SYM-AM-19-067

PROCEEDINGS
OF THE
SIXTEENTH ANNUAL ACQUISITION RESEARCH SYMPOSIUM

THURSDAY SESSIONS
VOLUME II

Acquisition Research:
Creating Synergy for Informed Change

May 8–9, 2019

Published: April 30, 2019

Prepared for the Naval Postgraduate School, Monterey, CA 93943.

A Framework for a Defense Systems Effectiveness Modeling and Analysis Capability: Systems Effectiveness Modeling for Acquisition

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Abstract

The purpose of this paper is to present a response to two current Department of Defense (DoD) initiatives. The first is the DoD National Defense Strategy of 2018, which encourages the adoption of new practices to improve system performance and affordability to meet current and future threats. The second initiative is the DoD Digital Engineering Strategy, which outlines five strategic goals in support of the first initiative. The first strategic goal—"Formalize the development, integration, and use of models to inform enterprise and program decision making"—is the specific subject of this paper. The response is a conceptual methodology that addresses an analytic deficiency identified by a 2017 congressional commission that examined the capabilities of the DoD civilian staff in their determination of force and weapons systems requirements. Specifically, this paper presents a framework for a "Defense Systems Effectiveness Modeling and Analysis Capability" whose metric is the probability of mission success. The objective is the application of modeling and analysis to guide decisions leading to fielding systems having optimum effectiveness constrained by affordability and reduced development time. While the current U.S. focus is on systems readiness, it is an integral element of the more robust systems effectiveness.

Introduction

The 2018 National Defense Strategy (NDS; DoD, 2018) makes readiness and warfighter needs a priority, with lethality and warfighting the primary objective. The strategy emphasizes affordability with sustained and predictable investment to achieve greater performance through modernizing the military and restoring readiness. Within this context, improvement of readiness involves developing the right systems or systems of systems with alacrity.

To support the goals of the NDS, the DoD's Under Secretary of Defense for Research and Engineering has initiated the Digital Engineering Strategy (DES), which has five goals intended to drive the acquisition of future systems (Office of the Deputy Assistant Secretary of Defense for Systems Engineering, 2018). The five goals promote a model-based, systems engineering (MBSE) wherein systems are digitally rendered. The resulting digital artifacts become the means of communications between stakeholders. The goals are as follows:

1. Formalize the development, integration, and use of models to inform enterprise and program decision making;
2. Provide an enduring, authoritative source of truth;
3. Incorporate technological innovation to improve the engineering practice;
4. Establish a supporting infrastructure and environments to perform activities, collaborate, and communicate across stakeholders; and
5. Transform the culture and workforce to adopt and support digital engineering across the lifecycle.

Purpose

An approach to the first goal of the DES is the purpose of this paper. A crucial element of the formalization process is the development of an effectiveness modeling and analysis framework. The advent of DES is important because recent criticism by a bipartisan congressional commission noted that civilian analytical capabilities for force and weapons development within the DoD have severely degraded since their original establishment in the 1960s by Robert McNamara (Gordon & Lubold, 2018). The truth of this statement is borne out by the lack of an established methodology within the DoD for acquiring systems of systems. There is current work underway addressing systems of systems, mission engineering, and capability portfolio analysis but not at the level of the Weapon System Effectiveness Industry Advisory Committee (WSEIAC) study to be discussed shortly.

Specific Contribution of This Paper

The contribution of this paper is twofold. First, it provides clarity of purpose for readiness, an oft used and abused term. Why not readiness? A focus on readiness may lead to sub-optimum system solution because it ignores three other factors important to systems effectiveness and mission success. Mission success is the applicable measure because it drives force projection and war-fighting capability. Second, the paper presents a framework that addresses the role of readiness within the context of mission success. This framework applies to both systems and systems of systems acquisition, providing the stakeholders with quantified results.[1]

Organization of Paper

The paper provides a brief discussion of relevant past work that is foundational to the development of the Defense Systems Effectiveness Modeling and Analysis Capability (DSEMAC). Key terms are defined mathematically, followed by a brief discussion of the requirements for a framework that provides the needed structure for the DSEMAC, which in turn is followed by a description of the proposed framework. A summary and a description of future work conclude the paper.

