NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

SYSTEMS ENGINEERING AND INTEGRATION AS A FOUNDATION FOR MISSION ENGINEERING

by

David F. Beam

September 2015

Thesis Advisor:	Gary Langford
Second Reader:	Joseph Sweeney

Approved for public release; distribution is unlimited

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704–0188*

1. AGENCY USE ONLY ***(Leave blank)***	**2. REPORT DATE** September 2015	**3. REPORT TYPE AND DATES COVERED** Master's Thesis

4. TITLE AND SUBTITLE SYSTEMS ENGINEERING AND INTEGRATION AS A FOUNDATION FOR MISSION ENGINEERING	**5. FUNDING NUMBERS**
6. AUTHOR(S) Beam, David F.	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000	**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A	**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. government. IRB Protocol number ____N/A____.

12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited	**12b. DISTRIBUTION CODE**

13. ABSTRACT (maximum 200 words)

This paper investigates the emerging term "mission engineering" through the framework of systems engineering and systems integration. Systems engineering concepts, processes, and methodologies are extrapolated for use in conjunction with a systems integration, life-cycle based framework to effect mission engineering. The specific systems engineering concepts of measures of effectiveness, performance and suitability are recommended as foundational to establishing mission-engineering processes to satisfy mission user requirements, and ultimately provide a context for definition of mission engineering.

14. SUBJECT TERMS mission engineering, systems engineering, measures of effectiveness, measures of performance, measures of suitability	**15. NUMBER OF PAGES** 63
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540–01-280-5500

Standard Form 298 (Rev. 2–89)
Prescribed by ANSI Std. 239–18

THIS PAGE INTENTIONALLY LEFT BLANK

SYSTEMS ENGINEERING AND INTEGRATION AS A FOUNDATION FOR MISSION ENGINEERING

David F. Beam
Civilian, Department of the Navy
B.S., The George Washington University, 2007
M.S., The George Washington University, 2011

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN SYSTEMS ENGINEERING MANAGEMENT

from the

NAVAL POSTGRADUATE SCHOOL
September 2015

Author:	David F. Beam
Approved by:	Gary Langford, Ph.D. Thesis Advisor
	Joseph Sweeney Second Reader
	Ronald Giachetti, Ph.D. Chair, Department of Systems Engineering

ABSTRACT

This paper investigates the emerging term “mission engineering” through the framework of systems engineering and systems integration. Systems engineering concepts, processes, and methodologies are extrapolated for use in conjunction with a systems integration, life-cycle based framework to effect mission engineering. The specific systems engineering concepts of measures of effectiveness, performance and suitability are recommended as foundational to establishing mission-engineering processes to satisfy mission user requirements, and ultimately provide a context for definition of mission engineering.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

EXECUTIVE SUMMARY

The term “mission engineering” has been used recently in academic and Department of Defense (DOD) circles without formal definition or scope. However, the use of the term in systems engineering contexts implies a relationship that can be explored in an attempt to define mission engineering.

The purpose of this paper is to explore key aspects of the systems engineering discipline for applicability and utility in defining the new concept of mission engineering. This is accomplished by examining the definition and critical processes of systems engineering, and then applying those key systems engineering attributes to defining mission engineering and proposing mission engineering processes.

Systems engineering is a well-defined field of study with a multitude of formal definitions. Systems engineering can be defined as an interdisciplinary approach and means to enable the realization of successful systems (INCOSE 2015) or “a methodical and disciplined approach for the specification, design, development, realization, technical management, operations, and retirement of a system” (Department of Defense 2013, 158). Irrespective of definition, systems engineering encompasses several key processes that will be useful in providing context to mission engineering. Those key processes are identification of user needs, decomposition of needs into executable requirements, and verification and validation that system requirements and user needs are met by the resulting systems engineering solution. Additionally, in order to effect successful execution of these foundational systems engineering processes, specific metrics need to be defined and data collected. Several metrics used in systems engineering are measures of performance, measures of suitability, and measures of effectiveness. Measures of performance assist the systems engineer with verifying requirements are satisfied, measures of suitability provide evidence that validates the system for a specific user-defined environment, and measures of effectiveness demonstrate the system is useful to meet operational needs.

A simple definition for mission engineering is postulated, derived from the definitions of the terms “mission” and “engineering,” as the application of science and mathematics in the execution of a specific task with which a person or a group is charged. However, the purpose of this paper is to use systems engineering concepts as a framework to define mission engineering. First, similar to systems engineering, user needs and the derivation of mission requirements must be an iterative process to clearly articulate executable requirements to the mission developers, so planners can determine the best solution within performance, cost, schedule, and other constraints. Second, systems engineering processes of verification and validation are needed in a mission engineering process to ensure mission solutions meet user needs and derived requirements. Measures of performance and suitability provide the necessary data to verify and validate that the mission requirements are satisfied and to what degree. This allows for mission engineering, including iterative trade-space decision making similar to iterative systems design and development cycles. Finally, measures of effectiveness are recommended for use in the final stages of mission engineering during mission execution to provide the end user and other mission stakeholders with quantifiable data that shows the level of mission success, allowing the mission engineer to refine mission requirements or mission parameters as needed.

Mission engineering is expected to be complex and in need of clear definitions, processes, and methodologies. This thesis recommends the use of specific systems engineering processes supported by measures of effectiveness, performance, and suitability as foundational elements from which to build mission engineering processes. In addition, a more detailed definition of mission engineering is proposed, extrapolated from definitions of systems engineering and systems integration (INCOSE 2004; Department of Defense 2013; Langford 2012) is as follows:

> Mission Engineering is a life cycle based, integrative approach to develop and implement capabilities and functions from stakeholder needs into executable missions while balancing performance, risk, cost and schedule.

This thesis concludes that execution of mission engineering requires a life-cycle perspective using systems integration methods and systems engineering tools and processes. Systems engineering and integration have well-developed terminology and clear, executable processes that are applicable and are recommended to be used in the execution of mission engineering. Specifically from systems engineering, stakeholder and requirement analysis, verification and validation processes, and associated measures of effectiveness, performance, and suitability are foundational elements that can be tailored for unique missions and mission-focused processes to ensure mission requirements are clearly defined, allocated, and ultimately met by the mission solution. Additionally, systems integration is a framework for understanding mission engineering as mission engineering involves the integration of systems or systems of systems to execute stakeholder defined capabilities and functions. Systems integration provides a means to develop capabilities, functions, and solutions to problems beyond those of individual systems. The major processes within mission engineering are the mission requirements derived from stakeholder needs, mission conceptualization, mission design, and mission architecting. Within each of these iterative phases, and throughout the mission engineering process, life-cycle considerations must be accounted for and reacted to, as needed. Iterations of design architecture are based upon measures of effectiveness, performance, and suitability depending on the specificity of the capability or function in question and the stage in the mission engineering process. Performance measures may be used early and often to verify specific aspects of the mission design, whereas measures of suitability and effectiveness are more often used later in the mission engineering process when closer to a final solution. Mission engineering is a life-cycle based, integrative approach to develop and implement capabilities and functions from stakeholder needs into executable missions while balancing performance, risk, cost and schedule.

A recommendation for future study is to further explore the emerging field of mission engineering. While this thesis proposes a construct of mission engineering utilizing the framework of systems integration and the tools and processes of systems engineering, additional specificity for mission engineering unique processes may be beneficial. Additional detail in mission engineering processes and terminologies may allow for greater application of mission engineering and may result in an entirely separate field of study from systems engineering.

LIST OF REFERENCES

Department of Defense. 2013. *Defense Acquisition Guidebook*. Washington, DC: Department of Defense.

International Council on Systems Engineering (INCOSE). 2004. *Systems Engineering Handbook*. INCOSE-TP-2003-016-02. Version 2a. San Diego, CA: INCOSE

International Council on Systems Engineering (INCOSE). 2015. “What is SE?” Accessed on July 10. http://www.incose.org/AboutSE/WhatIsSE

Langford, Gary O. 2012. *Engineering Systems Integration Theory, Metrics, and Methods*. Boca Raton, Florida: CRC Press.

ACKNOWLEDGMENTS

I want to thank my wife, Emily, for her support throughout this program and my son, Ethan, for providing the necessary motivation to complete this program on time.

THIS PAGE INTENTIONALLY LEFT BLANK

I. BACKGROUND

A. SYSTEMS ENGINEERING

Unlike traditional engineering disciplines (e.g., mechanical engineering or electrical engineering), systems engineering does not have a single, clear definition that is used throughout the academic and public arenas. However, all of the definitions highlight specific aspects of systems engineering and expose the user to the importance of those aspects of systems engineering over other aspects. The following definitions are provided as context to demonstrate how systems engineering can be defined in a broad context with a multitude of processes but also defined more narrowly based upon the interests or preferences of the organization generating that definition:

The International Council on Systems Engineering (INCOSE) defines systems engineering as “an interdisciplinary approach and means to enable the realization of successful systems” (INCOSE 2004, 12):

> Systems Engineering is an overarching discipline, providing tradeoff analyses and integration between system elements to achieve the best overall product and/or service. Although there are some important aspects of project management… it is still much more of an engineering focus than a management discipline. (INCOSE 2004, 10).

