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THESIS

DIGITAL TEST AND EVALUATION FOR NAVAL SYSTEMS

by

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September 2023

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13. ABSTRACT (maximum 200 words)

Digital engineering is revolutionizing the field of systems engineering. The United States Navy is implementing digital engineering concepts and methods, including digital twins, digital threads, authoritative sources of truth, model-based systems engineering, and digital tools and technologies to design and build complex naval systems. This thesis explores the use of digital engineering for naval system test and evaluation (T&E). It provides an insightful examination of the current state of naval acquisition T&E, explaining associated challenges and limitations that underscore the need for a modern approach. It offers a comprehensive overview of digital engineering, illustrating its impact through several use cases within the Navy and across industry. It proposes a new concept: "digital T&E" as the application of digital engineering methods to the test and evaluation phase of systems engineering. This research reveals how digital T&E can be used to address and overcome present naval T&E challenges. It concludes with a proposed roadmap for implementing a digital T&E approach for the Navy. These insights aim to have practical implications for the naval T&E community, guiding the development of new strategies and policies that harness digital engineering to achieve improved performance and contribute to modernizing the traditional T&E process.

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DIGITAL TEST AND EVALUATION FOR NAVAL SYSTEMS

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ABSTRACT

Digital engineering is revolutionizing the field of systems engineering. The United States Navy is implementing digital engineering concepts and methods, including digital twins, digital threads, authoritative sources of truth, model-based systems engineering, and digital tools and technologies to design and build complex naval systems. This thesis explores the use of digital engineering for naval system test and evaluation (T&E). It provides an insightful examination of the current state of naval acquisition T&E, explaining associated challenges and limitations that underscore the need for a modern approach. It offers a comprehensive overview of digital engineering, illustrating its impact through several use cases within the Navy and across industry. It proposes a new concept: "digital T&E" as the application of digital engineering methods to the test and evaluation phase of systems engineering. This research reveals how digital T&E can be used to address and overcome present naval T&E challenges. It concludes with a proposed roadmap for implementing a digital T&E approach for the Navy. These insights aim to have practical implications for the naval T&E community, guiding the development of new strategies and policies that harness digital engineering to achieve improved performance and contribute to modernizing the traditional T&E process.

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LIST OF ACRONYMS AND ABBREVIATIONS

AAF	Adaptive Acquisition Framework
AI	Artificial Intelligence
ASN RD&A	Assistant Secretary of the Navy for Research Development and Acquisition
ASOT	Authoritative Source of Truth
AWS	Amazon Web Services
CAD	Computer-Aided Design
CBT&E	Capabilities-Based Test and Evaluation
CDD	Capability Development Document
CDT	Chief Development Tester
CNO	Chief of Naval Operations
COI	Critical Operational Issue
COTS	Commercial Off-the-shelf
CPD	Capability Production Document
DAS	Defense Acquisition System
DAU	Defense Acquisition University
DAWG	Data Analysis Working Group
DE	Digital Engineering
DL	Deep Learning
DMAP	Data Management & Analysis Plan
DOD	Department of Defense
DODI	Department of Defense Instruction
DOE	Design of Experiments
DON	Department of Navy
DOT&E	Director of Operational Test and Evaluation
DT	Developmental Testing
DTE&A	Developmental Test, Evaluation, and Assessment

DWG	Digital Warfare Office
ETD	Enhanced Test Design
IL6	Impact Level Six
IME	Integrated Modeling Environment
INCOSE	International Council of Systems Engineering
IT	Integrated Testing
LVC	Live Virtual and Constructive
MBSE	Model-Based Systems Engineering
MBTE	Model-Based Test and Evaluation
ME	Mission Engineering
MIT	Massachusetts Institute of Technology
ML	Machine Learning
MVL	Model Validation Level
NAVSEA	Naval Sea Systems Command
OEM	Original Equipment Manufacturer
OMG	Object Management Group
OT	Operational Testing
OTA	Operational Test Agency
PEO	Program Executive Office
PLM	Product Life cycle Management
PM	Program Manager
PMO	Program Management Office
RDT&E	Research Development Test and Evaluation
RWG	Requirements Working Group
SE	Systems Engineering
SERC	Systems Engineering Research Center
SoS	System of Systems
STAT	Scientific Test and Analysis
SW	Software

SWFTS	Submarine Warfare Federated Tactical Systems
SWG	Scenario Working Group
T&E	Test and Evaluation
TEMP	Test and Evaluation Master Plan
TES	Test and Evaluation Strategy
TOWG	Test Objective Working Group
TP4	TEMP Part Four
TPM	Technical Performance Parameters
TRR	Test Readiness Review
TTP	Tactics Techniques and Procedures
WIPT	Working-Level Integrated Product Team

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EXECUTIVE SUMMARY

Digital engineering is revolutionizing the field of systems engineering. In 2018, the U.S. Department of Defense launched their *Digital Engineering Strategy* and defined it as an "integrated digital approach using authoritative sources of system data and models as continuum across disciplines to support life cycle activities from concept through disposal" (DOD 2018, 3). It symbolizes a fundamental transformation in systems engineering practices, shifting from traditional methods to model-based techniques within a digital environment (Giachetti 2022). This strategic shift necessitates the development, utilization and distribution of formal models and digital information throughout the entire engineering process and organizational structures via a reliable "authoritative source of truth." The implications of this emergent field are far-reaching, likely affecting the U.S. defense industry and various other sectors, reshaping the practice of systems engineering. Digital engineering paves the way for a dynamic phase of rapid progress and technological advancements by enabling improvements in operational efficiency, system performance, and innovation in the methods used to design and build systems.

In 2020, the Department of the Navy (DON) published a strategy formalizing its commitment to digital engineering, outlining the vision for its use throughout the naval system life cycle. The Navy is applying digital engineering concepts with emerging initiatives such as the Forge software factory, which aims to accelerate software upgrades to the Aegis Combat System (Katz 2022). Another notable application is the Submarine Warfare Federated Tactical System (SWFTS), where digital engineering has enabled flexible architecture for quick submarine technology integration, seamless updates, and improved system interoperability (Herber and Batchelor 2023). More recently, the Navy's planned development of an Integrated Modeling Environment (IME) aims to revolutionize system design using digital engineering. This digital environment aims to provide a cohesive framework that unites various system models and simulations to drive innovation, enhance system performance, and elevate the overall capability of the fleet.

This thesis explores the application of digital engineering for naval system test and evaluation (T&E). It provides a groundbreaking opportunity to modernize the

traditional process and enhance the capabilities delivered to the warfighter. By leveraging modern techniques, digital tools, and advanced technologies, digital engineering has the potential to streamline the T&E process for naval systems. However, the intersection of these two domains is marked by limited available research, revealing a gap in the literature. It involves more than merely converting traditional test processes and products like test plans and analysis reports into digital format. Instead, digital engineering requires a holistic digital perspective of a system's entire life cycle. As the Navy adopts digital engineering concepts such as model-based systems engineering and digital twin in system development, T&E becomes essential to the rapid deployment of naval acquisition programs.

This thesis commences with an in-depth exploration of the current state of naval acquisition T&E. It provides foundational insights into the terminology, background, and statutory types of tests while outlining a complex organizational structure. It emphasizes the significance of the Navy's T&E Working-level Integrated Product Team (WIPT), comprising of scientists and engineers from various naval branches. This team is vital in conducting the planning, execution, analysis and reporting of T&E activities for naval acquisition programs. During this research, limited information was found about the specific steps in the naval T&E process. To address this gap, a diagram of the current T&E process was created, detailing the process steps, milestones, and deliverables.

This research identified nine specific challenges and limitations confronting the naval T&E community: Inadequate Infrastructure, Limited Test Space, Evolving Threats and Scenarios, Test Integration, T&E Spending, T&E Cost Perception, Schedule Delays, Lack of Data Strategy, and Testing AI and ML. These challenge areas are restricted by the limitations of the physical environment and the traditional T&E process. Such an approach is increasingly out of step with the current technological environment, lacking the necessary agility and adaptability required in today's rapidly evolving world.

Digital engineering is comprised of model-based principles combined with an authoritative source of truth (ASOT) and advanced digital tools. The model-based tenets include digital twin, a digital replica of a physical system; digital thread, an interconnected and continuous flow of information that weaves through the system life cycle; and model-based systems engineering (MBSE), a methodology that emphasizes the use of system models to support system design over the traditional document-based systems engineering process. The ASOT serves as a centralized repository for consistent and up-to-date information, unifying data, models, and other system-related information throughout the entire system life cycle (DOD 2018, 8). Together, these principals signal a transformative shift from traditional document-centric methodologies to a comprehensive and dynamic digital environment.

Through an in-depth examination of four digital engineering case studies spanning various industries, coupled with an extensive literature review, this thesis constructed a matrix to demonstrate how digital engineering principles can be strategically deployed to solve existing challenges in T&E. This approach embraces all facets of digital engineering, including the concept of a digital engineering ecosystem. This ecosystem integrates infrastructure, environment, and methodology, uniting processes, methods, and tools to manage and analyze system data and models, aligning with stakeholder needs.

The cumulation of this research led to the development of a new approach termed "digital T&E." This concept represents the application of digital engineering methods within the test and evaluation phase of systems engineering. Instead of persisting with the conventional design-build-test approach, this proposal calls for a more sophisticated model-simulate-analyze-build-validate iterative methodology. It offers a more precise and clearly defined framework, revealing a path toward greater efficiency and accuracy in system development. The steps in this approach are detailed below:

- **Model:** Initiate the process by creating an accurate representation of the physical system, ideally through a high-fidelity digital twin that captures system details.
- **Simulate:** With the model developed, run a simulation in a virtual operational environment to mimic real-world conditions.
- **Analyze:** Perform analysis of simulation data using metrics to assess performance and identify issues. Employ advanced digital technologies to automate and streamline the process. If changes to the system model are needed based on the

analysis, adjust the model, and return to the previous step. This iterative cycle continues until the model produces the desired outcomes.

- **Build:** Once the system model has satisfied all system requirements and achieved the desired outcomes, construction of the actual physical systems begins.
- **Validate:** Validate the system model using data from the physical system as the authoritative source of truth, ensuring the virtual representation accurately aligns with the physical system.

Applying this approach to the current T&E process, an innovative methodology for executing digital T&E emerges, as illustrated in Figure 1. This cutting-edge digital T&E approach, comprised of ten steps, revolutionizes the existing process by incorporating digital engineering principles. It moves beyond the traditional, sequential, and document-centric phases of planning, preparation, execution, analysis, evaluation, and reporting. Instead, it enables a more dynamic, flexible, and iterative approach, emphasizing continuous feedback and system enhancement.

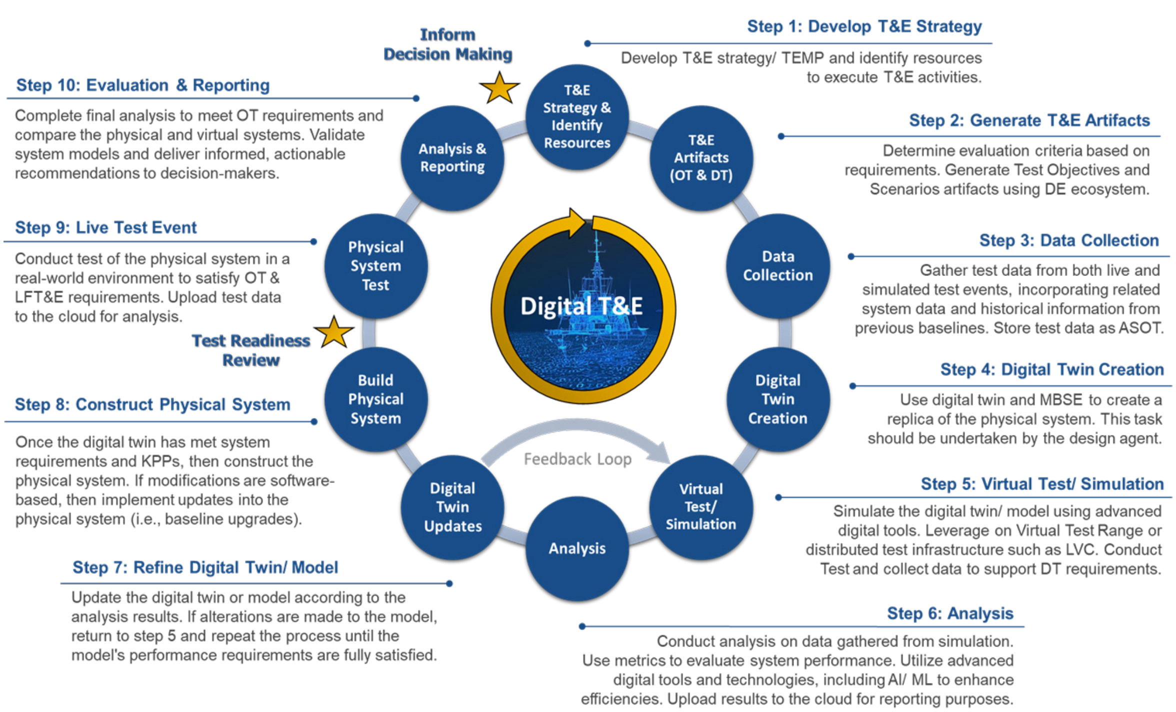

Figure 1. Digital T&E Roadmap for Naval System

This thesis explored the integration of digital engineering and T&E in naval systems, aiming to answer the primary research question. Through literature review and analysis of four case studies, it proposed a digital T&E roadmap using a model-simulate-analyze-build-validate approach, emphasizing the role of digital engineering. The findings offer a path to enhance efficiency in naval system development, with potential broader applications across the defense industry. Recommendations emphasize investment in digital infrastructure like cloud-based platforms, network upgrades, digital tools, and digital twins. It also calls for new policies with defense contractors for securing access to technical data packages and system models. Furthermore, it encourages collaboration across the T&E community, academia, industry, and contractors. Looking ahead, areas for future work include ontology's role in T&E data management, the needs of the digital workforce, the use of mission engineering to test multiple system models in support of complex naval operations, and determining the optimal organizational structure to support digital T&E. These promising avenues present opportunities to further refine and expand the proposed roadmap for digital T&E.

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I. INTRODUCTION

A. OVERVIEW

The Navy's adoption and rapid deployment of digital engineering across the department is beginning to transform the way we design, test, deliver, deploy, and sustain naval acquisition systems. The implementation of digital engineering has very promising benefits to an organization including improved efficiency, reduced costs, increased collaboration, improved quality, and increased agility. However, multiple organizations within the Navy have yet to fully grasp the concept of digital engineering and its impact on their programs. This is especially true in the Test and Evaluation (T&E) community, where digital engineering is still a relatively new concept that is struggling to gain acceptance due to its integrated model-based approach. Historically, T&E has heavily relied on physical assets, live targets, instrumentation equipment, test ranges, operators, and live fire events to support both Development and Operational Testing. However, the Navy's T&E community is facing challenging times ahead with shrinking budgets, fewer live targets, inadequate test ranges, limited resources, and more complex threats. To compete with near-peer adversaries and to rapidly field new capabilities to the warfighter, the T&E process needs to migrate from a traditional document-centric approach based in a physical domain to a model-based approach based on a digital environment.

B. GOAL

The goal of this thesis is to explore the use of digital engineering (DE) across the defense and technology industry to provide recommendations on how to improve the Navy's acquisition test & evaluation (T&E) process. The benefit of this research is to provide T&E practitioners and program managers a roadmap on how to apply digital engineering best practices and key elements such as model-based design, digital thread, authoritative sources of truth, and digital twin to improve the Naval acquisition T&E process. This research identifies the current challenges and opportunities within the existing naval T&E process and recommends alternative solutions using digital engineering techniques. This thesis heavily leverages on digital engineering case-studies, industry publications, presentations, journals, existing research, and best practices to evaluate the current state of digital engineering and provide recommendations on usage with the goal to improve the T&E process for the average naval system.

C. BACKGROUND

To maintain technological superiority in a time of rapidly evolving technologies and threats, tight budgets, aggressive schedules, and global trends towards the use of digital techniques, the U.S. Navy is embracing digital engineering. In 2020, the U.S. Navy released the *Digital Systems Engineering Transformation Strategy* to leverage "digital engineering as a means to maximize agility, interoperability, reusability, and scalability across the DON" (Bray 2020, 2). The strategy defines digital engineering as an "integrated digital approach using authoritative sources of system data and models as continuum across disciplines to support life cycle activities from concept through disposal" (Department of Defense 2018, 3).

The primary purpose of this strategy is to utilize digital engineering concepts to change current engineering practices to speed up the Naval acquisition process and reduce its long-term sustainment costs. To date, the Navy has started leveraging digital engineering strategies to build virtual replicas of physical naval systems to improve the process of integrating new technologies and capabilities into the fleet. Efforts are underway to determine the best use of digital engineering practices and principles to transform the way we test and evaluate naval systems. Stacy Cummings, the Undersecretary of Defense for Acquisition and Sustainment said, "digitalizing the acquisition life cycle could be especially helpful in areas like development and operational testing…we also can't continue to look at testing as being something that is only done in physical environment" (Serbu 2021).