Past Work

A focus on readiness ignores the larger context of systems effectiveness and the additional attributes of mission reliability, mission survivability, and mission capability. It is

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[1] *System* will be used throughout this paper.

the premise of this paper that system effectiveness and mission success are the same and the overarching goal. Readiness is a subset of the larger picture that includes mission reliability, mission survivability, and mission capability as shown in Figure 1. This view is not a new concept. The relationships have a long history that started in the 1950s and was extensively documented in a report published by the Weapon System Effectiveness Industry Advisory Committee (WSEIAC) in the 1960s (WSEIAC, 1965). Figure 1 is based on the WSEIAC report and illustrates the relationship between overall mission effectiveness and its constituent components of mission readiness, mission reliability, and mission capability. Note that mission survivability is not included in the report and thus omitted from Figure 1. Survivability is included in this paper for completeness, as shown in Figure 2.

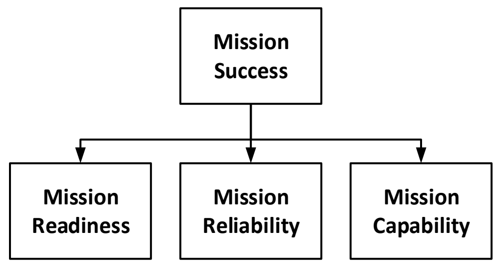

Figure 1. The WSEIAC Systems Effectiveness Hierarchy
(WSEIAC, 1965)

As defined by the WSEIAC report, mission readiness (often known as operation availability [A_o] or operational readiness [OR]) quantifies the percentage of time that the system is ready at the start of the mission. Mission reliability (or dependability) quantifies the likelihood that the system will perform its mission essential functions throughout the mission. Both these terms are well represented in the literature. Mission capability quantifies the adequacy of the system to meet the mission goals. Capability is about ways and means. It matters not if the system is available and reliable throughout the mission if it cannot achieve the desired results because the said ways and means were insufficient or incorrect.

Figure 2 presents a complete view of the relationships with the addition of mission survivability. The probability of mission success is a function of the four terms. Therefore, the graphic is a top-level objective hierarchy. As an objective tree, the goal is to maximize the probability of mission success. The lower-level objectives each describe a specific aspect of mission success and are, therefore, inherently important. The lower-level objectives can be expanded by including another level of detail. For example, mission survivability can be expanded to susceptibility and vulnerability. In this case, the goal is to reduce both to increase survivability.

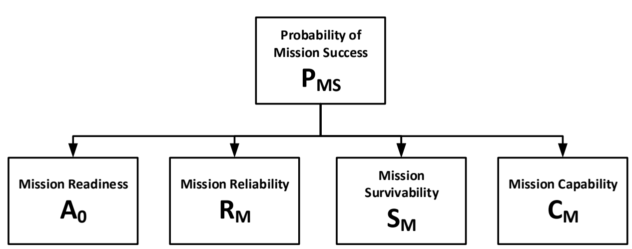

Figure 2. The Revised WSEIAC Systems Effectiveness Hierarchy

The systems effectiveness hierarchy and the following equation for P_{MS} provides a quantitative basis for the acquisition of weapons systems and systems of systems. The WSEIAC report provided a general mathematical relationship for mission success as follows:

$$P_{MS}=(P_{Ao})(P_{RM})(P_{SM})(P_{CM})$$

where,

P_{MS} ≡ the probability of mission success for a specified mission

P_{Ao} ≡ the probability that the system is available at the start of the mission

P_{RM} ≡ the probability that the system will successfully perform specified mission essential functions by mission phase

P_{SM} ≡ the probability that the system will survive the mission

P_{CM} ≡ the probability that the system meets the capability objectives

Note the probabilistic formulation of mission success. There are several valid reasons for this approach. First, military operations are characterized by random variables, for example, probability of detection or probability of kill. Second, probabilities are dimensionless, making them easier to work with across diverse system elements such as sensors and weapons.