These definitions focus on the development of a specific product and the use of specific systems engineering processes to support that development. Furthermore, the INCOSE definitions highlight the blending of an engineering discipline and management. The organization and management of the processes employed by the systems engineer is just as important as the execution of the processes themselves, especially when planning and managing a system through its life cycle.

The Institute of Electrical and Electronics Engineers (IEEE) describes the goal of systems engineering as

> developing, producing, testing, and supporting an integrated set of products (hardware, software, people, data, facilities and material) and processes (services and techniques) that is acceptable to stakeholders, satisfies enterprise and external constraints and considers and defines the

> processes for developing, producing, testing, handling, operating, and supporting the products and life cycle processes. (Institute of Electrical and Electronics Engineers 2005, iv)

While this definition parallels the INCOSE definition to develop a system, it is important to note the focus on a complete life cycle balanced solution and the satisfaction of internal and external demands. Looking at systems engineering through this lens, a systems engineer will emphasize the involvement and satisfaction of the customer but also assign high importance to the satisfaction of other internal and external demands.

The *Defense Acquisition Guidebook* (*DAG*) defines systems engineering as "a methodical and disciplined approach for the specification, design, development, realization, technical management, operations, and retirement of a system" (2013, 158). The *DAG* definition of systems engineering is a narrowly focused definition of systems engineering. The systems engineering process is presented as a linear systematic process to define, realize, manage, and ultimately dispose of a system. However, within each phase of the systems engineering process, an iterative process is used to determine the outcome. Additionally, the *DAG* definition specifies a methodical and disciplined approach, whereas previous definitions simply stated an approach was used. Enhanced discipline and adherence to rigorous methods in the *DAG* definition is due to the high focus on compliance, traceability, and oversight in the government arena.

The varying definitions of systems engineering highlight the universality of systems engineering concepts and the flexibility with which those concepts can be applied. Some organizations use a broader definition of systems engineering while others focus on specific aspects of systems engineering that are more important to service their needs.

B. MISSION ENGINEERING

Mission engineering is a hitherto undefined term that affords great latitude when proposing a definition. A good starting point is the definition of the individual constitutive words. Merriam-Webster provides the following definitions for "mission" applicable in a military context: "a specific task with which a person or a group is charged" and "a definite military, naval, or aerospace task." It also provides the following definitions of engineering as “the application of science and mathematics by which the properties of matter and the sources of energy in nature are made useful to people” and “the design and manufacture of complex products.” At an elemental level, one can define mission engineering as the application of science and mathematics in the execution of a specific task with which a person or a group is charged. However, this definition is general and does not provide a user with an understanding of how mission engineering is performed or what processes to use in the execution of mission engineering. This is where the context of a well-defined discipline, such as systems engineering, provides the framework and limits to better define mission engineering.

Due to the broad applicability of systems engineering concepts and methods, the term “mission engineering” may be defined in terms well established in the systems engineering field of study. This thesis explores answers to the questions, “What is mission engineering?” and “How can systems engineering processes be used to lay a foundation for consistent application of mission engineering?” This thesis answers these questions by establishing a framework to define mission engineering through the use of accepted definitions, processes, and methodologies already existing in the field of systems engineering. Through the systems engineering lens, mission engineering as a systems process is explored and in that manner provides a foundation for developing a formal definition.

THIS PAGE INTENTIONALLY LEFT BLANK

II. SYSTEMS ENGINEERING

A. SYSTEMS ENGINEERING AS A FRAMEWORK

Systems engineering is a well-documented engineering discipline with codified processes, methodologies, and definitions used to design and develop systems to suit user needs. The formalized definitions and processes of systems engineering are a logical framework to explore, understand, and define the new term mission engineering.

As the name implies, systems engineering is the use of specific processes to design and develop systems. However, systems engineering is unique from other engineering disciplines. Langford (2012, 218–219) describes the uniqueness of systems engineering through its focus on "(1) the product or service as an enabler of the desired user behaviors, (2) satisfying the stakeholders' needs can be done in one of many ways, (3) and the desired consequences of the product or service for people, infrastructure, and environment need to be incorporated by design and architecture." Systems engineering methods and processes are used to derive a multitude of potential solutions from user needs and requirements, focus solutions on satisfying the users' needs, and consider internal and external influences on the system both near term and long term. In this regard, systems engineering is a life-cycle approach to designing and building products and services.

Systems engineering covers a broad range of activities in a product life cycle from deriving requirements from stakeholder needs, implementing requirements into design of systems and subsystems, and verifying and validating that the resultant product or service has met the original stakeholder needs and requirements. This high-level system engineering process is iterated continuously at varying levels of specificity throughout the life cycle of the system. Figure 1 illustrates this high-level system engineering approach to satisfying stakeholder needs. This thesis focuses on a portion of the systems engineering cycle – the derivation of stakeholder needs and requirements and the verification and validation that the product meets those needs and requirements. These areas of the system engineering cycle are used to provide context and basic definition to the term "mission engineering."

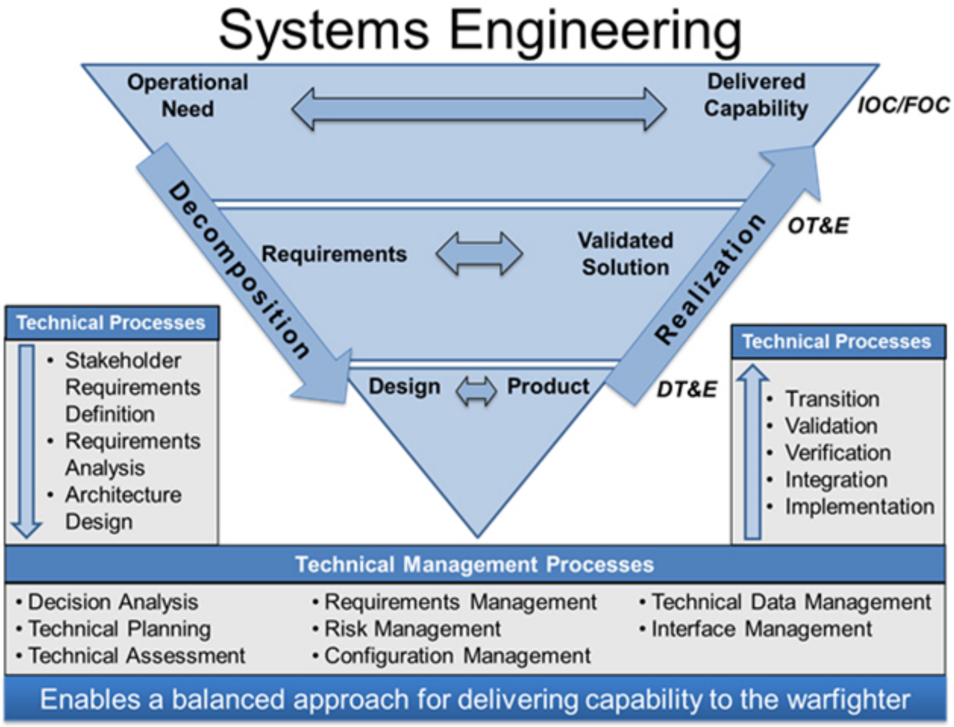

Figure 1. Systems Engineering Model (from Department of Defense 2012[d])

B. NEEDS AND REQUIREMENTS

The starting point, and one of the most important elements in the systems engineering process, is the development of stakeholder needs and derivation of system and subsystem requirements. The requirements development stage is paramount to successful system engineering and development because all subsequent processes and steps in the design cycle require clear definition of requirements that are attainable and suitable to satisfy the stakeholder needs.

The development of a new system begins by clearly identifying a problem in order to identify the need for a new system to delineate solutions that respond to that problem. It is paramount to have a clearly identified need prior to requirement generation, in order to avoid the system engineering process being driven by personal or political interests. The satisfaction of stakeholder needs and the subsequent requirements that are derived from those stakeholder needs are the driving force behind the systems engineering process. Therefore, the verification and validation of those needs and requirements is equally important to successful execution of systems engineering.

1. Needs and Requirements Generation Processes

One of the technical processes to ensure successful systems engineering is the requirements generation process. During the requirements development phase (may also be referred to as the requirements analysis phase), user needs are translated into functional and performance requirements. The resulting set of system requirements will define functionally what the system is required to do and define the performance required for each function (Defense Acquisition University 2015). An iterative process of functional analysis and allocation of requirements is used to ensure the final requirements are understandable, unambiguous, executable, concise, and completely define the needs.