The Navy's T&E community is facing challenging times with reduced budgets, inadequate infrastructure, fewer live targets, and more complex threats. All of this is happening at a time when near-peer adversaries are increasing their military budgets and investments in technological innovations (Lawrence 2019). Paul Mann, the Navy's Chief

Engineer for Research Development Test and Evaluation (RDT&E) best described the current state of T&E:

> This is a very different world than five to 10 years ago. The enemy is proliferating and there is evidence it is challenging us. What we've done in the past is unaffordable and unsupportable. Profound change is needed. We [must] change engineering rigor so that it's delivered with different procedures and digital engineering processes. (Naval Sea Systems Command [NAVSEA] 2022)

Digital engineering was originally conceived in 1975 in the "context of electronic and logic circuit design" with the potential use in the development of digital concepts, systems, and product life cycle management (Papadonikolaki 2021). Over the years, digital engineering has become part of the systems engineering process by integrating digital concepts utilizing a model-based systems engineering methodology. According to the System Engineering Body of Knowledge, "digital engineering represents a transformation of how [organizations] normally conduct systems engineering that is based on models in a digital engineering environment" (Giachetti 2022).

In recent years, digital engineering has gained much interest due to the Department of Defense (DOD) adoption as a strategic initiative to streamline the defense acquisition process. Digital engineering combines model-based techniques, digital tools, and computing infrastructure necessary to enable affordable solutions at a much faster speed. The DOD's *Digital Engineering Strategy* aims to improve the way it designs, develops, builds, tests, and sustains military systems with the following goals (DoD 2018):

1. Formalize Development, Integration, and Use of Models – focuses on developing and using system models to support engineering activities and decision making across an acquisition's program life cycle.

2. Provide an Authoritative Source of Truth – establishes guidance for a single and authoritative source of system data along with program records such as requirements, engineering information, and capabilities all accessible by the program stakeholders.

3. Incorporate Technological Innovation – expand and transform the practice of engineering by using cutting edge technology, tools and methods such as advanced data analytics, automation, robotics, machine learning (ML), Deep Learning (DL), and artificial intelligence (AI).
4. Establish Infrastructure & Environments – modernize digital environments across research and development enterprises to support model-based system approach and to enable live, virtual, and constructive simulations. This also means setting up the infrastructure of high bandwidth networks and databases to support the transition to a digital environment.
5. Transform Culture and Workplace – provide training and development in new digital engineering skills, proficiency, and knowledge areas across the workforce.

This strategy is currently being discussed and deployed at every military base and command across the department of the defense. Digital engineering combines model-based techniques, digital tools and infrastructure to foster innovation and speed across the defense acquisition process. The DOD's *Digital Engineering Strategy* across the defense acquisition process can be seen in Figure 1.

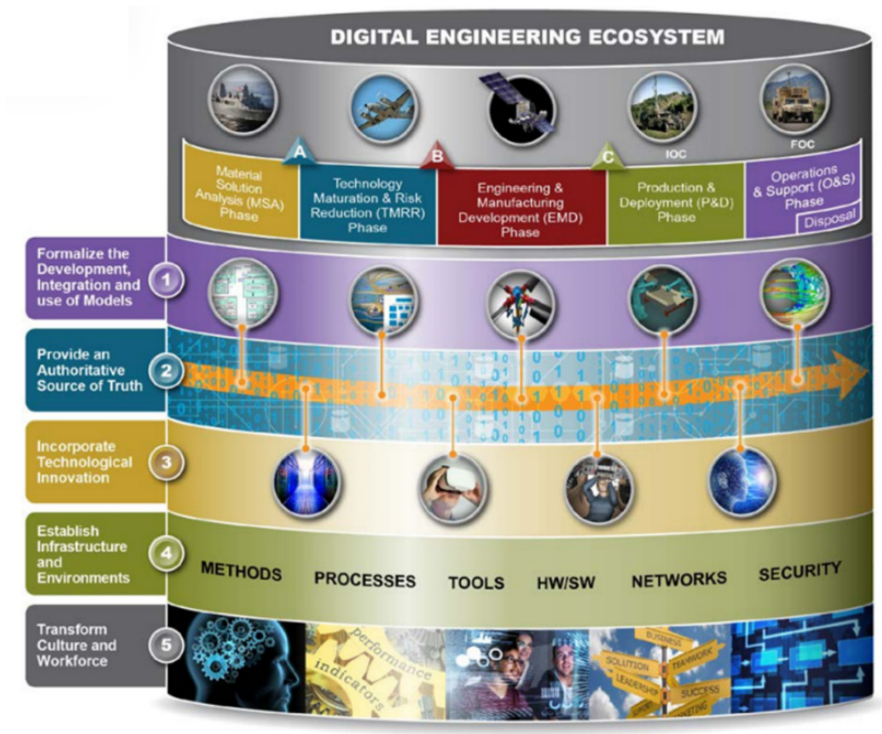

Figure 1. Digital Engineering in Defense Acquisition. Source: Zimmerman (2019).

As of 2022, success stories in digital engineering can be seen in the Navy's Forge, a software factory utilizing a shared digital environment, which is being used to rapidly develop, test, and distribute upgrades to Aegis combat system platforms. In 2021, the Forge was able to successfully provide new software updates to the USS Monterey as it was transitioning to the Mediterranean Sea (Katz 2022). Traditionally, upgrading the ship's systems software would have taken years to accomplish in addition to requiring the ship to return to port.

It is not just the Navy that has embraced digital engineering, but the Air Force has already been using these same concepts to streamline their acquisition process. For example, the Air Force Sixth-Generation Stealth Fighter was developed ten years earlier than anticipated thanks to digital engineering's model-based design approach. The Air Force generated aircraft computer models to simulate, test, and analyze several types of configurations to identify the best performance attributes. All of this was completed without having to build any physical prototypes (Osborn 2021).

Digital engineering has the potential to transform the way the Navy conducts T&E. For example, digital engineering tools and techniques can be used to design and develop robust system models by leveraging on data collected during T&E events. Using these same concepts, the Navy could develop automated testing systems that can quickly and accurately evaluate the performance of software, hardware, or other systems. Digital engineering can also be used to design data management and analysis systems that can help T&E teams analyze large volumes of data and extract meaningful insights. Additionally, digital engineering can be used to develop visualizations and other data-driven decision-making tools that can help T&E teams better understand and communicate test results. These tools can be used to identify trends, patterns, and other important trends in the data, and to make recommendations for further testing or improvement.

Digital engineering in Test and Evaluation possesses the potential to deliver better and faster capabilities to the warfighter by providing the techniques, tools, and technologies needed to design, develop, and analyze complex systems and processes. However, limited research has been conducted on how to best apply these concepts to the naval acquisition T&E process. It involves more than merely converting traditional test processes and products like test plans and analysis reports into digital format. Instead, digital engineering requires one to think digitally about a system from its requirements through its test period, evaluation, and deployment. As the Navy shifts to digital engineering concepts such as model-based systems engineering and digital twin to develop new systems, T&E will play a critical role in supporting the rapid deployment of naval acquisition programs. This paradigm shift in T&E must take place as soon as possible to ensure procedures and processes are in place to test, assess, and validate naval systems in a digital environment.

D. RESEARCH SCOPE

The focus of this thesis is to explore the use of digital engineering across the Navy's acquisition test and evaluation process. Topics researched include T&E challenges and opportunities, digital engineering, digital transformation, systems engineering, digital twin, digital thread, model-based systems engineering, authoritative source of truth, and digital tools. This research considers literature review from both government and industry publications at an unclassified level available in the public domain.

1. Research Questions

Primary research question:

- How can digital engineering be applied to improve the test and evaluation process for naval systems?

Secondary research questions include:

- What specific digital engineering methods will be most effective for improving the naval T&E process and how can each be used?
- What is the recommended roadmap for a future naval T&E process that leverages digital engineering?
- Will the roadmap support T&E for most naval systems or will it have to be significantly tailored for distinct types of naval systems?

2. Research Approach

This research identifies and documents the current T&E process along with its challenges and limitations to provide recommendations for process improvement using digital engineering techniques and best practices. This research conducts (1) a comprehensive literature review, (2) develops a map of current T&E process for naval systems, (3) identifies naval system T&E case studies and best practices to gather data, (4) develops a future state process map (roadmap) that incorporates digital engineering in the T&E process, and (5) evaluates the roadmap for process improvement using an operational analysis based on the case studies and literature review. The five phases are described as follows:

1. Literature Review: Identify the Navy's current initiatives and application of digital engineering in Test & Evaluation. Collect related research, case studies, and best practices of digital engineering concepts and methodologies. Gather data on Naval Acquisition T&E process throughout its life cycle.
2. Current T&E Process Map: Utilizing data from literature review, develop process flow charts of the current state of the T&E process for the average naval system. Identify the inputs and outputs of the process to determine dependencies and identify bottlenecks.
3. Analysis: Identify challenges, limitations and opportunities based on developed T&E process map and data gathered from literature review. Determine areas that can be improved by the application of digital engineering principles and techniques. Identify negative effects and roadblocks of incorporating digital engineering in the T&E process.
4. Digital Engineering T&E Process Roadmap: Develop a conceptual T&E future state process using digital engineering that attempts to address the current challenges and limitations of the existing process. Utilize industry and government best practices of digital engineering along with Systems Engineering concepts and process improvement techniques to identify improvement areas.
5. Evaluation and Recommendations: The digital engineering T&E process roadmap is evaluated based on an operational analysis of the Navy system case studies and literature review identified in step 3. This research provides a recommended roadmap on how to apply digital engineering techniques to improve the Naval Acquisition T&E process.

E. BENEFITS OF STUDY

The DOD's acquisition T&E process has proven successful in enhancing overall system performance and sustainment over the life cycle. Despite this success, some critics argue that this process contributes to an increase in overall program cost and delays the delivery of new capabilities to the warfighter. The Defense Business Board's

2017 study on T&E concluded that the DOD did not prioritize or have a clear understanding of the overall T&E cost. In 2021, the National Academies of Science, Engineering, and Medicine conducted a study revealing key challenges to T&E across the services. These challenges fell into several areas: the development of new testing capabilities, inadequate infrastructure, the need for realistic threats and scenarios, limited space for testing, issues with modeling and simulation, data-related problems, security concerns, a deficit in knowledge and skills in digital engineering, and financial constraints (National Academies 2021a).

With the increasing complexity of naval systems and the global trend towards digital transformation, the T&E process must migrate from a document-centric approach to digital-centric model to allow for rapid fielding of new capabilities. This research explores the utility of digital engineering to Naval T&E and provides recommendations that may improve the overall T&E process. The benefits of this research include:

- Provides answers to the primary and secondary research questions.
- Provide T&E practitioners and program managers with a roadmap on how to apply digital engineering best practices and techniques.
- The results of the thesis research can be generalized to make recommendations across DOD for using digital engineering to improve T&E.
- Provides an analysis method for evaluating new T&E processes – through the identification of use cases, the development of evaluation criteria, and an operational analysis of the use cases (stepping through their T&E processes with and without digital engineering).
- Provide a foundation of knowledge for the field of Systems Engineering (SE) for improvements to T&E processes.

F. THESIS ORGANIZATION

This thesis is structured into five chapters:

- **Chapter 1:** Introduction of the research objectives and goals, background, research questions, research approach, and benefits of study.
- **Chapter 2:** A comprehensive review of the literature provides background, terminology, types of tests, and organizational structure in naval acquisition T&E. It identifies and details the current challenges and limitations and includes a process map reflecting the current state of naval T&E for a Major Capability Acquisition program.
- **Chapter 3:** This section provides literature review of digital engineering key components, tenets, case-studies, existing research, adoption, current strategies, best practices, and implementation challenges.
- **Chapter 4:** Presents data and analysis findings pertaining to the benefits of digital engineering. Highlight current defense priorities and initiatives to integrate digital engineering into T&E. Addresses existing T&E challenges and limitations using DE. Proposes a future state T&E roadmap using digital engineering concepts, techniques, and best practices.
- **Chapter 5:** Provides research summary, limitation, recommendations, and future work.

II. CURRENT STATE OF NAVAL ACQUISITION T&E

To enhance the current Naval Acquisition Test & Evaluation process through digital engineering, it is crucial to offer a comprehensive understanding of both domains. This literature review is split into two chapters. The first chapter sheds light on the present state of naval T&E, providing background and outlining the significant problems and challenges facing the community. Utilizing data gathered from this research, a visual illustration of the current state of the T&E process is provided towards the end of the chapter. The second chapter delves into the concept of digital engineering, its key elements, case studies, best practices, and hurdles of implementation cross industry. Together, these two literature reviews establish a framework necessary to comprehend the extent and evaluation of the primary research question.

A. OVERVIEW

The U.S. Navy Acquisition T&E process is a well-structured, rigorous, and robust method for evaluating the capabilities and performance of naval systems such as combat systems, weapons systems, sensors, ships, aircraft, and more. The process adheres to the guidelines established by the Department of Defense Acquisition Instructions, DODI 5000.2, but is specifically implemented for the purpose of acquiring systems for the U.S. Navy. The Secretary of the Navy Instruction (SECNAVINST) 5000.2 governs the Navy's acquisition process with specific guidance, policies, and procedures (Department of Navy [DON] 2022). Moreover, the Navy's T&E process places a stronger focus on evaluating the performance of systems in a maritime environment. Over the years, the Navy has continually improved its process for acquiring and assessing system capabilities by developing policies, regulations, and procedures. The current T&E process has undergone a gradual evolution and refinement to align with the changing needs of the Navy, the evolving threat landscape, and advancements in technology.

The fundamental purpose of T&E is to "enable the [military services] to acquire systems that support the warfighter in accomplishing their mission" (DOD 2020a, 7). As a vital element in the Systems Engineering process, T&E plays an instrumental role in helping to characterize system performance and aids in identifying and correcting system deficiencies and limitations. "T&E provides engineers and decision-makers with knowledge to assist in managing risks; to measure technical progress; and to characterize operational effectiveness, operational suitability, interoperability, survivability (including cybersecurity), and lethality [of systems]" (DOD 2020a, 7). According to the DODI 5000.2 Instruction, there are three major statutory types of tests within the acquisition process which are executed by the Navy:

- **Development Test & Evaluation (DT&E):** verifies that a system has been built properly, adheres to the technical specification outline in the contract, and identifies any issues that need to be addressed before the system can be put into operational use. The results of DT&E inform the system engineering process, acquisition decision, and help manage design and programmatic risks. DT&E typically involves a combination of laboratory testing, hardware-in-the-loop, modeling and simulations, and prototype testing to assess system performance (DOD 2012, 86-87).

- **Operational Test & Evaluation (OT&E):** Evaluates the system's ability to carry out its intended mission within a real-world operational setting, assessing both its operational effectiveness and suitability.

    - Operational effectiveness is "the degree to which the system accomplishes its missions when employed by operational personnel in a realistic scenario (natural, electronic, threat) with the appropriate organization, doctrine, supportability, survivability, vulnerability, and threat environment, and using tactics and techniques" (DOD 212, 122).

    - Operational suitability is "the degree to which the system can be placed in operational field use, with specific evaluations of availability, compatibility, transportability, interoperability, reliability, wartime usage rates, maintainability, safety, human factors, manpower supportability, natural environmental effects and impacts, logistics supportability, and documentation and training requirements" (DOD 2012, 133).

- **Live Fire Test & Evaluation (LFT&E):** provides an assessment of the effectiveness, survivability, and lethality of a system through the design and development phases. It involves firing live ammunition to assess the system in a realistic operational condition. However, this can extend to testing at levels such as components, subassemblies, and sub-systems, and might utilize design analyses, modeling and simulation, combat, and safety data. This type of testing is a requirement for surface ships, munitions, missile programs, and covered systems (DON 2022a, 7).

Figure 2 shows a high-level diagram of T&E across the acquisition process.

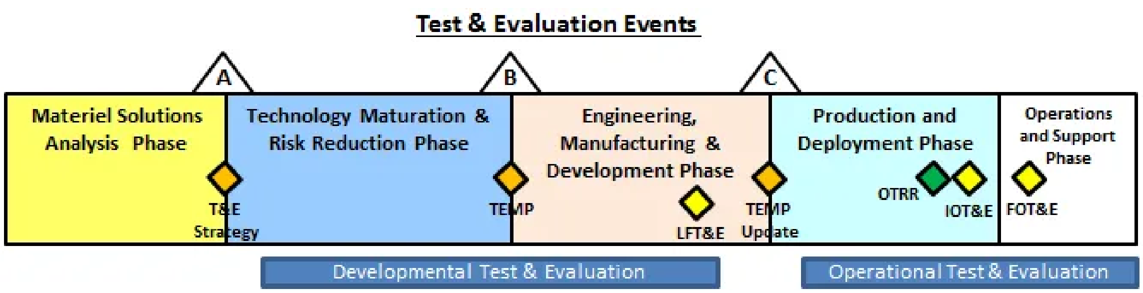

Figure 2. Test & Evaluation across the Acquisition Process. Source: AcqNotes (2021).