Figure 3 is a summary of the relationships that contribute to a framework for system effectiveness.

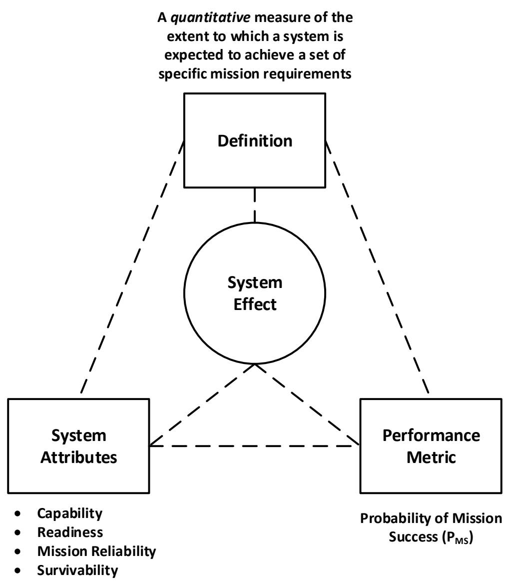

Figure 3. Systems Effectiveness Relationships

In systems terminology, Figure 3 is a context diagram that becomes a starting point for the framework requirements discussed in the following section.

Framework Requirements

A framework is a structured way of relating objects of interest and their resulting interactions. The importance of a framework in the acquisition of systems cannot be understated. First, a framework organizes theory and practice and provides a structure for methods. Second, complex systems and systems of systems are typically not developed as a single architecture. Thus, there are time-phasing and contractual issues. Individual systems are usually single function, and system couplings are interdependent (Luman, 2000).

Third, there currently is no systematic method of measuring systems effectiveness. The literature is devoid of theory and standards. Most approaches center on qualitative methods, which are subjective at best.

Basic Requirements

There are four major requirements for the framework: The supporting methods must be quantitative, the supporting methods must present results probabilistically, the supporting methods must be reliability based, and, finally, the framework must support hierarchy and abstraction. The end goal is a framework that supports evaluation of mission success versus cost, where the emphasis is on the likelihood of mission success.

Quantitative

One of the first steps in an analysis is to describe the processes involved. Mathematics is precise and explanatory, facilitating analysis and explanation of more complex problems than possible using qualitative methods. The model for the probability of mission success must be based on proven methodology. The challenge is developing and maintaining a model for each mission which will be large and complex for complex systems.

Probabilistic

Military operations are about achieving success and the estimation of event probabilities, typically described as measures of effectiveness (MOE) or measures of performance (MOP). Often parametric values are used incorrectly as measures. For example, detection of a threat is expressed as a probability of detection and is a function of several parameters including range. The outcome is the probability of detection as a function of range.

Reliability-Based

Reliability theory is based on the premise of system success and failure ($P_{success} = 1 - P_{failure}$). Many of its concepts are foundational precepts to quantifying system effectiveness. Further, most of the system variables of interest are reliability related. Figure 3 identifies them as key system attributes.

Hierarchy and Abstraction

Systems are hierarchical by nature with increasing detail at each level of expansion. The framework must support models that describe each level of expansion. This paper suggests a black box approach at each layer.

A Notional Effectiveness Model

Systems concepts are based on a need to meet an operational requirement. The effectiveness of how well this need is met (mission success) is a measure of its tactical utility and its value to the force structure. Figure 4 is a notional model adapted from Figure 2-1 found in the *Reliability Engineering Handbook* (Bureau of Naval Weapons, 1964). It summarizes the first three figures and is intended to convey several points: how well the system will perform, how long the system will perform, and how often the system can perform.

