	Maximum	Mean	Std. Deviation	Variance	Skewness		Kurtosis	
	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Std. Error	Statistic	Std. Error
govt service	27	15.8	.2	16.0	9.304	4.5677	20.863	-.377	.448	-.917	.872
acq time	27	12	0	12	3.89	3.965	15.718	.713	.448	-.614	.872
GPA	26	1.30	2.40	3.70	3.1442	.30882	.095	-.230	.456	-.167	.887
Time	27	2.50	1.00	3.50	2.2611	.78328	.614	.059	.448	-.876	.872
Ease	27	4	2	6	3.52	1.014	1.028	.424	.448	.049	.872
Confidence (L/M/H 1/2/3)	27	2	1	3	2.11	.847	.718	-.223	.448	-1.588	.872
A	27	4	1	5	3.04	1.126	1.268	-.427	.448	-.881	.872
B	27	3	2	5	4.19	.681	.464	-1.034	.448	2.984	.872
C	27	4	1	5	2.70	.912	.832	.653	.448	.159	.872
D	27	4	1	5	3.33	1.074	1.154	-.335	.448	-.686	.872
E	27	4	1	5	3.07	1.238	1.533	-.150	.448	-1.055	.872
F	27	3	2	5	3.44	.934	.872	-.438	.448	-.870	.872
G	27	3	1	4	2.93	.997	.994	-.345	.448	-1.091	.872
H	27	3	1	4	2.33	1.109	1.231	.365	.448	-1.162	.872
I	12	3	1	4	2.50	.798	.636	.000	.637	.150	1.232
J	12	3	1	4	2.83	1.115	1.242	-.088	.637	-1.688	1.232
K	27	4	1	5	3.33	1.240	1.538	-.174	.448	-1.360	.872
Number of Incompatibilities found	27	14	2	16	7.04	3.414	11.652	.993	.448	.720	.872
Valid N (listwise)	11										

Table 75 - Descriptive statistics for student participants in each data category

Table 76 - Hypothesis test summaries for distributions of responses between the Legacy method and CAM participants (Part 1 of 2)

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of govt service is the same across categories of Method.	Independent-Samples Mann-Whitney U Test	.249	Retain the null hypothesis.
2	The distribution of acq time is the same across categories of Method.	Independent-Samples Mann-Whitney U Test	.530	Retain the null hypothesis.
3	The distribution of GPA is the same across categories of Method.	Independent-Samples Mann-Whitney U Test	.855	Retain the null hypothesis.
4	The distribution of Time is the same across categories of Method.	Independent-Samples Mann-Whitney U Test	.277	Retain the null hypothesis.
5	The distribution of Ease is the same across categories of Method.	Independent-Samples Mann-Whitney U Test	.271	Retain the null hypothesis.
6	The distribution of Confidence (L/M/H 1/2/3) is the same across categories of Method.	Independent-Samples Mann-Whitney U Test	.897	Retain the null hypothesis.
7	The distribution of A is the same across categories of Method.	Independent-Samples Mann-Whitney U Test	.043	Retain the null hypothesis.
8	The distribution of B is the same across categories of Method.	Independent-Samples Mann-Whitney U Test	.667	Retain the null hypothesis.
9	The distribution of C is the same across categories of Method.	Independent-Samples Mann-Whitney U Test	.433	Retain the null hypothesis.

Asymptotic significances are displayed. The significance level is .05.

This test checked for homoscedasticity in participant backgrounds, responses, and their findings. Analysis of the student participants was performed using the non-parametric Mann-Whitney U Test to inspect distributions of the participants' characteristics. The characteristics of the groups across the methods suggested no differences in the distributions of years in government service, the amount of time in acquisition-related positions, and student undergraduate grade point averages.

For the participants' time to execute the project, the distributions were suggested to be the same. Similarly, the participants' reported ease of performing the assigned method and their confidence in the results they reported were the same for both groups.

Differences in the distributions of participant responses appeared when queried about their recommendations about using the method they were assigned or if an alternate, better-defined method would be preferred. The Legacy method group indicated a preference to more structure while the CAM group requested more freedom in the method. Another area of distribution differences was in the number of incompatibilities that the participants found.