Bijan et al. (2011) review and discuss several methods for requirements generation, prioritization, and analysis however, conclude that more work may be needed to codify an end-to-end process for translating user needs into precise, unambiguous requirements for successful systems engineering of complex systems. One process described for initial identification and organization of requirements is Quality Function Deployment; in this process stakeholder needs are defined and grouped diagrammatically to aid the systems engineer in understanding the relationships between various needs and to identify similarities, differences, or redundancies. Another method for generating requirements is the use of a use case, or a scenario in which the requirement may be satisfied. The use case process is aimed at identifying unnecessary requirements or identifying functional or performance gaps in the requirements set that may lead to articulating additional requirements, or requesting clarification from stakeholders. Ultimately the requirements generation process may be uniquely based upon the size, complexity, or other features of the specific system, but some common features of successful requirements development processes are: keep users involved; iterate and refine requirements; organize, monitor, and track requirements; and clearly document all requirements and how and why they change (Turk 2005).

2. Needs and Requirements Management

The monitoring and tracking of requirements through the system life cycle necessitates a method for requirements management. Requirements management is important to a successful system engineering approach because requirements may evolve and the system engineer will need to respond to those changes. Some reasons for requirements evolution are changing stakeholder needs, changing technologies, budgetary constraints, modifications within an organization, or working with new vendors, which may impose additional constraints on the system (Turk 2005). Chapter 4.3.5 of the *DAG* describes the requirements management process as a method of requirements traceability from stakeholder need, or high-level system requirement, through system level elements in a functional breakdown of the system to the lowest level of design (Department of Defense 2013). This level of traceability enables the systems engineer to manage efficiently requirements modifications and their impact on a developing or developed system.

C. REQUIREMENTS VERIFICATION AND VALIDATION

While the derivation of requirements from stakeholder needs is one of the initial steps to the systems engineering process, verifying and validating that stakeholder needs have been met is one of the final stages of the systems engineering process. The derivation of and the verification and satisfaction of stakeholder needs in the form of system requirements are two of the most important elements of the systems engineering process. Furthermore, the metrics and methods used to measure successful validation and verification are necessary for the systems engineer and the stakeholders to accept the final solution as an effective solution to the initial problem. The measure used to validate the solution is effective and to verify the solution is suitable for the user are critical metrics for demonstrating successful systems engineering and a successful solution.

1. Verification

Verification is an assessment of a system's limitations in an effort to determine whether the requirements have been satisfactorily met. This assessment is performed throughout the system engineering and development process in order to identify and correct issues early in design. The *DAG* (2013, Chapter 4.3.15) defines verification as the process that "provides evidence that the system or system element performs its intended functions and meets all performance requirements listed in the system performance specification and functional and allocated baselines." The DAU defines verification as the process of confirming that each element of the system "meets the design-to or build-to specifications." Verification is a critical feedback mechanism throughout the systems engineering process to ensure the systems and subsystems being designed, built, and integrated meet the requirements defined at the outset of the systems engineering process. To maximize benefit, verification is not only performed at the end of the design and integration cycle, but throughout the design, development, and integration phases of a system in order to correct any deficiencies and to provide evidence that the system is adequate to meet the defined requirements.

The process for executing verification is reliant on the requirement or feature of the system being verified. Chapter 4 of the *DAG* describe four verification methods: examination, demonstration, analysis, or test. Examination is a visual inspection to determine if the system or sub-system is in compliance with requirements. Demonstration is similar to examination in that visual observations are used to verify requirements; however, demonstration involves inspection while functions of the system are operated. Analysis verifies the system or sub-system through the use of analytical techniques, such as computer models or hand calculations, to explain performance. Finally, testing is an activity to demonstrate performance of a system element or function in a controllable scenario (Department of Defense 2013). Some or all of these processes may be used to verify the system throughout the life cycle, from initial concept through final design. As an example, analysis may be a preferred verification method early in design due to cost and faster iteration as needed to correct performance issues, whereas demonstration and testing may be used later in design when physical mock-ups or prototypes are generated to verify acceptable performance.

2. Validation

Validation is similar to verification in that it is a check of the design process to ensure the solution and end result of the systems engineering process meets the user's needs. The validation process confirms that the realized system complies with stakeholder needs (INCOSE 2004). While verification focuses on the system, subsystem, or constitutive elements meeting specific and defined requirements in the form of specifications, validation tests the resulting system to acquire confidence that the system produces the desired result for the user. In effect, validation of the system is an endorsement that the process of translating user needs into requirements was successfully executed. As such, validation is paramount to the systems engineering process producing a product or service that is useful and effective for the user.

Processes used for validation are similar to those used for verification with the major difference being that validation activities are centered on performance of the resulting system in an intended operational environment. Early in the systems engineering life cycle, modeling and simulation may be used to estimate the performance of the system in an operational setting. However, final validation of the system involves testing of an operational, production-representative system in the intended operational, or suitably simulated, environment. Additionally, end-user and other external stakeholder involvement in validation activities can ensure independent confirmation that the correct system has been developed and functions as needed (Department of Defense 2013).

D. SYSTEMS ENGINEERING MEASURES

1. What Is a Measure?

Defining a measure provides a foundation for discussion of specific measures used in systems engineering. A measure is a quantitative or qualitative value that has specific meaning within a context (Langford 2012). For example, the five is simply a number, but may be used as a measure when a context is established such as time, specifically seconds; five seconds is a measure of time. Measures as used in this thesis are properties or attributes that are either qualitatively or quantitatively determinable (Langford 2012).

2. Measures of Effectiveness

Verification and validation are evidence-based processes and rely on metrics and data to support justification that a system meets functional and performance requirements as well as the ultimate needs of the user. In order for the systems engineering to successfully employ verification and validation, metrics must be well defined and articulated to ensure the effectiveness of the resultant product or service of the systems engineering process. One metric used to quantify the performance of a system, product, or process with respect to what degree the real objective is achieved is a measure of effectiveness (INCOSE 2004). According to the DAU, measures of effectiveness are “the data used to measure the military effect (mission accomplishment) that comes from the use of the system in its expected environment” (2012 (a)). According to Langford (2014, 7), “measures of effectiveness are intended to demonstrate to what extent objectives are accomplished and how well the results compare with the desired results.” The goal of systems engineering is to produce a product or service that is useful and valuable to the end user. Measuring the effectiveness of the resulting system is critical to defining the systems engineering processes and methodologies as successful. If the system is not deemed useful or valuable to the end user based upon the measure of effectiveness, the systems engineering processes used must be scrutinized and adjusted, as needed, to affect a solution that is more useful to the user. This iterative approach can be used to re-scope and redefine the systems engineering processes used to define the solution. Therefore, measures of effectiveness are important to understanding the systems engineering process and may be leveraged to understand and help define mission-engineering processes. Who and how does one determine measures of effectiveness? Sproles (2000) suggests that measures of effectiveness are determined by the stakeholders because the stakeholders will determine if the resulting system satisfies their needs. Expanding on that observation, the method to determine measures of effectiveness is to identify specific properties of the system that are needed to satisfy the end-user or stakeholder. Sproles (2000, 55) suggests the question be asked: “If a candidate solution cannot do this, would I reject it?” Once the critical properties of the system are established, a measure must be assigned to those properties to afford the system engineer a qualitative or quantitative means by which to assess various system solutions. It is necessary to be able to test a system with respect to a specific measure of effectiveness; otherwise, the measure adds little value to the system engineer or stakeholder. Since measures of effectiveness are used to demonstrate to the stakeholder acceptability of the system, the viewpoint or perspective of the stakeholder(s) is important to consider. The steps to determining measures of effectiveness are to determine the viewpoint from which the measure will be used, establish the functionality or performance desired by the system, draft a notional measure of effectiveness, analyze the measure of effectiveness for utility and application for the system in question, and to iterate and revise the measure of effectiveness as needed (Sproles 2002).

Langford (2014, 10—12) describes a nine step process for reliably choosing measures of effectiveness. The process includes defining terminology, delineating boundaries and functions through functional analysis, performing a life cycle analysis, defining requirements from stakeholder needs, hypothesizing a solution, determining theoretical foundations, formalizing a framework, determining any losses, and analyzing the resulting effectiveness.

Regardless of the method used to generate the measures of effectiveness, they are necessary to validate the final system solution in the intended application and are therefore a critical part of the systems engineering and systems integration processes. In addition to measures of effectiveness, measures of performance and measures of suitability are used in the systems engineering life cycle to verify and validate that sub-system and system requirements are satisfied.

