2019-09

A CONCEPTUAL ARCHITECTURE TO ENABLE INTEGRATED COMBAT SYSTEM ADAPTIVE OPERATIONAL READINESS ASSESSMENTS

Brown, Jonas

Monterey, CA; Naval Postgraduate School

http://hdl.handle.net/10945/63437

NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

A CONCEPTUAL ARCHITECTURE TO ENABLE INTEGRATED COMBAT SYSTEM ADAPTIVE OPERATIONAL READINESS ASSESSMENTS

by

Jonas Brown

September 2019

Thesis Advisor:	Bonnie W. Johnson
Co-Advisor:	John M. Green

Approved for public release. Distribution is unlimited.

THIS PAGE INTENTIONALLY LEFT BLANK

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

1. AGENCY USE ONLY ***(Leave blank)***	**2. REPORT DATE** September 2019	**3. REPORT TYPE AND DATES COVERED** Master's thesis

4. TITLE AND SUBTITLE
A CONCEPTUAL ARCHITECTURE TO ENABLE INTEGRATED COMBAT SYSTEM ADAPTIVE OPERATIONAL READINESS ASSESSMENTS

5. FUNDING NUMBERS

6. AUTHOR(S) Jonas Brown

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.

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release. Distribution is unlimited.

12b. DISTRIBUTION CODE
A

13. ABSTRACT (maximum 200 words)

Delivering on the power of data to ships in austere or contested environments requires careful consideration of system capacity, bandwidth, and processes to drive capability. Ship-based and shore-based applications and processes must be married into a system that progressively improves own-ship algorithms in real time and fleetwide algorithms in near real-time. Once this operational picture is achieved, system readiness becomes a known value and a decision aid rather than a set of derived metrics. Additionally, real-time mission posture assessment becomes a "must do" prior to the execution of a mission.

This paper identifies the current state of mission readiness assessment and ultimately fills a known gap within naval combat systems by laying out a shipboard and shore-based architecture used to translate information into action. In doing so, the study addresses information configuration management and processes needed to synthesize multiple disparate data sets into an eventual adaptive operational readiness assessment based on mission need.

This paper develops a conceptual design and model using Innoslate and other tools that establishes data nodes, data interrelationships, and a high-level data management operational viewpoint. The conceptual model will be analyzed to study Operational Availability (Ao) and Probability of Successful Mission (Psm) improvements in operational scenarios.

14. SUBJECT TERMS
machine learning, artificial intelligence, data, operational availability, readiness, combat system, radar, neural network, cloud, data reduction, data transfer, aggregation, analysis, probability of successful mission

15. NUMBER OF PAGES
95

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

A CONCEPTUAL ARCHITECTURE TO ENABLE INTEGRATED COMBAT SYSTEM ADAPTIVE OPERATIONAL READINESS ASSESSMENTS

Jonas Brown
Civilian, Department of the Navy
BS, North Carolina State University, 2006

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN SYSTEMS ENGINEERING MANAGEMENT

from the

NAVAL POSTGRADUATE SCHOOL
September 2019

Approved by: Bonnie W. Johnson
Advisor

John M. Green
Co-Advisor

Ronald E. Giachetti
Chair, Department of Systems Engineering

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

Delivering on the power of data to ships in austere or contested environments requires careful consideration of system capacity, bandwidth, and processes to drive capability. Ship-based and shore-based applications and processes must be married into a system that progressively improves own-ship algorithms in real time and fleetwide algorithms in near real-time. Once this operational picture is achieved, system readiness becomes a known value and a decision aid rather than a set of derived metrics. Additionally, real-time mission posture assessment becomes a “must do” prior to the execution of a mission.

This paper identifies the current state of mission readiness assessment and ultimately fills a known gap within naval combat systems by laying out a shipboard and shore-based architecture used to translate information into action. In doing so, the study addresses information configuration management and processes needed to synthesize multiple disparate data sets into an eventual adaptive operational readiness assessment based on mission need.

This paper develops a conceptual design and model using Innoslate and other tools that establishes data nodes, data interrelationships, and a high-level data management operational viewpoint. The conceptual model will be analyzed to study Operational Availability (Ao) and Probability of Successful Mission (Psm) improvements in operational scenarios.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF FIGURES

LIST OF TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF ACRONYMS AND ABBREVIATIONS

AI	artificial intelligence
Ao	operational availability
ASW	anti-submarine warfare
AW	air warfare
BDT	bulk data transfer
BIT	built-in test
CBO	Congressional Budget Office
CJCSM	Chairman of the Joint Chiefs of Staff Manual
CSEA	combat system engineering activity
DoD	Department of Defense
DRRS-N	Defense Readiness Reporting System – Navy
EDMS	Exhaust Debris Monitoring System
EOR	element OEM review
FMECA	failure modes, effects, and criticality analysis
ICS	integrated combat system
IDMS	Ingested Debris Monitoring System
IoT	Internet of Things
JROC	Joint Requirements Oversight Council
LAN	local area network
LRU	line replaceable unit
MBOET	Mission-Based Operational Effectiveness Tool
ML	machine learning
MLDT	mean logistics delay time
MRDB	Material Readiness Database
MTBF	mean time between failure
MTTR	mean time to repair
NMETL	Navy mission essential task list
OODA	observe, orient, decide, act
OPTEMPO	operating tempo
OV	operational viewpoint

PESTONI	personnel, equipment, supply, training, ordnance, networks, infrastructure
PHM	prognostics and health monitoring
PLM	product life cycle management
PLMS	Product Life cycle Management System
Psm	probability of successful mission
RBD	reliability block diagram
RCM	reliability centered maintenance
RUL	remaining useful life
SDSAS	Shore-based Data Storage and Access System
SDTS	Satellite Data Transmission System
SER	sustainment engineering review
SME	subject matter expert
SoS	system of systems
UJTL	universal joint task list

EXECUTIVE SUMMARY

As naval combat systems continue to grow in complexity and capability, new ways of characterizing system readiness are required to maintain a competitive edge. Naval combat systems are a combination of multiple individual systems designed to deliver multi-mission offensive and defensive capability. Levels of readiness required to achieve this capability are often defined in multiple ways, by multiple entities, and are defined once during design and poorly managed over the life-cycle. In order to apply advanced concepts of readiness assessment, a group of new systems is necessary to achieve real-time readiness.

This paper investigates the nature of mission planning, current methods of assessing system readiness, application of standards in allocating functional and physical capability to tasks and missions, and develops a broad conceptual architecture that enables a seamless flow of data from ship to shore and back.

By applying the processes laid out by Blanchard and Fabrycky (2011), this paper applies needs analysis, operational requirements definition, functional analysis, and finally conceptual architecture and analysis.

This conceptual architecture defines four systems: 1) the Mission-based Operational Effectiveness Tool, which assess combat system readiness in real time, 2) the Satellite Data Transmission System, which transmits stored health, status, and environmental data, 3) the Shore-based Data Storage and Access System, which stores information and brokers access to aggregated fleet data, and 4) the Product Lifecycle Management System, which houses authoritative system suitability measures and software baselines. These systems come together to enable real-time own-ship combat system readiness assessment, near real-time fleet level assessment, and longer term software and supportability product lifecycle management of all naval combat systems.

In establishing this architecture, the resulting conceptual system of systems also positions naval systems to apply advanced techniques in artificial intelligence, machine

learning, and systems engineering to aid users in real time performance assessment and aid experts in detailed system of systems optimization.

The paper details specific conceptual requirements needed to enable both shipboard and shore-based systems that enable execution, and these requirements could be used as a starting point for future combat system software baseline capability enhancement.

Lastly, the paper defines areas for additional study and follow-on work that would further aid in defining system operational requirements and system context in multi-service, multi-mission environments.

References

Blanchard, Benjamin S., and Wolter J. Fabrycky. 2011. *Systems Engineering and Analysis*. 5th ed. Upper Saddle River, NJ: Pearson Education.

ACKNOWLEDGMENTS

To my wife Grace, who ensured that I was able to complete my work, and to my children, Annabelle and Josephine, who tried to ensure I wasn’t.

THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION

A. BACKGROUND

Naval systems continue to grow increasingly complex and have become increasingly integrated (Moreland 2015). Naval ships are designed to operate for several decades and during this timeframe, new technology capabilities are integrated onto them that can provide significant operational improvements. Recent technology advancements in system diagnostics provide an opportunity for the Navy to benefit from systems that can self-diagnose their health and identify faults. These capabilities can provide data that enable the Navy to quickly and efficiently assess operational readiness at the system level, at the system of systems level, and at the force level. This thesis conducted a systems engineering analysis of this problem domain with the objective of developing a conceptual data architecture to gather and process system diagnostic data to support operational readiness assessments.

The measure of naval system readiness is often too-constrictively defined as a single required value. This greatly limits system design as well as system utilization during operations. Naval systems are designed to meet these singular requirements that are established during the acquisition phase; but, during operations, these singular values become standards that must be met by the naval systems in order to be deemed operationally available. Many system requirements related to readiness are better specified as a range of acceptable values. Moreover, a system is often viewed through a binary lens of being “up” or “down,” with a possible third assessment of being “degraded.” In a complex tactical environment full of intelligent, self-reporting systems, these assessments do not meet the need for a well-planned mission.

The measure of naval system readiness is highly dependent on the mission(s) at hand, as well as environmental and external factors. The probability of naval mission success (P_{sm}) may be impacted by a number of factors, as shown in Figure 1. These factors include the operating environment, the stress of the mission scenario itself, the number of available systems to achieve an objective, and the health and status of the naval systems in a ship's configuration.

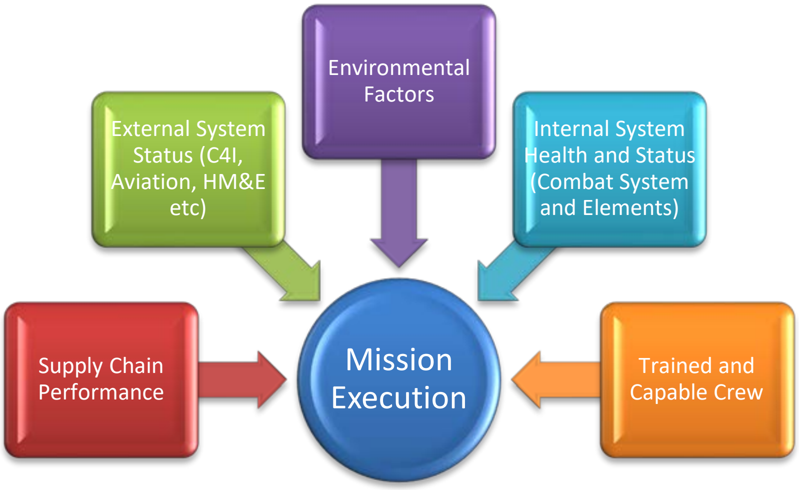


Figure 1. Effects on Probability of Successful Mission of a Combat System

Conceptually, these myriad factors could serve as data inputs to a capability that could translate them into meaningful outputs at both a shipboard and shore-based level, such as a continuous analysis of naval ship readiness, and predictive projections of successful operations according to warfare area.

Under general circumstances, Operational Availability (A_o) in acquisition can be tracked by specifying requirements to meet target objective or threshold values under a set of ground rules and assumptions that include:

1. Reliability of a system under design
2. Maintainability of a system under design
3. An assumption of a logistics delay time based on the criticality of failure
4. A design reference mission to baseline the analysis

However, the current naval tactical fleet Ao assessments are deficient in their ability to identify current system conditions with respect to actual mission needs during operations.

The naval surface community is beginning to study and employ both design-driven and data-driven techniques that have been applied in other areas, such as the commercial and defense aviation community. Examples of design-driven techniques include the Ingested Debris Monitoring System (IDMS) and the Exhaust Debris Monitoring System (EDMS) (Powrie and Novis 2006) in the F-35. Data-driven techniques have been employed in the Airbus A350, which uses two modules called "Expert" and "Prognostics and Risk Management," designed to analyze over 400,000 input parameters to either identify degradation of performance or apply statistical analysis to system health (Canaday 2016)

Successful product life cycle management, data management, and analysis must be treated as the "force multipliers" that they are. This planning, acquisition, and integration process requires careful and complete coordination amongst numerous program offices, original equipment manufacturers, combat system integrators, and sponsors (DeLuca 2013). Moreover, it requires careful coordination of investments, infrastructure, and capabilities.

A holistic shipboard and shore-based conceptual capability would require a few key tasks to be performed to frame the problem set: 1) understand how missions are created, 2) define mission essential tasks and capabilities, 3) allocate systems and standards to mission success, 4) establish infrastructure to utilize vast amounts of system generated data, and 5) apply a framework to optimize mission performance.

Naval operators are continuously adjusting operations plans as a result of variable inputs and constraints (Department of the Navy 2005). At a tactical level, these inputs and constraints are more clearly defined than at a strategic level. To compete in a near-peer tactical environment (Mattis 2018) naval combat systems must utilize system-generated information in a way that contributes to increased readiness, faster and more confident decision making, and a capability that is adaptive enough to ingest new inputs and alter the course of battle preparation.

This thesis studied the utilization of advanced planning and digital techniques at sea and process techniques ashore to establish a conceptual design and architecture incorporating a broad, cyclical flow of information to enable own-ship and fleet-wide readiness knowledge and self-awareness. Figure 2 provides an operational viewpoint (OV-1) of the thesis' conceptual capability.

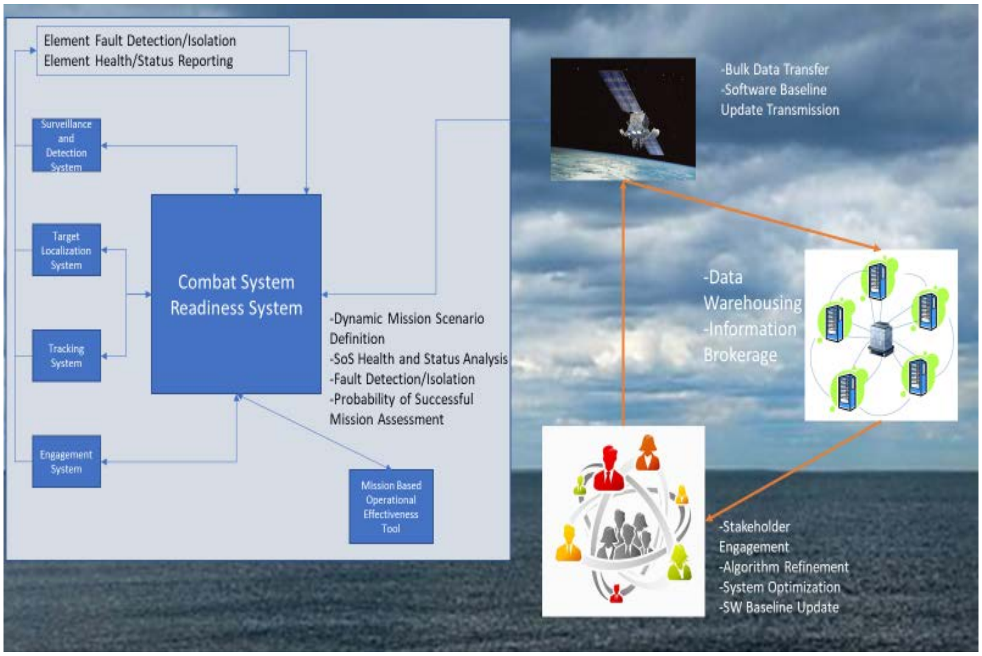


Figure 2. OV-1: Cyclical Flow of Information to Support Real-Time Readiness Assessment

Via this ship and shore infrastructure, the study developed a framework from which a mission-based operational assessment is defined and the thresholds of performance of naval assets at the force level are identified and continually optimized. The operational picture is achieved, and system readiness becomes a known value and a decision aid rather than a set of derived metrics.

B. STUDY OBJECTIVES

The objective of this study was to develop a conceptual design of a system architecture to provide a naval operational readiness assessment capability. The study sought to accomplish this objective by examining:

- how current naval operational plans and assessments are generated
- ways to calculate the likelihood of success in these plans

- how to incorporate the effects of naval missions, the environment, and other external factors into operational readiness assessments
- how to leverage acquired system self-diagnostic data to enable a conceptual architecture that provides adaptive and timely operational readiness assessment

C. STUDY SCOPE, ASSUMPTIONS, AND CONSTRAINTS

The scope of the study was focused on Navy ships and shipboard systems. The study used a generic surface ship combat system as an example, based on the Aegis Combat System, which is a multi-mission system of systems designed to meet a wide array of offensive and defensive capabilities (DeLuca et al. 2013). By referencing a generic combat system, key concepts are communicated in a way that would be achievable and executable on any surface ship.

In order to conceptualize an operational readiness assessment architecture for such a complex naval system of systems (SoS), the study made the following overarching assumptions:

- that alignment of program offices and combat system development activities is actively taking place at both executive and working levels
- that a Combat System Engineering Activity (CSEA) is utilized as an integrated design agent that actively and successfully coordinates combat system and element interface requirements
- that requirements do not yet exist to transmit adequate and accurate information across the Local Area Network and from ship to shore
- that the combat system and ship are provided an interface to ingest variable mission sets and adjust expected levels of performance as necessary.
- that hardware and software engineers can and will successfully apply theory in areas of physics and failure propagation
- that Program Executive Offices are willing and able to invest in central, singular infrastructure that tracks system suitability metrics in a product life cycle management environment

Study constraints included:

- limitations on local area network bandwidth due to higher priority, tactical latency allocations will constrain operational effectiveness tools
- variability in bandwidth from ship to shore will not facilitate immediate and complete upload of system data to remote locations
- complexity of an acknowledged system of systems (Baldwin 2008), in which multiple stakeholders will create an environment will make it difficult to coordinate effectively
- capability for robust modeling and simulation will not exist at a shipboard level

D. METHODOLOGY

This project applied systems engineering methods from Blanchard and Fabrycky (2011) to analyze the Navy's needs for operational readiness assessments and to develop a conceptual design solution that addresses this need. The methodology started with a known problem and translated it into a set of requirements that led to a functional architecture and conceptual architecture design. The steps in the systems engineering methodology were:

1. Identify problems and translate them into a definition of need, where existing processes, capabilities, and user needs were assessed, and gaps defined.
2. Identify and analyze system operational requirements, where systems were contextualized, and high-level conceptual requirements were developed.
3. Conduct a functional analysis, where the system functions and interactions were defined and placed into functional flows.
4. Study technologies and develop a conceptual design solution, where a total conceptual design was generated, and user interactions were defined and abstracted.