In addition to DT&E, OT&E, and LFT&E, there are two types of test phases that are important components of the acquisition process called Integrated Test and Interoperability Test & Certification (DON 2022a, 116).

- **Integrated Test (IT):** is a collaborative process that integrates the efforts of multiple T&E organizations to produce shared information that supports each party's evaluation objectives. According to the *DOD T&E Management Guide*, "the goal of integrated testing is to conduct a seamless test program that produces credible qualitative and quantitative data useful to all evaluators and to address developmental, sustainment, and operational issues early in the acquisition process to the decision maker” (DOD 2012, 108). Some of the benefits of Integrated test include the following:

  - Improved coordination and collaboration among DT and OT communities
  - Increased efficiency and reduced duplication of effort
  - Improved data sharing and use of common data sets and tools for evaluation
  - Increased transparency and visibility for all stakeholders
  - Improved decision-making by providing a comprehensive view of system performance
  - Improved T&E results due to early coordination planning
  - Reduced overall T&E cost by sharing resources among participating programs and organizations

- **Interoperability Testing and Certification:** As part of operational testing, programs that exchange data with other military systems, including those in the cloud, must demonstrate interoperability. The Navy’s Operational Test Agency (OTA) is responsible for assessing progress towards joint interoperability during each major phase of testing and supports the Joint Interoperability Test Command (JITC) during DT, IT, and OT. Interoperability testing includes not only internal evaluations within the Navy and Marine Corps, but also extends to Joint Services, allied and coalition forces (DON 2022a, 34).

B. T&E ORGANIZATIONAL STRUCTURE

The Navy’s T&E organizational structure is comprised of several organizations that work together to acquire, test, and evaluate naval systems. At the top level, the office of the Chief of Naval Operations (OPNAV) is responsible for overseeing T&E activities across the Navy. The Chief of Naval Operations (CNO) has full responsibility for the Test & Evaluation Master Plan (TEMP) process, T&E policy and guidance, operational requirements, and resources across the enterprise. At the same level, the Assistant Secretary of the Navy for Research, Development, and Acquisition (ASN RD&A) oversees the research and development of new technologies and systems for the Navy and Marine Corps. ASN RD&A and its Program Executive Office (PEO) have the authority, responsibility, and accountability for all acquisition functions and programs across the Navy (DOD 2012, 18). Figure 3 illustrates the Navy's T&E organizational structure.

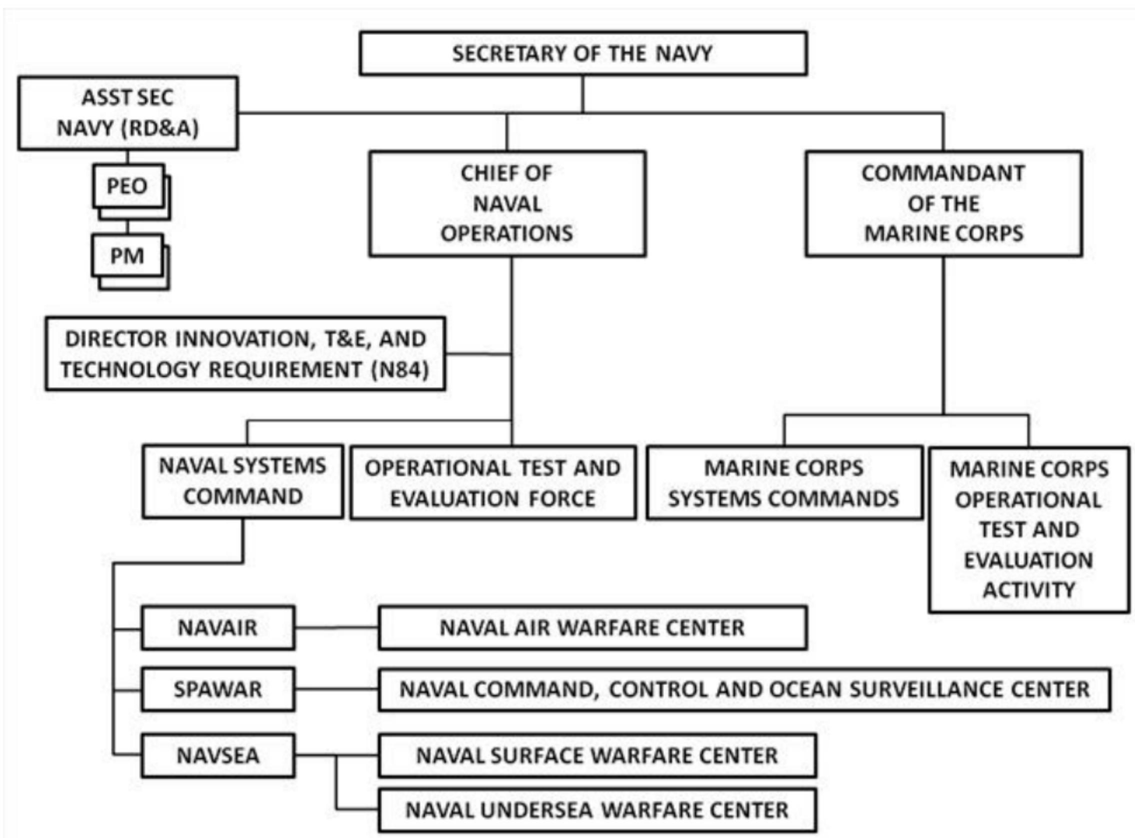

Figure 3. Navy's Test & Evaluation Organization. Source: DOD (2012).

At the middle of the T&E organizational structure reside the Naval Systems Command (SYSCOM) and the Operational Test & Evaluation Force. These two organizations, comprised of engineers, technicians, and scientists, conduct most of the actual T&E work in the acquisition process. These professionals and organizations are aligned to two T&E communities which are primarily focused on supporting DT and OT.

1. DT&E Organizations

- **Naval Sea Systems Command (NAVSEA)** – responsible for development and execution of DT&E on surface ships, submarines, and corresponding weapons systems. This includes propulsion systems, hull and mechanical systems, combat systems, and interoperability (DOD 2012, 18).

- **Naval Surface Warfare Centers (NSWC)** – within NAVSEA, there are ten Warfare Centers that provide technical support, engineering services, logistics, and fleet support that meet the operational needs of the warfighter. These centers function as the Navy's central locations for Research, Development, Test and Evaluation (RDT&E), as well as analysis and assessment of surface ship and submarine platforms, combat systems, ordnance, mines, and strategic systems. Additionally, the Warfare Centers are tasked with supplying depot maintenance and in-service engineering assistance, guaranteeing that naval systems are properly maintained and equipped to perform their designated function (NAVSEA n.d.).

- **Naval Air System Command (NAVAIR)** – tasked with the development and execution of DT&E on aircraft and their integral weapon systems (DOD 2012, 18). Like the NAVSEA construct, there are multiple aircraft and air weapon divisions within NAVAIR that are responsible for testing and evaluating new aircraft systems and subsystems. NAVAIR's mission is to deliver integrated air warfare capabilities to enable the fleet to win. (NAVAIR n.d.).

- **Naval Information Warfare System Command (NAVWAR)** – formerly known as the Space and Naval Warfare Systems Command (SPAWAR), this organization plays a pivotal role in the DT&E of information technology, secure networks, and communications systems. The organization's overarching mission is "to identify, develop, deliver and sustain information warfare capabilities and services that enable naval, joint, coalition and other national missions operating in warfighting domains from seabed to space; and to perform such other functions and tasks as directed" (NAVWAR n.d.). In pursuit of this goal, NAVWAR provides comprehensive services that include "research and development, systems engineering, testing and evaluation, technical, in-service, and support services to its respective acquisition program executive offices (PEOs) during all phases of a program's life cycle" (NAVWAR n.d.).

2. OT&E Organization

- **Operational Test and Evaluation Force (OPTEVFOR)** – the Navy's independent Operational Test and Evaluation Agency (OTA) that reports directly to the Chief of Naval Operations (CNO). The organization is responsible for conducting independent and objective testing and assessment of new systems in a realistic operational environment. In the pursuit of this goal, OPTEVFOR works closely with the Navy's DT&E organizations to ensure that new systems undergo thorough testing before they are deployed to the fleet. This collaborative approach ensures that the Navy's systems are fielded with the utmost confidence, having undergone rigorous testing in a realistic operational setting (DOD 2012, 19).

3. T&E Working-Level Integrated Product Team

The T&E Working-Level Integrated Product Team (WIPT) is a group of individuals from various T&E organizations within the Navy who are responsible for planning, executing, and reporting T&E activities for Navy acquisition programs. The purpose of the WIPT is to provide oversight of the T&E Strategy and ensure that T&E

considerations are integrated throughout the acquisition life cycle of a system. As such, the WIPT is the structure commonly used to support Major Capability Acquisition Programs. The WIPT team supports the Program Manager (PM) and Program Management Office (PMO) in all aspects of a program's T&E effort (DOD 2012, 27). The Navy's T&E WIPT structure consists of several key individuals:

- **Chief Developmental Tester (CDT)/ T&E Chair:** This is typically a senior-level civilian who is responsible for overseeing the T&E WIPT and ensuring that T&E activities are properly integrated into the acquisition process. This person is the PM's primary lead for T&E and is responsible for executing the T&E Strategy, developing the integrated test plan, and allocating resources to support T&E execution (DON 2022a, 8-9).

- **T&E Steering Group:** These are T&E professionals who hold leadership roles in the associated Working-level Integration Product Team (IPTs). This group is responsible for T&E planning, execution, and reporting activities. They assist the CDT/ T&E Chair in leading test activities, providing objective assessments of results, and steering T&E efforts to ensure proper execution of the program's Test & Evaluation Master Plan (TEMP).

- **Working-Level IPTs:** These are smaller teams that are responsible for executing specific T&E activities, such as creating T&E requirements and objectives, drafting scenarios and test plans, executing test events, conducting data analysis, and reporting on test results. These working-level IPTs work together in concert to ensure proper execution of the program's TEMP and guidance provided by the T&E Steering Group and CDT. In addition, these working level IPTs utilize various sub-working group vehicles such as the Test Objective Working Group (TOWG), Scenario Working Group (SWG), Data Analysis Working Group (DAWG) and others to accomplish their assigned levels of responsibilities.

Figure 4 illustrates a notional T&E WIPT structure for a Major Capability Acquisition program.

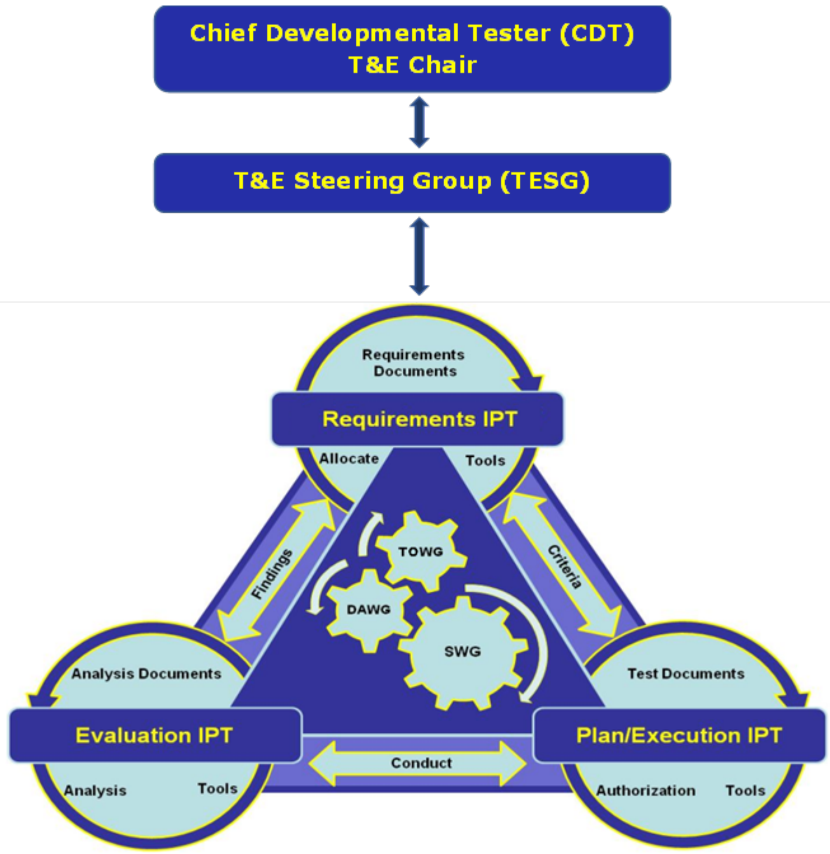

Figure 4. Notional T&E WIPT Structure

The T&E WIPT structure facilitates communication and collaboration among the various organizations involved in T&E activities to ensure proper planning, execution, evaluation, and reporting.

C. T&E CHALLENGES AND LIMITATIONS

The United States Navy has made efforts in recent years to accelerate the delivery of new systems and technologies. One of the key initiatives can be found in the Navy's Strategic document called *Design for Maritime Superiority 2.0*, which outlines plans to modernize the Navy and Marine Corps to meet future challenges. The vision is to rapidly field new platforms, payloads, and technologies to maintain a technological edge over our near-peer adversaries. In 2019, the CNO, Adm. John Richardson, gave a speech at the Naval Post-Graduate School where he stressed the need for faster development of naval systems as "we need to be able to move our technological capabilities into the hands of the warfighter at a relevant speed, because in the modern information age it matters to be first. That means we need to have a way to prototype, produce and deliver our systems before our adversaries" (Dionne 2019). However, speeding up the naval acquisition process and thereby reducing the T&E timeline without addressing the existing issues can lead to more problems down the line.

The T&E community is currently experiencing challenging times due to several factors such as reduced budgets, inadequate infrastructure, fewer live targets, and evolving threats. The Navy's guidance to accelerate the deployment of systems at a faster rate than ever before, without providing a detailed plan on how to achieve that transformation might initially create more problems than solutions. While the push for faster results and testing is being discussed by Navy Program Managers and T&E practitioners, it is essential to note that prioritizing acquisition speed can lead to life cycle sustainment issues, short-sighted system design, and trigger scrutiny from congressional overseers according to Jonathan Wang, a professor and researcher at the RAND institute (Wong 2020). While the positive effects of this strategy might lead to faster delivery of new capabilities to the warfighter at a lower cost, rushing T&E can have negative consequences such as inaccurate results, reduced system quality, increased safety risk to the warfighter, and encourage poor decision making while reducing accountability. Before accelerating the T&E process, it is important to understand the existing challenges and issues facing the community:

1. Inadequate infrastructure

The Navy's testing infrastructure comprised of test ranges and laboratories is aging and quickly becoming absolute. According to a 2017 study by the Defense Business Board, current military "T&E infrastructure will not be able to support future testing of new technologies, such as hypersonic and autonomous systems without increased funding" (Defense Business Board 2017, 6). Meanwhile, the demand to test weapons and other military systems across all services has only increased. Based on a 2021 study on DOD test ranges by the National Academies of Science and Engineering, the increasing complexity and sophistication of new and upgraded systems have led to growing testing needs by the T&E community. However, many of the nation's test ranges were established during World War II and upgraded in the Cold War era but have not kept pace with recent technological developments (National Academies 2021a, 2).

The Acting Director of Operational Test and Evaluation (DOT&E) has serious concerns that, looking ahead to the next ten to fifteen years, the T&E community may not be sufficiently prepared to carry out its mission. Additionally, the same 2021 study concluded that neither the operational test system, process or the "ranges that support testing are optimized to increase speed of capabilities to the field" (National Academies 2021b, 17).

It is not just the test ranges that are having issues, but the problem can also be found in the infrastructure of today's Naval laboratories. A 2019 study on Naval laboratory readiness found that the current infrastructure management system and associated resourcing is inadequate to maintain the Navy's laboratory infrastructure in adequate state of readiness (Summers 2019). For example, laboratories could easily be impacted by an electrical outage or fiber optics issue that could quickly disrupt critical testing timelines. Moreover, the report also noted that the current infrastructure management system was initially built to support the industrial age concept and is no longer suitable to meet the demands of today's highly technical requirements (Summers 2019).

2. Limited Test Space

Testing advanced systems such as hypersonic missiles and long-range weapons requires a large and isolated space that does not currently exist. According to the 2021 report by the National Academies of Science regarding test ranges, the U.S. Navy is expressing significant concerns over the impending challenges of obtaining enough space to conduct all OT&E. The primary difficulty stems from the need to perform intricate and advanced tests on emerging systems within the confines of progressively restricted test ranges. The report indicates that testing these new long-range systems will require expanding the boundaries of existing test ranges such as Naval Air Weapon Station China Lake or the Point Mugu Sea Range. However, expanding the boundaries of test ranges will be exceedingly difficult due to encroachment issues across commercial and residential areas, environmental concerns with disruption of endangered species, and interference with consumer electromagnetic spectrums such as 5G transmitters (National Academies 2021a, 5-6).

3. Evolving Threats and Scenarios

The Navy is not keeping up with the evolving threat regarding intelligence gathering, model development, and target upgrades. During a 2021 public T&E workshop among military experts from industry and Government, Ed Greer, the former deputy assistant secretary of defense for developmental test and evaluation, shared his concern with the intelligence gathering timeframe. According to Greer, "it takes an average of 3 to 5 years from the time that intelligence is collected on threats to the time those threats are instantiated into testing, during which time adversaries can build new systems faster than intelligence centers can build models" (National Academies 2021b, 18).