Table 77 - Hypothesis test summaries for distributions of responses between the Legacy method and CAM participants (Part 2 of 2)

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
10	The distribution of D is the same across categories of Method.	Independent-Samples Mann-Whitney U Test	.119	Retain the null hypothesis.
11	The distribution of E is the same across categories of Method.	Independent-Samples Mann-Whitney U Test	.512	Retain the null hypothesis.
12	The distribution of F is the same across categories of Method.	Independent-Samples Mann-Whitney U Test	.232	Retain the null hypothesis.
13	The distribution of G is the same across categories of Method.	Independent-Samples Mann-Whitney U Test	.356	Retain the null hypothesis.
14	The distribution of H is the same across categories of Method.	Independent-Samples Mann-Whitney U Test	.194	Retain the null hypothesis.
15	The distribution of I is the same across categories of Method.	Independent-Samples Mann-Whitney U Test	.	Unable to compute.
16	The distribution of J is the same across categories of Method.	Independent-Samples Mann-Whitney U Test	.	Unable to compute.
17	The distribution of K is the same across categories of Method.	Independent-Samples Mann-Whitney U Test	.013	Reject the null hypothesis.
18	The distribution of Number of Incompatibilities found is the same across categories of Method.	Independent-Samples Mann-Whitney U Test	.011	Reject the null hypothesis.

Asymptotic significances are displayed. The significance level is .05.

Table 78 - Numbers of incompatibilities found by participants using Legacy and CAM processes

Number of Incompatibilities Found

t-Test: Two-Sample Assuming Unequal Variances

	CAM	*Legacy*
Mean	5.25	8.47
Standard Deviation	2.26	3.56
Variance	5.11	12.70
Observations	12.00	15.00
Hypothesized Mean Difference	0.00	
df	24.00	
t Stat	-2.85	
P(T<=t) two-tail	0.01	
t Critical two-tail	2.06	

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Appendix E – The development of CAM

The table presented in this appendix shows the development of the Compatibility Assessment Method as each of the developmental cases was performed. The transition from the basic IDEF0 model to parameterization along with changes in terminology and the addition of additional data that were requested by users is shown.

Table 79 - The history of the development of CAM and the case studies that informed changes to the method.

Case Study	Changes to method
Priors	None. IDEF0 used as published.
Lift Truck 1	Parameters were added for each of the ICOM components.
Mouse	Control component was renamed as "constraint" to alleviate practitioner confusion on terminology.
Mouse	Parameters were expanded to add a "Metric" and a "Value" to capture the information for each of the ICOM components.
CMDS	New category of information was added to categorize the "Severity" of the delta between systems.
B-52	New category of information was added to identify the "Resolution Authority" to address issues of authorizing changes to systems based on incompatibility issues.
B-52	New category of information was added to document the "Stakeholders" involved in the decision.
ARC-210	New category of information was added to capture the "Cost Estimate" of resolving the deltas between systems.
Post-development case studies	The method appeared to be stable and practitioners began using the method. No other changes were made.

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Appendix F – Fast and frugal heuristics

A heuristic is a commonsense rule or set of rules that is intended to help solve a problem. The use of heuristics is based on experiences or "rules of thumb" instead of data calculations. Heuristics are also known as maxims, conventional wisdom, and aphorisms (Maier & Rechtin, 2000). Their use is employed to solve problems quickly and accurately based on previous experiences. The heuristics rely on identifying patterns, developing a rule, identifying the pattern in other situations, and correctly applying the heuristic in new situations. Maier and Rechtin (2000) developed an extensive list of heuristics that can be applied to system architecting.

A fast and frugal heuristic allows a solution to be determined within a short time and uses very little information. An example of a fast and frugal heuristic is the "gaze heuristic" that baseball players use. Shortly after the bat hits the ball, a fielder fixates on the ball and starts moving to a position that will allow a catch. The fielder uses a frugal set of information to move into position, then uses the angle of the ball's flight to solve for the final position. He ignores many other pieces of data that are available: spin, speed, wind speed, and other factors that have little effect on the final intercept solution (G. Gigerenzer, 2004).

One proposed fast and frugal heuristic is Take The Best (TTB), which facilitates choice-making between two alternatives that are described by several dichotomous cues (G. Gigerenzer & Goldstein, 1996). The TTB heuristic has three distinct parts: a search rule, a stopping rule, and a decision rule. The search rule establishes the order for information searching. The clues that are considered to be most valid – the most likely to render a correct result – are used first. The stopping rule is executed when the decision-maker identifies the first discriminating information. Finally, after the search has been completed and the stopping rule has been satisfied, the decision is made to select the better alternative (Garcia-Retamero *et al.*, 2007).