3. Measures of Performance

Measures of performance are a subset of measures of effectiveness that are used to specifically gauge the abilities of a system. Sproles (2000) highlights the distinction between measures of effectiveness and measures of performance as the former describes the effectiveness of any solution with respect to the user needs, whereas the latter describes the performance of a specific solution, system, or sub-system. DAU defines measures of performance as "system-particular performance parameters such as speed, payload, range, time-on-station, frequency, or other distinctly quantifiable features" (2012 (b)). Measures of performance are used to quantify the ability of the system to achieve specific, individual attributes and are consequently tied to verification of the system. The system, and its subsystems, is verified throughout the systems engineering process to ensure the requirements and necessary abilities of the system are achieved, or to gauge the extent to which the system is unable to meet the requirements. Selecting the most appropriate measures of performance is paramount to successful and meaningful verification of the system and ensuring the system solution meets stakeholder requirements. The selection of measures of performance may also guide the final solution as the system is iterated and verified throughout the design process.

Measures of performance are selected and iterated through requirement allocation to features of the system. Performance of specific functions or features of the system are only necessary to be measured when they relate directly to a requirement to be satisfied. Therefore, establishing the measures of performance for a system, sub-system, function, or feature of the system involves tracing of requirements through the functional breakdown of the system in order to specify a measure. Iteration may be needed to revise the measure or measures of performance used to quantify a specific function or feature of a system. For example, a manufacturing process employing a performance measure tied to units produced may add specificity and define performance by units produced over a specified time period. Ultimately, the measure of performance is used to influence the systems engineering process and, as such, the measure must be linked through a system function or element to a specific requirement.

4. Measures of Suitability

Measures of suitability are also a subset of measures of effectiveness. Measures of suitability are used to define how well a system performs in a particular end-user environment (i.e., how suitable is the product or service at meeting the user's needs). DAU defines measures of suitability as the "measure of an item's ability to be supported in its intended operational environment" (2012 (c)). Defining and implementing effective measures of suitability allows the systems engineer to track and refine the progress in designing a system to meet the user needs. Since measures of suitability relate to the user's intended environment, they are typically used during validation testing. The system is validated to meet the user's needs in the user's defined environment using the objective quality evidence of measures of suitability. In this regard, measures of suitability are just as important as measures of performance in honing the systems engineering solution and ensuring the final product or service meets the user's needs.

The process of identifying measures of suitability is similar to identifying measures of performance but must also consider the system as a whole and the requirements for implementation or use of the system in stakeholder specified use cases. Measures of suitability describe how the features or functions of a system perform in a specified environment. Therefore, the process to develop a measure of suitability is similar to the process for measures of performance; however, the system is measured in a user-defined or operational environment. The process of determining a measure of suitability begins with identifying those aspects of the system that meet the user's need (i.e., tracing a user need through the requirement allocation to specific functions or features). Next, the measure must be viewed from the perspective of the environment or use-case in which the system will be tested to ensure the measure is applicable and sufficient to demonstrate the satisfaction of the requirement. Finally, iteration may be needed to adequately capture all the measures needed to capture the overall system performance in its user-defined environment.

III. SYSTEMS ENGINEERING INTEGRATION

A. WHAT IS SYSTEMS INTEGRATION?

Systems engineering is an iterative process concerned with the design and development of a product or service as a solution to stakeholder requirements; by contrast, systems integration is the combination of systems or systems of systems to satisfy stakeholder needs that cannot be satisfied by an individual system. "Systems integration is the unification of the objects and their interactions of energy, matter, material wealth, and information to provide system-level functionalities and performances" (Langford 2012, 174). Systems integration is useful to provide a system with function or performance that is unachievable through the use of the constitutive parts.

1. Energy, Matter, Material Wealth, and Information

The process of integration involves the interaction of the item's constitutive parts. In other words, something significant about each individual item has created a need for it to be integrated with another to form a new system. At a fundamental level, these interactions take place via interaction of energy, matter, material wealth, or information. A brief exploration of the products of interaction will aid in understanding systems integration.

Energy exists in many forms (e.g., heat, chemical, and kinetic). As such, the transfer of energy from one object to another is of major importance to systems integration. The interaction of objects due to integration can transfer energy internal to the system and interact with energy external to the system. As an example, the integration of objects and systems in an automobile engine transfer and translate energy in the form of chemical reactions (i.e., combustion of fuel) to kinetic energy (i.e., rotary motion of engine drive shaft) useful for the system to perform function "to move." By-products of that interaction are non-useful chemicals and heat that are transferred into the external environment.

All objects are made of matter and therefore the integration of objects creates interaction of matter. Matter can be transferred through integration or matter can be unaltered, but play a critical role in the interactions of constitutive elements. For example, matter may be transferred as described in the automobile example above wherein gasoline is burned to generate kinetic energy and by-products. Matter may also interact but be unaltered, as seen in a tire's interaction with the road – the material composition, shape, and other factors can affect the friction and therefore the interaction of the car system with the road.

Material wealth plays a critical role in the development of systems and in turn, the integration of systems. Material wealth can include cash, its equivalents, or anything that can be converted into cash or its equivalents. Material wealth in a natural system may take the form of abundance of resources, such as water or oil (Langford 2010).

The interaction of information is critical to systems integration in the digital age. Many systems developed currently take in, utilize, and expel information in mass quantities. In fact some systems, such as a computer program, are entirely based upon the interaction of information. The integration of the computer program with a computer and user interface enables the system to interact with another system (i.e., a person) and perform useful functions.

2. Systems Integration, Capability and Mission

Systems integration can be viewed as the integration of functions or capabilities from constitutive elements to form a new system, with new, unique capabilities or functions, and new boundary conditions or limitations. MITRE Corporation defines systems integration as "the composition of a capability by assembling elements in a way that allows them to work together to achieve an intended purpose" (MITRE 2013). The development of a capability or functionality that the individual system components cannot achieve singularly is an important foundation for discussion of mission engineering. The need for systems integration is therefore the identification of capability gaps and the integration of the functionality of systems to fill that capability gap. The ability for systems integration to develop capability from existing systems that lack that capability has profound impact upon the application of systems integration for the purposes of mission engineering.

B. THE PROCESS OF SYSTEMS INTEGRATION

The process of systems integration is linear, vice the iterative approach used commonly in systems engineering. The major tasks of systems integration are to (1) identify and characterize the item (products or services) to be integrated, and (2) to define the specific interactions and integrations of the items that will produce the desired operational effectiveness to meet the needs of the stakeholders (Langford 2010). In order to identify and characterize items to be integrated, systems integrators must identify the limitations, functions, and characteristics of each item, understand the potential interactions between items to identify functions useful in meeting specified requirements, and finally, testing the functions identified to evaluate performance parameters and ascertain any limitations.

The systems integration process necessitates a life cycle perspective and approach. A life cycle framework is needed for systems integration due to the focus on functions generated by the interaction and integration of objects. The functions produced may be beneficial, detrimental, or neutral and it is the job of the system integrator to sort the functions and prioritize them based upon the need, problem, or requirement identified by the user or other critical stakeholder. Using the example of a gasoline-powered automobile, the functions of to steer, to drive, to cool (for those with air conditioning) are all beneficial functions of the systems of systems integration. However, the exhaust and heat produced are detrimental functions of this systems integration. Therefore, when analyzing the constitutive elements to be integrated for their potential interactions, the system integrator must consider all life cycle implications and not focus on one item or function. Langford (2010, 173) proposes that an effective strategy for systems integration is to analyze “the totality of the system’s objects, identifying the expected (1) system-level functionalities, performances, losses to achieve those performances, and boundary and boundary conditions; (2) physical entities and their mechanisms, EMMI [energy, matter, material wealth, and information], boundaries, and boundary conditions; and (3) the expected behaviors from users of the new system as well as their behaviors due to the anticipation of tasks for the new system, their boundaries, and boundary conditions.”

IV. MISSION ENGINEERING

A. SCOPE OF MISSION ENGINEERING

Mission engineering is the use of systems or integration of systems to operationalize and execute a task. Systems integration methods may be used to compose subtasks and sub-functions of a mission to develop a mission capability. Likewise, systems engineering and integration processes and concepts are used to design the mission and verify and validate the mission solution. Mission engineering is postulated to be an application of system integration using concepts and terminology extended from the field of systems engineering.

Figure 2 depicts a notional framework for executing mission engineering. The figure shows the flow of requirements from stakeholder needs to mission requirements, then the iterative processes of mission concept, mission design, and mission architecting. These functions of mission engineering are used to optimize a mission solution to the mission requirements and ultimately satisfy the stakeholder needs.