E. BENEFITS OF STUDY

Developing a data architecture and approach for assessing combat readiness for the fleet provides critical input into tactical decisions. This study performed a needs analysis, requirements analysis, functional analysis, and conceptual design of a technology solution and data architecture for a naval fleet capability that assesses system-level and force-level readiness for ship systems and determines the probability of mission success given variable inputs.

The study developed a conceptual future fleet capability that has the potential to improve future mission planning, multi-ship coordination, and tactical operations by providing self-awareness of warfare assets and combat readiness knowledge.

The results of this systems engineering analysis facilitate further requirements definition and contractual action and will guide future combat system baseline development efforts related to integrated and dynamic readiness assessment. Moving forward, the results of this study provide a foundation of knowledge that can lead to developing incremental software baseline updates and an approach to gradually introduce an operational readiness assessment capability into a future wholesale baseline development effort.

THIS PAGE INTENTIONALLY LEFT BLANK

II. NEEDS ANALYSIS

A. INTRODUCTION

In binding the problem set, one must recognize the current state, the definition of need, and the future state. Defining the current state includes understanding how missions are planned and created at the strategic level and at the tactical level, how the probability of success is determined, and what inputs are used to create useable outputs.

This analysis enables the next step, which is that of applying a conceptual framework to applying a recommended solution set to the two primary application areas, which are that of a shipboard architecture and a shore-based architecture, working together to achieve seamless and continuous update.

By understanding the needs from both a capability perspective and a user perspective, a complete needs-based solution can be generated by applying theories of supportability analysis, mission engineering, and machine learning.

B. NAVAL READINESS

When assessing a surface ship for initial estimates on whether it will be able to achieve a commander's intent, the state of combat system readiness plays a primary role for most missions of great consequence.

However, readiness within the Department of Defense takes on broad meaning. Readiness can include training, manning, supply, hardware, software, facilities and more. (Rowe 2019) describes additional considerations for readiness, to include:

- Communications: Platforms need to coordinate plans with superiors and among each other.
- Weapons: Adequate weapons must be available to achieve mission goals.
- Navigation: Ships and their important systems must be usable.
- Avionics: Aircraft and their important systems must be usable.
- Radar: Platforms need functioning radar to anticipate threats.

- Electronic warfare: Platforms need defensive capabilities, and possibly offensive capabilities depending on the platform.
- Information warfare: Platforms need defensive capabilities. (Rowe 2019)

Given the consistent variability that is presented by ever-changing inputs, there exists a need to apply theories of readiness for combat in real-time. Betts (1995) makes a critical distinction in types of readiness, which is that of actual capability versus potential capability.

Potential capability is best described as an "as designed" capability. Under projected circumstances, in expected scenarios, under predictable conditions, the system will be able to deliver a capability. A pure assessment of "potential capability" in this sense, serves little practical purpose when commencing a mission, and actual capability is the far better metric of preparedness. "Actual capability" is an assessment of current inputs and variables, including constraints on the system design, constraints on system condition, or constraints on the system's environment.

Moreover, the point at which the readiness assessment of equipment must take place is immediately preceding mission start, not in a projected future state, as potential capability insinuates.

Rowe (2019) builds on the work by Betts (2005) to define these actual versus potential assessments as, in the former instance, "general" or "strategic" readiness and in the latter, "mission specific" or "tactical" readiness (2019).

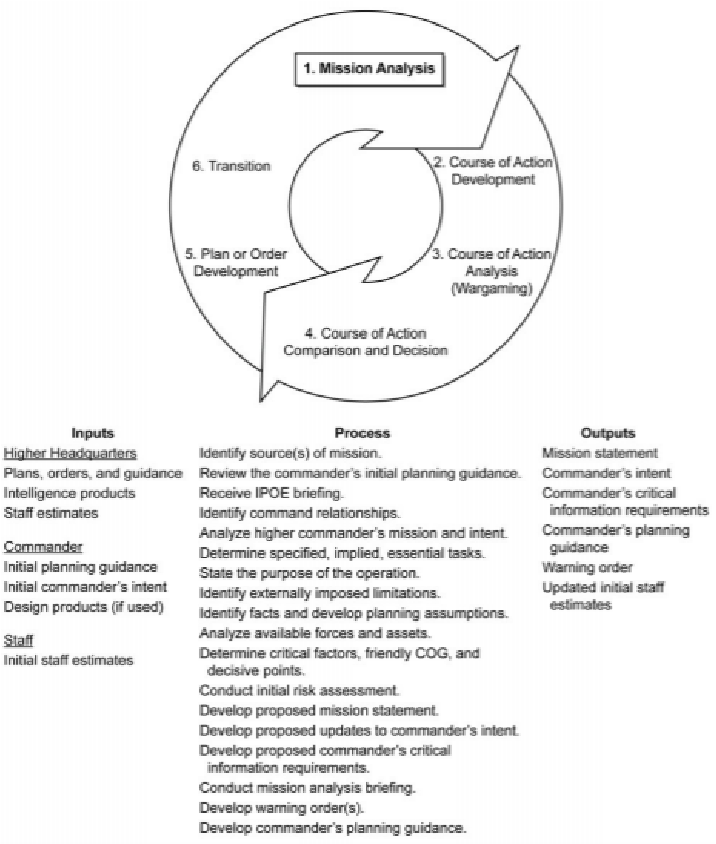
C. NAVAL MISSION PLANNING, MISSION ANALYSIS, AND MISSION-ESSENTIAL TASKS

The Navy has adopted regimented and robust planning processes and procedures that are codified within the Navy Warfare Publication 5–01 (Department of the Navy 2013).

This publication documents high-level steps and focuses on key inputs, processes, and outputs in the planning of missions that are adaptable to any echelon of command. The key tenets fall into six broad categories: 1) mission analysis, 2) course of action development, 3) course of action analysis (wargaming), 4) course of action comparison and decision, 5) plan or order development, and 6) transition. Without an accurate survey of capability and readiness of existing forces, establishment of an achievable mission becomes either more difficult, or based on faulty assumption.

Mission analysis serves as the first assessment of the scenario and includes inputs, processes, and outputs designed to establish the first take on the mission at hand. This paper dedicates its time and effort on analyzing this operational planning step.

Sample inputs to mission analysis would include intelligence products, planning guidance, and staff estimates. From these inputs, planners execute processes that define tasks and purpose of the mission, limitations and constraints on the mission, forces and assets available, available support assets, gaps of knowledge, and risks. This analysis feeds mission statements, commander's intent and guidance, warning orders, and staff estimates. This process is reflected in Figure 3.



Inputs

Higher Headquarters
Plans, orders, and guidance
Intelligence products
Staff estimates

Commander
Initial planning guidance
Initial commander's intent
Design products (if used)

Staff
Initial staff estimates

Process

Identify source(s) of mission.
Review the commander's initial planning guidance.
Receive IPOE briefing.
Identify command relationships.
Analyze higher commander's mission and intent.
Determine specified, implied, essential tasks.
State the purpose of the operation.
Identify externally imposed limitations.
Identify facts and develop planning assumptions.
Analyze available forces and assets.
Determine critical factors, friendly COG, and decisive points.
Conduct initial risk assessment.
Develop proposed mission statement.
Develop proposed updates to commander's intent.
Develop proposed commander's critical information requirements.
Conduct mission analysis briefing.
Develop warning order(s).
Develop commander's planning guidance.

Outputs

Mission statement
Commander's intent
Commander's critical information requirements
Commander's planning guidance
Warning order
Updated initial staff estimates

Figure 3. Mission Analysis Stage of Mission Planning. Source: Department of the Navy (2013).

It is in the mission analysis domain where the quality and quantity of inputs can be both critical and cumbersome. During mission analysis, defining specified, implied, and essential tasks are vital to the clarification of mission and to understand what assets are required (Department of the Navy 2013). Specified tasks are assigned to a specific unit by a commanding organization, implied tasks are not stated but are assumed to be required to complete a mission, and mission-essential tasks are deemed vital to achieving success.

Missions themselves are defined by numerous discrete tasks of all types, and most often they can originate from Chairman of the Joint Chiefs of Staff Manual (CJCSM) 3500.04, the Universal Joint Task List (UJTL). The UJTL serves as a "hierarchical listing of the tasks that can be performed by a joint military force" (Kross 1995). By listing these tasks, planners can integrate strategic, operational, and tactical taskings in a methodical way. Naval tasks typically fall at the operational and tactical level and are defined in the subset of the UJTL, the Navy Mission Essential Task List (NMETL).

NMETLs provide "a comprehensive command and mission-specific list of Navy Mission-Essential Tasks (NMETs)" that "allow a commander to quantify the level and scope of effort required to achieve mission objectives" (Brown 2012). Understanding and mapping mission scenarios allows commanders to identify force capability, but these can serve more than one purpose, including that of taking system-produced data and assessing readiness for combat. The relationship of tasks is shown in Figure 4.

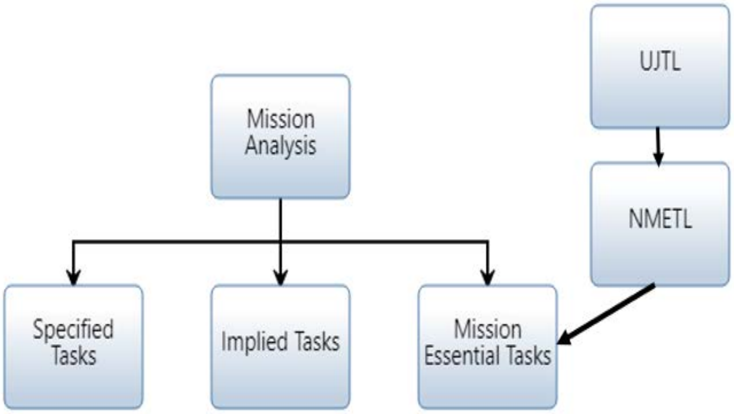


Figure 4. The Relationship between Task Lists and Mission Analysis

For a naval combat system. these essential tasks, which are deemed most critical to mission success, form a foundation upon which adaptive mission analysis can rest.

D. NAVAL STRATEGIC MISSION READINESS: THE DEFENSE READINESS REVIEW SYSTEM

Once essential tasks have been defined, the next step of mission planning is that of surveying the availability of forces and assets able to conduct the mission. In this domain, a need for adaptability also resides.

At senior decision levels, the Navy has implemented the Defense Readiness Reporting System – Navy (DRRS-N), which "retains the ability to inform senior leadership of a unit's ability to fight and win in major combat operations…DRRS-N permits the examination of specific mission-essential tasks (METs) within a unit's mission-essential task list (METL) to identify units that have attained the appropriate level of readiness to perform a required specialized mission" (Baker 2012).

A sample dashboard of strategic tasking represented in DRSS-N is reflected in Figure 5.

Mission Assessment > CMDR COCOM (DJUUUU) > Overall

Mission: Overall

	Plan 00	Plan 07	Plan 20	Plan 05	Plan 06
Mission Assessment	Y	Y	Y	Y	Y
Last Approved Date	10-Jul-2010	10-Jul-2010	10-Jul-2010	10-Jul-2010	10-Jul-2010
Approval Status	Approved	Approved	Approved	Approved	Approved
MET					
ST 1 Deploy, Concentrate, and Maneuver Theater Forces	N	Y*	Y*	N	Y*
ST 2 Conduct Theater Strategic Intelligence, Surveillance, and ...	Q	Q	Q	Q	Q
ST 3.1 Process Theater Strategic Targets	Y*	Y*	Y*	Y*	Y*
ST 4 Sustain Theater Forces	Y	N	Y	N	Y
ST 4.2.4 Establish and Coordinate Training of Joint and Combin...	Y*	Y*	Y*	Y*	Y*
ST 5.1 Operate and Manage Theater C4I Environment	Y	Y	Y	Y	Y
ST 5.3 Determine Strategic Direction	Q	Q	Q	Q	Q
ST 5.5 Conduct Theater-Wide Information Operations (IO)	Y	Y	N	Y	Y
ST 6.1 Provide Theater Aerospace and Missile Defense	Y*	Y*	Y*	N	Y*
ST 6.2 Coordinate Protection for Theater Forces and Means	Q*	Q*	Q*	Q*	Q*
ST 8 Develop and Maintain Alliance and Regional Relations	Y*	Y*	Y*	Y*	Y*
ST 9 Conduct Combating Weapons of Mass Destruction (CWMD...	Q	Q	Q	Q	Q

Figure 5. An Illustrative Dashboard of the Defense Readiness Review System. Source: Trunkey (2013).

While DRRS-N serves its purpose as a high-level readiness reporting system, its focus lies in the larger assessment of personnel, equipment, supply, training, ordnance, networks, and infrastructure, or PESTONI (Zvijac 2017). Real-time adaptive feedback does not feed seamlessly into the DRRS-N reporting system, so critical inputs associated with combat system readiness may be outdated or possibly misinterpreted, as variable functional capability thresholds have not been defined, assessed, or accounted for.

The Congressional Budget Office (CBO) has identified other issues with DRRS, including:

- limited standardization across services because missions are defined differently
- mission assessments are subjective
- "DRRS has no way to distinguish between assigned missions, potential missions, hypothetical missions, and missions for which a unit has received no formal training" (Trunkey 2013)

The absence of real-time feedback, combined with the noted deficiencies in standardization and of subjective input, result in a readiness status system that is not being optimally employed, and does not assess "mission specific" readiness (Rowe 2019). Alternatively, an employment of real-time assessment within DRRS-N would more clearly articulate the status of readiness of naval forces and allow for higher order analysis of both actual and potential system capability.

E. OPERATIONAL AVAILABILITY AND PROBABILITY OF SUCCESSFUL MISSION

1. Operational Availability (A_o)

For the purposes of readiness for combat, the overarching metric of preference within the Department of Navy remains A_o. Indeed, as part of the Joint Capabilities Integration and Development System, new Capabilities Development Documents establish A_o as a Key Performance Parameter in almost all new systems (Ierardi 2018).

At lower levels, the Navy introduced elements of data aggregation and manipulation for calculation of A_o over the past two decades by utilizing the Material

Readiness Database (MRDB). While useful, the system has limitations borne by the fact that the database does not intake and configuration manage detailed baselined information from the system design phase, is limited in its connectivity with many Program Executive Offices, and does not take direct, real-time inputs from fielded assets in theater (Clarke 2018).

Operational Availability, though, tells a partial story, given the fact that even a system not even in theater is still "available." In a contested, high OPTEMPO environment, an aggregated fleet level assessment of A_o combining all potential environments is not always actionable information. Naval assets must be able to adapt to unique environments and understand own-ship availability as it relates to these environments.

2. Probability of Successful Mission (P_{sm})

An improved metric, then, is "Probability of Successful Mission," or P_{sm}, which can be used as a variable metric based on the mission performed and based upon equipment condition of the unit preparing to perform it.

For example, a redundant string of servers with pooled resources utilized to process and compute sensor information could be assessed prior to commencing an air defense mission. If there is a failed node, there may be no functional effect on the mission itself, but the state of the probability of successful mission has degraded simply for the fact that should another node fail, the system would lose some level of functionality.

The system is "available" at the start of the mission, but in a riskier state than if all redundancy was restored. Under well-planned circumstances, functionality can be degraded intentionally based on necessity, utilization of resources, or any number of other items to mitigate impacts. In less carefully planned systems, it might mean that overall system stability would suffer or crash.

At its basest form, $P_{sm} = e^{-\lambda t}$, a form of exponential decay, and reflects the probability that a system experiences no failures during a specified time interval *t* (Reliability Education 2007). During the design phase of a program, the time *t* would be attributable to a period of time defined in the Design Reference Mission, under various scenarios and conditions.

A design reference mission “defines the specific projected threat and operating environment baseline for a given force element, which may range from a single-purpose weapon system to a multi-mission platform to a multi-system, multi-platform system of systems” (Lilly and Russell 2003), While it serves as a baseline for acquisition phase vendor performance by defining how the vendor will be measured, and against what criteria, it does not account for the wide variations in system utilization, in operating environment, or in mission length.

3. Complexity of Psm

Upon reviewing UJTL and associated service sub-documents, the number and scope of mission sets that a DoD platform can ultimately execute is immense, and the probability of success does not ultimately break down neatly into a singular mission length. As systems transition from acquisition design phases into sustainment phases, the DRM would give way to discretely modeled mission scenarios that could be aggregated and simulated to improve upon a preliminary analysis of the DRM.

For example, in a defensive scenario, a ship may track the probability of an anti-ship cruise missile detection, probability of successful hard kill of an inter-continental ballistic missile, or probability of successful track and recovery of aircraft.

In these scenarios, the P_{sm} function serves as the point of entry for analysis but serves little practical purpose in a contested environment under increased operating tempo (OPTEMPO). When operating in the contested environments, system downtime for maintenance is not welcomed, and information gathering, aggregation, and dissemination is paramount. P_{sm} assumes a finite period and a fully functioning system at the start of a mission. Thus, P_{sm} requires the ability to accommodate variability according to mission.

F. MISSION ENGINEERING AND MISSION THREADS

The concepts behind mission engineering continue to be resolved and defined, but it has been discussed as “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" (Beam 2015). The foundational aspects of mission engineering are critical to the adaptive assessment of readiness. An important task to perform when looking to assess current states of readiness is to fully decompose and understand the mission as it is expected to be performed.