During that same workshop, several experts concluded that the current threat scenarios being used are old and require updating. In most cases, the T&E community gravitates towards the use of existing test scenarios instead of developing new scenarios that reflect Today's threat profiles. Conrad Grant, the Chief Engineer for Johns Hopkins University Applied Physics Laboratory said that "today's range targets are generally threat-representative in some flight profiles but that threats are constantly evolving and it is difficult for the target providers to keep up with that evolution" (National Academies 2021a, 5). In addition, acquiring targets have become challenging due to its dwindling supply, which has created a situation where it is not possible to do as much testing as desired (National Academies 2021a, 5).

Effective testing of naval weapons systems requires upgrading the limited number of available targets and their capabilities. For example, this includes updating the radar emulators utilized in the Nevada Test and Training Range and Point Mugu Sea Test Range, which are over a decade old. Greer emphasized the necessity of upgrading threats in open-air ranges, ground-based simulations, and modeling and simulation laboratories. Specific threat environments, such as surface-to-air missile models, threat aircraft models, and threat weapon models, must also be kept current. Additionally, the current open-air ranges are unable to handle the necessary threat density to adequately challenge modern weapons systems, posing a significant issue for the T&E community (National Academies 2021a, 5).

4. Test Integration

As the U.S. Navy moves towards the use of Capabilities-Based Test & Evaluation strategy following the "test like we fight" concept, testing in multiple domains at a force level is becoming a huge challenge. The issue resides in utilizing multiple test ranges to properly recreate a realistic multi-domain environment. According to the 2021 study from the National Academies of Science (2021a), the challenge is twofold. The first challenge is dealing with combining existing test ranges into one overly complex "range of ranges." The second challenge arises from the need to test multiple systems with different services in one single test event. While possible, this type of test has been conducted in the past primarily in support of joint training exercises to develop or improve new tactics, techniques, and procedures (TTPs). For example, the 2021 Large-Scale Exercise (LSE) was successfully conducted by the Navy utilizing the Live, Virtual, and Constructive test construct. The LSE event demonstrated the capability to connect multiple test ranges and naval systems to share sensors, weapons, and platforms globally. According to the Navy the "LSE 2021 is part of an on-going series of exercises that demonstrates the U.S. Navy's ability to employ precise, lethal, and overwhelming force globally across three naval component commands, five numbered fleets, and 17 time zones" (U.S. Fleet Forces Command 2021). If planned properly, tests like LSE can provide an opportunity to test experimental technologies and new capabilities in support of DT&E or OT&E. While the concept of connecting multiple ranges and/or laboratories to support a realistic multi-domain environment is the most effective strategy to test naval systems, it is also the most difficult to coordinate and costly to execute (National Academies 2021a, 7).

5. T&E Spending

T&E spending across the Navy has fluctuated in the past 20 years. Based on data gathered by the Forecast International Corporation, the Navy's RDT&E budget fell below 20 billion from 2010 to 2020 as seen in Figure 5 (Aeroweb n.d.).

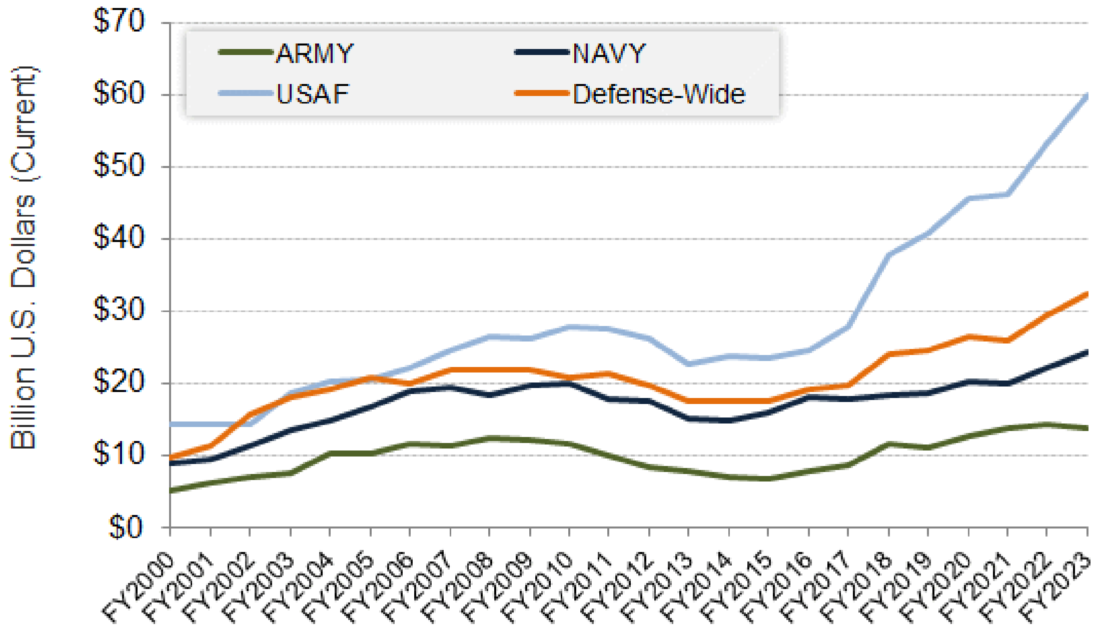

Figure 5. RDT&E Spending by Services from FY2000–FY2023. Source: Aeroweb (n.d.).

However, according to the Fiscal Year (FY) 2023 Department of Navy Budget Report, the Navy has gradually increased its RDT&E budget in just the past three years as followed (DON 2022b, 26):

- FY 2021: $20,151 billion
- FY 2022: $22,152 billion
- FY 2023: $24,079 billion (projected)

While this might seem like a step in the right direction, the true cost of T&E is more difficult to ascertain from the recent increase in RDT&E funds. The reason behind this is that RDT&E funds are usually combined with research and development projects that might not translate directly to T&E. Upon closer examination of the Navy budget report, it can be observed that the funding allocated for RDT&E Management Support has decreased by 23% from FY 2021 to FY 2023 (DON 2022b, A-11). This funding category encompasses T&E activities, as well as the maintenance of installations for general research and development. Additionally, it covers expenses related to test ranges, military construction, maintenance support for naval laboratories, and upkeep of test aircraft and ships.

6. T&E Cost Perception

Historically, T&E has been viewed as an expensive endeavor requiring substantial amounts of resources to execute. Consequently, previous attempts have been aimed at reducing T&E by Program Managers as the primary measure to overcome budgetary constraints. This perception has led some to suggest transferring T&E responsibilities from the government side to the private sector as a means of achieving cost savings.

In a 2017 study, the Defense Business Board concluded that "accurate tracking of T&E costs is not generally viewed as a priority by the Department" (DBB 2017, 5). The same study also concluded that private industry does a better job at tracking T&E expenses as these costs are examined routinely (DBB 2017, 8). However, the counter argument to this study was published in a memo during that same year by the Director, Operational Test & Evaluation (DOT&E), which revealed that the overall allocated resources for both DT and OT are documented in the program's TEMP (Gilmore 2017). In addition, the same report referenced a 2011 study by DOT&E on 76 Acquisitions programs across DOD, which reported the average marginal cost of OT&E to be approximately 0.65% of the total acquisition cost (Director of Operational Test and Evaluation [DOT&E] 2011). This number is illustrated in Figure 6.

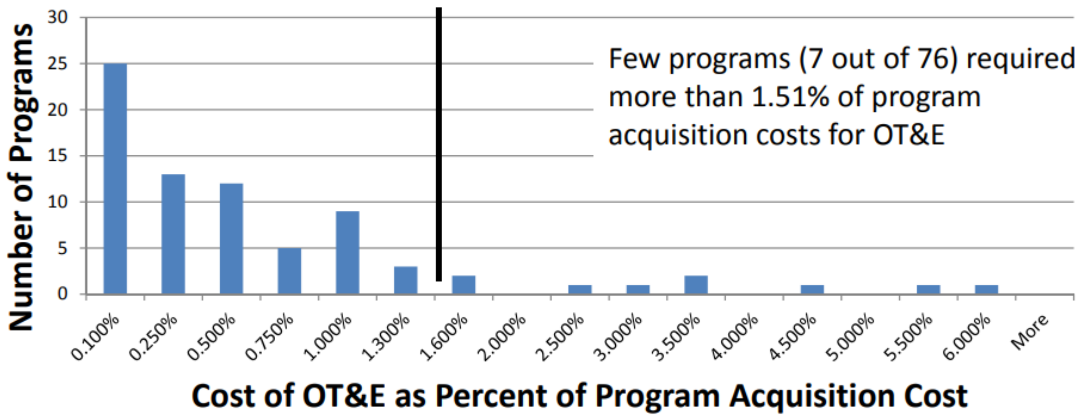

Figure 6. Cost of OT&E as a Percentage of the Acquisition Cost. Source: DOT&E (2011).

The evidence presented by OT&E data strongly suggests that the expense incurred in T&E activities is considerably low when compared to the overall acquisition cost, thereby contradicting the perception or myth that has become widespread in the acquisition community.

7. Schedule Delays

Naval system acquisition programs are complex, long-term projects that involve significant investment of resources. One of the challenges facing the acquisition community is how to properly conduct T&E without causing program delays. This is especially true for new cutting-edge technologies that have not been fielded before.

During the T&E process, new naval systems are subjected to a range of tests and evaluations to assess their performance and capabilities. If any issues or deficiencies are identified during this process, additional testing or modifications may be required, which can add time and cost to the overall acquisition program. In some cases, delays in the T&E process may be caused by technical challenges, test range or target unavailability, or the need for additional testing. For example, if a new naval system encounters unexpected problems during testing, additional tests may need to be performed to ensure that the issue has been resolved. This can add time to the overall schedule for the acquisition program.

According to a 2014 study by DOT&E on the reasons for program delays, it concluded that Navy programs are statistically more likely to experience problems in test conduct. The study examined 43 Naval acquisition programs of which 16 were found to have the following test execution problems resulting in schedule delays ranging from 0.5 years to 14 years:

- Unavailable ships, system under test, or targets
- Improper test instrumentation/ telemetry
- Improper test procedures (DOT&E 2014)

Out of the 43 naval programs examined, there were also other problems that contributed to schedule delays such as performance issues discovered in DT&E and OT&E, programmatic challenges, and manufacturing, software development, and integration issues (DOT&E 2014). Figure 7 breaks down the composition of issues that impacted program delays in DOT&E study.

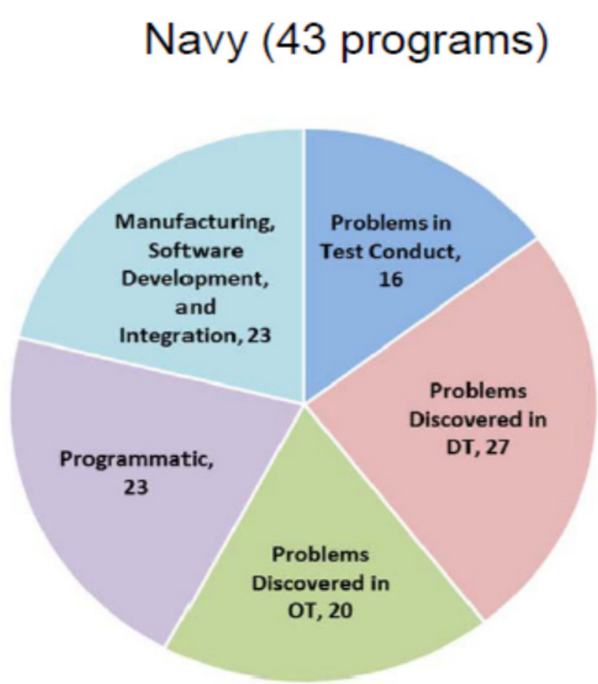

Figure 7. Reasons Behind Program Delays in Naval Acquisition. Source: DOT&E (2014).

The study also revealed that the primary reason for program delays is linked to the discovery of system performance issues during DT and OT (DOT&E 2014). Such issues must be addressed before the program can move forward. It is worth noting that performance issues discovered during T&E help ensure that naval systems are safe, suitable, and effective. After all, the purpose of T&E is to help identify these design flaws and vulnerabilities to provide superior quality systems in the hands of the warfighter. By rigorously testing and evaluating these complex systems, the Navy can increase its confidence that they will perform as expected when deployed in real-world scenarios.

8. Data Strategy

The significance of extremely large data sets known as big data is on the rise within the Navy's T&E communities due to the deployment of new and advanced systems such as unmanned vehicles, sophisticated sensors, and intricate weapon systems. The exponential growth in data generated by these new systems poses a major challenge for the Navy, which is to identify effective ways of utilizing all this data to facilitate in the decision-making process.

To date, the Navy has yet to clearly define a data strategy for T&E. Most program managers do not consider developing a data strategy or if they do, it usually happens once the system is ready for testing, which is often too late. In the 2021 study on test ranges, Joshua Marcuse, the Head of Strategy and Innovation at Google, made a significant observation about the T&E process. He noted that program managers frequently overlook the importance of implementing a data strategy while developing systems, resulting in the failure to gather the necessary data to meet operational testing requirements. Marcuse commented that planning for data collection to support T&E efforts needs to be considered early in the system design phase (National Academies 2021a, 9).

Presently, most T&E organizations continue to rely on physical hard-drives and disks to manually transfer system data between test ranges, ships, and laboratories. However, the use of secure networks such as the Secret Internet Protocol Router (SIPRNet) and Secure Defense Research and Engineering Network (SDREN) are becoming popular as efficient methods to pipe test data between test ranges and analysis organizations. Below are some of the key challenges when it comes to working with big data:

- **Data Integration** – The Navy generates data from various sources during T&E events, including sensors, simulators, stimulators, telemetry instrumentation, targets, and the system under test. The challenge is to integrate and standardize this data to ensure that it is accurate, consistent, and usable. To date, most system data is unique from each other and requires proprietary data dictionaries and custom data reduction tools to convert it into a readable format before it can be used for analysis purposes.

- **Data Storage and Security** – Effective data storage and security are of importance in the Navy's T&E efforts. Due to the immense volume of data generated during testing, it is crucial that the Navy stores this data in a manner that is both secure and easily retrievable. This is particularly important given that most T&E data collected today is generated from tactical systems. This type of data is commonly classified at a secret level and therefore requires special handling and robust security measures to ensure that it is safeguarded from unauthorized access or intrusion.

- **Data Quality** – Ensuring that data is of high quality and free from errors, inconsistencies, or biases is a critical challenge. Data collected during T&E events comes from multiple sources and in different formats. To effectively use this data for data analytics, it is essential to clean and process it to ensure its accuracy and consistency. Data cleaning involves identifying and correcting errors, removing duplicates, applying unit conversions, and filling data gaps. It is a critical step in the data analysis process, as poor data quality can result in incorrect insights that can lead to poor decision making.

- **Data Infrastructure** – To effectively manage vast amounts of data and conduct comprehensive analytics, the Navy requires advanced technology infrastructure with high-performance computing, robust storage, and secure network capabilities. This entails modernizing existing infrastructure, upgrading equipment to support faster bandwidth, and expanding data storage capabilities to gain a strategic information advantage. Despite the Navy's commitment to invest in this critical area, as demonstrated by the Information Superiority Vision 2020, the T&E community has yet to fully benefit from these advancements.

- **Data Sharing –** Data sharing has remained a significant challenge for the T&E community for many years. A 2019 study by the RAND Institute on the use of data analytics to enhance acquisition outcomes found that data sharing across the services remains a significant barrier. Several reasons contribute to this situation, such as a culture of limiting access to data, concerns over security, mistrust in how the data might be used, and the burden of data reporting (Anton et al. 2019, xii). For instance, many acquisition program managers are hesitant to share their program's test data without their explicit permission. Additionally, certain data may have releasability restrictions in place, such as "need-to-know" or security concerns, as system data is often classified at a secret level. Unless the Navy can devise effective solutions to overcome these obstacles, data collected from test events will continue to reside on multiple servers across numerous T&E organizations, with limited access.

9. Testing AI and ML

The Navy does not have the infrastructure and the methodology to properly test adaptive emerging technologies like machine learning (ML), deep learning (DL), or artificial intelligence (AI). These technologies are so new that most T&E practitioners are still scratching their heads on how to begin their testing endeavors. In a 2020 publication exploring the importance of building trust though testing AI systems, the author, Michele Flournoy, contends that the current defense acquisition T&E process is insufficient for testing iterative development approaches of ML/DL. Furthermore, the author notes that characterizing ML/DL system performance is challenging, and the fragility of such systems necessitates frequent system updates and testing. Moreover, conducting extensive up-front testing is impractical for these types of non-deterministic systems. Instead, the author recommends the adoption of commercial best practices, such as Development, Security, and Operations (DevSecOps), which offer an integrated, iterative, and automated approach to development and testing (Flournoy 2020). The author list additional challenges to development and testing of these non-deterministic systems:

- **Infrastructure not suitable for testing** – To enable the successful development and testing of these new technologies, it is imperative to invest in targeted infrastructure improvements for both test ranges and laboratories. In particular, the creation of a dedicated infrastructure environment designed to facilitate the training, testing, and transition of AI technologies is of utmost importance. Additionally, advancements in computing power, storage capacity, increased bandwidth, cloud-based resources, and cutting-edge tools are also essential.