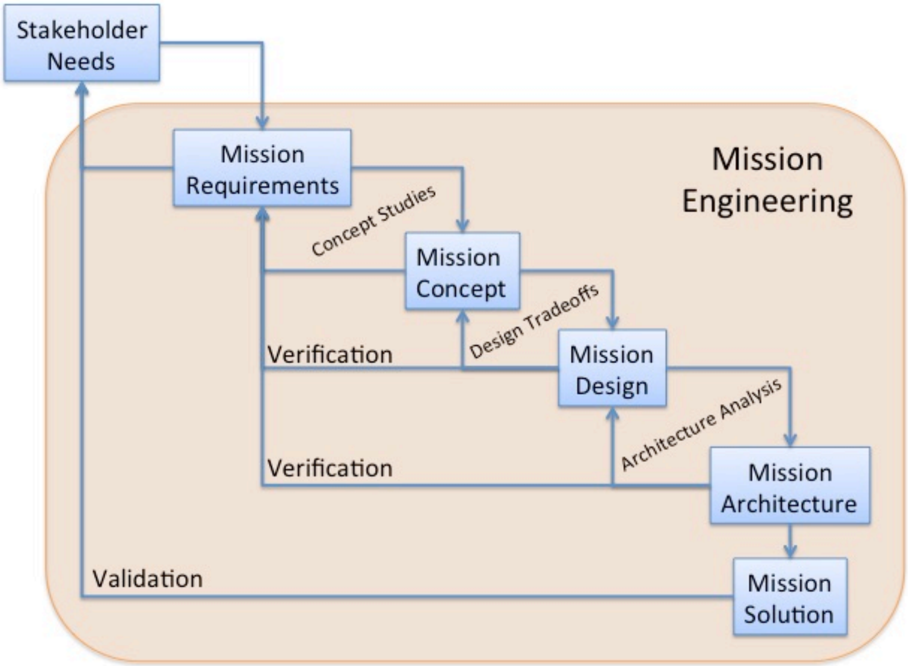

Figure 2. Mission Engineering Process Diagram

Mission engineering may be viewed as a process of functions to realize stakeholder and user mission needs. As such, developing an understanding of mission engineering requires analysis from a functions perspective. Identifying the individual functions and sub-functions that constitute the overall process of mission engineering allows the mission engineer to more accurately define the steps necessary to proceed through a successful mission engineering iteration. Additionally, specific functions of mission engineering may be used to develop performance, suitability, and effectiveness measures. For example, Figure 3 shows a functional decomposition of mission engineering; in the architecting phase, the function of “to analyze human interfaces” may be used to map specific measures of performance or suitability to human systems integration requirements. In this manner, a functional view of mission engineering is important to develop successful processes and metrics for implementing mission engineering.

Figure 3. Functional Decomposition of Mission Engineering

The focus of mission engineering is on a life cycle basis, as opposed to focusing on the design and development of a specific system to meet specified requirements. Mission engineering requires a life cycle perspective because it is more than the integration of an operational user with a system; the mission performance is impacted by aspects such as evolving stakeholders and evolving stakeholder requirements, future changes to constraints placed on the mission, and evolution of the mission itself due to upgrade or obsolescence. Figure 4 illustrates mission engineering life cycle concerns that must be addressed in parallel with and are integral to mission development.

Figure 4. Mission Engineering Life-Cycle Considerations

B. MISSION CONCEPT

1. Defining Mission Concept

In order to understand a mission concept, similar concepts in industry are explored. In business, a mission statement is used to declare a purpose or strategic vision of an organization. The mission statement can be defined as a strategic posture and establishes the framework for a business to evaluate alternatives for how to proceed in potential product or service opportunities (McGinnis 1981). The mission statement distinguishes a particular business from others in the field, providing direction, objectives, and strategy (Forest 2003). In the military, a mission concept can be elucidated as a concept of operations. A concept of operations as defined in the United States *Department of Defense Dictionary of Military and Associated Terms*, a concept of operations is a clear, concise verbal or graphic statement that describes what is intended to be accomplished and what resources will be used (Department of Defense 2015). The concept of operations establishes a baseline framework for conceptualizing and analyzing the mission objectives and requirements. The concept may be iterated upon until the true need of the user or stakeholders is satisfied. A parallel can be drawn between the establishment of the concept of operations and the identification of system level requirements. The system level requirements are decomposed into specific sub-system or functional element solutions with traceability back to the system level need through the use of allocated requirements. Similarly, a concept of operations is used to describe the overall mission concept and any systems used or integrated to solve the mission need. A mission concept as used herein is a clear, brief explanation or diagram of the mission objectives or operational needs, limitations, and resources to be used.

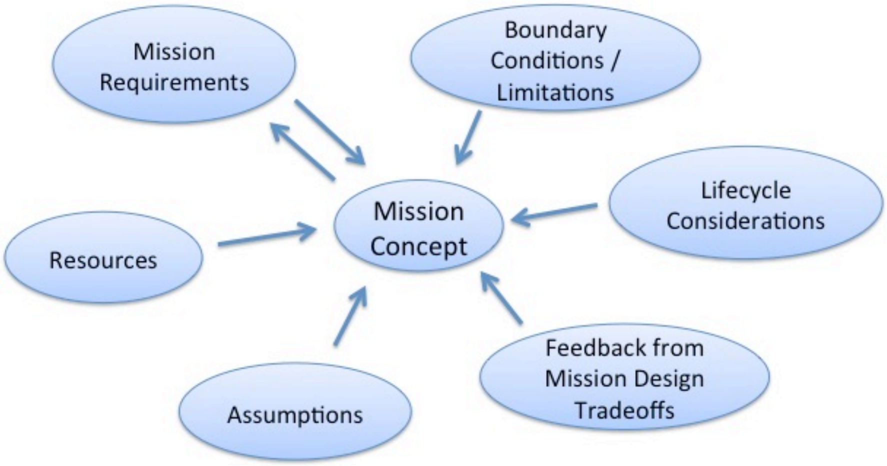

Figure 5. Mission Concept Context Diagram

The mission concept, depicted in Figure 5, provides the mission engineer with a framework to understand the operational needs to be satisfied and the limitations or constraints that bound the solution space for defining a mission. Mission engineering, and therefore mission concepts, must consider life cycle implications and interactions. The operational needs, limitations, and resources available may all change over the course of the mission life cycle and therefore must be considered and actively planned for during the mission concept phase. One mechanism to incorporate life cycle considerations into the mission concept phase is through analysis of the feasibility of the mission concept.

2. Analyzing Feasibility of Mission Concept on Life Cycle Basis

A mission concept will form the basis to flow through the mission engineering process. As such, the mission concept must have a solid foundation based upon analysis of life cycle considerations. In brief, a mission concept must be attainable, practicable, and effective to support the operational needs and objectives. Analysis from a life cycle perspective will enable the mission engineer to develop mission concepts that can meet the current operational needs but also be agile to support evolving operational needs, stakeholders, mission designs and architectures, policies, and other life cycle considerations. Some life-cycle considerations identified and discussed in more detail include management of stakeholders, requirements, configuration, communication, and logistics; risk assessment and management; human systems integration; energy and sustainability; information assurance and cybersecurity; safety; security; policy, media, and legal support services; training and documentation.

C. MISSION DESIGN

1. Developing Mission Design

Following the mission concept phase, the mission engineering process, shown in Figure 2, proceeds into the mission design phase. Mission design, illustrated in Figure 6, is the decomposition of the mission objectives and necessary functions, in the form of mission requirements, using the guidance of the mission concept as a framework, to develop sub-tasks and sub-functions that must be satisfied to perform the mission. In this manner, mission design is not dissimilar to the systems engineering processes of top-down requirements derivation and systems design and development to satisfy specific functions. Additionally, systems integration processes may be leveraged during mission design to satisfy functions and capabilities that cannot be accomplished at an elemental level (i.e., with an individual system solution).

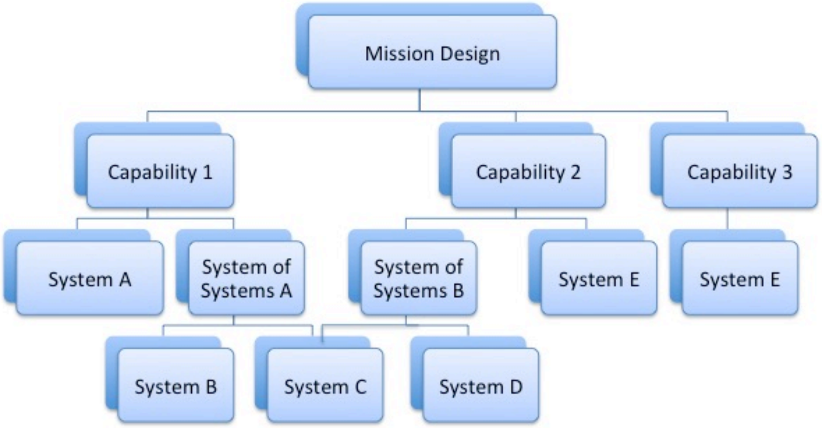

Figure 6. Mission Design Diagram

The mission design process incorporates methods to assess the capabilities and functions performed by the mission design, but also evaluates the interaction of the mission design with life cycle factors. Verification and validation processes leveraged from systems engineering are proposed to maximize the effectiveness of mission design. Clear, concise definition of mission sub-tasks and sub-functions will enable more successful verification and validation of the ultimate mission design solution. Measures of performance and suitability provide the data to track the progress of the mission design in satisfying the mission sub-functions as well as the overall required capabilities. As used in systems engineering, measures of performance are used to provide evidence and justification to a mission design verification process; the mission design verification process is used to ensure mission requirements are satisfied. Measures of suitability are used in a mission design validation process to demonstrate a proposed capability or proposed mission solution in a prescribed environment; for example, a mission function or capability that is required to be executable in multiple environments (e.g., humid, jungle climate or cold, wintery climate) may be validated individually to demonstrate suitability in each environment.