Under these circumstances, a more granular approach that incorporates the tenets of mission planning, blended with capability assessment of systems, the current status of systems, and external environmental factors, creates a holistic picture against which P_{sm} can be assessed. These can frequently be articulated by the concept of a mission thread.

1. Mission Threads and Combat Systems

Gagliardi, Wood, and Morrow (2013) define an operational mission thread as "how the system of systems nodes (and perhaps the systems within the nodes) react to an operational stimulus. It is given as an end-to-end sequence of steps (external events, operator activities, and automated activities) that take place over a time period." Defining a mission thread can follow a conceptual process such as Figure 6. In this process, both new and existing system attributes and functions are integrated with expert system inputs.

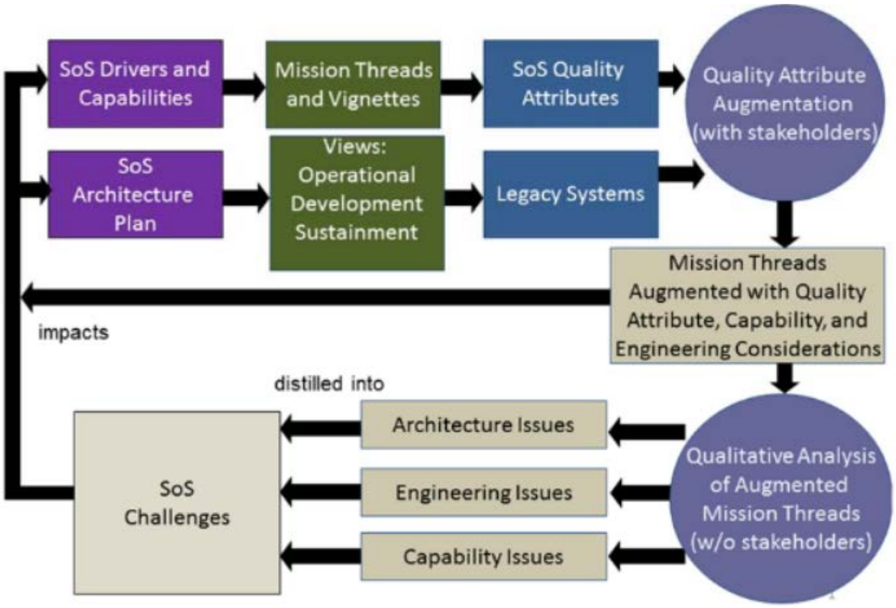


Figure 6. Conceptual Development Process of Mission Thread. Source: Gagliardi, Wood, and Morrow (2013).

Utilizing the framework from Gagliardi, Wood, and Morrow, developing a combat system mission thread means developing the mission architecture, understanding what systems are drivers of capability, and building out the mission narrative and steps in a resource flow diagram, ultimately iterating this thread until there are agreed-upon scenarios and definitions of success.

2. Detect to Engage and Combat System Readiness

Integrated combat systems themselves are largely computing infrastructure and associated system of systems integration efforts. The term system of systems is used to describe an "integrated force package of interoperable systems acting as a single system to achieve a mission capability" (Murphy, Sheehan, Richardson 2013).

These integrated systems follow a beginning to end process of target detection through engagement, which includes target identification, tracking, illumination, guidance, and eventual engagement and kill assessment (Integrated Publishing 2018), often referred to as a "kill chain." The number of systems required to execute any specific mission is robust and sometimes variable depending on the threat, on system functionality, and on system availability. The detect to engage process is one driven largely as the successful generation of information and integration/aggregation of this information into a series of commands and decisions.

In focusing on the operational mission thread for a combat system, one would define the systems, tasks, external inputs, and activities needed to detect a threat and ultimately engage and assess that a target has been eliminated. The detect to engage sequence is also described as a sequence known as Find, Fix, Track, Target, Engage, and Assess. An example of a kill chain is provided in Figure 7, which depicts a multi-layered capability designed to eliminate a specific threat or threats.

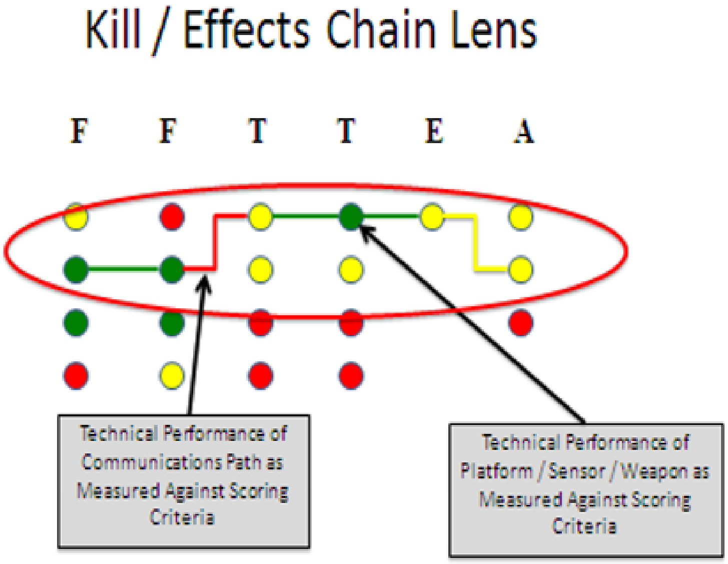


Figure 7. The Kill Chain and Readiness. Adapted from Brown (2012).

In this example, there are layers of complexity that are greatly reduced to "red/yellow/green." Better mission and performance level analysis and probabilities of success would drive more information, and mission-specific information, into the mission planning process.

G. REMOTE READINESS MONITORING

In day to day operation, individuals rely on consumer products (e.g., automobiles, computers) that already utilize enhanced diagnostics to monitor product health and optimize performance (Janasak and Beshears 2007).

Newly developed naval systems have been designed to have robust fault detection and isolation, though they have not kept pace with consumer technology in relating the impact of complex system failure and then identifying and capitalizing upon the knowledge of the internal and external indicators that led to failure.

A naval combat system fundamentally acts as its own edge computing equipment, bounded by domains and linked centrally on shipboard networks. As laid out by Hassan, et al. (2018), edge computing operates as an aggregator and analyzer of information within an "Internet of Things" ecosystem. An example of a high-level cloud and edge-based computing solution can be seen in Figure 8.

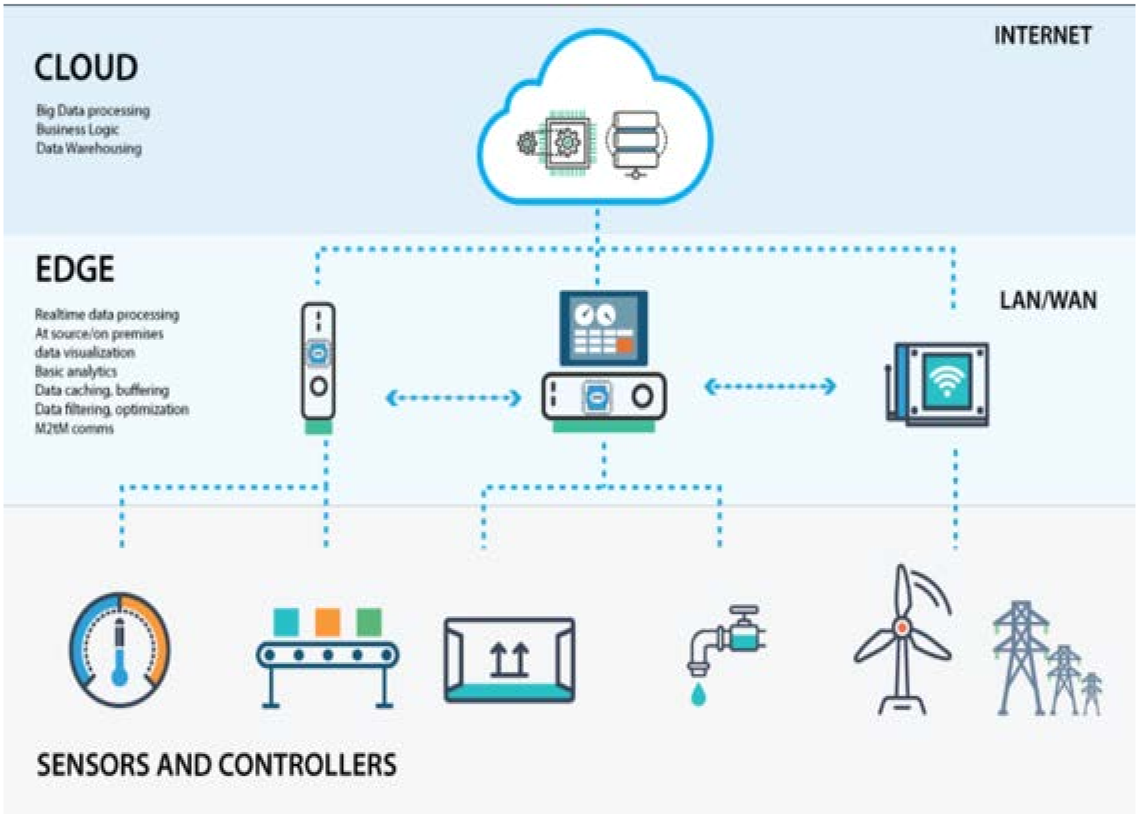


Figure 8. Cloud, Edge, and Sensor Computing Reference. Adapted from Open Automation Software (2019).

While consumer IoT and edge computing ecosystems revolve around smart hubs, telephones, tablets, appliances, and commercial analytical tools, naval edge computing revolves around combat systems and their constituent systems and subsystems.

The "smartness" of combat system sensors, controllers, and edge computing equipment is variable, given the gap in time of initial development among different hardware systems and combat system software baselines. Newer naval systems, such as the Joint Strike Fighter (Powrie and Novis 2006), hold more robust self-reporting capability, but even older systems such as the SPY-1 radar have developed "bolt-on" solutions that can diagnose and detect some level of system health (PR Newswire 2002).

These systems and subsystems provide individual reporting, but combat system-level analysis is sub-optimized to report capability.

The next actionable phase of data access and aggregation in an IoT environment is putting it to action within a Product Life-cycle Management (PLM) tool, defined as an data environment that enables a “strategic business approach that applies a consistent set of business solutions that support the collaborative creation, management, dissemination, and use of product definition information” (CIMdata 2019).

H. SUPPORTABILITY ANALYSIS AND BUILT-IN TEST

Within a PLM environment lives the configuration and information about systems being analyzed. Naval combat systems are often designed and developed with a few key design aid documents that fall into the concept of supportability analysis. Examples of these products would include reliability block diagrams (RBD), fault tree analysis, Failure Modes, Effects, and Criticality Analysis (FMECA), reliability estimates, maintenance task analysis, and level of repair analysis (Blanchard and Fabrycky 2011). Each one of these products contributes to the overall “Operational Availability” (A_o) equation, most commonly interpreted as a decomposition of “the system’s reliability (mean time between failure (MTBF)), maintainability (meantime to repair (MTTR)), and supportability (mean logistics delay time (MLDT))” (Naval Sea Systems Command n.d.). Just as these parameters can be utilized to calculate A_o, they can be used to calculate P_{sm}.

As complex systems are becoming more and more reliant on built-in test, ease of maintainability drives efficiency in system utilization. The faster failures can be resolved, the less time systems are down for maintenance and by extension, the more time they are available for use. However, this BIT capability is not purely for maintenance. Fault detection and fault isolation techniques continue to advance (Yin, Ye, and Chen 2013) to the point that detailed mapping of design phase deliverables such as the FMECA can link individual failure modes to detailed, automated test procedures. These test procedures provide an ever-changing, and variable snapshot of system performance that is predicated on several key inputs, including unique line replaceable unit runtime, line replaceable unit redundancy, environmental indicators, duty cycle, and software reliability. By having these test procedures in place, faults in systems are known at any given point, affording the ability to adaptively analyze the impact of failure on a mission based on additional parameters.

1. Unique Line Replaceable Unit Run Time

Time is a critical component to understanding the probability of failure in any component or system in most probability distributions. The longer an item has been operating, the more exposure to potential failure modes, and therefore, the higher the likelihood of failure. Individual LRU run time is a key building block that is critical for the execution of the concept of "Remaining Useful Life" (RUL). RUL remains a standard of prognosis and health monitoring and can be simply defined as a "prediction on the time remaining before a machine part is likely to require repair or replacement." (Barrett 2019).

By individually tracking line replaceable unit (LRU) run times, the variability in system health can be captured and assessed, as well as applied against a baseline determination of performance, which is that of "as designed performance."

2. Line Replaceable Unit or System Redundancy

The physical and functional characteristics of systems can be captured by both Functional Block Diagrams and Reliability Block Diagrams (RBD). Reliability block diagrams serve as a visual representation of components and by extension the functional characteristics of those components, and are a method used to analyze systems and assess their reliability (Cepin 2011). When viewing an RBD, such as in Figure 9 below, one can note the presence of redundancy that can "absorb" failure in the system and still fulfill the intended function.

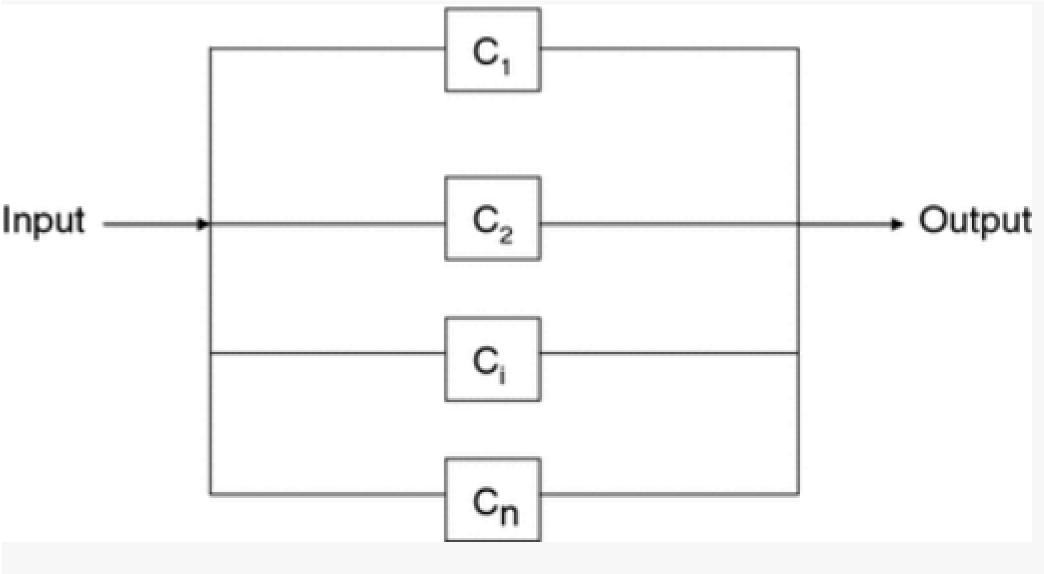


Figure 9. Reliability Block Diagram for Redundant Components. Source: Cepin (2011).

3. Environmental Indicators

Integrated Combat systems are composed of large amounts of electronic components, which degrade and fail based on a few critical factors such as humidity, temperature, or vibration (Souza et al. 2014).

Various elements of the physical environment serve a critical role in the behavior of systems, subsystems, LRUs, and components. An overly humid environment can create a situation that drives electronic component failure at a more frequent rate than a drier environment. An environment with elevated levels of vibration can create problems in both electronic and mechanical components.

A system-level assessment would need to understand the effects of these environmental indicators and apply a weighting or factoring that is compiled with time to assess impact to mission performance.

4. Duty Cycle

System operating tempo (OPTEMPO) and stress is a critical, an under-represented input to the system of systems failure scenario. When systems (and systems of systems) are under development, the outcomes are largely governed by inputs and controls defined in the Design Reference Mission. The analysis breaks down under stressing, realistic scenarios, where increased OPTEMPO pushes systems beyond the design intent. An assessment of readiness must include the potential to operate outside of design parameters.

5. Software Reliability

Combat systems are complex and characterized by thousands of interfaces and messages traveling in concert to execute a given mission. Individual systems, such as sensors, require signal processing and computing capacity in order to translate analog inputs to digital and ultimately detect hostile threats. The millions of lines of code that are required to execute the scope of missions within a major naval combat system inevitably lead to software defects that degrade capability. An understanding of software architecture and failure propagation must be considered when seeking to analyze the mission of a combat system.

6. Use of FMECA in Supportability Analysis

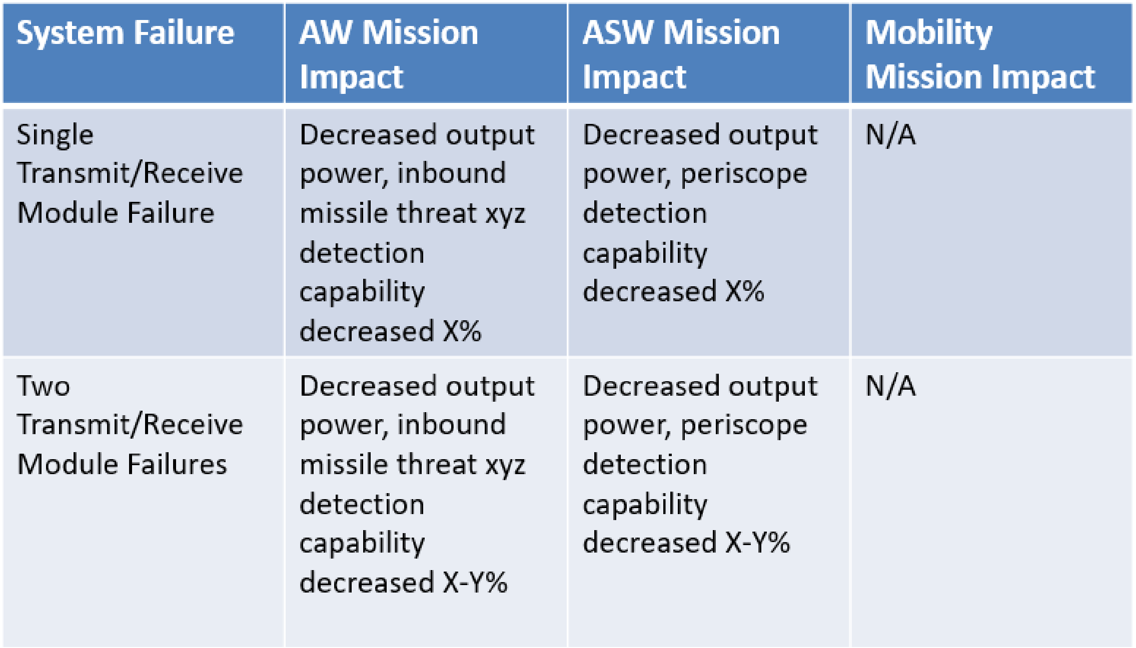
In a singular system, thresholds of performance such as up, down, or degraded are set during design using supportability analysis. These parameters are only revised if careful attention is paid and managed through rigorous configuration control and data management/linkage.