- **Large representative data sets** – In order to effectively test learning systems, it is essential to have access to large amounts of representative scenario data. The more data is available for training, the more accurate and effective these algorithms can be in recognizing patterns and trends that lead to making predictions. However, data challenges, such as the inability to properly share system data across the enterprise, can make it difficult for the T&E community to test system performance against realistic conditions.

- **Integration into System of Systems** – Given that ML/DL technologies are set to be integrated into a range of software and hardware systems, is crucial for developers and testers to adopt a systems architecture approach when building and evaluating these systems. Testers will also need to test these algorithms not just at the element or unit level, but also at the force-level or system of system level.

- **Traceability and Interpretability** – Deep learning systems are different from other types of computer or weapon systems because it may be difficult to trace how and why a decision was made in a specific situation. This lack of traceability can create challenges for the T&E community. It can also erode confidence in the chosen solution, as operators and testers may be hesitant to trust the decisions made by these systems without a clear understanding of how they relate to requirements (Flournoy 2020).

Addressing these issues will not be easy and require continued investment in test infrastructure as well as the development and integration of new technologies and methodologies to improve the overall process.

D. CURRENT STATE PROCESS

This section documents the current T&E Process from both a DT&E, OT&E and IT perspective. Throughout the course of this research, the body of accessible literature revealed limited information regarding the detailed steps involved in the naval T&E process. As such, the diagram contained in this section was created using information derived from the 2022 DOD T&E Enterprise Guidebook, SECNAV Instruction 5000.2G, and personal knowledge of the naval T&E process. Table 1 provides a summary of the differences between DT&E and OT&E, while Figure 8 depicts the DOD T&E events and milestones for a Major Capability Acquisition program.

Table 1. DT&E and OT&E Differences. Adapted from DAU (n.d.e).

	DT&E	OT&E
What is Tested?	"Measures technical performance against the design specifications."	"Determines operational effectiveness and suitability as defined in the Capability Development Document (CDD) and Capability Production Document (CPD)"
Responsible	Program Manager and Chief Developmental Tester	Operational Test Agency (OTA)
Test Team	Government (T&E WIPT) and Contractor	Government (T&E WIPT)
Test Location	Controlled Environment (laboratory and test ranges)	Field Environment (realistic operational environment)
Focused	"Program Focused"	"Warfighter Focused"
Acquisition Timeline	Starting in Milestone A until end of Milestone B	Milestone C

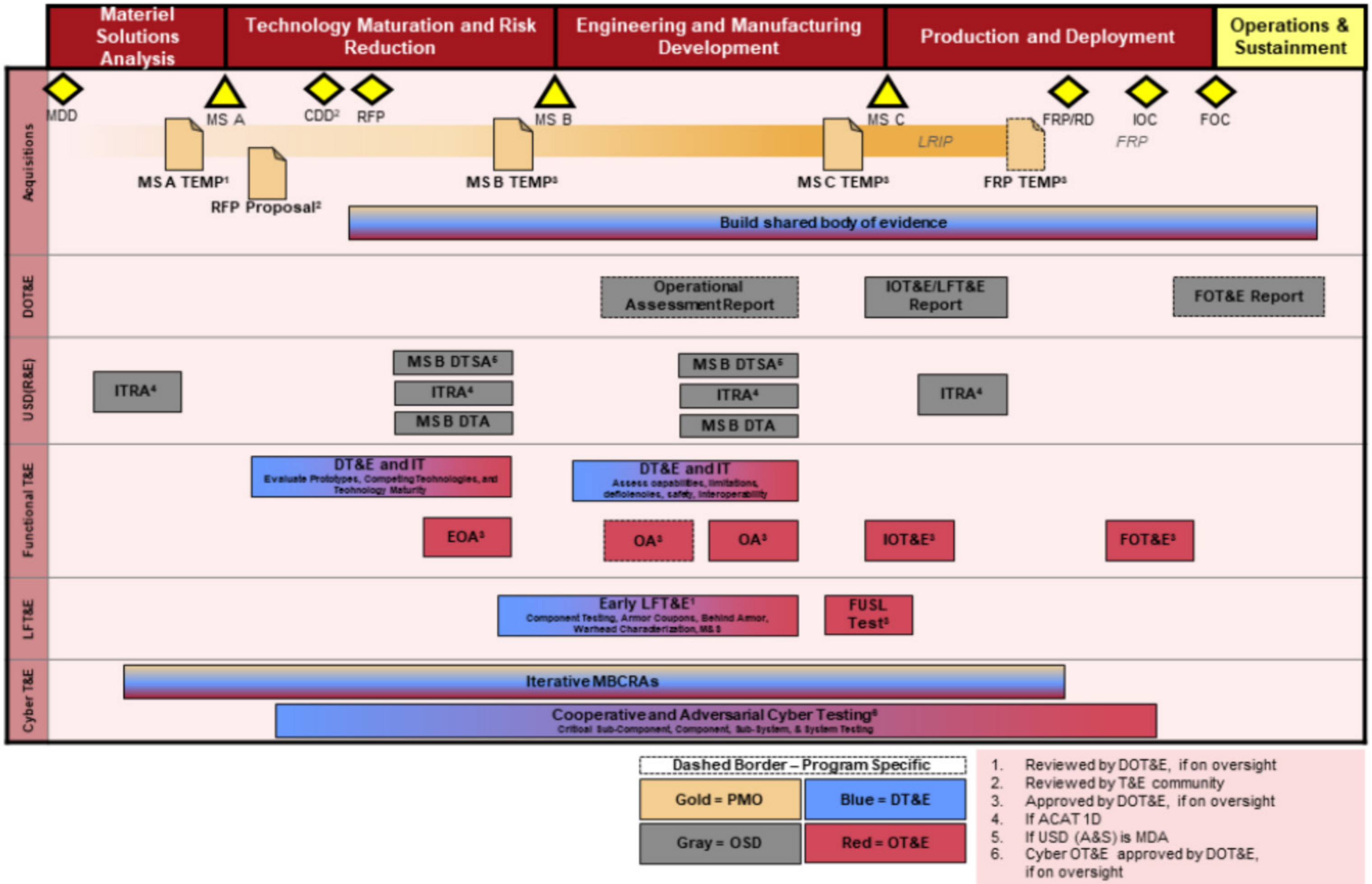

Figure 8. DOD T&E Events & Milestones for Major Capability Acquisition Program. Source: DOD (2022a).

Figure 9 illustrates the current naval T&E process, based on the following phases:

- **Planning** – Develop the Test & Evaluation Strategy (TES), considering operational requirements (warfighter needs), system capabilities, and technology risk. Review requirements to formulate evaluation criteria that will guide T&E activities throughout the acquisition process. Establish the T&E WIPT team, devise the test schedule, identify necessary resources, and project cost estimates. Determine data requirement for evaluating system performance, critical operational issues (COI), key performance parameters (KPP), and key system attributes. Roll out the TEMP and initiate the formulation of test objectives and scenarios.
- **Preparation** – Establish test objectives, scenarios, and evaluation criteria. Develop the test plan, and the data management and analysis plan. Secure funding for T&E organizations and allocate necessary resources for test execution. Update and set up required tools and equipment for testing. Compile test artifacts for the Test Readiness Review (TRR) milestone.
- **Execution** – Carry out the test event, overseeing resources, safety, schedule, and risk mitigation. Validate the completeness of the collected raw test data for system evaluation. Establish cybersecurity measures to safeguard test data integrity. Distribute data as outlined in the data management plan for analysis and overall evaluation.
- **Analysis** – Interpret and verify data from test systems and tools, identifying any gaps or outliers that could impact analysis. Reduce raw data and conduct analysis to support the evaluation and reporting phases. Reconstruct test runs and scenarios and calculate performance metrics to identify system issues. Document system issues and limitations and conduct collaborate root-cause analysis via the Data Analysis Working Group.
- **Evaluation** – Align analysis findings with test objectives for system performance assessment. Ensure test data can accurately support the approved TEMP evaluation framework. Link test outcomes and evaluation conclusions to performance specifications and operational significance. Evaluate how hardware/

software components function together as required and contribute to the broader system of systems' performance.

- **Reporting –** Provide T&E insights for technical and programmatic reviews aiding acquisition decisions. Apply lessons learned from data collection, analysis, and evaluation to improve processes. Deliver necessary T&E reports capturing test methodology, results, evaluations, and recommendations for acquisition decisions and user needs, including Tactics, Techniques, and Procedures (TTPs). Archive data throughout T&E phases to support future efforts.

The outcome of the T&E process is a comprehensive assessment of a system's performance, effectiveness, and suitability. The results provide decision-makers with the critical information needed to make informed judgments about the system's readiness for operational use, potential for system improvement, and overall value. An extensive list of T&E activities corresponding with these six phases are detailed in Appendix A.

Figure 9. Current Naval Acquisition T&E Process

E. RECENT T&E STRATEGIES

In April 2022, the Secretary of the Navy published SECNAV Instruction 5000.2G detailing the implementation of the DOD Defense Acquisition System (DAS) and the Adaptive Acquisition Framework (AAF) across the Navy (DON 2022a, 1-4). The DAS is a DOD policy designed to support the National Defense Strategy by the development of a more lethal force. The DAS promises to deliver cutting-edge products and services that meet the needs of end-users, while delivering measurable and timely enhancements to mission capability, material readiness, and operational support, all while maintaining cost-effectiveness. The DOD and the services are adopting the AAF to achieve the objectives of the DAS (DOD 2022b, 4).

The AAF is a dynamic acquisition policy designed to provide a responsive and adaptable approach to developing and acquiring new capabilities. Unlike traditional acquisition models, the AAF prioritizes a flexible, tailored approach that aligns with program-specific requirements and operational needs, while promoting innovation and collaboration with industry partners. The AAF comprises six distinct pathways: Urgent Capability Acquisition, Middle Tier of Acquisition, Major Capability Acquisition, Software Acquisition, Defense Business Systems, and Acquisition of Services. Each pathway offers a unique set of procedures and requirements tailored to specific needs of a program, enabling the services to remain agile and adaptable in the face of evolving technological advancements and emergent threats (DOD 2022b, 12-16). Figure 10 illustrates the Adaptive Acquisition Framework. The same SECNAV 5000.2G instruction details guidance for Naval acquisition programs to use Capabilities-Based T&E (CBT&E) to integrate DT&E, OT&E, and LFT&E into a single T&E continuum to support the six AAF pathways (DON 2022a, 85).

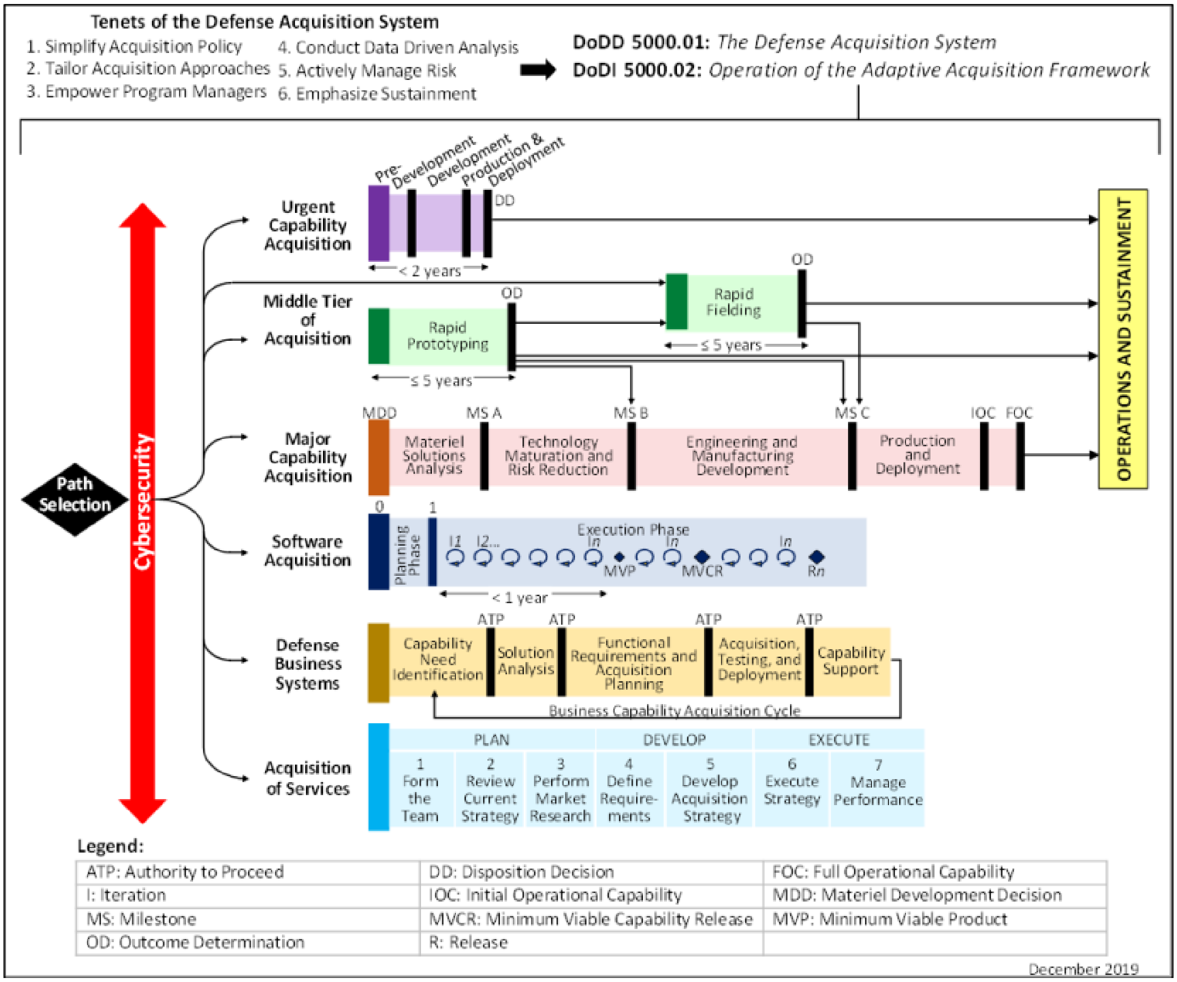

Figure 10. The Adaptive Acquisition Framework (AAF). Source: DOD (2022b).

Capability-based Test and Evaluation (CBT&E) is a strategic approach to testing and evaluation that focuses on the assessment of a system's overall capability to meet specified requirements and mission objectives. This approach evaluates a system's ability to perform its intended mission and functions under realistic operational conditions, rather than simply assessing individual components or subsystems in isolation. This method changes the traditional T&E approach from specification compliance at the element level to assessing mission capability by integrating all phases of testing. It considers the system's performance in terms of its mission effectiveness, suitability, and survivability, providing a more comprehensive assessment of the system's capabilities in real-world scenarios. This approach is particularly relevant in evaluating complex systems, where the performance of individual components must be integrated and assessed in the context of the system's overall mission objectives (Lednicky and Silvestrini 2013).

The integration of CBT&E into common testing practices has been gaining momentum in recent years as a promising approach to improve test and evaluation outcomes. However, its maturity level across all Naval SYSCOMs is not yet consistent, as the paradigm shift requires the adoption of best practices and incorporation of advanced statistical tools and techniques, such as Design of Experiments (DOE) and Modeling & Simulation. Additionally, efforts are being made to leverage distributed test environments, including Live, Virtual and Constructive (LVC), to support complex multi-mission scenarios at a reduced cost and schedule. These efforts aim to improve the overall efficiency and effectiveness of the T&E process, with the goal of better supporting the AAF's six distinct pathways. The main challenges with CBT&E are the lack of understanding, cultural barriers, resource constraints, and complexity associated with the adoption of a new "test like we fight" paradigm. The traditional T&E process is already complex and involves many stakeholders, such as sponsors, design agents, support contractors, and industry partners, across different T&E organizations. Therefore, integrating CBT&E requires careful coordination, early planning, and collaboration among all stakeholders involved in T&E. This poses a significant challenge, as it requires a shift in mindset and operational processes.

III. DIGITAL ENGINEERING

In this chapter, the comprehensive literature review continues by focusing on digital engineering. The key components are delved into, providing definition and context. The U.S. Navy's strategy approach is discussed, adoption practices are examined using real-world case studies, and implementation challenges across the industry are highlighted. When considered in conjunction with the previous chapter, the insights serve to construct an analytical framework. This foundation is critical as it facilitates a thorough understanding and in-depth evaluation of the principal research question.