2. Evaluating Mission Design for Effectiveness on Life Cycle Basis

Functional analysis and decomposition of mission design is used to identify and quantify the capabilities and functions needed to meet the mission requirements. The functional analysis of "to design a mission" highlights the influences on mission design allowing parameters for specific sub-functions to be determined for measuring mission design effectiveness. The function decomposition of mission design depicted in Figure 7 shows the processes and influences upon mission design. The identification and analysis of requirements and constraints are a major consideration when designing a mission (just as they are when engineering a system). Additionally, management of life-cycle considerations is important for the mission engineer to establish measures of effectiveness that will accurately characterize the mission solution and how well it satisfies the needs of the stakeholders. Figure 7 shows a notional functional diagram to describe the process of designing a mission. The figure also shows an example of how a measure of effectiveness for the system may be derived through the functional breakdown for life-cycle issues that influence the mission design.

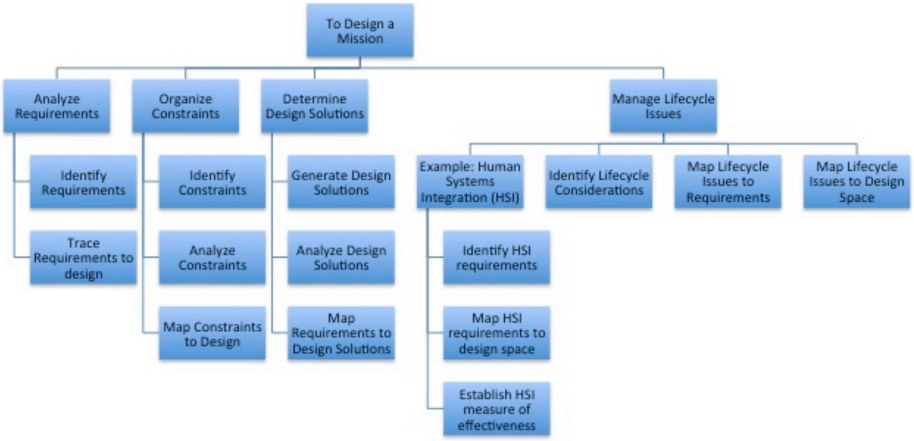

Figure 7. Functional Diagram of Mission Design

The effectiveness of a mission design in satisfying the stakeholder needs must also consider life cycle factors. Life cycle factors may be described as external influences upon a system (the mission design). Mission design meets the stakeholder requirements for a desired capability using a systems engineering framework, but the mission design also employs systems integration methods to consider capabilities derived from the interrelation of systems as well as life cycle influences. Life cycle factors may drive an agile mission design solution that can adapt to changing stakeholders, needs and requirements or may drive the design solution to very specific solutions, such as restrictions based upon requirement for a human interface. For successful mission design, in addition to the decomposition of mission capabilities into sub-tasks, life cycle considerations and their impact, interactions and boundary conditions with each capability, sub-task, and function are analyzed. The discretization of the elements of mission design and their interactions with life-cycle considerations enables the mission engineer to use measures of effectiveness with life cycle focus determined for each sub function and the overall mission design and iterate or trade-off mission trade-space as needed.

D. MISSION ARCHITECTURE

1. Selecting Mission Architecture

In general, the architecture of an object is its structure or form. Langford (2012, 353) describes architecture as "conceptual or logical structures of objects and processes." In that vein, mission architecture is the representation, structure or implementation of the mission design. While mission design is centered upon the satisfaction of required capabilities and functions, mission architecture focuses on how the mission design is implemented, or the structure of the mission. As such, the dominant activity in selecting a mission architecture it the tradeoff between the effectiveness of the mission design, cost, and risk.

2. Analyzing Mission Architecture, Tradeoff Cost, Effectiveness, and Risk on a Life Cycle Basis

In the mission architecture phase of mission engineering, tradeoffs between mission effectiveness, cost, and risk are conducted to determine the optimal mission solution. With unbounded resources of schedule and cost, mission design and architecture could be optimized to maximize effectiveness. However, we live in a world bounded by cost and schedule considerations and therefore the mission engineer must balance the mission architecture solution with overall mission effectiveness to deliver an acceptable mission solution. Life-cycle considerations influence the trade space because they interact with and potentially modify the boundary conditions of the architecture and mission design, thereby influencing the effectiveness, cost, and risk assumed by the mission solution. The mission architecture delineates how the mission design is structured and conveyed to the end-user and other key stakeholders.

The boundary of an object or function is where it interacts with other objects, functions, or the surrounding environment. Langford (2012, 354) describes boundary conditions as the "mediation of capabilities that enact across boundaries." Boundary conditions limit the interaction of objects or functions or prescribe how the interaction of objects or functions takes place. Life-cycle considerations, such as stakeholder or requirements management, modify the boundary conditions of the mission trade space. For example, modification, addition, or deletion of a requirement may greatly influence the mission design and architecture. Likewise, other life-cycle considerations, such as risk management, are dependent upon the mission design and architecture and the boundary conditions that exist due to both mission requirements and the interaction of the mission with life-cycle influences.

Risk is an important consideration during mission design and architecture trade studies. Risk management is a formal process to identify, track, mitigate, and manage potentially negative impacts to a program (Department of Defense 2013). Risk assessment and management is a life-cycle consideration because it affects the mission engineering process throughout. The mission architecting phase is the final stage before a mission solution is achieved and therefore is the culmination of risk identified throughout the mission engineering process. The iteration of the mission architecture will tradeoff risk identified and generated by the architecture, with cost and effectiveness of the solution.

E. LIFE CYCLE CONSIDERATIONS

1. Stakeholder Management

In systems engineering, stakeholder analysis is a process for identifying and classifying stakeholders, understanding stakeholder relationships, determining key stakeholders, and defining stakeholder requirements (Langford 2012). Stakeholder management goes a step further by actively engaging and interacting with stakeholders in order to more effectively and efficiently perform continuous stakeholder analysis.

Stakeholder management is also a business management term relating to the relationships businesses form with their stakeholders. The principles of stakeholder management, shown in Table 1, are also applicable to mission engineering. Of specific importance to mission engineering is the focus on communication and cooperation with stakeholders. Stakeholders cannot be controlled, but should be managed with openness and active communication to promote positive relationships, teamwork, and more efficient understanding of stakeholder requirements and needs. Positive stakeholder relationships can promote trust and collaboration, which can generate success and understanding through teamwork. Negative stakeholder relationships can foster distrust promoting formalized discussions resulting in time delays and cost increases (Philosophy Documentation Center 2002).

Table 1. Principles of Stakeholder Management (after Philosophy Documentation Center 2002)

Principle 1	Managers should acknowledge and actively monitor the concerns of all legitimate stakeholders, ad should take their interests appropriately into account in decision-making and operations.
Principle 2	Managers should listen to and openly communicate with stakeholders about their respective concerns and contributions, and about the risks that they assume because of their involvement with the corporation.
Principle 3	Managers should adopt processes and modes of behavior that are sensitive to the concerns and capabilities of each stakeholder constituency.
Principle 4	Managers should recognize the interdependence of efforts and rewards among stakeholders, and should attempt to achieve a fair distribution of the benefits and burdens of corporate activity among them, taking into account their respective risks and vulnerabilities.
Principle 5	Managers should work cooperatively with other entities, both public and private, to insure that risks and harms arising from corporate activities are minimized and, where they cannot be avoided, appropriately compensated.
Principle 6	Managers should avoid altogether activities that might jeopardize inalienable human right (e.g., the right to life) or give rise to risks, which, if clearly understood, would be patently unacceptable to relevant stakeholders.
Principle 7	Managers should acknowledge the potential conflicts between (a) their own role as corporate stakeholders, and (b) their legal and moral responsibilities for the interests of stakeholders, and should address such conflicts thorough open communication, appropriate reporting and incentive systems, and where necessary, third party review.