An example use case would be to consider an obsolete Transmit/Receive module in an active phased array radar that required a redesign to accommodate new components. This redesign undoubtedly results in impacts on the way the transmit/receive module behaves within the system, including lower or higher reliability, availability, and maintainability.

This change requires an adjustment to the definition of “failure” within system built-in test software since new failure modes may have introduced, older failure modes may have been eliminated, or the same failure modes exist but are more or less frequent. The Failure Modes, Effects, and Criticality Analysis is defined as “a design technique that can be applied to identify and investigate potential system (product or process) weaknesses (Blanchard and Fabrycky 2011). Depending on the program, these analyses take place iteratively from the preliminary design phase through the critical design phase. If approached from a life cycle perspective, the FMECA should live with the system and be revised until system disposal. In all circumstances, the changes to this supportability analysis impact the ability to perform mission essential tasks.

Applications of the FMECA then must be expanded. In development, failure modes must tie not to system functional performance, but to overall mission performance. A simplified example can be seen in Table 1, which looks at the Air Warfare (AW), Anti-Submarine Warfare (ASW), and mobility mission areas.

Table 1. Failure Modes and Capability Impact to Mission Area



System Failure	AW Mission Impact	ASW Mission Impact	Mobility Mission Impact
Single Transmit/Receive Module Failure	Decreased output power, inbound missile threat xyz detection capability decreased X%	Decreased output power, periscope detection capability decreased X%	N/A
Two Transmit/Receive Module Failures	Decreased output power, inbound missile threat xyz detection capability decreased X-Y%	Decreased output power, periscope detection capability decreased X-Y%	N/A

Understanding distributions of failure and impacts across a system or system of systems, then allows for “up, down, and degraded” estimates to apply to warfare area readiness. As such, the failure in the AW example above in Table 1 may result in mission termination, whereas the same failure in the ASW mission area may mean the mission continues. These instances would be captured in the mission threads and scenario development. These mission threads, the FMECA, and the system built-in test are inextricably linked, and all are a vital reason they must live within a PLM system.

I. THE DEFINITION OF NEED: ADAPTIVE READINESS ASSESSMENT IN DEPLOYED ASSETS

It has been established that requirements in combat systems do not incorporate a cohesive readiness assessment tool that is based on the mission performed. Existing tools are an amalgamation of reliability centered maintenance (RCM), fault detection and isolation, and are gradually incorporating some aspects of Prognostics and Health Monitoring (PHM) (Federal Information and News Dispatch, Inc. 2001).

Concepts of RCM focus on allowing equipment to operate under normal environment and normal load until failure occurs or a sensor system determines maintenance is necessary (Pritchett 2018). Fault Detection and Isolation encompasses a broad range of practice, but when comparing to the prescriptive capabilities of PHM, serves as a reactive analysis of the determination of failure in a component or system. More frequently, all of these practices include the utilization of sensors and software to run tests and search for prescribed value sets that correspond to “functional” or “not functional.” PHM techniques are a combination of both expert system knowledge and data-driven techniques.

To get the next level of detail, though, a coordinated effort from each individual element of a combat system (i.e., sensors, target localization systems, tracking systems, engagement systems) needs to be developed to form a common “baseline.” Naval combat systems need a capability to decompose and functionally allocate missions to systems, and these systems need to incorporate built-in test, supportability analysis, and mission threads into simulated scenarios that provide a probability of successful mission.

Moreover, an off-ship architecture that combines both existing and new capability can eventually transform strike groups into data ecosystems that feed each other, each one providing continuous feedback for algorithm improvement. Machine learning and artificial intelligence, combined with robust fault detection software design in new systems, now offers an ability to assess system health based on equipment condition and to perform risk assessment at the mission/functional level.

The core problem of the end to end “mission to data” linkage problem lies in defining ownership of information nodes, freeing the paths of information flow between those nodes, methodically incorporating gradually improving data, and then translating data into action – this problem is both a technical and managerial one. There is a requirement to bridge the operational picture with the acquisition of systems in order to assess readiness.

J. STAKEHOLDER ANALYSIS

In a naval ship’s combat system control center, there are multiple shipboard stakeholders that are all accessing information from warfare areas and combining both internal and external data sets.

Each ship then reports back to the Type Commander (e.g., Commander, Naval Surface Forces, Pacific/Atlantic), who reports to either U.S. Fleet Forces Command or Commander, Pacific Fleet, whose motives are driven even larger strategic decision processes.

The Navy then has various other stakeholders, such as the Naval Supply Systems Command, and its various contracted depots and maintenance centers.

In the acquisition chain of command, there are system engineers, functional leads, program managers, resource sponsors, original equipment manufacturers, and combat system integrators.

Each stakeholder has a varying level of interest in understanding the readiness of systems in the fleet, but all maintain a vested interest in inserting processes and architecture that supports continued evolution of readiness reporting both shipboard and ashore. A high-level stakeholder analysis shows these interests in Table 2.

Table 2. Stakeholder Analysis

Stakeholder	**Desires**
User	-Know the current state of Combat System readiness -Know the probability that, through simulation, the current combat system can meet mission
Fleet Commanders	-Fleet level knowledge of system readiness for specific mission sets -Knowledge of better capable options within the area of responsibility -Joint level information to fill gaps for degraded capability -More comprehensive tactical picture
Supply System	-Information on known failures (demand) -Information on possible future failures (potential demand) -Location of failed components (inventory optimization)
Combat System Engineering Activity	-Drive integrated monitoring capability that results in a “must-have” for the combat system -Seamless information exchange among elements
OEM	-Know the performance of own systems -Know how internal and external factors affect performance
Warfare Center	-Pull together analysis from all stakeholders into meaningful Common Operational Picture -Assist with the push of real-time feedback/assistance
Combat System Program Managers	-Simplify interfaces among Combat System elements -Maximize performance within existing design constraints -Know that the combat system can meet the intended mission
Element Program Managers	-Know system meets Ao Key Performance Parameter -Know when the system is failed and that support system in place can respond quickly enough

The resulting conceptual system from the need statement and stakeholder analysis results in four systems, the ship-based Mission-based Operational Effectiveness Tool (MBOET), the spaced-based Satellite Data Transmission System (SDTS), and the cloud-based Shore-based Data Storage and Access System (SDSAS) and Product Lifecycle Management System (PLMS), that come together in the contextual diagram represented in Figure 10.

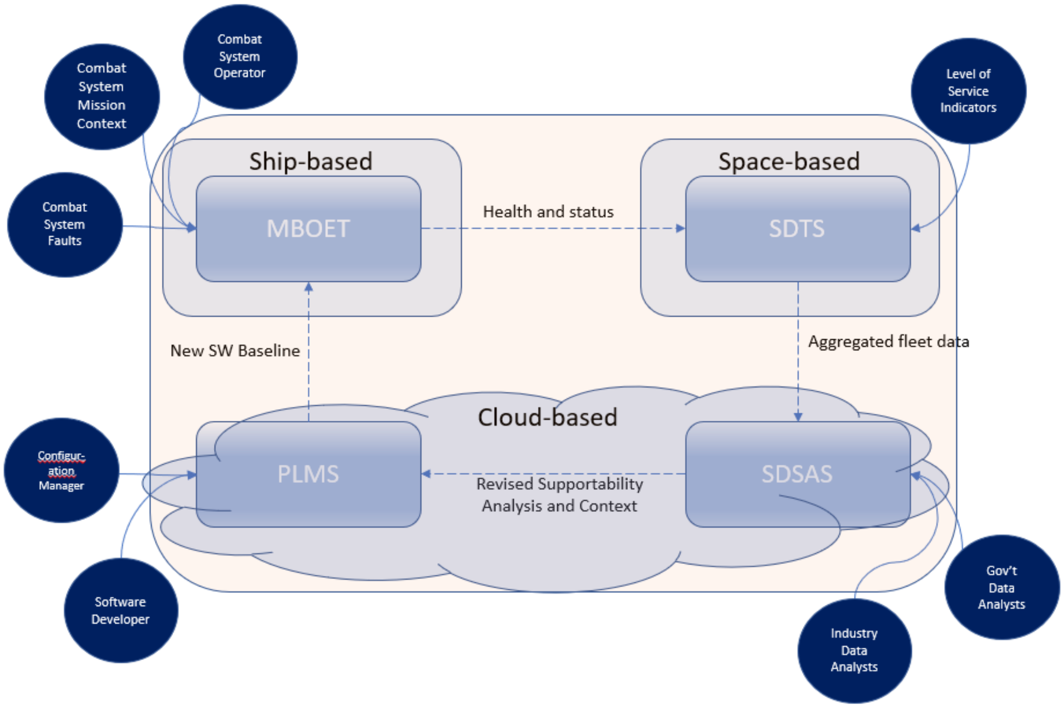


Figure 10. Mission Analysis System Context

THIS PAGE INTENTIONALLY LEFT BLANK

III. SYSTEM OPERATIONAL REQUIREMENTS ANALYSIS

Blanchard and Fabrycky (2011) define the operational requirements analysis process as a set of discrete tasks:

- Mission Definition, which is the prime or alternate missions of the system.
- Performance and physical parameters, or the operating characteristics and functions of the system.
- Operational deployment, or the quantity of equipment and resources in the expected operating environment.
- Operational life cycle, or the projected time the system will be in use.
- Utilization requirements, or how the system will be used by the various stakeholders.
- Effectiveness factors, or requirements tied to reliability, maintainability, personnel skill and efficiency.
- Environmental factors, or the environment in which the system is supposed to operate.
- Interoperability requirements are also included, and for the proposed system of systems to perform adaptive readiness assessment, these will be important.

As earlier defined, the ship and shore concept for the need statement involves four primary systems and their associated sub-systems:

1. The Mission-based Operational Assessment Tool (MBOET)
2. Satellite Data Transmission System (SDTS)
3. Shore-based Data Storage and Access System (SDSAS)
4. Product Life cycle Management System (PLMS)

Requirements defined in this section are deemed to be at the system level, to be decomposed across associated subsystems as required during a future state.

A. MISSION DEFINITION

In order to simplify the problem, this document generalizes a single mission warfare scenario. The system of systems demonstrates the process of pre-mission analysis and simulation designed to assess the probability of mission success over a defined time period for a discrete mission set. Next, the system of systems will transfer, analyze, and re-baseline the combat system software for continually improved fidelity of predictions of success.

There are varying ways in which the previously defined stakeholders provide inputs to the MBOET to receive output data used for similar or entirely different purposes. This relationship is reflected in Figure 11.

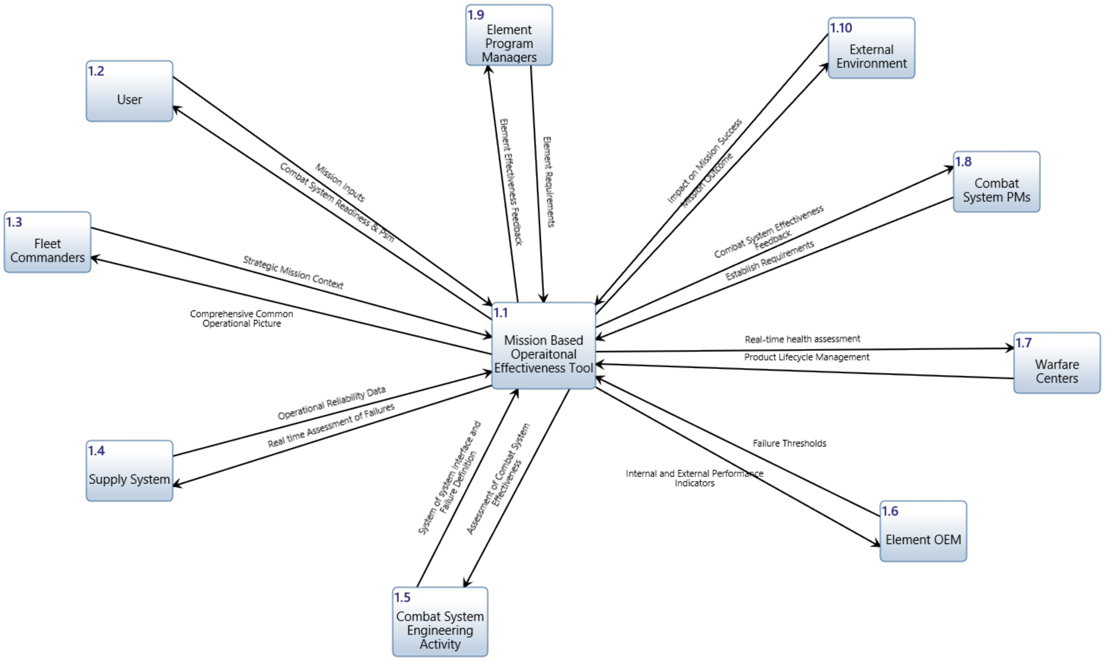


Figure 11. Inputs and Output to and from the MBOET

B. PERFORMANCE AND PHYSICAL PARAMETERS

The conceptual shipboard system will be incorporated into future software baselines and designed to interface with both operational and acquisition phase data, to include failure modes, failure effects, failure reporting, reliability, availability, maintainability, and fault identification information. The system will be able to capture system health information and transmit via SDTS to a shore-based location (SDSAS) for further analysis. The shore-based aggregating site will provide a product life cycle management environment (PLMS), with brokered access to all government and private entities that perform design, development, test, evaluation, and sustainment on individual systems and combat systems. The system will have the ability to redistribute software baseline updates to all systems on shore and at sea.

The shipboard system (the MBOET) is responsible for mission analysis, data ingestion, and simulation. It is limited by the overall latency of the combat system itself, as well as by physical space, weight, power, and cooling requirements.

Satellite and shore-based systems (SDTS, SDSAS, and PLMS) are responsible for data transfer, aggregation, brokerage, manipulation, and re-distribution.

1. Shipboard Systems

1. The MBOET and shall aggregate internal, external, OPTEMPO, duty, environmental and personnel indicators, including:

- Component humidity, component vibration, and component temperature, where these indicators are known to contribute to the degradation of performance or indicate failure or potential failure
- Duty cycle for critical mission systems as defined in the FMECA
- Failure modes (via Fault Detection)
- LRU run time
- LRU redundancy (RBDs)
- Functional Block Diagram
- Application of software reliability

2. The MBOET shall be able to adaptively apply mission boundaries, allocated performance, and scenarios.

3. The MBOET shall apply weightings for contributing mission systems according to defined mission threads and mission reliability block diagrams

4. The MBOET shall assess missions based on mission threads that are defined and refined throughout the development and sustainment phases of the program.

5. The MBOET shall be able to simulate at least XX number of mission simulations within XX timeframe.

6. The MBOET shall include failure simulation, environmental parameter impact, and human error impact.

7. The MBOET shall fit within a XX space, XX weight, XX power, and XX cooling envelope.

8. The MBOET shall be able to interpret fault identification codes from all elements of the combat system.

2. Satellite and Shore-Based Systems

1. The SDTS system shall be able to transfer up to XX megabytes in any given 24-hour period.

2. The SDTS system shall be able to transfer both classified and unclassified data.

3. The SDSAS shall be able to store XX petabytes of data.

4. The SDSAS shall provide visualization tools and allow users to assess shipboard baseline deviations for more detailed analysis.

5. The SDSAS shall provide brokered access for XX number of government and contractor users to be able to access information as controlled by the government.

6. The PLMS shall store all unique logistics product data that exists for systems, subsystems, line replaceable units, and components, to include:

- FMECA
- reliability block diagrams
- mission threads
- part numbering and nomenclature
- reliability data

- maintainability data
- supply data
- part run time and repair history
- part cost for repair
- part cost for replacement

7. The PLMS shall link directly to the combat system software baseline and automatically populate software with revisions of suitability metrics upon change.

C. OPERATIONAL DEPLOYMENT

Shipboard systems will be deployed as part of combat system baselines and developed under managed, new baseline development efforts. Shore-based systems will be deployed in a manner that facilitates growth in data transfer and storage. PLM systems will be deployed as part of a coordinated effort to align all combat system life cycle management under a singular tool.

1. Shipboard Systems

1. The MBOET shall be deployed with a new Baseline update of a combat system.
2. MBOET shall interface will all shipboard systems that are allocated to the detect to engage sequence as defined by NMETLs for all platform warfare areas.

2. Satellite and Shore-Based Systems

1. The SDSAS shall be deployed within the continental United States.
2. The PLMS shall be deployed within the continental United States.

D. OPERATIONAL LIFE CYCLE

The shipboard system shall be composed of both software and interfaces and shall be managed centrally and updated as configurations of combat system and combat system element hardware and software is updated over its life cycle.

Shore-based infrastructure shall be in operation for the duration of the combat system program. As combat system software baselines are retired, the shipboard and shore-based systems will cease support.