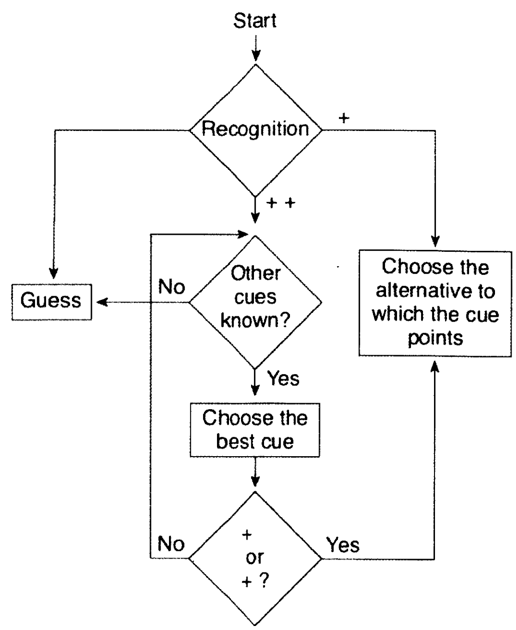

Figure 61 - Flow diagram for the "Take The Best" heuristic (G. Gigerenzer & Goldstein, 1996)

Fast and frugal heuristics can be applied appropriately in many situations. Game show contestants regularly apply heuristics to formulate their responses in order to answer before their competitors, or to minimize their response time. Medical applications include simple decision trees for assessing incoming heart attack patients to ensure proper priority and treatment (Todd & Gigerenzer, 2000). The TTB heuristic does not perform well, however, when a predicted value is required. For example, using TTB, one may predict that one competitor will win over another, but TTB will not help predict the margin of victory of the red car over the yellow car. This analysis is better left to regression models (Gerd Gigerenzer & Todd, 1999).

Appendix G – Action research

The spiral process employed an action research (AR) model to guide the method development to assess compatibility. AR first appeared in the late 1940s when Kurt Lewin used the term "action research" in a 1946 paper that characterized AR as he worked to resolve social problems by using participative group processes to resolve conflicts, crisis and change that appeared within organizations, while he worked at Massachusetts Institute of Technology (Lewin, 1946). AR is also known by several other names throughout the literature: participatory research, collaborative inquiry, emancipatory research, action learning, contextual action research, experiential learning, and others (Dick & Swepson, 2003; O'Brien, 2001). AR's focus is to apply an action while learning about the situation through research. It pursues action and research at the same time and is applied where the action is expected to yield changes or solve problems (Center for Enhanced Learning and Teaching, 2009). AR employs an action by affecting a change on a system while simultaneously developing a deeper understanding of the environment where the change is applied (Dick & Swepson, 2003).

Action research is commonly employed to develop knowledge or understanding in an area of application in situations where other research methods may not be appropriate for use. AR allows flexibility, involves the personnel who operate within the boundaries of the system being researched, facilitates change at the time of research, and can be applied in areas where the situation is too ambiguous to develop a crisp research question. AR is commonly applied by practitioners who desire a deeper understanding of their practice, by those wishing to engage research clients as researchers (Dick & Swepson, 2003). AR strives to make people into involved researchers as they solve real problems in real-world situations. The essence of AR is "learning by doing." Groups of people identify a problem, develop a resolution, measure the success, and repeat if necessary (O'Brien, 2001).

"Action research...aims to contribute both to the practical concerns of people in an immediate problematic situation and to further the goals of social science simultaneously. Thus, there is a dual commitment in action research to study a system and concurrently to collaborate with members of the system in changing it in what is together regarded as a desirable direction. Accomplishing this twin goal requires the active collaboration of researcher and client, and thus it stresses the importance of co-learning as a primary aspect of the research process."(Gilmore *et al.*, 1986)

Table 80 - Similarities and Differences between Action Research and Consulting (Center for Enhanced Learning and Teaching, 2009; Coughlan & Coghlan, 2002; Dick & Swepson, 2003; O'Brien, 2001)