As a system, or mission, progresses through its life cycle, relationships with stakeholders may change, or the relative influence of stakeholders may change. For example, in the development stages of a product, stakeholders that represent manufacturing abilities may initially be considered higher priority than stakeholders that represent how the product is maintained. As the product progresses through its life cycle, the relative importance of those stakeholders may shift. Additionally, the interaction or relationships between stakeholders may influence stakeholder's perspectives. When viewing a system or mission from the lens of its entire life cycle, these shifts in stakeholder priority or the modification of or interrelations between stakeholders must be considered and addressed. Therefore, the principles for effective stakeholder management from Table 1 are recommended for use within the mission-engineering construct. Open communication, cooperation, and avoiding activities and issues that alienate stakeholders are basic principles that will enable the mission engineer to more effectively identify needs and requirements for the mission functions and capability, as well as work collaboratively with stakeholders in identifying mission design and architecture solutions.

2. Requirements Management

Requirements management refers to all activities related to requirements following the initial development of requirements (Hood 2008). Requirements management is important because requirements may be modified, added, or deleted during the course of the life cycle due to changes in stakeholder needs or changes in the stakeholders themselves. Requirements are integral to successful systems engineering and systems integration to ensure, because the processes to design, develop, integrate, test, verify, and validate systems relate back to the requirements. Therefore, management of requirements throughout the life cycle is critical to successful systems engineering, systems integration, and likewise mission engineering. In mission engineering, requirement may take the form of a function, capability, objective, or problem to overcome through the execution of a function or capability. Therefore, requirements management includes the activities related to the tracking of mission capabilities throughout the mission concept, design, and architecting phases. Requirements management involves communication with stakeholders to understand how mission capabilities are evolving and internal communication and coordination to ensure the capabilities are properly implemented in the mission design and architecture. A recommendation for successful mission engineering is to plan for evolving requirements and capabilities through open architectures and universal interfaces.

3. Configuration Management

The United States DOD's *Defense Acquisition Guidebook* defines configuration management as "the principle methodology for establishing and maintaining consistency of a system's functional, performance, and physical attributes with its requirements, design, and operational information throughout the systems life cycle" (Department of Defense 2013, 311). Configuration management aids the mission engineer in tracking the evolution of requirements, the mission concept, mission design, and mission architecture throughout the life cycle. As such, configuration management can aid the mission engineering process by ensuring continuity in the rationale behind decisions and trade space decisions. A well-developed configuration management system can also enable trade space decisions by tracking the relative performance, suitability, and effectiveness of mission solutions.

4. Risk Assessment and Management

Risk is the potential for something to go wrong and therefore planning for risk and actively mitigating risk is important to a successful program, system development, or mission. Risk management is the iterative process to plan, identify, assess, analyze, and track risks (Blanchard and Fabrycky, 2011). The *DAG* describes risk management as the oversight program for identification, analysis, mitigation planning and implementation, and tracking of risk throughout the life cycle. Risk analysis and management mitigates uncertainties and therefore impacts cost, schedule, and performance goals throughout the life cycle (Department of Defense 2013).

Risk analysis and management are important considerations during the mission-engineering life cycle. Since mission engineering is analogous to systems integration, an active and robust risk program needs to be integral and pervasive to the mission engineering processes in order to effect early and often identification of risks, planning and implementation of mitigation strategies, and tracking of risks. Throughout the mission engineering process, trade space is used to balance the programmatic influences of cost and schedule with satisfying requirements in a manner that produces a solution that is effective to satisfy the needs of the stakeholder. Risk is therefore pervasive in the mission engineering process as design and architecture decisions are made.

5. Communication Management

Communication management includes the oversight of all processes by which information is generated, collected, stored, retrieved, and disposed of on a project. Communication in mission engineering is important for interfacing with members within the organization (e.g., team members or management) and external to the organization (e.g., stakeholders or sponsors). The management of communication both internal and external to the mission engineering organization is important for stakeholder interaction, correct interpretation and implementation of requirements, and managing the flow of information pertinent to the organization.

6. Human Systems Integration

Many definitions and implementations of human systems integration exist, and so several are explored to provide context to a discussion of human systems integration. Next the implications of human systems integration in the field of mission engineering are discussed.

Blanchard and Fabrycky (2011) state that for a system to be operationally effective, human factors must be considered early and throughout the system life cycle. Additionally, and of note, is the identification that human factors are not solely due to the direct interaction of humans with the final system; humans may be involved in training, maintenance, planning, manufacture, and many aspects of the systems engineering life cycle. As such, human factors planning, or human systems integration is truly a consideration across the life cycle.

The U.S. *Air Force Human Systems Integration Handbook* (Department of Defense 2009, 8) describes human systems integration as “a robust process to design and develop systems that effectively and affordably integrate human capabilities and limitations.” A key emphasis of the *Air Force Human Systems Integration Handbook* is that humans and their limitations are integral components of a developed system and therefore a human's capacities and limitations must be considered throughout the design and development of a system (Department of Defense 2009).

The *DAG* promotes a total systems approach to human systems integration, meaning that human aspects of system design such as manpower, training, environment, safety, occupational health, and personnel survivability considerations are incorporated into the design and acquisition process. It is argued that successful human systems integration can only be achieved through comprehensive integration of human systems requirements in order to identify and close technology and performance gaps in the system (Department of Defense 2013). This definition of human systems integration is important because it highlights that human systems integration is not a process to derive requirements based upon human limitations to be satisfied during the design phase; rather, this definition focuses on the need to consider human-system interactions throughout the life cycle of a product.

Human systems integration is a consideration across the mission-engineering life cycle. Human interaction and integration with the mission engineering process may be in many forms, such as training, planning or execution of the mission. Therefore, the role humans play in the system to affect or limit mission capability and functionality is an important metric to judge the effectiveness of a mission.

7. Sustainability

The *DAG* describes sustainability as the trait of using fewer resources over the life cycle and having fewer impacts on human health and the environment (Department of Defense 2013). Sustainability from a mission engineering perspective helps to reduce cost, increase mission readiness, and improve mission effectiveness. Reducing the life-cycle resources required or the human and environmental impacts helps to reduce the life-cycle cost due to a general reduction in resources required to support the system, or a reduction in necessary resources allocated to a solution to compensate for human or environmental impacts. Mission readiness and effectiveness may also be improved if fewer resources are required as there are fewer points of failure, which could impede successful execution of the mission.

8. Information Assurance and Cybersecurity

The *Department of Defense Dictionary of Military and Associated Terms* defines information assurance as “actions that protect and defend information systems by ensuring availability, integrity, authentication, confidentiality, and nonrepudiation” (Department of Defense 2015, 118). Advances in computer networks, information technology, and the growth of the Internet have contributed to a high degree of information sharing, often at a global level (Tipper 2008). As such, information is pervasive in society including in systems engineering, systems integration, and mission engineering. Information is used for interactions with stakeholders, the communication within and external to the organization, and the data or documents used in the design, development, implementation, training and other aspects of the life cycle.

Information assurance relates to other life cycle considerations, such as security, information technology management and network services management. Information assurance provides the policies and processes for an organization to secure their information technology and networks, to provide assurance that when the information is needed it is available and can be trusted. Everything from personnel records to design data to training materials to contracts require some degree of and consideration for information assurance. As an example, the DOD has many policies and procedures for information assurance: DOD Instruction 8500.2 describes information assurance implementation practices (Department of Defense 2003); the *DAG* Chapter 7, Section 5 is devoted to information assurance, describing applicable policies, processes and strategies for information assurance (Department of Defense 2013). In 2015, DOD Instruction 8500.01 replaced the term “information assurance” with “cybersecurity” (Department of Defense 2014). Cybersecurity is a critical life cycle consideration for mission engineering due to the pervasive use of information in modern systems and organizations. Methods to achieve cybersecurity may create derived requirements on the mission design and mission architecture and create additional trade space for satisfying the mission concept within allowable policies, cost, schedule, and other factors. The mission engineer, therefore, needs to consider all applicable policies early in the mission-engineering life cycle, generate a cybersecurity plan, and implement a cybersecurity process through the mission life cycle.

9. Safety

Safety can be a driving life cycle consideration, especially when there is the potential for human injury or loss of life. Safety concerns may be addressed within the mission design space due to human systems integration concerns. Identification of safety concerns may also relate to the successful or unsuccessful preparation for, execution of, or recovery from the mission. For example, testing mission functions and capabilities may necessitate specific safety procedures be followed to be in compliance with local ordinances or laws.