1. Shipboard Systems

1. The MBOET shall be configuration managed by a singular combat system engineering activity.
2. The combat system readiness system shall be updated over its life cycle to accommodate new systems, subsystems, and LRUs as well as new missions and data sets.

2. Satellite and Shore-Based Systems

1. The SDTS shall have an operational life cycle of XX years, or until replaced.
2. The SDSAS shall have an operational life cycle of XX years, or until replaced.
3. The SDSAS shall have the ability to transfer proposed updates to suitability metrics to the PLM database for review.
4. The PLMS shall have an operational life cycle of XX years, or until replaced.
5. The PLMS shall be managed jointly by a government activity and a combat system engineering activity.
6. The PLMS shall be able to store information up to and including Secret classification.

E. UTILIZATION REQUIREMENTS

Knowledge of the state of readiness is a capability that has asymmetric utilization requirements but is always required. Shipboard capability retains a higher priority, as it is the first support tool that deployed assets will utilize to assess preparedness for a mission.

1. Shipboard Systems

1. The MBOET shall be in operation prior to the execution of any combat system mission.

2. The MBOET shall be able to operate during the execution of the mission and reflect revisions of the probability of operational success based on combat system element system input.
3. The MBOET shall include projections beyond initially defined mission scenarios.
4. The MBOET shall be available at all times the combat system is available for tasking.

2. Satellite and Shore-Based Systems

1. The SDTS shall be able to handle XX transmissions per day.
2. The SDTS shall be able to transfer XX megabytes of data per day.
3. The SDTS shall be able to transfer data at a speed of XX megabytes/second.
4. The SDSAS shall be able to broker and manage user access.
5. The SDSAS shall hold information up to and including the Secret level of classification.
6. The PLMS shall be able to manage up to XX users.
7. The PLMS shall store baselined combat system mission threads.

F. EFFECTIVENESS FACTORS

The MBOET system is to be measured against its own predictions in order to improve the overall efficiency and accuracy of the projected probability of success of a mission. As such, any time a system projects success above XX% and a mission terminating failure occurs, the overall readiness projection system will have been deemed to have “failed.”

1. Shipboard Systems

1. The MBOET shall have an availability of XX%.
2. The MBOET shall have a Mean Time Between Software Critical Failure of XX hours.
3. The MBOET shall have a Mean Simulations Between Failure of XX simulations.

4. The MBOET shall maintain an XX% accuracy rate, graduating to a XX% accuracy rate over a period of XX years.

2. Satellite and Shore-Based Systems

1. The SDTS shall have an availability of XX%.
2. The SDSAS shall have an availability of XX%.
3. The PLMS shall have an availability of XX%.

G. ENVIRONMENTAL FACTORS

The shipboard and shore-based systems are to be designed to operate in their respective environment, with the shipboard systems assumed to be kept below deck with the rest of combat system processing equipment.

1. Shipboard Systems

1. The MBOET will operate within a XX environment.

2. Satellite and Shore-Based Systems

1. The SDTS system will operate in a XX environment.
2. The SDSAS will operate in a XX environment.
3. The PLMS will operate in a XX environment.

H. INTEROPERABILITY REQUIREMENTS

After aggregating the varied inputs, the MBOET must apply a framework by which the inputs can be ingested and transformed into a probability of successful mission calculation. Moreover, the P_{sm} may be decomposed further into lower-level probabilities of success, such as the probability of successful hard kill or probability of successful soft kill. These are not discussed in this paper.

1. All systems shall be able to interoperate.
2. All systems shall use a publish/subscribe data model for sharing of data.

IV. FUNCTIONAL ANALYSIS

Blanchard and Fabrycky (2011) define the Advanced System planning process as one tied to linking the definition of need to an overarching architecture and plan. Leading up to the process outlined in this study, feasibility analysis, support analysis, and design trades will have already been studied.

Given the nature of the need statement for the capability to adaptively assess health, much of the effort is known to be feasible within existing combat system architecture or is commercially available, provided the correct input data is coordinated to enter the shipboard and shore-based systems. Thus, this capability need moves directly into the creation of a technical approach and application of functional analysis.

A. TECHNICAL APPROACH TO SHIPBOARD READINESS ASSESSMENT

The complex tactical environment for combat systems clearly aligns to the performers of NMETs. In doing so, integrated combat systems can use structured missions defined by “mission analysis” and “mission planning” phases of operational planning, using the NMETL to identify system boundaries and allocate systems and subsystems to mission-essential tasks. System physical and functional data sets are then tied to mission and a common baseline is set.

In reviewing NMETs associated with a warfare scenario, specific taskings are aligned to systems and subsystems the operate as part of an integrated system of systems. These systems perform discrete functions and have been designed to meet specific performance parameters, to include reliability, maintainability, and availability requirements under the constraints of a design reference mission.

Combat systems are multi-mission, and warfare scenarios can be either more or less demanding depending on the threat set. For advanced threats or high intensity environments, a higher OPTEMPO will need to be considered as opposed to that used for the design reference mission. Thus, variable assessment of these mission scenarios is considered.

1. System Functional Allocation Example: Air Warfare Scenario

As an example, a genericized hierarchy of systems organized by capability in the detect to engage sequence is seen in Figure 12. The primary sensor that serves surveillance, detection, localization, and tracking (NMETs) is a singular system, Sensor 1. Sensors 2 and 3 serve as redundant or back-up systems.

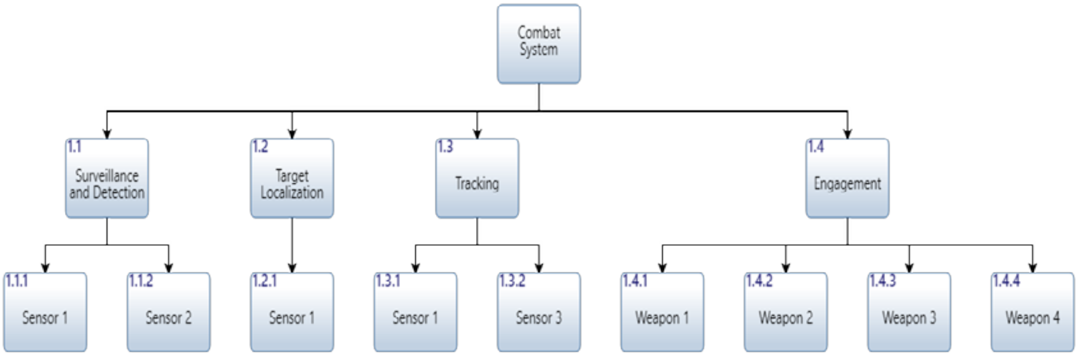


Figure 12. Hierarchy of System in the Detect to Engage Sequence

For sensor 1 to meet each capability, a threshold of performance must be established under defined conditions and duration. As such, an adaptive readiness assessment would need to include all three capabilities (Surveillance and Detection, Target Localization, and Tracking) and each associated demand on the system from that capability.

Where allocations for the system-level performance of Sensor 1's reliability was a mean time between mission terminating failure of 500 hours under the stress of the design reference mission, it may become 275 hours based on the stress of the task at hand. The true demand and failure rates of the system rely on tracing sensor self-reporting through the rest of the conceptual architecture.

2. Scenario Development

Once systems have been functionally allocated, the MBOET must build scenarios predicated on the tasking defined by the NMETLs associated with the warfare scenario, to include such tasks as those reflected in Attachment 1, the CG required operational capabilities and projected operating environment for a notional air warfare tasking (Fanta 2014).

The MBOET builds mission scenarios and associated OPTEMPO profiles necessary to meet these NMETLs, initially reflecting multiple pre-generated scenarios. The MBOET must then update scenarios dynamically over time based on actual mission execution data and system tasking and health data. An example of a notional pre-generated scenario (similar to a design reference mission) is reflected in Figure 13 and Figure 14.

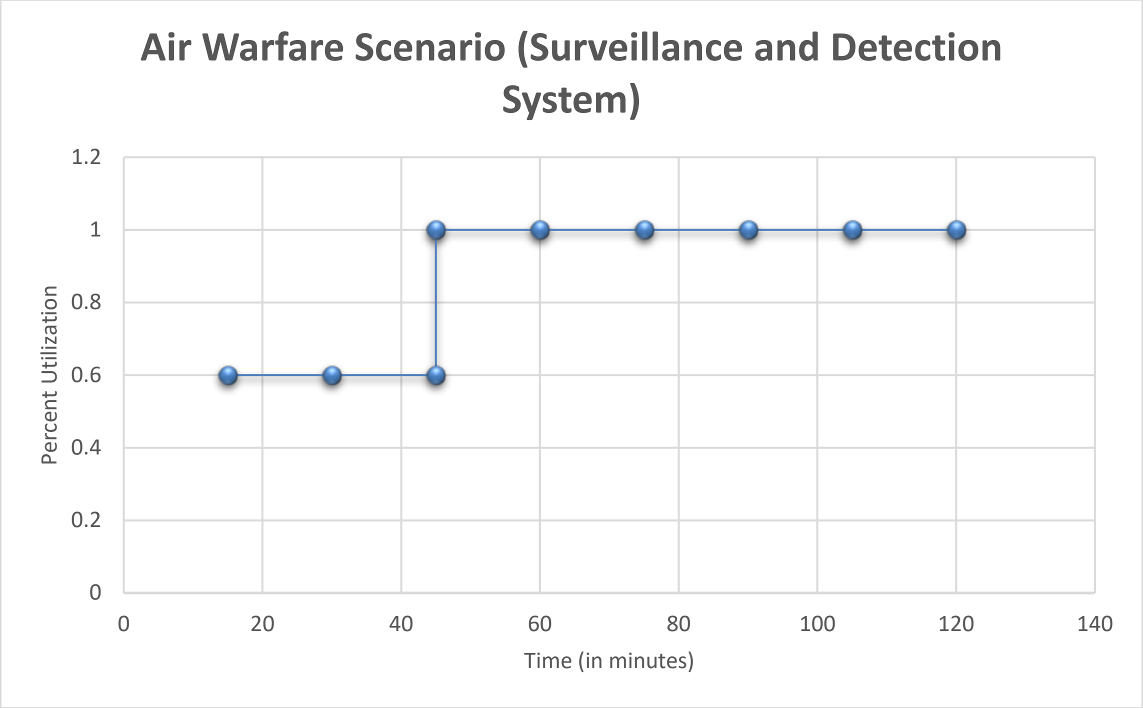


Figure 13. Notional Surveillance and Detection System Utilization in Air Warfare Scenario

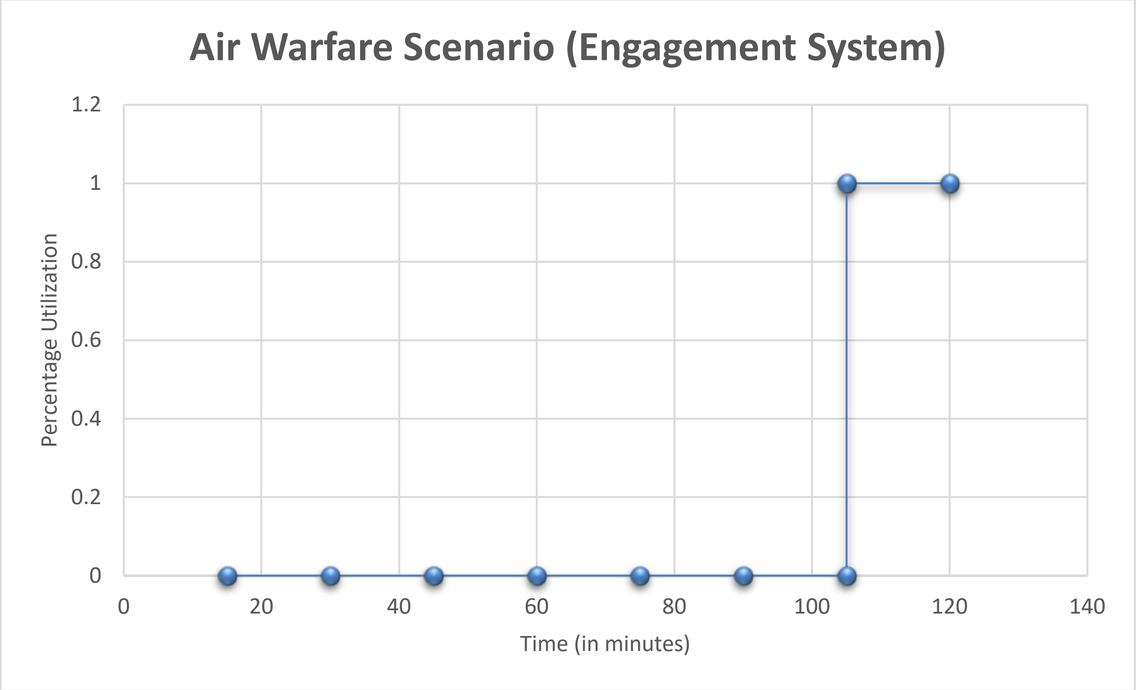


Figure 14. Notional Engagement System Utilization in Air Warfare Scenario

It is critical to recognize that for both the surveillance and detection and the engagement functional capabilities, the redundant systems in the kill chain (e.g., Sensor 2 and Sensor 3) will have wholly different utilization profiles.

As actual input variables are recorded over defined mission sets, the percentage utilization of the sensor will be tracked over time and aggregated for future machine learning and artificial intelligence application, ultimately resulting in a refined mission scenario simulation that best reflects a mission-based baseline scenario for an air warfare mission.

3. Usage of Analysis

By this point, each system, based on the task at hand and via expert analysis, has been assigned a threshold of performance that must be met in order to achieve success, which is defined as the successful execution of all mission essential tasks, in the projected environment, for the projected duration of the mission.

Due to the complexity of potential naval mission sets, an iteratively improving process must be adopted in order to refine P_{sm} calculations. In a base scenario, simulations of system-level performance may be run on the ship to verify the P_{sm} under multiple threat sets and combined scenarios.

Each threshold of functional failure varies depending on the mission, creating a unique scenario each time a simulation is run. This mission simulation would be populated with system thresholds and simulated with weighted external environmental indicators from sensors to determine the contribution to the probability of failure within the system.

Next, the MBOET would combine these inputs with reliability block diagrams that would determine both the likelihood of multiple failures and the impact of the loss of redundancy. It may also be used to simulate beginning the mission without redundancy restored.

4. Information and Interfaces

As discussed, multiple indicators can be utilized to assess the impact on system performance during one of many scenarios. In the instance of a combat system, a Mission-Based Operational Effectiveness tool would be developed with interfaces to various external systems that seamlessly provide information through common messaging traffic. As defined in the requirements, the MBOET is responsible for ingestion of material condition parameters including:

- operating environmental conditions, to include temperature, humidity, and vibration
- information on critical component faults as defined in the Failure Modes, Effects, and Criticality Report
- current system condition at every level of indenture

These parameters are merged with assessments of known design information, such as reliability block diagrams, FMECA, maintainability information, mission parameters, mission length, and current system condition to generate a probability of successful mission.

If a risk-based assessment has been conducted by the commanding officer and they deem the mission un-executable, relevant outputs from the MBOET could provide actions to take to improve the probability of success of the mission, to include:

- targeted preventative maintenance
- targeted corrective maintenance
- a viable reduced OPTEMPO that heightens the probability of mission success
- a viable reduction of mission length that increases the probability of mission success

As the last resort, in the event that any of these MBOET assessments do not meet the established threshold of performance necessary to execute the mission over a defined period of time, as allocated by NMETs, a broader survey of forces should be conducted to identify other available naval assets.

The whole process of mission assessment is seen as an activity diagram in Figure 15.

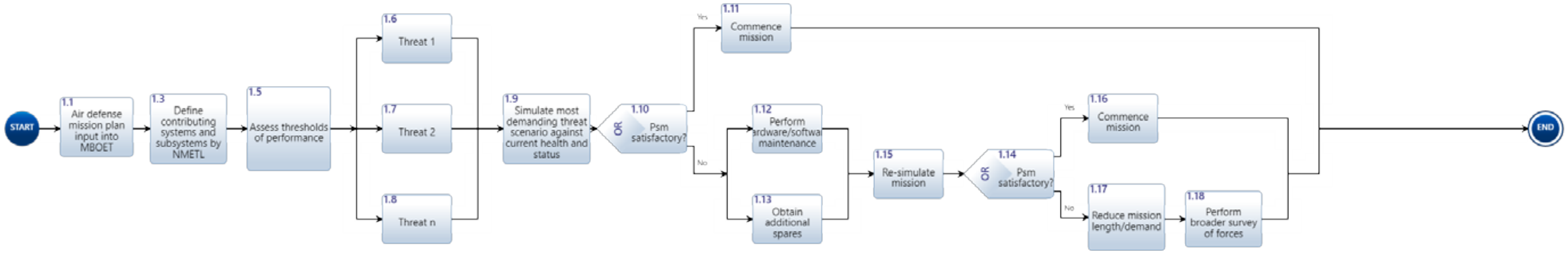


Figure 15. Mission Assessment by NMETL

THIS PAGE INTENTIONALLY LEFT BLANK

V. ARCHITECTURE ANALYSIS

In consolidating a primary problem set that spans multiple program offices, companies, and other organizations, there are gaps that must be filled. In execution, the simple act of aligning one of the four proposed systems in the conceptual architecture is a challenging array of software development and interfacing.

A. BRIDGING THE SHIP AND SHORE IN A SYSTEM OF SYSTEMS

To successfully streamline data management, the shipboard combat system architecture must merge with that of the shore-based. A high-level event trace diagram as seen below helps visualize how the transition of data from ship to shore comes together. As seen in Figure 16, the four major systems combine to provide a flow of information that is aggregated from the ship, disseminated to shore, updated in a product life cycle management tool and in the combat system software baseline, and re-constituted as a revised fleet-level software update.