Similarities and Differences between Action Research and Consulting	
Similarities	**Differences**
Affect a change in an organization Attempts to earn buy-in from clients Fundamentally about change Interventionist nature	**Action Research** Apply an action while learning through research Cyclic in execution Buy-in and continuation by local participants Reflection and learning part of process Research in action Concurrent with action Solve a problem AND contribute to science Facilitate clients to inquire into their own issues Can be performed from within an organization Emergent process Theoretical justifications May generate theory Scientific approach to study
	Consulting Applying a linear process Potentially scripted process Potentially tighter time and constraint budgets Solutions to immediate problems Outsider comes into the environment Well-framed problem and solution set Doctor-patient model with directed, prescriptive outcomes Empirical justifications

AR can be performed by individuals or groups. The common thread is that the practitioners' focus is improving or changing their practice (Center for Enhanced Learning and Teaching, 2009). When an outside researcher is invited into a situation to employ the practices of AR, several differences from traditional research methods exist. Some of these differences appear to blur the line between research and consultation, but fundamental differences do exist. First, an action researcher should strive to develop a mutually agreeable solution for all participants. While this may seem similar to a consultant, the goal of the AR leader is to develop local leaders to take ownership of the process. In this capacity the leaders will be able to continue the work without the tutelage of the AR specialist (O'Brien, 2001). The consultant would prefer to continue to be employed in the consulting capacity. AR searches for understanding the situation and places strong emphasis on critical reflection of the environment and solution implementation (Center for Enhanced Learning and Teaching, 2009). AR is characteristically more deliberate in attaining understanding, reflects critically on the process and solutions critically, and performs the reflections formally and centrally to the processes. (Dick & Swepson, 2003) Some authors suggest that while many reviews of AR have been published to criticize the similarities to consulting, the disciplines could benefit from each other. Consulting could benefit from AR's practice of critical reflection (Davison & Martinsons, 2007).

While the differences between AR and consulting have been highlighted, similarities between the two also exist. One of the criticisms of AR is that it is "consulting masquerading as research" (Coughlan & Coghlan, 2002). Four guidelines are accepted in differentiating AR from consulting: AR mode is required to be more rigorous in inquiry and documentation; researchers require theoretical justifications while consultants use empirical justifications; consultants often have tighter time and funding constraints; consultation is often linear while AR processes are cyclic (Coughlan & Coghlan, 2002). Some other parallels between consulting and AR include the focus of achieving change, generally qualitative in nature, both are often participatory with the local participants, the methods and processes can be flexible, and the process employed is cyclic (Dick & Swepson, 2003).

AR is not appropriate for all research situations. Experimental research has a different purpose. Experimental or quasi-experimental research should be applied when the research intends to learn about a limited number of variables and the associated causal relationships. Ethnographies should be considered with other qualitative research methods when learning about an organization or group.

AR has a set of four guiding principles: cyclic in temporal aspects, participative by the researcher and the process constituents, often qualitative by delving into text instead of numbers, and deeply reflective on the process and the outcomes(Center for Enhanced Learning and Teaching, 2009). In performing AR, Dan MacIsaac developed a simple, 4-part cyclic pattern for the process: plan, act, observe, and reflect (MacIsaac, 2003). A more detailed view of the process was presented by the cycle: identify problem, collect data, propose solutions, implement course of action, analyze results, interpret findings, and repeat as desired (Susman, 1983).

The process for a researcher to perform AR could follow this pattern: First, the researcher is motivated by a problem in his domain. This problem identification may be the result of working in the domain and experiences problems that the researcher wants to solve. Next, the researcher may enlist assistance from others in the domain who are experiencing similar problems. The cohort collects data on the problem and proposes several solutions. The team selects and implements a course of action, measures the results, and reflects upon the process and solution. If the solution is determined to be inadequate, the researcher(s) would determine what changes could be made to the AR cycle for their domain, implement the changes, and repeat the cycle as desired.