10. Security

Security encompasses the aspects of the system that prevent the intentional harm or destruction of the system, personnel, the surrounding environment, or society (Blanchard 2011). Security can come in many forms, from physical security such as locks, alarms, and security guards, to non-physical forms of security, such as cyber security. Cybersecurity is related to information assurance and is discussed in this thesis in that context. Physical security measures may depend on the stakeholders, the subject of a system or mission, or the purpose to a system or mission. Some organizations impose physical security measures to secure trade secrets and proprietary information, while others, especially the DOD and other government organizations, may use physical security as one tenet in protecting classified information whose release could harm the interests of the U.S. Government. Security policies and procedures need to be documented early in the mission-engineering life cycle and addressed on a continual basis as needed due to other life cycle considerations such as evolving stakeholder involvement, requirements modifications, development of new technologies, or changes to the mission parameters.

11. Policy, Media, and Legal Support Services

Policy, media, and legal support services are important considerations throughout the life cycle of mission engineering. However, the scope of these areas may vary widely depending on the level of human interface and involvement, the capabilities and purposes of the mission, or the perceptions of society or the environment in which the mission is executed. In the government arena, policy and laws will act as boundary conditions to shape the mission concept, design, and architecture. Additionally, government spending and actions are often public knowledge and therefore the media may be a factor in public perception of a government developed or executed mission. Finally, legal support services may be needed throughout the mission engineering process in areas such as contract development and execution, and compliance with applicable policies, laws and statutes.

12. Training and Documentation

Training and documentation are an important consideration throughout the life cycle of mission engineering. Documentation during the development of a mission is important for managing the mission engineering processes and all of the internal and external interactions. Training must also be considered throughout the mission engineering life cycle because in order for humans to interact with the system or systems and perform an effective mission the capabilities, functionalities, and limitations must be conveyed. As such, early attention to training may influence the development of an easier to perform mission. Likewise, late attention to training and how humans may interface with the mission systems may lead to ineffectual or impossible missions to perform.

13. Logistics Management

Logistics, or the flow of resources, is inherently critical to the mission engineering process. Properly managed logistics can enable mission success, whereas poor logistics management will doom a mission to failure. Every system, system of systems, and therefore mission, relies on the supply and flow of resources. These may include resources to initially create a system or integrate a system, or may include resources needed to sustain a capability or function. For example, fuel for vehicles integral to the mission performance is a critical resource to manage to ensure continued mission execution. Logistics management early in the mission engineering process can enable a more versatile and agile mission solution.

F. DEFINING MISSION ENGINEERING

Using systems integration as a framework and extrapolating systems engineering concepts, the following definition of mission engineering is proposed:

Mission Engineering is a life cycle-based, integrative approach to develop and implement capabilities and functions from stakeholder needs into executable missions while balancing performance, risk, cost and schedule.

This definition offers the emerging field of mission engineering a baseline construct to continue to define mission engineering processes and vernacular. Systems engineering processes of stakeholder analysis, requirements analysis, and life cycle consideration analysis are extrapolated to a management paradigm, whereby the mission engineer is chartered with actively managing those life cycle concerns in order to produce a successful mission. Specific systems engineering terms and processes such as verification, validation, and their associated metrics of effectiveness, performance, and suitability are recommended to aid in more efficient and effective mission engineering.

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

Execution of mission engineering requires formalized definitions and processes to ensure consistency, repeatability, and effectiveness. Systems engineering and integration have well-developed terminology and clear, executable processes that are applicable and are recommended to be used in the execution of mission engineering. Specifically from systems engineering, stakeholder and requirement analysis, verification and validation processes, and associated measures of effectiveness, performance, and suitability are foundational elements that can be tailored for unique missions and mission-focused processes to ensure mission requirements are clearly defined, allocated, and ultimately met by the mission solution. Additionally, systems integration should be used as the framework for understanding mission engineering as mission engineering involves the integration of systems or systems of systems to execute stakeholder defines capabilities and functions. Systems integration provides a means to develop capabilities, functions, and solutions to problems beyond those of individual systems. In this manner, systems integration is a good foundation for mission engineering. Figure 2 provides a notional process depiction for executing mission engineering. The major processes within mission engineering are the mission requirements derivation from stakeholder needs, mission conceptualization, mission design, and mission architecting. Within each of these phases, and throughout the mission engineering process, life cycle considerations must be accounted for and reacted to, as needed. Each phase of mission engineering by itself is iterative to ensure tradeoffs and decisions are well developed and executed; however, the ultimate flow of mission engineering is linear, proceeding from mission concept to mission design to mission architecture. Iterations of design architecture are based upon measures of effectiveness, performance, and suitability depending on the specificity of the capability or function in question and the stage in the mission engineering process. Performance measures may be used early and often to verify specific aspects of the mission design, whereas measures of suitability and effectiveness are more often used later in the mission engineering process when closer to a final solution. Mission

Engineering is a life cycle-based, integrative approach to develop and implement capabilities and functions from stakeholder needs into executable missions while balancing performance, risk, cost and schedule.

B. RECOMMENDATIONS

A recommendation for future study is to explore further the emerging field of mission engineering. While this thesis proposes a construct of mission engineering utilizing the framework of systems integration and the tools and processes of systems engineering, additional specificity for mission engineering unique processes may be beneficial. Additional detail in mission engineering processes and terminologies may allow for greater application of mission engineering and may result in an entirely separate field of study from systems engineering.

LIST OF REFERENCES

Bijan, Y., Yu, J., Stracener, J., and Woods, T. 2013. Systems Requirements Engineering—State of the Methodology. *Systems. Engineering*. 16: 267–276.

Blanchard, Benjamin S., and W. J. Fabrycky. 2011. Systems Engineering and Analysis. 5th ed. Englewood Cliffs, NJ: Prentice-Hall.

David, Forest R., and Fred R. David. 2003. "It's Time to Redraft Your Mission Statement." *The Journal of Business Strategy* 24: 11–14. http://search.proquest.com/docview/202726026?accountid=12702.

Defense Acquisition University. 2012(a). "Measures of Effectiveness (MOE)." Accessed on July 10. https://dap.dau.mil/glossary/Pages/2236.aspx

———. 2012(b). "Measures of Performance (MOP)." https://dap.dau.mil/glossary/pages/2237.aspx

———. 2012(c). "Measures of Suitability (MOS)." https://dap.dau.mil/glossary/Pages/2238.aspx

———. 2012 (d). "Systems Engineering Process." https:/dap.dau.mil/acquipedia/Pages/ArticleDetails.aspx?aid=9c591ad6-8f69-49dd-a61d-4096e7b3086c

Department of Defense. 2003. *Instruction 8500.2 Information Assurance Implementation*. Washington, DC: Department of Defense.

———. 2009. *Air Force Human Systems Integration Handbook: Planning and Execution of Human Systems Integration*. Washington, DC: Department of Defense.

———. 2013. *Defense Acquisition Guidebook*. Washington, DC: Department of Defense.

———. 2014. *Instruction 8500.01 Cybersecurity*. Washington, DC: Department of Defense.

———. 2015. Joint Publication 1–02 *Department of Defense Dictionary of Military and Associated Terms*. Washington, DC: Department of Defense.

Hood, Colin. 2008. *Requirements Management the Interface between Requirements Development and All Other Systems Engineering Processes*. Berlin: Springer.

Institute of Electrical and Electronics Engineers (IEEE). 2005. IEEE P1220:2005*, Standard for Application and Management of the Systems Engineering Process*, New York, NY.

International Council on Systems Engineering (INCOSE). 2004. *Systems Engineering Handbook*. INCOSE-TP-2003-016-02. Version 2a. San Diego, CA: INCOSE

International Council on Systems Engineering (INCOSE). 2015. “What is SE?” Accessed on July 10. http://www.incose.org/AboutSE/WhatIsSE

Langford, Gary O. 2012. *Engineering Systems Integration Theory, Metrics, and Methods*. Boca Raton, FL: CRC Press

———. 2014. *Building the Determinants of Cyber Deterrence Effectiveness*. Monterey, CA.

McGinnis, Vern J. 1981. “The Mission Statement: A Key Step in Strategic Planning.” *Business* 31: 39. http://search.proquest.com/docview/203758572?accountid=12702.

Philosophy Documentation Center. 2002. “Appendix: Principles of Stakeholder Management.” *Business Ethics Quarterly* 12: 257–264

Sproles, N. 2000. “Coming to Grips With Measures of Effectiveness.” *Systems Engineering* 3:50–58.

Sproles, N. 2002. “Formulating Measures of Effectiveness.” *Systems Engineering* 5: 253–263.

The MITRE Corporation. 2013. “Systems Integration.” Accessed June 25, 2015. http://www.mitre.org/publications/systems-engineering-guide/se-life cycle-building-blocks/systems-integration

Tipper, David. 2008. *Information Assurance Dependability and Security in Networked Systems*. The Morgan Kaufmann Series in Networking. Elsevier Science & Technology.

Turk, Wayne. 2005. “Mission Possible…With Good Requirements.” *Defense AT&L*, September-October, 20–22

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California