A. OVERVIEW

The convergence of disruptive and innovative technologies like artificial intelligence and connected devices such as smartphones have propelled the world into a new phase of technological advancement referred to as the Fourth Industrial Revolution, or simply Industry 4.0 (Schwab 2016). This revolution is expected to empower businesses to better control and understand every aspect of their operation and leverage data to boost productivity, improve processes, and drive growth. A characteristic aspect of this industrial revolution is digitalization, which is "the use of digital technologies to change a business model and provide new revenue and value-producing opportunities" (Gartner n.d.). Digitalization is already triggering a profound and pervasive digital transformation, rippling through every aspect of human society around the world. At the heart of Industry 4.0 resides digital engineering, signifying the "manifestation of digital transformation in the field of engineering" (Huang et al. 2020, 3). More precisely, it represents the transformation of how organizations normally conduct systems engineering that is based on models in a digital environment (Giachetti 2022).

In 2018, the U.S. Department of Defense launched their *Digital Engineering Strategy* and defined it as an "integrated digital approach using authoritative sources of system data and models as continuum across disciplines to support life cycle activities from concept through disposal" (DOD 2018, 3). This strategy calls for the development, use, and distribution of formal models and digital information across the entire engineering process and organizational structures via a reliable 'authoritative source of truth.' This approach is anticipated to influence the U.S. defense industry significantly, with repercussions extending to various other industry sectors, and consequently reshape the practice of engineering. The transformation into digital engineering signifies an essential shift in the engineering paradigm as part of the Fourth Industrial Revolution, employing model-based methodologies along with digital tools and technologies as critical enablers (Huang et al. 2020). Digital engineering offers the potential to enhance operational efficiency, optimization, and innovation within the engineering sector, paving the way for an exciting era of rapid innovation and technological advancements. Figure 11 illustrates the Digital Transformation in the context of the Fourth Industrial Revolution.

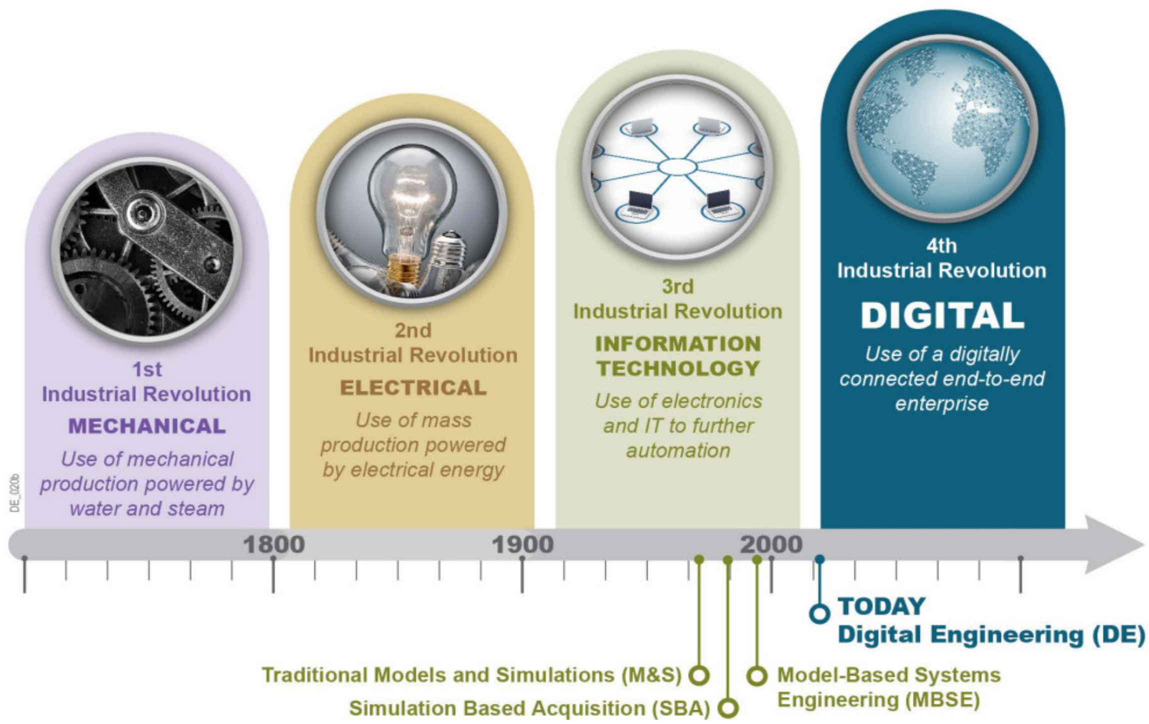

Figure 11. Digital Transformation as the 4th Industrial Revolution. Source: Gold and Zimmerman (2018).

From an engineering process perspective, digital engineering is transforming the traditional engineering paradigm of design-build-test to a more modern, model-analyze-build methodology. Figure 12 depicts an engineering process represented as a model with inputs, outputs, enablers, and controls. The digitalization of key engineering elements such as artifacts, processes, and the enterprise itself serve as the backbone of this transformation journey. Without digitalization, the use of new digital technologies could be restricted or short lived. Nevertheless, by leveraging digital artifacts and processes, it is possible to effectively harness the power of digital technologies, model-based concepts, and artificial intelligence. This fusion has the potential to refine and transform the engineering practice (Huang, forthcoming, 6). Such an evolution would enable a more streamlined and efficient engineering process, capable of addressing the challenges inherent in the design and development of complex systems.

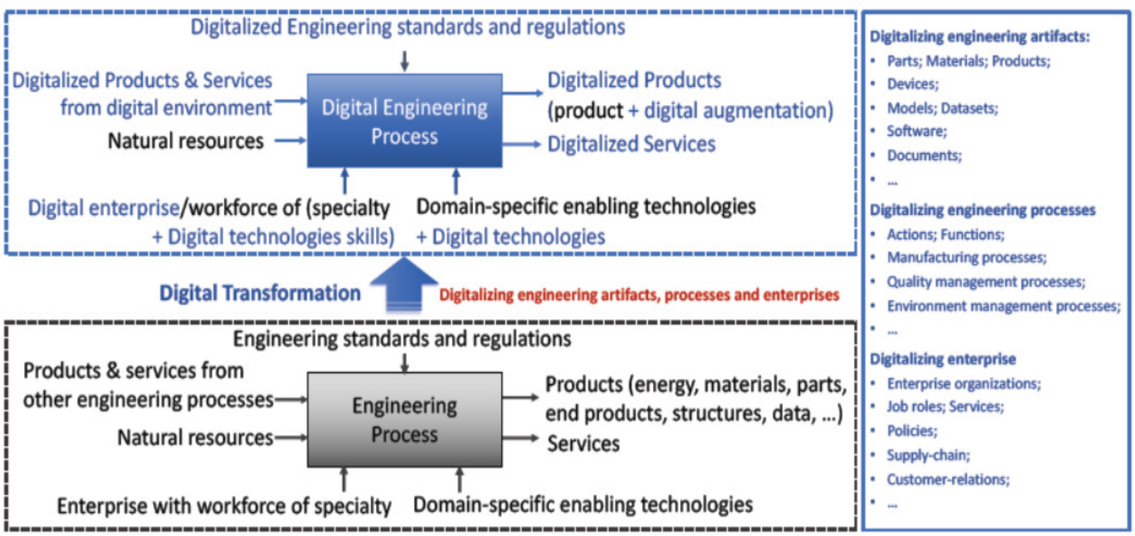

Figure 12. Digital Engineering Transformation from a Process Perspective. Source: Huang (forthcoming).

Some of the key expectations and benefits in the application of digital engineering include: "(1) Informed decision making, and greater insight through increased transparency, (2) Enhanced communication, (3) Increased understanding for greater flexibility/ adaptability in design, (4) Increased confidence that the capability will perform as expected, (5) Increased efficiency" (Zimmerman, Gilbert, and Salvatore 2019, 337). These expectations, alongside their accompanying benefits, are depicted in Table 2

Table 2. Digital Engineering Expectations and Benefits. Source: Zimmerman, Gilbert, and Salvatore (2019).

Expectations (IAWG)	Digital engineering benefits
(1) Informed decision making, and greater insight through increased transparency	• Optimizes decisions prior to live implementation • Provides access to accurate, consistent, up-to-date information for decisions • Provides rich visualization and reporting capabilities
(2) Enhanced communication	• Stakeholders across various organizations and distributed locations work from an authoritative source of truth • Provides a shared understanding of the system • Multiple views are generated from the same source to address different stakeholders' concerns • Impacts to changes can be quickly evaluated, and updates and traceability can be automatically propagated
(3) Increased understanding for greater flexibility/adaptability in design	• Models reduce misinterpretations and provide increasingly accurate results • Provides rigorous traceability within and between as-designed, as-built, as-maintained, as-operated baselines • Provides insight into how elements of the design can be added, replaced, removed, and integrated
(4) Increased confidence that the capability will perform as expected	• Enables prototyping, experimenting, and testing of solutions virtually before they are delivered to the warfighter • Provides systematic and rigorous exploration of trade space • Provides early and continuous verification and validation so defects, risks, and issues can be discovered up-front
(5) Increased efficiency	• Automation and autonomy • Enhances historical knowledge capture and reusability of existing models to reduce redundancy and re-work • Enables rapid assessment of effects of changes

IAWG: Interagency Working Group.

B. KEY TENETS OF DIGITAL ENGINEERING

Digital engineering is a comprehensive approach that incorporates multiple elements and principles, integrating infrastructure, data, models, networks, tools, and processes into a single, cohesive framework that spans the entire continuum. According to a 2019 journal article on digital engineering transformation across the Department of Defense, the author indicates that DE is comprised of existing model-based tenets such as digital twin, digital thread, and model-based systems engineering (MBSE). (Zimmerman, Gilbert, and Salvatore 2019, 325). These model-based tenets work together to enable the shift from a traditional document-centric approach based in a physical domain to a model-based approach based on a digital environment.

Incorporating model-based principles alone is insufficient to achieve the full potential of digital engineering. It also requires the incorporation of an authoritative source of truth (ASOT) and digital tools as essential components. ASOT is essential in digital engineering as it provides all stakeholders with a single source of consistent and up-to-date information throughout the entire system life cycle. Unlike traditional engineering methods that often scatter information across multiple documents and systems, the ASOT serves as a central repository for all data, models, and other system-related information. It provides reliable, consistent, and trusted data such as requirements, standards, system data, and technical reports, which support the decision-making process throughout the system's life cycle. Meanwhile, digital tools enable engineers to design, develop, test, and manage engineering systems using cutting-edge technologies such as computer-aided design software, modeling and simulation software, cloud computing, Artificial Intelligence (AI) and Machine Learning (ML) algorithms, and data analytics software.

For the purpose of this research, the following key tenets of digital engineering are explored: digital twin, digital thread, MBSE, ASOT and digital tools.

1. Digital Twin

The concept of digital twin has been defined in multiple ways across a range of industries. Nevertheless, most of the definitions share a common thread as a digital representation of a physical product, process, or system. As per the Digital Twin Consortium, which is comprised of Industry, Academia, and Government, a digital twin is defined as "a virtual representation of real-word entities and processes, synchronized at a specific frequency and fidelity" (Digital Twin Consortium n.d.). The fundamental elements of a digital twin include the physical system, also referred to as the physical twin, its digital representation referred to as the digital twin, and the connection that enables the communication between the two. According to the consortium, a digital twin can be used to make predictions about a process or system using real-time and historical data to support optimal decision-making (Digital Twin Consortium n.d.).

The concept of digital twin was first introduced in 1991 with the publication of *Mirror Worlds* by David Gelernter in the context of software models. However, it was Dr. Michael Grieves from the University of Michigan that is credited with being the first to apply the concept, referred at the time as "Mirrored Spaces Model" to manufacturing in 2002. It was not until 2010 that NASA started the use of the term digital twin in their technological roadmap (Singh 2021, 2-3). Since then, digital twin has achieved remarkable success in the automotive, aerospace, power-generation, healthcare, and manufacturing industries and is expected to revolutionize other industries (IBM 2022).

Digital twins work by enabling a bi-directional exchange of information between the physical system and its digital replica. First, data is gathered from the physical system and transferred to its digital representation to establish a baseline. Next, the data is carefully analyzed to determine parameters changes before a desired simulation can begin. Once the simulation is conducted and the results evaluated, the updated parameters are transferred back to the physical system, leading to a significant improvement in its performance, as shown in Figure 13. This iterative process is repeated until the physical and digital system meet its desired performance goals. It is this optimization process that allows the digital twin to be used to study performance issues, generate improvements, and predict the future behavior of the system (Unity 2017).

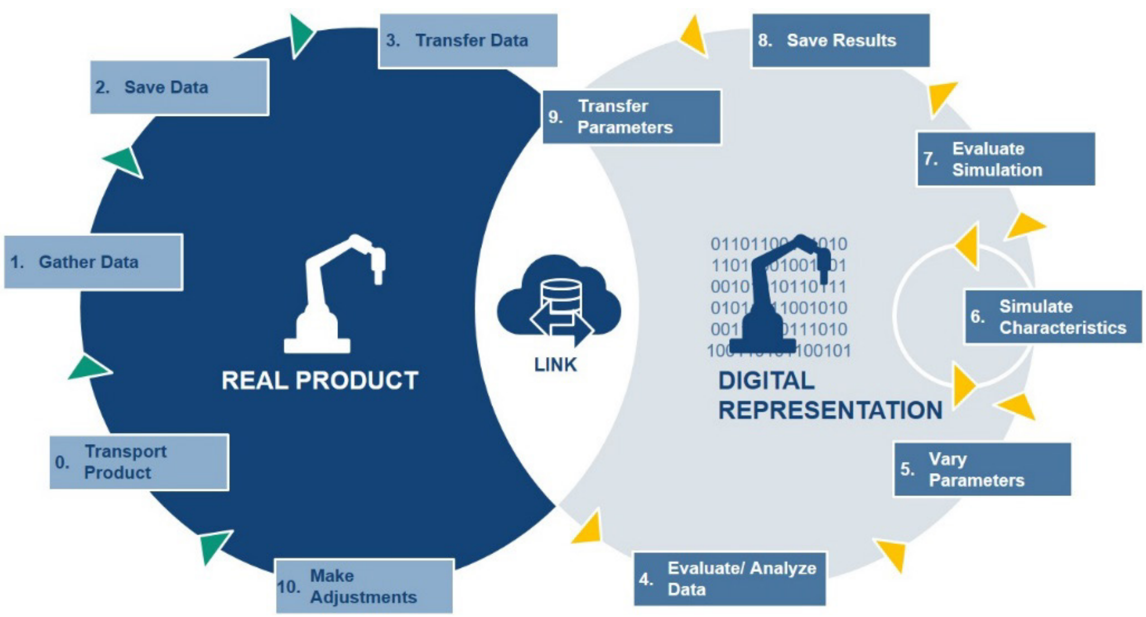

Figure 13. Concept of Digital Twin. Source: Unity (2017).

A digital twin requires continuous data consumption to understand the current state of the physical system, learn from new observations, and predict its current and future behavior. Utilizing this concept, it is possible to create a virtual representation, model, or simulation of a physical system. This approach could mitigate risks and costs associated with constructing or modifying a physical prototype, thus streamlining the development process, and enhancing cost-effectiveness.

2. Digital Thread

As with digital twin, the definition of digital thread can slightly vary depending on the context and the industry. The Defense Acquisition University (DAU) defines it as

> An extensible, configurable and component enterprise-level analytical framework that seamlessly expedites the controlled interplay of authoritative technical data, software, information, and knowledge in the enterprise data-information-knowledge systems, based on the Digital System Model template, to inform decision makers throughout a system's life cycle by providing the capability to access, integrate and transform disparate data into actionable information. (DAU n.d.c)

A more concise definition is found in a commonly cited journal on *Engineering Design with Digital Thread* by Victor Singh and Karen Wilcox from Massachusetts Institute of Technology (MIT), as a "data-driven architecture that links together information generated from across the product life cycle" (Singh and Willcox 2018, 4515).

The product development process is frequently characterized by disjointed efforts across multiple siloed teams, resulting in a multitude of risks including delays, defects, and escalating costs. Digital thread aims to address this challenge by establishing seamless process visibility and traceability across disparate data sources by serving as the communication framework. This allows enhanced cross-team collaboration while simultaneously facilitating early detection of potential issues, thereby mitigating quality concerns. It achieves this by leveraging digital technologies, tools, and processes to collect data and information throughout the entire system life cycle, from requirements and concept development to disposal. This process ensures that data flows seamlessly from one process to another, thereby enabling informed decision-making and reducing the likelihood of rework and uncertainty (Osofsky 2020). Furthermore, digital thread provides a holistic view that links diverse systems, processes, disciplines, and stakeholders involved in the product development process. For instance, it allows manufacturing engineers to review design revisions, technical specifications, and prototype test results to identify and address potential manufacturing risks. Using digital thread, data is constantly updated and accessible by stakeholders at every phase of the product development process. Figure 14 illustrates the concept of digital thread across the engineering process.