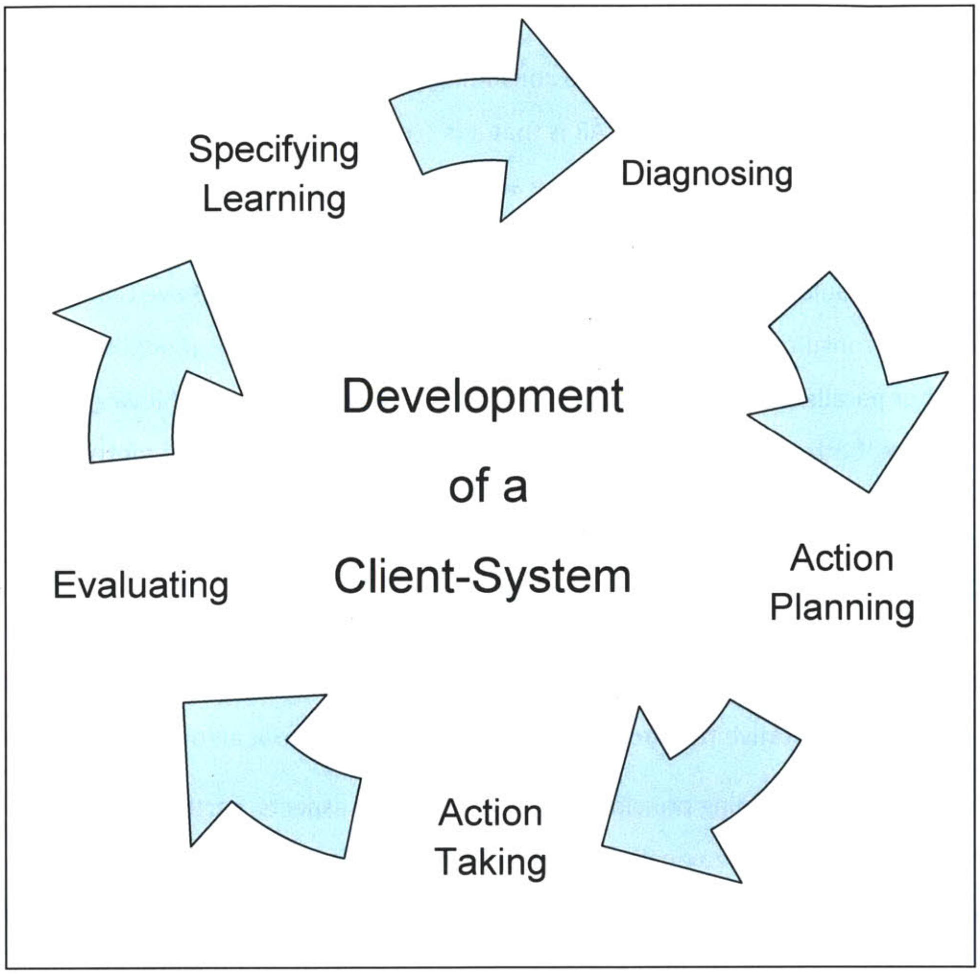

Figure 62 - The five-phase action research model (Susman, 1983)

Critics of the AR methodology identify the inability of identifying causal relationships between variables as a shortcoming of the method. AR can point out temporal aspects of processes such as "Event X precedes and probably causes Event Y." However, these precedence causal relationships are not central to the results of AR. The focus of AR is finding causal relationships between actions and outcomes. The actions of particular interest are those the researchers insert into the research processes and are tested through the iterations of the AR cycles. Instead of causal relationships, AR focuses on producing actions (Center for Enhanced Learning and Teaching, 2009; Dick & Swepson, 2003).

Much of AR work is centered on qualitative research aspects that focus on natural language as the elixir for intrapersonal communications. However, AR can also use quantitative research approaches. Some communities believe that qualitative and quantitative data are incompatible and should not be used together. Some opposing views see this as an artificial barrier that should be broken when appropriate. If the researcher finds difficulty with using both the quantitative and qualitative data, the quantitative data could be described in natural language to resolve the disconnect in data types (Center for Enhanced Learning and Teaching, 2009; Dick & Swepson, 2003).

A discussion of AR would be incomplete without identifying AR shortcomings. A common question about AR is its ability to result in results that can be generalized. In most cases, AR allows making claims only about the people or systems directly studied. The inability to generalize is often cited as a shortcoming. Normally, experimental research would be the correct method to allow generalizations. A generalization has global relevance while action research is focused on local conditions which yield local relevance instead of the sweeping generalizations (Dick & Swepson, 2003). However, generalizations may be made from AR processes if several AR studies were made in very different setting that showed similar results. In this case, the findings may indicate a generalized trend (Center for Enhanced Learning and Teaching, 2009).

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