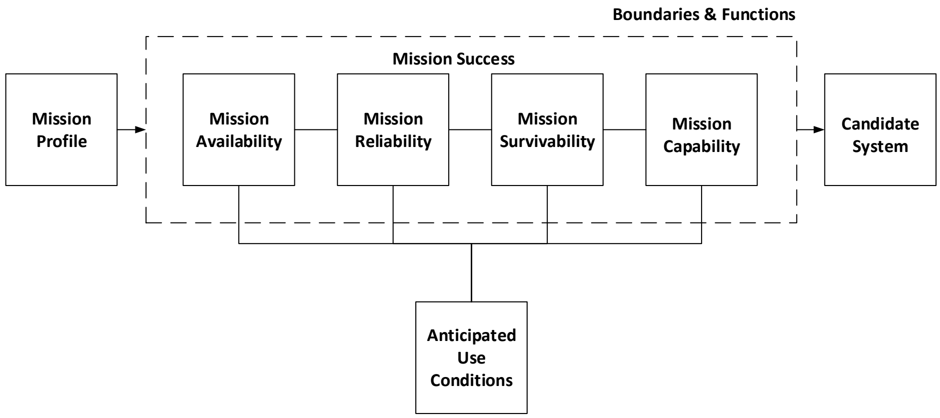

Figure 4. A Systems Effectiveness Model
(Adapted from Bureau of Naval Weapons, 1964)

This model, when combined with a decision process, becomes the basis for the overall framework model.

Proposed Framework

Figure 5 is a generic decision process. It serves as a guide to understanding how to incorporate Figure 4 into a larger context. Figure 6 is the resulting proposed framework.

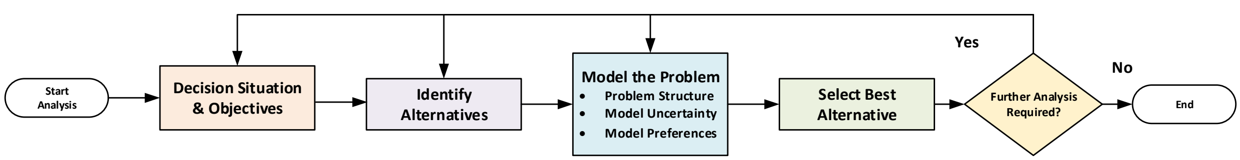

Figure 5. Generic Decision Process

Problem Formulation

With the framework in place, it is appropriate to return to the purpose of the framework to wit: to make decisions about system selection. There are three basic steps to the decision process. First, understand the set of system variables and how they interact quantitatively and accurately. Knowledge of the system is imperative. In the framework, this is represented by the upper five boxes (orange and purple). Second, select a single MOE expressible in terms of the variables represented by the blue boxes. A premise of this paper is that mission success is that MOE. The final step is to select the method by which the best system is selected represented by the green boxes.

The decisions involve making choices from a set of candidate solutions in order to find the most desirable solution. Once the decision is made, it becomes an irrevocable allocation of resources. Given the set of candidate solutions, the task becomes one of defining a system such that:

$$\text{Maximize } P_{MS} = (P_{Ao})(P_{RM})(P_{SM})(P_{CM}),$$

subject to the following constraints:

- Specified mission
- Required performance
- Budget

This is a basic optimization problem. It is decisive because the result is one system—the best one.