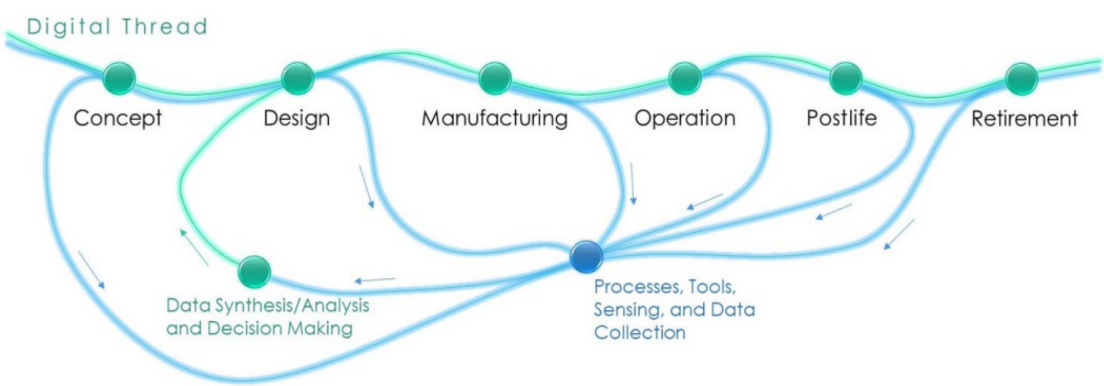

Figure 14. Digital Thread Concept. Source: Singh and Wilcox (2018).

Digital thread comprises a wide range of data, including system requirements, models, simulation and testing data, performance results, manufacturing information, maintenance and repair data, and reliability data. However, the digital thread is more than just a consolidated database of data. It also incorporates metadata to provide context and description about the data. Metadata includes information such as creation date, brief description, author, format, timestamp, dependencies, and other pertinent attributes. This metadata provides a more comprehensive view of the data in the digital thread, facilitating better search and retrieval and promotes data interoperability between various systems and tools (Rasheed, Gozluklu, and Johnson 2022). Furthermore, metadata plays a critical role in ensuring the accuracy, integrity, and usefulness of the data captured in the digital thread, as it aids in proper data management and maintenance throughout the product's life cycle.

The digital thread offers numerous advantages to organizations seeking to streamline operations, reduce costs, and enhance quality. With consistency management at its core, the digital thread ensures that requirements align with stakeholder needs, designs align with requirements, and simulations and models align with designs, and so on. Bi-directional traceability enables data and models to be seamlessly linked and traced across the entire product life cycle, enhancing communication and collaboration while promoting the establishment of organizational or industry-wide standards. This approach also facilitates the development of powerful analytical capabilities and promotes knowledge and model reuse by storing and properly indexing data and information. Finally, the digital thread supports model-based systems engineering (MBSE) and the calibration, verification, and validation of digital twins, leading to improved accuracy and increased confidence in its predictions (Roohi et al. 2023, 2).

In recent years, the implementation of digital thread has encountered various challenges. One of the major hurdles is the cost, which can be prohibitively high for many organizations. Setting up a full digital thread can be both expensive and time-consuming. According to a 2017 affordability study on the digital thread in the U.S. Air Force, it was projected that the total cost of setting up the full-scale implementation would range between a staggering $1 to $2 Trillion. The estimated timeline for the implementation of this complex technology was projected to be between 100 to 250 years, with annual maintenance costs of $100 Billion. However, the authors of the study recommended a more cost-effective approach by suggesting the creation of smaller, targeted digital threads that could be established within shorter time frames and for a fraction of the cost (Roohi et al. 2023, 3). Additionally, effectively handling the colossal volume of data generated by the digital thread necessitates substantial investments in IT infrastructure, including but not limited to upgrading networks, fortifying security measures, and expanding server storage capacities. Moreover, sharing data across organizational boundaries is crucial to reaping the benefits of the digital thread, but this raises concerns about data sensitivity and confidentiality, which continue to be a challenge for most government organizations. Finally, the lack of data standards and formats impedes collaboration and data interoperability within digital thread. To overcome these challenges, industry-wide, open standards are needed to promote effective data management and ensure data consistency and compatibility across the product's life cycle (Roohi et al. 2023, 3).

3. Authoritative Source of Truth

In the 2018 DOD *Digital Engineering Strategy*, the authoritative source of truth (ASOT) is described as the "central reference point for models and data across the life cycle." ASOT serves as a comprehensive repository of information that captures the current state and historical context of the technical baseline. It plays a critical role in providing traceability of the system as it evolves over time, allowing stakeholders to track and validate changes made to the system throughout the entire life cycle (DOD 2018, 8). According to the Object Management Group (OMG), an international technology standards consortium defines it as:

> An authoritative source of truth is an entity, such as a person, governing body, or system, that applies expert judgment and rules to proclaim a digital artifact is valid and originates from a legitimate source. (Allison et al. 2023, 2)

In other words, an ASOT refers to a source of accurate and reliable data that can be used by different stakeholders within an organization. Figure 15 shows how models are connected via the ASOT and Figure 16 illustrates the concept of ASOT across the defense acquisition process. The diagram depicts the various DOD stakeholders accessing and contributing to the ASOT, which is then used to support the defense acquisition process. It is important to note that ASOT usually resides in a centralized database, repository, or ecosystem, and serves as a key reference point for decision-making processes.

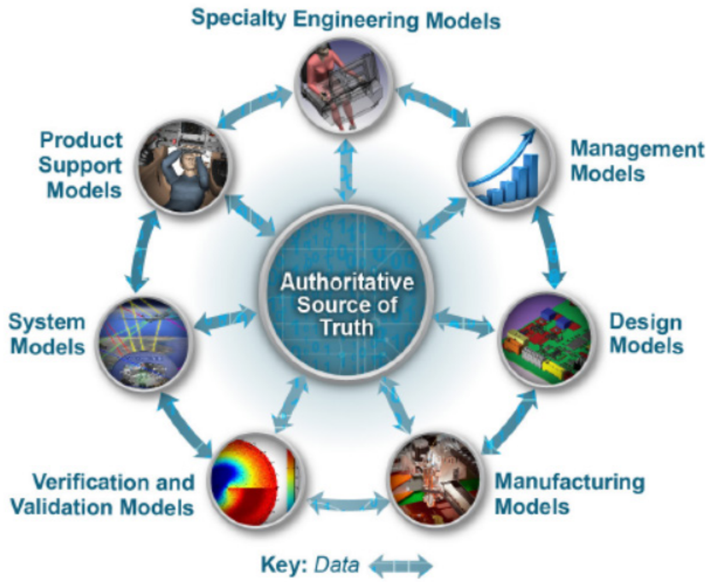

Figure 15. Models Connected via the Authoritative Source of Truth. Source: DOD (2018).

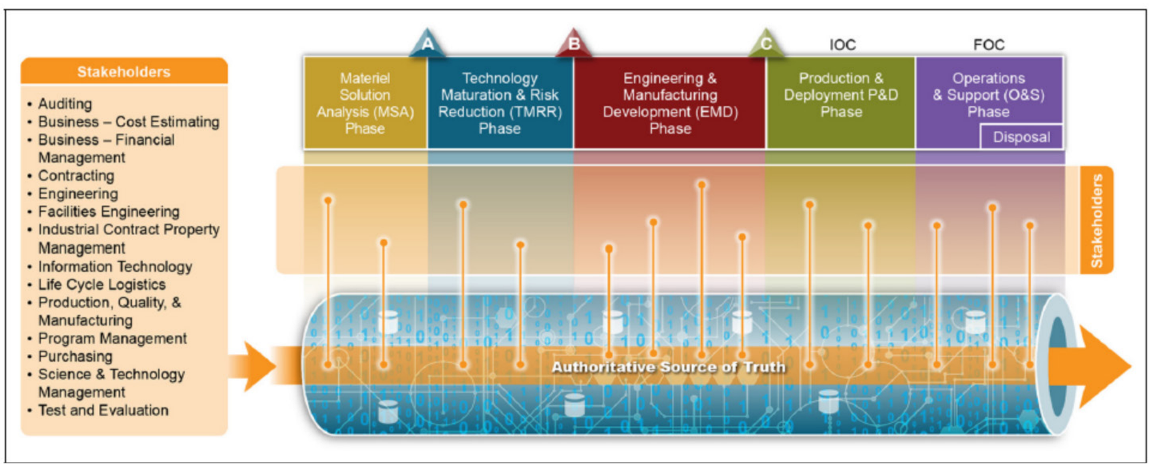

Figure 16. Illustration of the Authoritative Source of Truth. Source: Zimmerman (2019).

An example that clearly illustrates the function of ASOT is the process of changing a seat on a commercial flight. Suppose a passenger wants to change their seat before the flight departs, they can simply use the airline's app to select an available seat. Once the passenger confirms the new seat selection, the ASOT system automatically updates the seat map records of all relevant stakeholders, including the gate attendance records, airline records, airport records, and other passengers. This ensures that everyone has the most current and accurate information, promoting consistency and accuracy across different systems and processes (Rodriguez 2022). This example highlights the essential features of ASOT, including accessibility, visibility, trustworthiness, interoperability, and security. It is worth noting that an ASOT is not the same concept as a digital thread. ASOT and digital thread are related to the management of digital data, but they differ in scope. While ASOT is a source of trustworthy and reliable information used in digital engineering, digital thread is a framework that connects and integrates various data sources across the entire life cycle of a system. The ASOT is often used as a component of the digital thread, as it provides a single source of truth for the data used in the Digital Engineering Ecosystem.

Creating an ASOT involves defining precise standards, procedures, and guidelines that promote its value and maintain its integrity. Governance is crucial in managing data accurately and keeping stakeholders informed about the correct methods to collect, share, and maintain information. According to the guidance provided in the DOD *Digital Engineering Fundamentals* document,

> Organizations should establish a governance methodology for the ASOT across all engineering domains and stakeholder roles and responsibilities to include but not be limited to data protection, access control rules, data traceability, data quality, and acceptance criteria to establish data trust and model credibility. (DOD n.d.)

An essential aspect of governance is to designate the types of data classified as ASOT. As was implied with the OMG definition of ASOT, not every stakeholder can create ASOT information and consistency along with standards should help ensure trust in the information used for decision making. Moreover, governance practices can facilitate the identification and mitigation of potential risks, enhance the quality of data, boost transparency, and ensure compliance with regulatory obligations. Hence, governance establishes a robust framework for the management of the ASOT throughout its life cycle, fostering its precision, dependability, and effectiveness.

4. Model-Based Systems Engineering

One of the fundamental pillars of digital engineering is model-based systems engineering (MBSE), which is a specific approach to Systems Engineering (SE) that employs models to represent and analyze the behavior and structure of systems. According to the International Council on Systems Engineering (INCOSE), MBSE is defined as:

> The formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases. (INCOSE 2007)

By using a model to represent the system, MBSE enables system designers to simulate the system's behavior under various conditions and to evaluate the impact of changes to the system's design and performance. This can facilitate the early identification and resolution of issues within the design process, thereby minimizing the potential risk of costly errors. Additionally, MBSE enables the shift from the traditional document-based systems engineering approach to a model-based environment. Figure 17 illustrates the contrast between MBSE and the document-centric approach of traditional systems engineering.

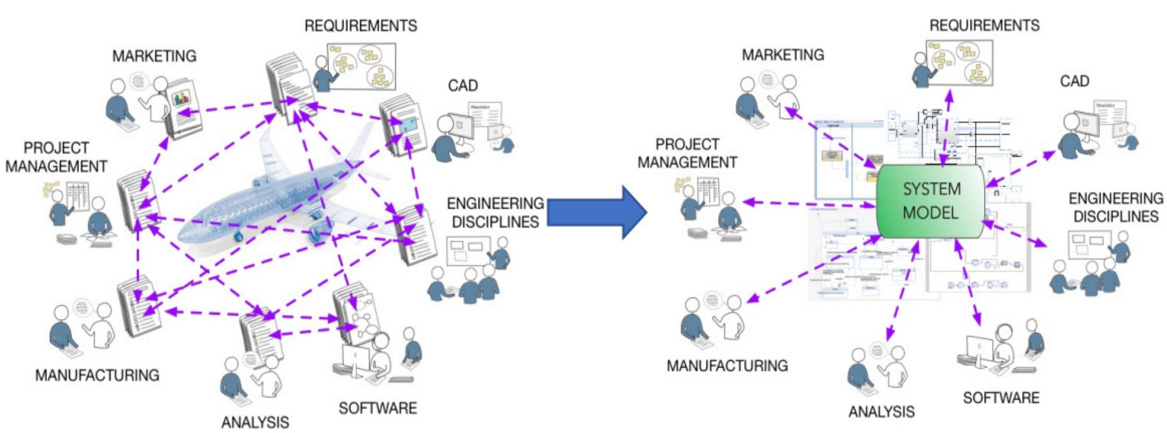

Figure 17. Traditional SE to MBSE Approach. Source: Joannou and Kalawsky (2020).

According to Dr. Warren Veneman's paper on *Considerations for Developing an Ontology for the Naval Enterprise*, the INCOSE definition of MBSE is not complete. Dr. Warren Vaneman argues that the INCOSE definition fails to fully encapsulate the differentiating factors that set MBSE apart from the traditional system engineering process, primarily due to the long-standing utilization of models within the discipline. Dr. Vaneman proposes a more holistic definition to MBSE as a

> Formalized application of modeling (static and dynamic) to support system design and analysis, throughout all phases of the system life cycle, through the collection of modeling languages, structures, model-based processes, and presentation frameworks used to support the discipline of systems engineering in a model-based or model-driven context. (Vaneman 2020, 2-3)

Dr. Vaneman (2020) further breaks down the definition of MBSE into the following four components:

- **Modeling Languages** – Serve as the basis of tools and enable the development of system models. Modeling languages are based on a logical construct (visual representation) and/or an ontology.
- **Structure** – Uses the ontology, and defined relationships between the systems entities, to establish concordance, thus allowing for the emergence of system behaviors and performance characterizations within the model.
- **Model-Based Processes** – Provides the analytical framework to build the system model and to conduct the analysis of the system virtually defined in the model. The model-based processes may be traditional systems engineering processes such as requirements management, risk management, or analytical methods such as discrete event simulation, systems dynamics modeling, and dynamic programming.
- **Presentation Frameworks** – Provides the framework for the logical constructs of the system data in visualization models that are appropriate for the given stakeholders. These visualization models take the form of traditional systems engineering models. These individual models are often grouped into frameworks that provide the standard views and descriptions of the models, and the standard data structure of architecture models. (Vaneman 2020, 3)

Furthermore, Dr. Vaneman indicates that the maximum MBSE effectiveness, which is the optimal level of efficiency and value that can be achieved by MBSE, occurs at the convergence of these four tenets as seen in Figure 18.

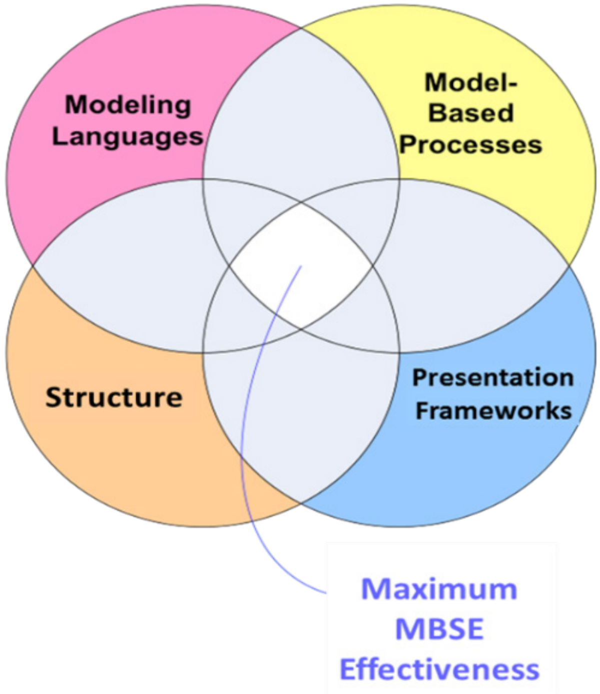

Figure 18. Four Components of MBSE. Source: Vaneman (2020).

The benefits of MBSE have long been debated but actual metrics have been difficult to gather until recently. In a comprehensive 2020 technical report analyzing 360 systems engineering publications and conference proceedings, the top measured, observed, perceived, and referenced benefits of MBSE were identified (McDermott et al. 2020, 31). These key findings are visually presented in Figure 19. According to the study, the perceived benefits make up 66.7% of the data, while the observed benefits account for 10% (McDermott et al. 2020, 31). From these findings, the top two benefits in both perceived and observed metrics of MBSE are:

- **Better Communication and Information Sharing:** MBSE facilitates better communication and information sharing among stakeholders. By utilizing a common modeling language such as System Modeling Language (SysML), MBSE enhances collaboration, reduces misunderstandings, and improves the overall effectiveness of communication within and across teams.

- **Increased Traceability:** MBSE enables enhanced traceability throughout the system development life cycle. By capturing requirements, design elements, and relationships within the model, MBSE supports comprehensive traceability, ensuring that system components are aligned with the specified requirements (McDermott et al. 2020).