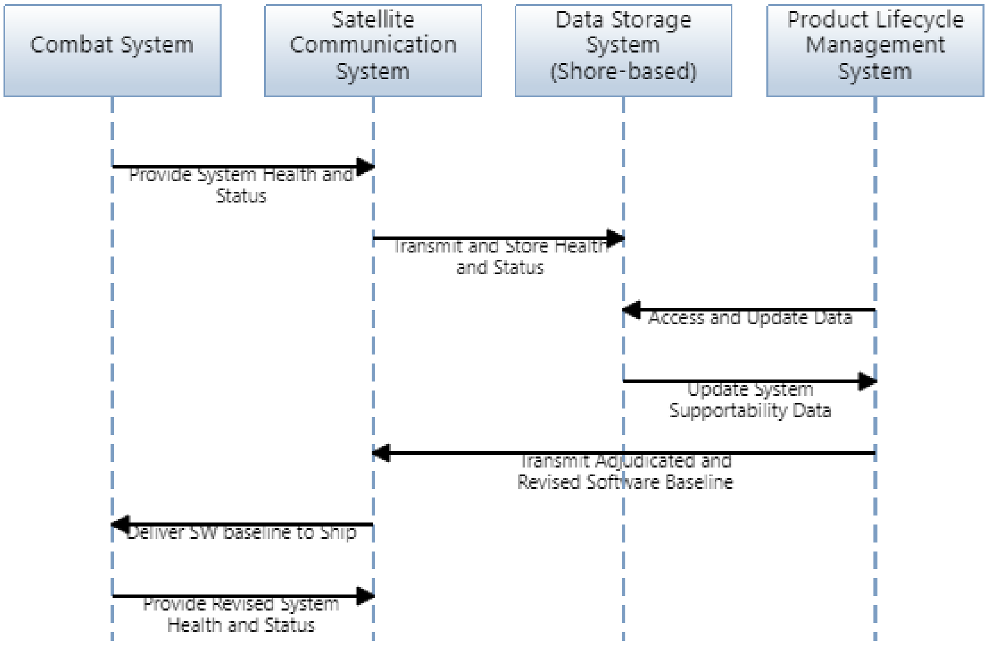


Figure 16. Event Trace of Information Flow in System of Systems

B. CLOUD-BASED READINESS AND FLEET ASSESSMENT

From the cloud, higher-order analysis can be performed in a centralized and coherent manner. Fragmented acquisition and implementation efforts can constrain the conceptual framework, so maintaining ownership under a singular sponsor and owner aids in execution. In this case, the owner is the government program office that maintains oversight of the combat system engineering activity (CSEA).

Each ship, in its own configuration, provides unique insights, managed in the cloud-based product life cycle management tool. Individual ships maintain their own characteristics and configurations, but once data is aggregated, fleet-level analysis may influence how software baselines carry thresholds of readiness in the future. The aggregation process is seen in Figure 17.

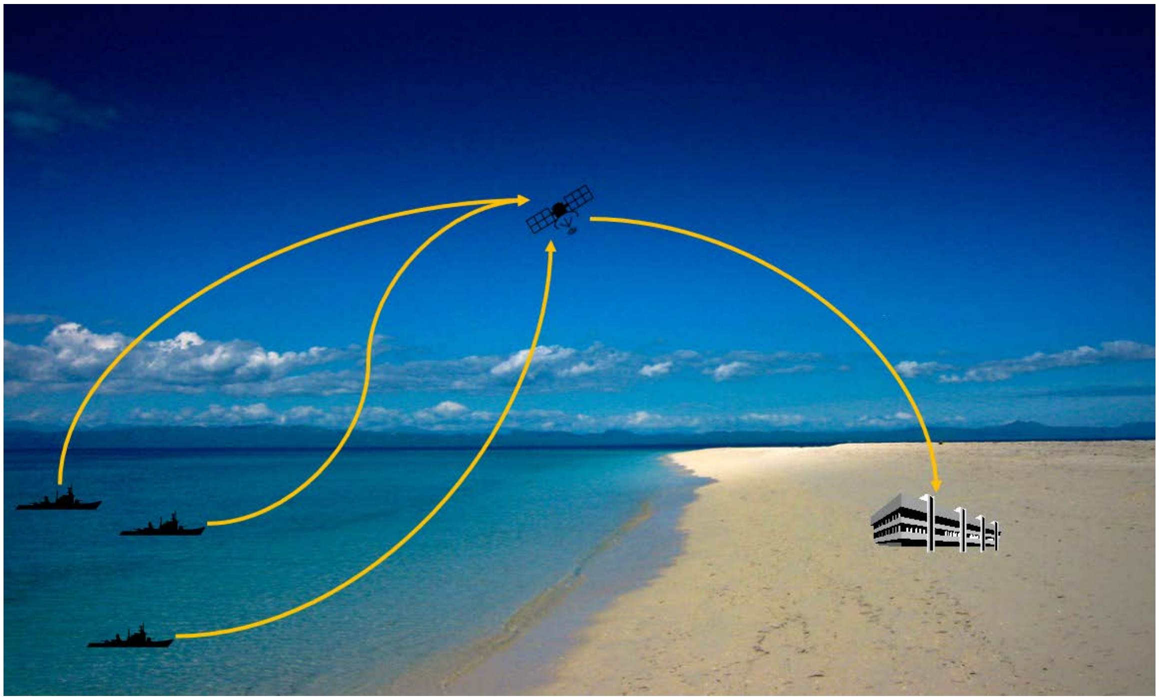


Figure 17. Multiple Ships Aggregating Information Ashore. Adapted from Flickr (2010) and Silver Bullet, Inc. (2005).

Centralizing information covers one step. The second step is the one that blends data-driven decision processes and expert system decision processes. Jung, Niculita, and

Skaf (2018) laid out a framework for fault diagnosis that covers the complexity of combat systems and their constituent systems.

In it, they define two primary methods of diagnosis, that being model-based or data-driven, covering qualitative and quantitative factors. In complex systems, data-driven solutions are still predicated on proper test point definition, trend analysis, and structured or unstructured data analysis. Thus, a blended approach is desired, combining this data with expert system developer input and data in an Observe, Orient, Decide, Act loop, as seen in Figure 18.

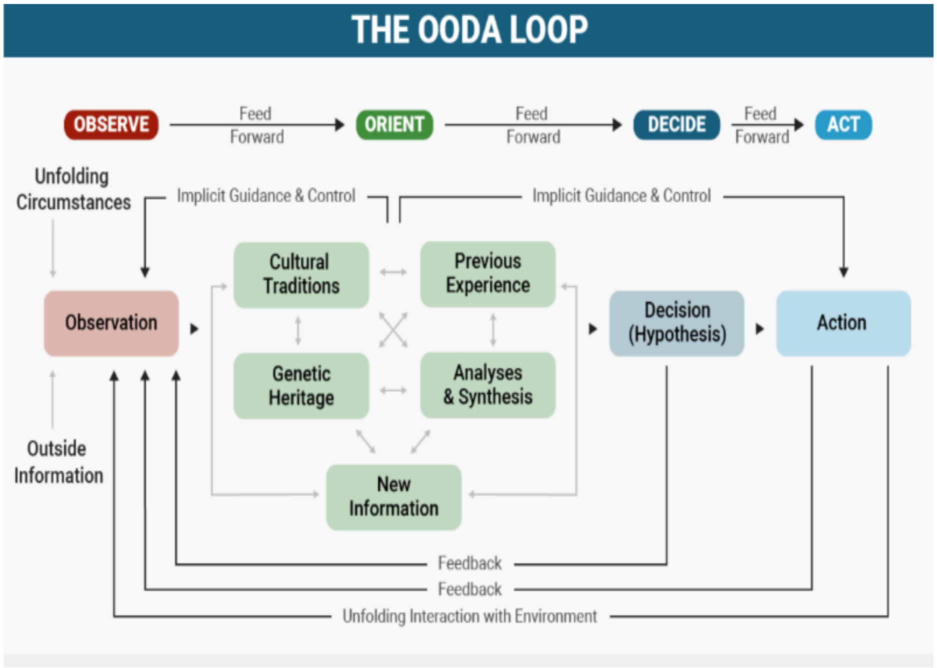


Figure 18. The OODA Loop. Source: Feloni and Pelisson (2017).

The OODA loop will be used to intake data-driven analysis (observe) and blend it with expert analysis (orient). The decision to update the software baseline is held by the government and combat system engineering activity, resulting in the final action (decide/act), that of pushing a new software update with updated scenarios and mission failure thresholds forward to deployed ships.

1. Refinement Process Decomposed

Figure 19 represents a combat system that has successfully baselined algorithms during development. The basis for this process is developed from initial failure mode analysis, which is then traced to mission readiness, and modeled. Via common interface messaging across elements, the ICS pulls pertinent system health information for an adaptive assessment of readiness.

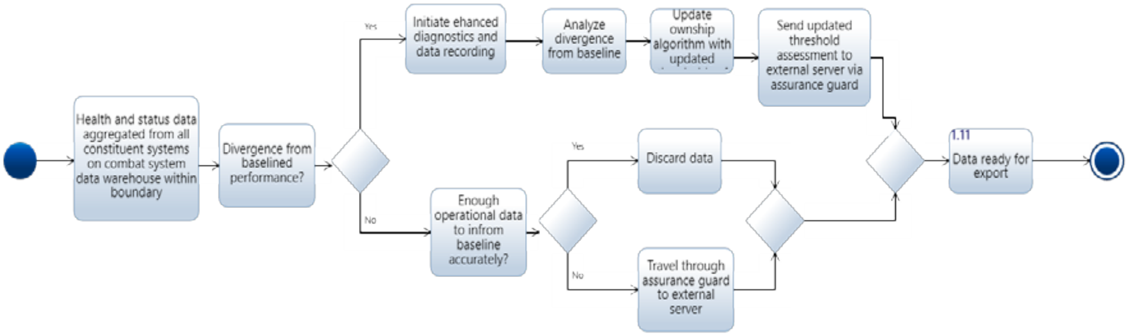


Figure 19. Combat System Update and Ship Information Ready for Export

By utilizing health message traffic and assessing divergence, the ICS can use fewer system resources and can utilize machine learning techniques to update shipboard algorithms within austere environments until a revised fleet baseline of performance can be delivered.

Once the information has reached the server external to the integrated combat system, a policy and process flow occurs that requires close coordination of most of the stakeholders identified.

The process decomposes into five major steps, all requiring strong process control. The steps include:

1. Bulk Data Transfer
2. Sustainment Engineering Review
3. Element OEM Review
4. Combat System Engineering Activity Review
5. Software Baseline Update

a. Bulk Data Transfer via the SDTS

BDT serves as a variable factor in the process, as the time and ability to execute rests in mission posture, resource allocation, time of day, and bandwidth capability. In practice, the process of transfer should take place during scheduled downtime, sending existing data in shipboard combat system servers back to the SDSAS. This data warehouse would provide a central repository for multiple user access across combat system element level original equipment manufacturers, the CSEA, and naval sustainment engineering activities.

b. Sustaining Engineering Review

The SER is a government activity review of all combat system element data sets. Its core purpose rests in being a central clearinghouse for sustainment modeling and for AI tool validation/verification. The output from this review are programmatic budgetary and readiness decisions. Participants in this review include element level subject matter experts (SME), combat system SMEs, and integrated combat system (ICS)/element program offices. This process is reflected in Figure 20.

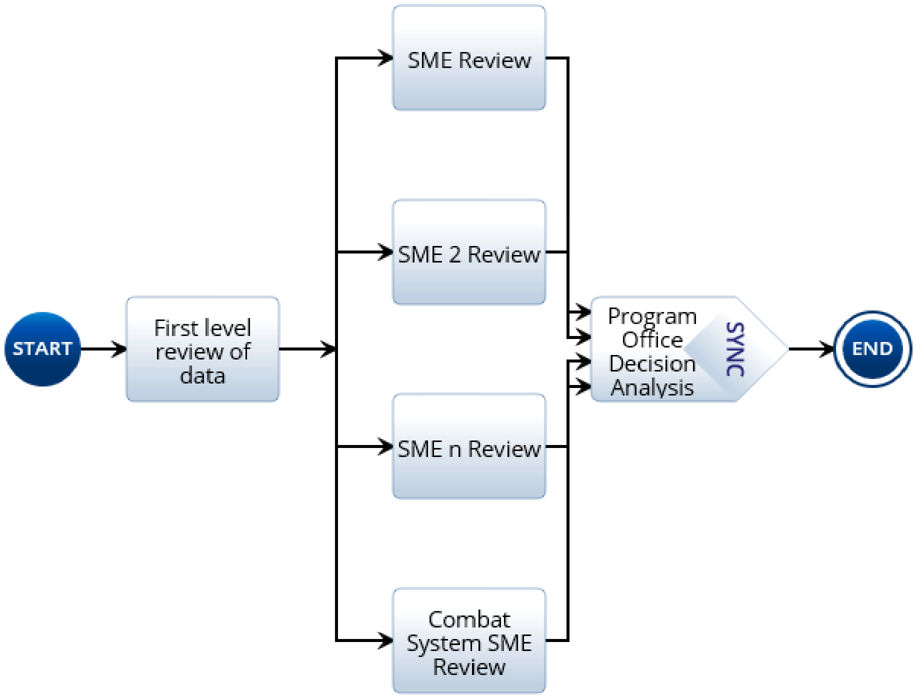


Figure 20. Government Sustainment Engineering Review

c. *Element OEM Review*

The EOR is an internal review from Design Agents of combat system elements (i.e., surveillance and detection system, tracking system, engagement system), and is meant to perform detailed analysis of failure modes, reliability metrics, fault identification, failure threshold refinement, element level functional performance assessment, and software update proposal for ICS integration. This includes a system and subsystem level analysis that assesses both data-driven recommendations from fielded systems and expert analysis for the incorporation of new improvement projects. The process is seen in Figure 21.

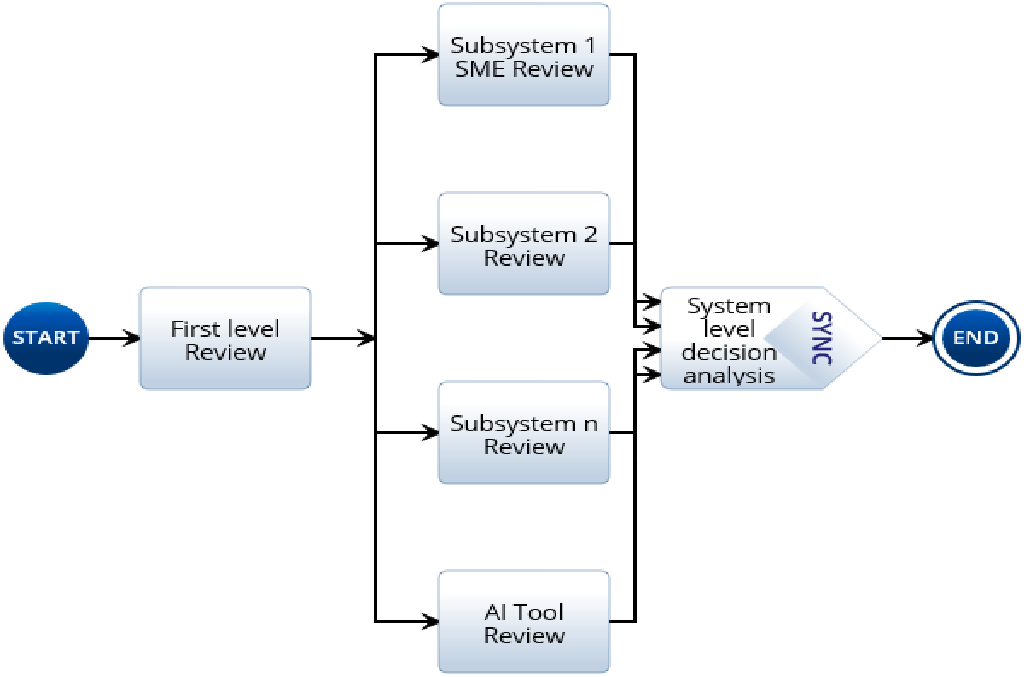


Figure 21. Element OEM Decision Analysis Process

d. *Combat System Engineering Activity Review*

The CSEA Review process is the central decisional process for synthesizing inputs from government and OEM experts. The CSEA develops and manages the baseline software code and is responsible for integrating variable inputs from external stakeholders and deriving a system of systems readiness assessment. Included in the CSEA scope are a probabilistic assessment of individual mission success across all integrated elements, fusion of element level functional performance assessment, and aggregation of multi-platform level data into a continuous refinement effort to reduce uncertainty in ICS readiness assessment. This process is reflected in Figure 22.