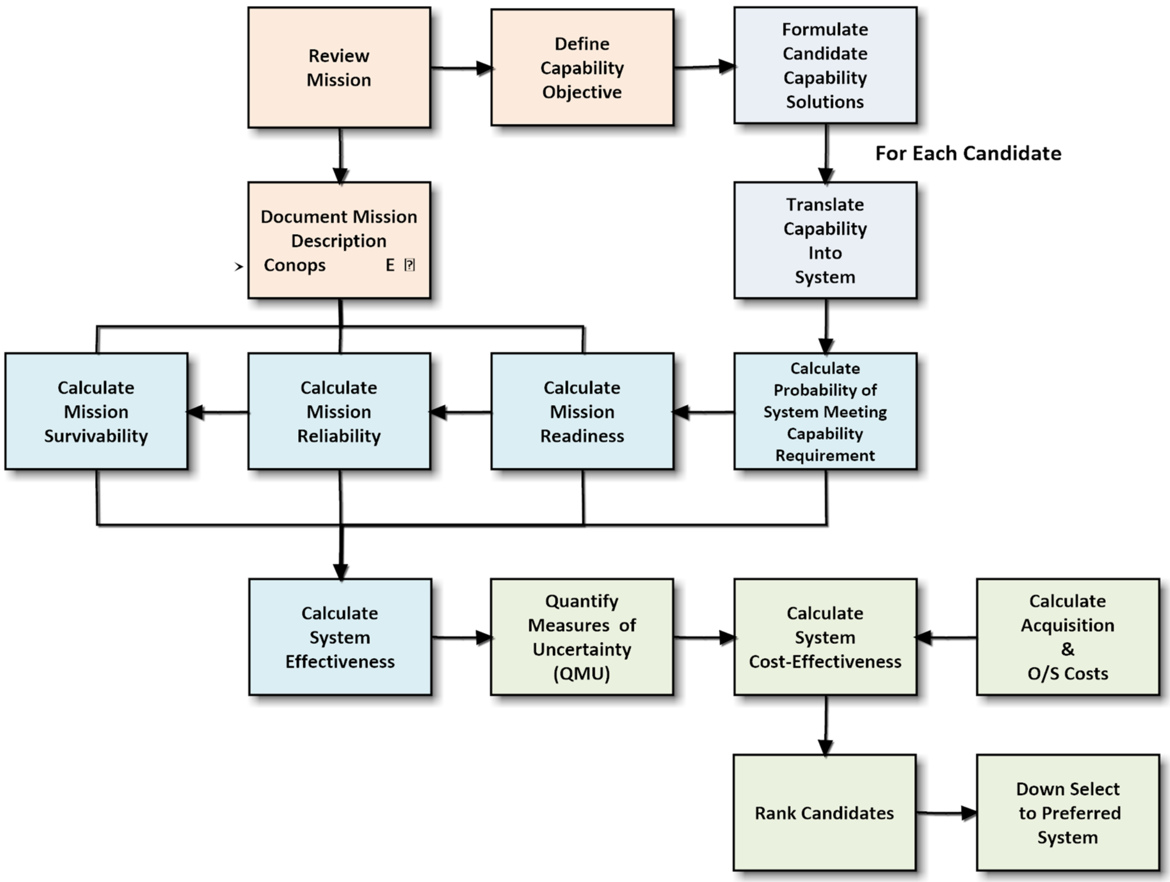

Figure 6. A Framework for a Defense Systems Effectiveness Modeling and Analysis Capability

Comments on Cost-Effectiveness

In the model described above, cost-effectiveness has been chosen as the criterion for the model because it is best used for ranking alternatives that are relatively similar especially when there is a single dominant objective whose attainment can be assessed directly or for which a good proxy value exists (Quade, 1982). It is axiomatic in the world of quantitative analysis that, in general, the possibility of selecting between two alternatives based on cost and effectiveness data alone is not possible. It is a choice between specifying performance or cost. If the former, then cost is minimized; if the latter, then effectiveness is maximized.

Summary

This paper presents the rationale for a framework for a Defense Systems Effectiveness Modeling and Analysis Capability. It describes why the key decision criterion is the probability of mission success and shows the approach to the derivation of the framework. This framework is inclusive of capability, readiness, mission reliability, and survivability (which is typically omitted in system effectiveness evaluations).

Future Research

As noted, survivability is not usually included. While availability and readiness have a large literature base, there is very little material on survivability.

A second research topic is Candidate Capability Architecture solution development. There is no literature on performance-based architecture development.

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