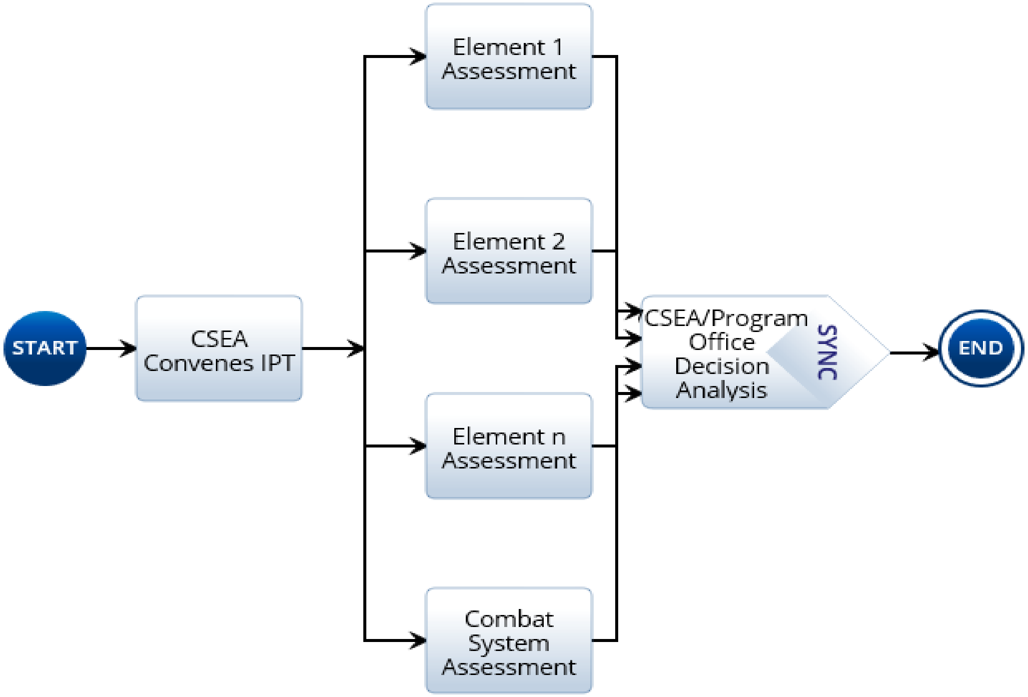


Figure 22. CSEA Synthesis and Assessment

e. Software Updates and Re-delivery

At regular intervals, data analysis groups convene to agree upon software configuration changes in alignment with the CSEA baseline deviation assessment. Algorithm updates would be pushed to all supported platforms and the cycle of data capture and refinement would begin again.

C. THE RESULTING OPERATIONAL PICTURE

Figure 23 represents the final conceptual framework by which data-driven decisions are reviewed by design agents, combat system engineering activities, government experts, and by machine learning (ML) and artificial intelligence (AI) tools, with the goal of facilitating and adjudicating the environment in which a threshold of functional failure is defined and articulated through the MBOET. Thus, a continual refinement process is implemented.

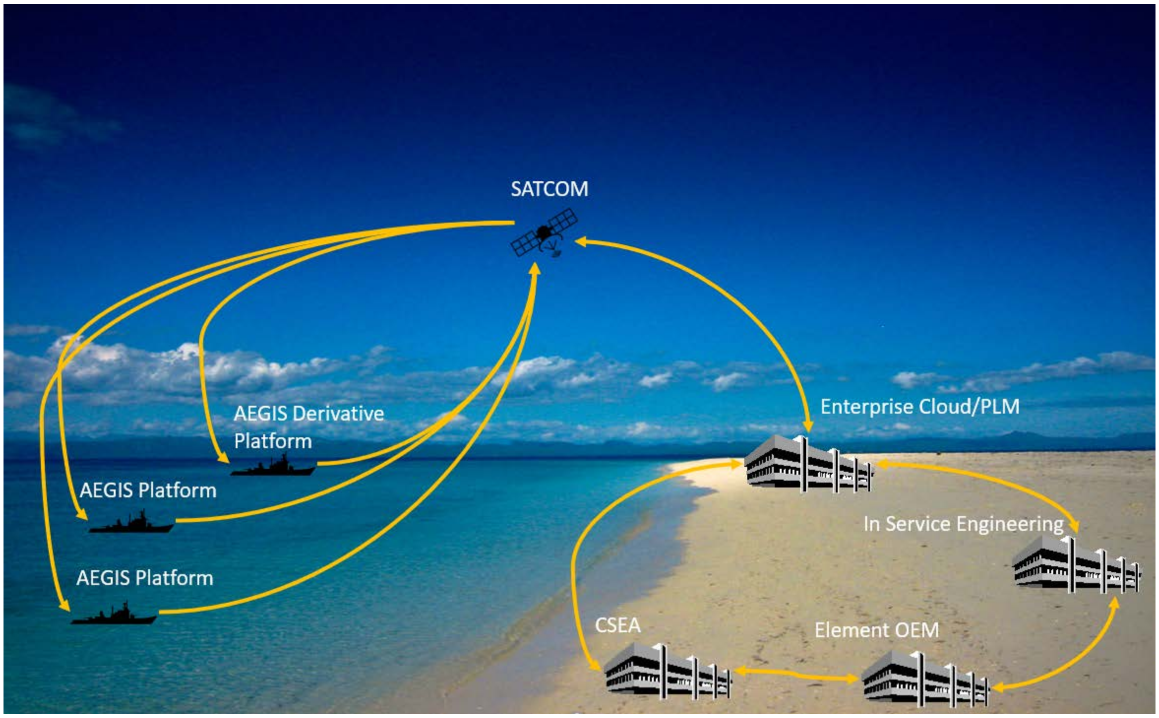


Figure 23. The Operational Context of the OODA Loop. Adapted from Flickr (2010) and Silver Bullet, Inc. (2005).

D. LIMITATIONS

A primary limitation of this analysis is the allocation of requirements in the functional analysis. Thus, requirement ownership should be assessed and decomposed amongst areas of programmatic responsibility, as well as aligned to the realities of resources and schedules. A dedicated product roadmap should reflect capability integration, roles, and responsibilities. An example of an integrated roadmap strategy that can be utilized is seen in Figure 24.

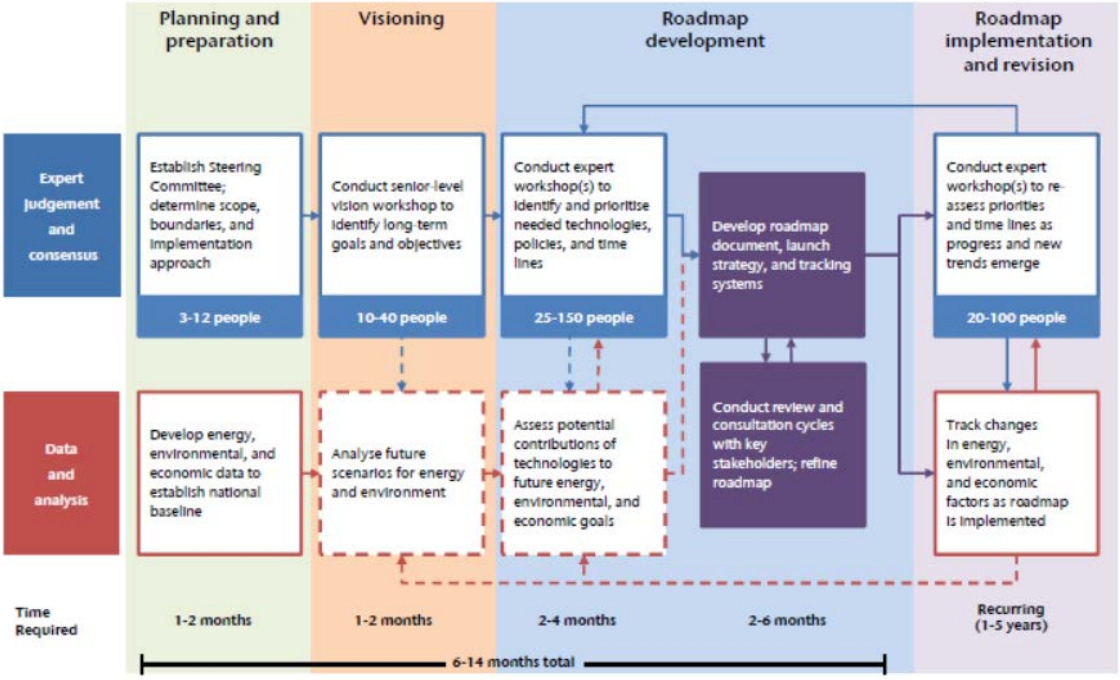


Figure 24. Sample IT Development Roadmap. Source: Acqnotes (2018).

As the concept matures, continued analysis and studies must be performed in order to identify requirements that are both feasible and meet the overall intent of the program. Specific requirements, such as latency, bandwidth, size, weight, power, cooling, and storage must all be assessed to determine the correct balance of capability and cost.

1. SDTS Considerations

This system requires additional analysis to understand how existing product roadmaps may support broadened data reduction and transfer needs. As the next generations of satellite communications are brought to bear, some of the fundamental barriers to real-time streaming of data and associated edge and cloud-based assessment become less restrictive. Defining system allocation/needs will be critical to scoping the development efforts of future satellite communication systems.

2. SDSAS Considerations

This system will require more study to understand both the quantity of information coming off sensors and edge equipment and the velocity at which that information is generated. Additionally, there are significant cybersecurity implications to housing the current status of readiness of all naval assets in a singular location. As this system matures, other conceptual solutions may be considered and/or utilized in the name of data integrity and security.

3. PLMS Considerations

The PLM system remains the heart of the configuration of the combat system software baseline as well as the configuration of mission analysis and threads. The revision of this data, which serves as the singular authoritative data source for all system suitability information will need to be integrated with both shipboard and shore-based architecture in order to facilitate streamlined data update and analysis.

Additionally, building a digital representation of systems within this environment will provide the ability to simulate off the ship and refine software baselines more quickly than by receiving shipboard feedback.

VI. CONCLUSION

As new naval combat system baselines are developed and delivered, a comprehensive, public/private integration effort must take shape to synthesize mission data sets and system analysis to achieve a desired end state of material and functional mission readiness assessment, both automatically and dynamically delivered.

Thresholds of performance and mission scenarios are living pieces of data and expert assumptions within the integrated combat system, as areall pieces of sensor information that stream across the combat system local area network. Changing these assumptions and inputs can vastly change the likelihood a system will be able to know if it can execute its mission.

Through careful planning and data management, ship level edge computing equipment can be utilized to consolidate internal and external data points, such as suitability metrics, reliability block diagrams, or environmental indicators, in order to provide ordered analysis of the combat system's current ability to achieve stated mission objectives.

Enabling shore-based architecture allows the assessment to learn and become higher fidelity over time, eventually resulting in the answer to the singular outcome every stakeholder needs to know: "Does the system work?"

A. FOLLOW-ON WORK

1. Joint Environment

Each constituent system in a complex System of Systems represents both production and consumption of data. A satellite communication system may consume data from an E-2D aircraft while also producing its own health and status information for internal or external use. An example of a complex integrated Operational View can be seen in Figure 25.

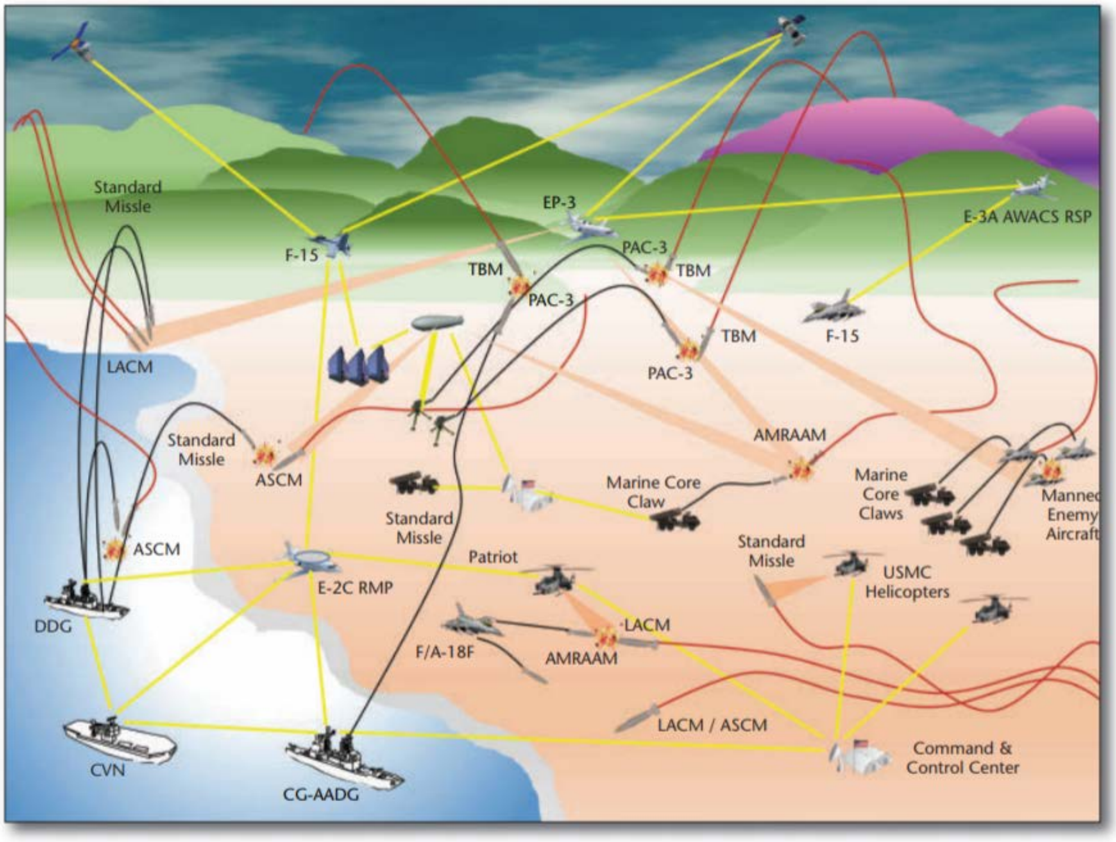


Figure 25. Sample Integrated Joint Tactical Environment. Source: Johnson (2019).

The complexity of this joint environment and the adoption of concepts of distributed lethality (Rowden, Gumataotao, and Fanta 2015) means the complexity of mission readiness increasingly becomes more multi-layered. Analysis of how joint systems relate total mission readiness assessments will also become more complex.

2. Failure Distribution

Complex combat systems will inevitably be an amalgamation of diverse failure distributions and properties. A mechanical failure distribution of a cooling system is different from an electrical failure distribution, and the indicators of failure are different for different components and systems.

Combining both external environmental inputs and system of systems failure propagation creates increasingly complex failure situations that present themselves as opportunities for utilization of advanced techniques that adaptive analysis can attempt to solve.

3. Complex System Failure

Kreinovich, et al. (2011) also define the set of information necessary to predict failure in complex systems as having a few key inputs:

- when the failure of components and subsystems lead to the failure of the complex system as a whole,
- reliability of components and subsystems, and
- whether the component failures independent events or they are caused by a common cause

The essence of this statement can be extracted to a need for functional block diagrams, associated allocation of reliability to both systems and components as it relates to these functions, and identification of whether failure events are independent or linked. If assessing a system in a benign environment or during concept development, these pieces of information may be satisfactory. In a naval environment, there are additional inputs that will have a significant impact on performance.

Furthermore, Kreinovich, et al. (2011) define various scenarios of SoS failures including when:

- Component Failures are Independent and Failure Probabilities P(A) Are Exactly Known
- Cases When We Know the Probabilities P(A) with Uncertainty
- Component Failures are Independent, Failure Probabilities P(A) Are Known with Interval Uncertainty

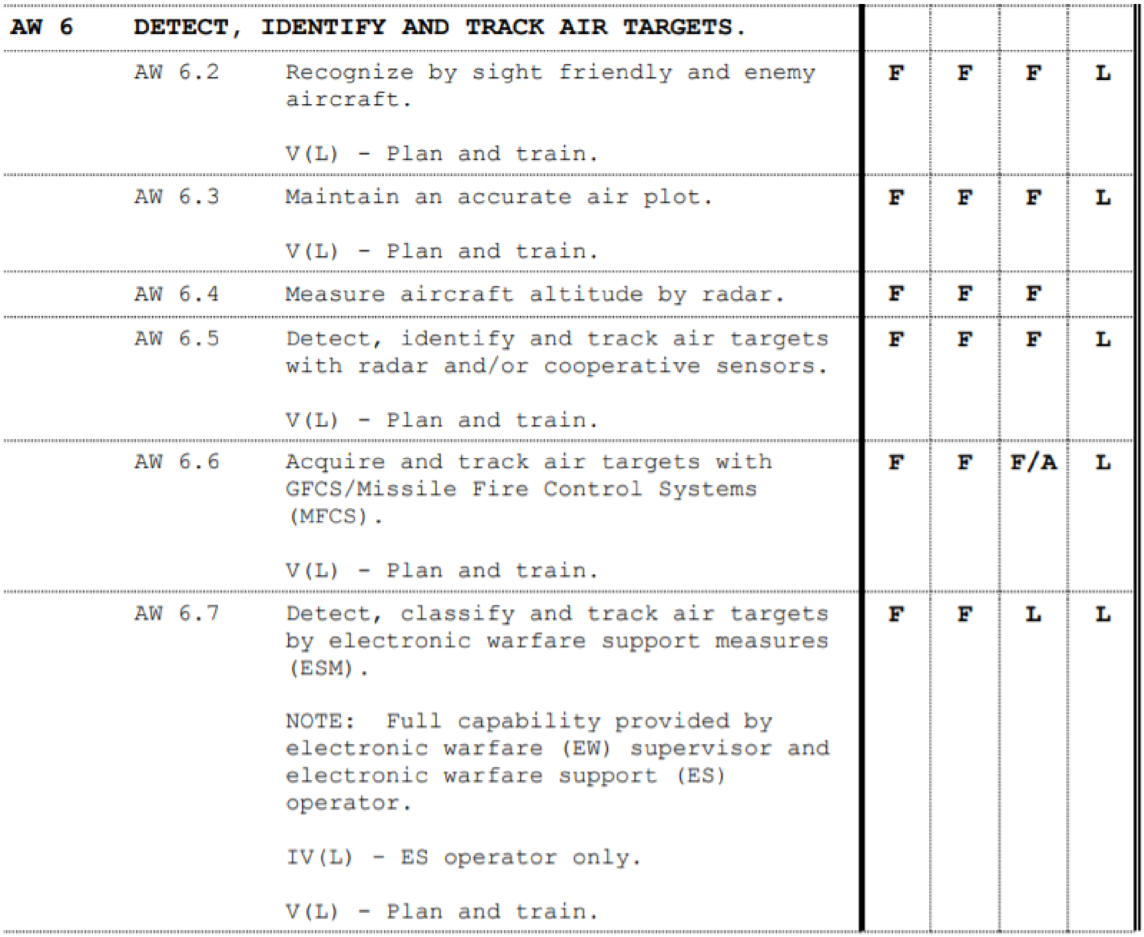
Any of these situations are complex in and of themselves and assuming independence from external and internal variables that can further increase the variability. This complex system of system behavior should be studied.

4. Software and Interface Considerations

As newer systems are being developed, adjustable parameters embedded within the delivered software code provide both flexibility and ambiguity, as they can be used to set thresholds of functionality tied to physical performance. This functionality is largely driven by the ability to detect failure in systems. Fault detection and isolation encompasses a broad range of practices. Frequently, all of these practices include the utilization of sensors and software to run tests and search for prescribed value sets that correspond to "functional" or "not functional." The improvement of fault detection capability will ultimately drive more accurate data reporting and could be studied.

Additionally, streaming information from the IoT in real-time is enabled by addressing constraints in the combat system themselves such as boundary defense, cybersecurity, built-in test capability, and mission to function mapping. Solutions to these problems have to be investigated.

APPENDIX. CG (TICONDEROGA CLASS) REQUIRED OPERATIONAL CAPABILITIES AND PROJECTED OPERATING ENVIRONMENT FOR AIR WARFARE



AW 6	**DETECT, IDENTIFY AND TRACK AIR TARGETS.**					
	AW 6.2	Recognize by sight friendly and enemy aircraft. V(L) - Plan and train.	**F**	**F**	**F**	**L**
	AW 6.3	Maintain an accurate air plot. V(L) - Plan and train.	**F**	**F**	**F**	**L**
	AW 6.4	Measure aircraft altitude by radar.	**F**	**F**	**F**	
	AW 6.5	Detect, identify and track air targets with radar and/or cooperative sensors. V(L) - Plan and train.	**F**	**F**	**F**	**L**
	AW 6.6	Acquire and track air targets with GFCS/Missile Fire Control Systems (MFCS). V(L) - Plan and train.	**F**	**F**	**F/A**	**L**
	AW 6.7	Detect, classify and track air targets by electronic warfare support measures (ESM). NOTE: Full capability provided by electronic warfare (EW) supervisor and electronic warfare support (ES) operator. IV(L) - ES operator only. V(L) - Plan and train.	**F**	**F**	**L**	**L**

AW 6.12	Detect, identify and track ballistic missiles with radar and/or cooperative sensors. IV, V(L) - Plan and train.	**F**	**F**	**L**	**L**
AW 6.13	Identify air targets as friendly/non-friendly using transponder interrogation equipment. V(L) - Plan and train.	**F**	**F**	**F**	**L**
AW 6.15	Identify air targets using non-cooperative target recognition. NOTE: Applicable to those ships with Shipboard Advance Radar Target Identification System installed. IV, V(L) - Plan and train.	**F**	**F**	**L**	**L**
AW 6.21	Correlate onboard sensor targeting information with link 16. IV, V(L) - Plan and train.	**F**	**F**	**F**	**L**
AW 6.22	Detect, track, classify, and identify cruise missiles. NOTE: Applicable in those ships with combined engagement capability (CEC) installed. III(L) - One of two launchers manned. Maximum use of automated engagement management systems. Requires manning of TAO, combat systems coordinator, missile systems supervisor and AW coordinator. Gun engagements using one of two guns require manning of GFCS console and EP2 operators. CIWS RCP operated by missile system supervisor. IV, V(L) - Plan and train.	**F**	**L**	**L**	**L**

AW 7	**CONTROL DCA (REQUIRES FULL ALLOWANCE OF AIR INTERCEPT CONTROLLERS (AIC)).** NOTE: Full capability during condition I and condition III requires one AIC on watch.				

AW 7.1	Support/conduct air intercepts/ engagement missions against aircraft and subsurface, surface, or air-launched missiles. V(L) - Plan and train.	**F**	**F**	**F/A**	**L**
AW 7.2	Support/conduct DCA/missile/gun coordination. V(L) - Plan and train.	**F**	**F**	**F/A**	**L**
AW 7.3	Provide continuous multiple air intercept/engagement control capability. V(L) - Plan and train.	**F**	**F**	**F/A**	**L**
AW 7.4	Control DCA under all conditions of active jamming. IV, V(L) - Plan and train.	**F**	**F**	**L**	**L**
AW 7.5	Plan/direct DCA/missile/gun coordination. IV, V(L) - Plan and train.	**F**	**F**	**L**	**L**

AW 8	**ENGAGE AIR TARGETS USING INSTALLED AIR-TO-AIR WEAPONS SYSTEMS.**					
	AW 8.7	Plan/direct engagement of air targets by air-to-air armament. IV, V(L) - Plan and train.	**F**	**F**	**L**	**L**
AW 9	**ENGAGE AIRBORNE THREATS USING SURFACE-TO-AIR ARMAMENT.**					
	AW 9.1	Engage medium/high altitude, high-speed airborne threats with medium/long-range missiles. III(L) - One of two launchers manned. Maximum use of automated engagement management systems. Requires manning of TAO, combat systems coordinator, missile systems supervisor and AW coordinator. IV, V(L) - Plan and train.	**F**	**L**	**L**	**L**

AW 9.3	Engage low altitude threats with missiles. III(L) - One of two launchers manned. Maximum use of automated engagement management systems. Requires manning of TAO, combat systems coordinator, missile systems supervisor and AW coordinator. IV, V(L) - Plan and train.	**F**	**L**	**L**	**L**
AW 9.4	Engage low/medium altitude airborne threats with gunfire. III(L) - Man Aegis combat system, one 5"/54 or 5"/62 mount (without gun or magazine crew). CIWS RCP operated by missile system supervisor. IV, V(L) - Plan and train.	**F**	**L**	**L**	**L**
AW 9.5	Engage airborne threats using installed anti-air weapons. III(L) - One of two launchers manned. Maximum use of automated engagement management systems. Requires manning of TAO, combat systems coordinator, missile systems supervisor and AW coordinator. Gun engagements using one of two guns require manning of GFCS console and EP2 operators. CIWS remote control panel operated by missile system supervisor. IV, V(L) - Plan and train.	**F**	**L**	**L**	**L**
AW 9.6	Engage airborne threats utilizing soft-kill weapons systems (e.g., chaff/decoys). NOTE: Reloading stations co-manned from other battle stations. III(L) - Reload capability provided by off-watch personnel. IV, V(L) - Plan and train.	**F**	**L**	**L**	**L**
AW 9.8	Plan/direct engagement of airborne threats by surface-to-air armament. IV, V(L) - Plan and train.	**F**	**F**	**L**	**L**

AW 6.12	Detect, identify and track ballistic missiles with radar and/or cooperative sensors. IV, V(L) - Plan and train.	**F**	**F**	**L**	**L**
AW 6.13	Identify air targets as friendly/non-friendly using transponder interrogation equipment. V(L) - Plan and train.	**F**	**F**	**F**	**L**
AW 6.15	Identify air targets using non-cooperative target recognition. NOTE: Applicable to those ships with Shipboard Advance Radar Target Identification System installed. IV, V(L) - Plan and train.	**F**	**F**	**L**	**L**
AW 6.21	Correlate onboard sensor targeting information with link 16. IV, V(L) - Plan and train.	**F**	**F**	**F**	**L**
AW 6.22	Detect, track, classify, and identify cruise missiles. NOTE: Applicable in those ships with combined engagement capability (CEC) installed. III(L) - One of two launchers manned. Maximum use of automated engagement management systems. Requires manning of TAO, combat systems coordinator, missile systems supervisor and AW coordinator. Gun engagements using one of two guns require manning of GFCS console and EP2 operators. CIWS RCP operated by missile system supervisor. IV, V(L) - Plan and train.	**F**	**L**	**L**	**L**

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF REFERENCES

AcqNotes. 2018. “Technology Development: Technology Roadmap.” Last modified June 2018. Accessed June 2019. http://acqnotes.com/acqnote/tasks/technology-roadmap.

Baker, Thomas. 2012. “The Right Readiness–Right Now.” *United States Naval Institute* 138, no, 2 (February): 82–83.

Baldwin, Kristen. 2008. *Systems Engineering Guide for Systems of Systems*. Accessed July 2019. https://www.acq.osd.mil/se/docs/SE-Guide-for-SoS.pdf

Barrett, E. 2019. “Remaining Useful Life in Predictive Maintenance.” https://medium.com/@RemiStudios/remaining-useful-life-in-predictive-maintenance-ffc91d7e4a97.

Beam, David. 2015. “Systems Engineering and Integration as a Foundation for Mission Engineering.” Master’s thesis, Naval Postgraduate School. https://calhoun.nps.edu/handle/10945/47229

Betts, Richard K. 1995. *Military Readiness : Concepts, Choices, Consequences* Washington, DC: Brookings Institution.

Blanchard, Benjamin S., and Wolter J. Fabrycky. 2011. *Systems Engineering and Analysis*. 5th ed. Upper Saddle River, NJ: Pearson Education.

Brown, David. 2012. “NMETLs and NWTS: The Path for Fleet Integration.” Last updated May 2012. Accessed July 2019. http://www.metls.com/sitebuildercontent/sitebuilderfiles/nmetls_and_nwts_the_path_to_fleet_integration_sep_2012-2.docx

Canaday, Henry. 2016. “Predicting Failures: Using Big Data to Solve the Most Expensive Problems.” *Aviation Week & Space Technology* 178 (1).

Čepin, Marko. 2011. *Assessment of Power System Reliability Methods and Applications* 1st ed. London: Springer London. https://doi.org/10.1007/978-0-85729-688-7.

CIMData, Inc. 2019. “Product Life Cycle Management Definition.” Accessed June 2019. https://www.cimdata.com/en/resources/about-plm

Clarke, Troy. August 2018. *Revolutionizing Readiness: Fleet Commander Sees Warfare Center’s Latest Advances*. NAVSEA News. https://www.navsea.navy.mil/Media/News/Article/1611086/revolutionizing-readiness-fleet-forces-commander-sees-warfare-centers-latest-ad/

DeLuca, Paul. 2013. *Assessing Aegis Program Transition to an Open-Architecture Model* Santa Monica, CA: RAND.

Department of the Navy, Office of the Chief of Naval Operations. 2013. "Navy Planning NWP 5–01." *Navy Warfare Development Command*. Norfolk, VA.

———. 2005. "The Navy Warfare Library NTTP 1-01." *Navy Warfare Development Command*. Norfolk, VA.

Fanta, P. 2014. "Required Operational Capabilities and Projected Operational Environment for CG 47 (Ticonderoga) Class Guided Missile Cruisers."*Office of the Chief of Naval Operations, Instruction 3501.160C.*

Feloni, Richard, and Anaele Pellison. 2018. "A Retired Marine and Elite Fighter Pilot Breaks Down the OODA Loop, the Military Decision-Making Process that Guide 'Every Single Thing' in Life." *Business Insider, Inc.* Last modified August 13, 2017. Accessed July 2019. https://www.businessinsider.com/ooda-loop-decision-making-2017-8.

OV-1 Template. 2005. Microsoft PowerPoint. Available from Silver Bullet, Inc: http://www.silverbulletinc.com/dm2/File_Browser_2/data/files/IDEAS/References/AUS%20DAF%20CD/DAF/DAFguide/powerpoint_users.htm. Accessed September 7, 2019.

GeekySpaz. *Heaven, Land, and Sea*. 2010. Color photograph. Available from: Flickr Commons, https://www.flickr.com/photos/geekyspaz/4729232602/. Accessed September 7, 2019.

Gagliardi, Mike, and Bill Wodd, Tim Morrow, and US Dept of the Air Force; Carnegie-Mellon University Software Engineering Institute. 2012. *Introduction to the Mission Thread Workshop*. Defense Technical Information Center. https://doi.org/10.21236/ADA610474.

Hassan, Najmul, Saira Gillani, Ejaz Ahmed, Ibrar Yaqoob, and Muhammad Imran. 2018. "The Role of Edge Computing in Internet of Things." *IEEE Communications Magazine* 56 (11): 110–15. https://doi.org/10.1109/MCOM.2018.1700906.f

Ierardi, Anthony. 2018. "Sustainment KPP Guide." *Manual for the Operation of the Joint Capabilities Integration and Development System*. p. B-G-D-2

Integrated Publishing. 2018. "Detect to Engage Sequence for Fire Control." *Fire Controlman Volume 02 – Fire Control Radar Fundamentals (Revised).* Page 2-15. Accessed May 2019. http://firecontrolman.tpub.com/14099/css/Detect-To-Engage-Sequence-For-Fire-Control-49.htm

ITEM Software. 2007. "Reliability Prediction Basics." *Reliability Education.* Accessed May 2019. https://www.reliabilityeducation.com/reliabilityeducation/ReliabilityPredictionBasics.pdf

Janasak, K. M, and Beshears, R. R. 2007. "Diagnostics To Prognostics - A Product Availability Technology Evolution." In *2007 Annual Reliability and Maintainability Symposium*, 113–18. https://doi.org/10.1109/RAMS.2007.328051.

Johnson, Bonnie. 2019. "Artificial Intelligence--An Enabler of Naval Tactical Decision Superiority." AI Magazine Volume 40, Number 1: 63–78. https://doi.org/10.1609/aimag.v40i1.2852.

Jung, Marcel, Octavian Niculita, and Zakwan Skaf. 2018. "Comparison of Different Classification Algorithms for Fault Detection and Fault Isolation in Complex Systems." *Procedia Manufacturing* 19: 111–18. https://doi.org/10.1016/j.promfg.2018.01.016.

Kreinovich, Vladik, Didier Dubois, Janette Cardoso, Martine Ceberio, Ildar Batyrshin, and Grigori Sidorov. 2011. "Estimating Probability of Failure of a Complex System Based on Inexact Information About Subsystems and Components, with Potential Applications to Aircraft Maintenance." In *Advances in Soft Computing: 10th Mexican International Conference on Artificial Intelligence, MICAI 2011, Puebla, Mexico, November 26 - December 4, 2011, Proceedings, Part II*, 7095:70–81. Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-25330-0_7.

Kross, Walter. 1995. "Universal Joint Task List." *Office of the Chairman of the Joint Chiefs of Staff, CJCSM 3500.4:* p. 2-1

Lilly, Trena, and Bruce Russell. 2003. "The Multi-Mission Maritime Aircraft Design Reference Mission." *Johns Hopkins APL Technical Digest* 24 (3): 257–62. http://search.proquest.com/docview/28871932/.

Mattis, Jim. 2018. *Summary of the National Defense Strategy*. Accessed July 2019. https://dod.defense.gov/Portals/1/Documents/pubs/2018-National-Defense-Strategy-Summary.pdf.

Moreland, James. 2015. "Mission Engineering Integration and Interoperability." In *Leading Edge, January 2015*: pp. 4-15. Dahlgren, VA. https://www.navsea.navy.mil/Portals/103/Documents/NSWC_Dahlgren/LeadingEdge/LE_IandI_Jan2015_FINAL_web.pdf.

Murphy, D., T. Sheehan, and A. Richardson. 2015. "The Importance of System of Systems Integration." In *Leading Edge, February 2013*: pp. 8-14. Dahlgren, VA. http://www.navsea.navy.mil/Portals/103/Documents/NSWC_Dahlgren/LeadingEdge/CSEI/CombSys.pdf.

"Mikros Systems Corporation Announces New Board Member and Officer." 2002. *PR Newswire*, May, 1. http://search.proquest.com/docview/449066256/.

Naval Sea Systems Command. n.d. "Readiness Based Sparing" In *Provisioning, Allowancing and Fitting Out Support Manual*, Change E: 2-7 https://www.navsea.navy.mil/Portals/103/Documents/NSLC/Chapter2.doc. Accessed July 2019.

Open Automation Software, Inc. 2019. "IIot Edge Computing vs. Cloud Computing." Accessed July 2019. https://openautomationsoftware.com/blog/iiot-edge-computing-vs-cloud-computing/

Powrie, H., and A. Novis. 2006. "Gas Path Debris Monitoring for F-35 Joint Strike Fighter Propulsion System PHM." In *2006 IEEE Aerospace Conference*, 8 pp. IEEE. https://doi.org/10.1109/AERO.2006.1656114.

Pritchett, Andrew. 2018. "A Systematic Approach to Reliability-Centered Maintenance." Master's Thesis, Naval Postgraduate School. https://calhoun.nps.edu/handle/10945/59568

Provided By Federal Information & News Dispatch, Inc. -. 2001. "59 -- Electrical and Electronics Equipment Components." *Commerce Business Daily*, June 26, 2001. http://search.proquest.com/docview/258885295/.

Rowden, Thomas, Peter Gumataotao, and Peter Fanta. 2015. "Distributed Lethality." *U.S. Naval Institute Proceedings*. http://www.usni.org/magazines/proceedings/2015-01/distributed-lethality.

Rowe, Neil. 2019. "Tactical Readiness Analysis for BREM." Monterey, CA: Naval Postgraduate School.

Souza, F., P. Pereira, Helder de Paula, Braz Filho, and A. Rocha. 2014. "Motor Drive Systems Reliability: Impact of the Environment Conditions on the Electronic Component Failure Rates." In *2014 IEEE Industry Application Society Annual Meeting*, 1–8. IEEE. https://doi.org/10.1109/IAS.2014.6978463.

Trunkey, Derek. 2013. "Implications of the Department of Defense Readiness Reporting System: Working Paper 2013-03." *IDEAS Working Paper Series from RePEc*, January. http://search.proquest.com/docview/1697977668/.

Yin, Ming, Xiaohui Ye, and Shaochang Chen. 2013. “Sensor Selection and Location Scheme for Prognostic and Health Management.” *Sensors & Transducers* 158 (11): 230–35. http://search.proquest.com/docview/1509394742/.

Zvijac, David. October 2017. “Risk and Reward in Investment Decisions.” *Center for Naval Analysis:* p.1. https://www.cna.org/CNA_files/PDF/DOP-2017-U-016138-1Rev.pdf .

THIS PAGE INTENTIONALLY LEFT BLANK

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California