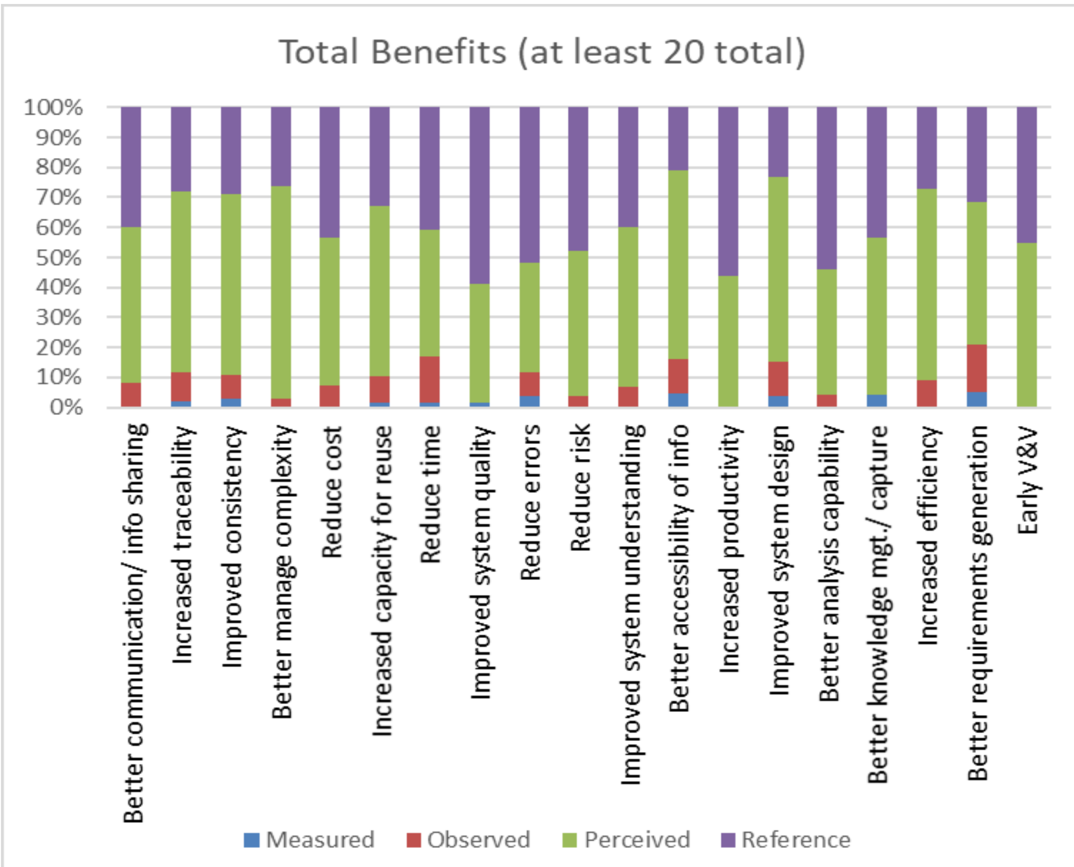

Figure 19. MBSE Top Benefits. Source: McDermott et al. (2020).

In summary, MBSE is a fundamental pillar of digital engineering, offering a structured and rigorous approach to developing and managing digital models of systems. It revolutionizes the conventional document-based system engineering approach by embracing a model-based paradigm. To fully capture the essence of MBSE, an expanded perspective integrates the use of modeling language, structure, model-based processes, and presentation frameworks, facilitating a more comprehensive and holistic approach.

By implementing MBSE, organizations can unlock the potential to enable efficient communication, improve information sharing, and establish robust traceability.

5. Digital Tools and Technologies

The term "digital tool" is interchangeably used when referring to software tools in the context of digital engineering or digital transformation. Predominantly used by the Air Force, this term encapsulates a range of software applications in support of, but not limited to, architecture modeling, product life cycle management (PLM), requirements management, software development, Computer-Aided Design (CAD), and model-based systems engineering (Costello 2021). A more recent definition of digital tools is provided by Walkme, an organization that focuses on driving digital transformation via software platforms: "Digital tools (DT) can be defined as programs, websites, applications, and other internet and computerized resources that facilitate, enhance and execute digital processes and overall digitization efforts" (Walkme 2023).

Digital tools enable the use of digital technologies such as artificial intelligence, machine learning, data analytics, modeling and simulation, cloud computing and much more. These technologies create the infrastructure that allows digital tools to operate and connect, forming a comprehensive and integrated digital engineering environment. Figure 20 illustrates examples of innovative digital technologies that are expected to transform the practice of engineering (DOD 2018, 12).

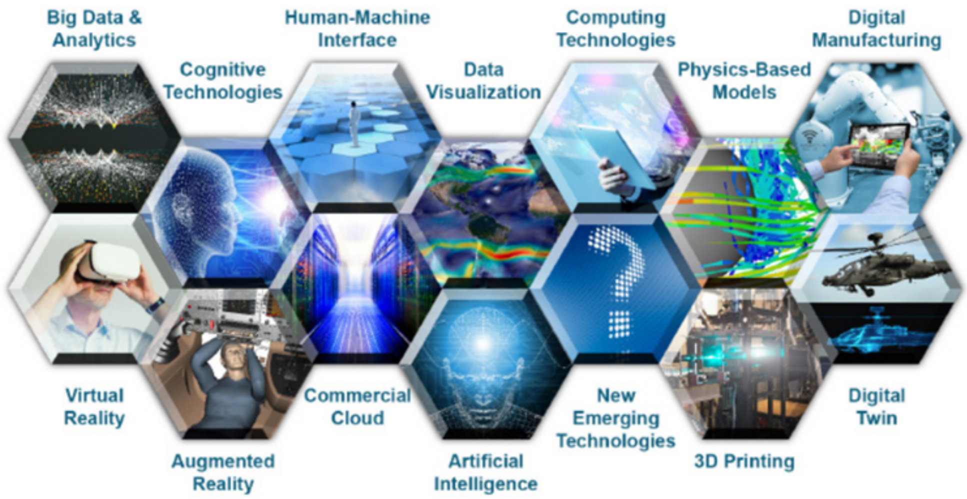

Figure 20. Innovative Digital Technologies. Source: DOD (2018).

Below are the most employed categories of digital technologies.

- **Computer-Aided Design:** frequently used by engineers, architects, designers, and other professionals to create precise 3-dimensional models of objects and technical drawings of physical components and assemblies. These tools offer various functionalities, including drafting, modeling, and simulation. By enabling virtual design before the actual production, CAD tools facilitate the visualization of the final product, the detection of potential flaws, the performance of simulations, and the provision of accurate blueprints for manufacturing.
- **Project Management:** these tools are designed to assist project managers, teams, and organizations in planning, executing, and managing projects with utmost efficiency. They foster a methodical approach to project management, decomposing complex tasks into manageable units, and aligning all resources seamlessly. These tools are further classified into subcategories including schedule management, requirements management, financial management, resource management, team collaboration, risk management, and reporting, each catering to a distinct aspect of project management.
- **Model-Based Design:** tools streamline the management of complex systems by creating cohesive models instead of scattered documents. These tools enhance

communication, understanding, and analysis, supporting every phase of the system life cycle from design to validation. By reducing developmental risks and improving efficiency, they foster innovation while maintaining a consistent source of truth to manage changes and trace requirements, thus ensuring system functionality and performance.

- **Enterprise Management:** these tools are integral in managing the product life cycle activities from initial concept through retirement. They provide a unified platform for integrating data, processes, workflows, supply chain, and business systems involved in product creation and management.
- **Modeling & Simulation:** these tools play a critical role in the design and analysis of systems, by providing a platform to create virtual representations of real-world scenarios. It enables testing of different design choices, allows for prediction of system behavior under various conditions, and identification of potential issues before physical prototyping or implementation. This results in significant cost savings, increased system reliability, and reduced development time.
- **Big Data & Analytics:** these tools empower organizations to make informed decisions by providing meaningful insights from system or process data. They facilitate the collection, processing, and analysis of data to detect patterns, trends, correlations, and anomalies. In addition, most of these tools support predictive modeling, forecasting, and optimization, which can lead to improved system performance or process improvement. Analytics tools play a vital role in various business and engineering functions, promoting data-driven decisions.
- **Data Visualization:** these tools transform complex datasets into more comprehensible and interactive graphical representations. By turning abstract numerical data into visual forms such as charts, graphs, and maps to allow users to detect trends, identify patterns, and derive insights more efficiently. They play a crucial role in the communication of data-driven findings, making complex data more accessible, understandable, and usable. Data Visualization tools help decision-makers to see analytics presented visually, enabling them to grasp

difficult concepts and identify new patterns, facilitating more informed and effective decision-making.

- **Cloud Computing:** are on-demand tools and services that provide scalable and flexible access to computing resources, storage, and services over the internet or dedicated networks. These tools enable organizations to reduce infrastructure costs, increase operational efficiency, provide scalability, connectivity, improved security, and enhance agility by leveraging the power of remote servers and distributed computing (Johnson et al. 2023).
- **Artificial Intelligence:** empower systems with the capability to learn, adapt, and make decisions. By modeling complex patterns in data and making predictions or decisions without being explicitly programmed, these tools can automate a wide variety of tasks and enable new types of services. They are commonly used to personalized experiences, optimize operations, detect anomalies, and forecast trends. Through enabling sophisticated analysis and decision-making based on large and complex datasets, ML and AI tools play a crucial role in driving innovation and competitive advantage.
- **Virtual & Augmented Reality:** These tools provide an entirely immersive experience, giving users a 360-degree digital environment that mirrors the real world. In certain scenarios, these instruments even project digital content directly onto the canvas of the user's existing reality. Their utility is vast, stretching across a multitude of sectors including but not limited to gaming, entertainment, education, healthcare, system design, training, and simulation. To truly unlock their immersive potential, these tools are often deployed in concert with compatible hardware equipment such as innovative virtual reality headsets and smart glasses.

Table 3 presents a list of industry-standard and defense digital tools, categorized according to their respective digital technologies.

Table 3. Commonly Used Digital Tools

Digital Technologies	Tool Categories	Digital Tools
Computer-Aided Design	Computer-Aided Design	Auto CAD, SolidWorks, Fusion 360
Project Management	Project Management	Microsoft Project, Asana, Jira
	Collaboration	Microsoft Teams, Slack, Jira, Zoom, Google Workspace, Atlassian Confluence
	Requirements Management	Jama, Visure, IBM DOORS, Jira, Polarion
Model-Based Design	MBSE/ Architecture Management	Cameo Systems Modeler, MagicDraw, Papyrus, Innoslate, and IBM Rhapsody
Enterprise Environment	Product Life cycle Management (PLM)	Siemens Teamcenter, Autodesk Fusion, Jira, Arena, Oracle Agile, PCT Windchill
Modeling & Simulation	Modeling & Simulation	ExtendSim, Open Modelica, Capella, Matlab with Simulink, HPCMP CREATE, SIMDIS
Big Data & Analytics	Big Data & Analytics	Minitab, SAS, R, Jupyter Notebook, Apache Hadoop, JMP, Microsoft Excel
Data Visualization	Data Visualization	Tableau and Power BI
Cloud Computing	High-performance Computing / Cloud-Based Computing	Amazon Web Services, Microsoft Azure, Google Cloud Platform, IBM Cloud, DOD HPCMP
Artificial Intelligence	AI, ML, and DL	Python (Keras, PyTorch, Scikit-Learn), KNIME, TensorFlow
Virtual & Augmented Reality	Virtual & Augmented Reality	Unity, Unreal Engine, Maya, Bender

C. DIGITAL ENGINEERING ECOSYSTEM

The concept of a Digital Engineering (DE) Ecosystem is referred to as an integrated and interconnected digital environment that employs digital tools and processes to enable the function of digital engineering. A formal definition is provided by DAU as "the interconnected infrastructure, environment, methodology (the processes, methods, and tools) used to store, access, analyze, and visualize evolving system's data and models to address the needs of the stakeholders" (DAU n.d.a). A DE ecosystem aims to enable and advance the practice of digital engineering by guiding a product or system from inception to disposal. It integrates digital tools, methodologies, and practices, enabling improved accuracy and efficiency, while facilitating collaboration among diverse stakeholders. At its core, it integrates IT infrastructure with a comprehensive digital environment, including methods and tools designed to meet digital engineering goals. It utilizes the power of technology with engineering goals to transform the way products and systems are conceived, developed, and managed. Figure 21 shows a conceptual representation of a digital engineering ecosystem.

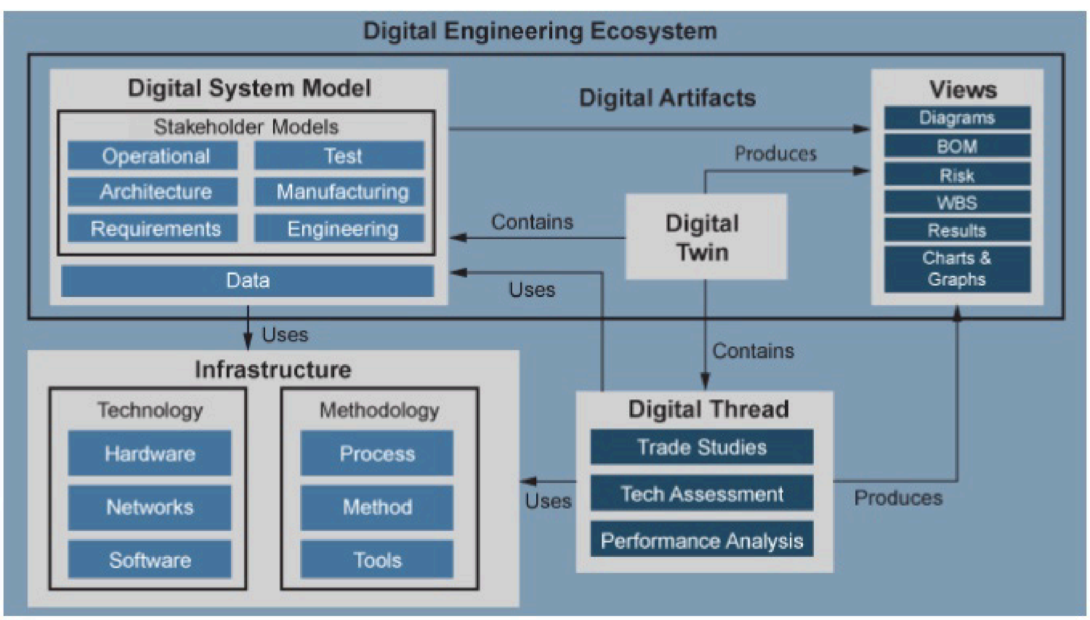

Figure 21. Digital Engineering Ecosystem. Source: Whitcomb, Corina White, Rhoades (2020).

A key concept of the DE ecosystem is the value of digital artifacts. DAU defines it as "an artifact produced within, or generated from, the digital engineering ecosystem. These artifacts provide data for alternative views to visualize, communicate, and deliver data, information, and knowledge to stakeholders" (DAU n.d.b). Digital artifacts are critical in conveying engineering data, information, knowledge, and wisdom in digital form. These artifacts offer different views pertaining to a system or product such as diagrams, charts, graphs, video, text information, results, and more (Coleman 2018). According to the Object Management Group, the core components of the digital engineering ecosystem are as follows:

- **The Value Exchange:** The engineering community will use digital artifacts produced within, or generated from, the digital engineering ecosystem to produce more innovative ideas. The interchange of digital artifacts provide data for alternative views to visualize, communicate, and deliver data, information, and knowledge to stakeholders. In the digital engineering ecosystem, the primary form of value exchanges are the novel ideas and innovations captured in digital artifacts. That said, the marketplace in related business ecosystems might use monetary value to influence the engineering ecosystem's value exchange; nevertheless, money is not its primary value. The engineering community appraises the value of a digital artifact by its ability to generate innovations. To aid the value exchange, the digital environment serves as the means to exchange digital artifacts; while, the authoritative source of truth ensures that valid digital artifacts originate from legitimate sources.
- **Digital Environment:** is as set of interconnected information, communication and software technologies. It is unique set of technologies designed to meet the needs of the community and its stakeholders. These may include one or more of the following: 1) integrated digital environment that integrates database systems and information content to increase sharing. 2) Immersive digital environments with virtual and augmented reality technology that enables interactions between participants. 3) integrated development environments that include a suite of software tools to complete a project or operation.
- **Stakeholder Network:** The digital engineering ecosystem's stakeholder network includes any entity that has an interest in exchanging digital artifacts related to specific project, program, technical platform, knowledge domain, or industry. It is a closed sharing model for its social network. In this closed sharing model, the community selects the stakeholders. There are several methods for

selection to include sponsorship, criteria based, or permissions. The sponsorship closed sharing model allows any current member in good standing to recommend or give the new member access. The criteria based membership involves the new member meeting some standard, criteria, or test before the system gives them access. Finally, the permission base, involves one or more gatekeepers that decide how and if a new member is granted permission to participate. Another aspect of the closed social network model is that parties in a transaction choose to accept information from each other. As such, not all communications and transactions are open to all participants. There is an invitation and reply to engage in any transaction.

- **Rule-Based Transactions:** The digital engineering ecosystem has some underlying rules-based or expert system technology based that defines, initializes, constrains, and instructs the transactions and interchanges of digital artifacts between the stakeholders. It may use emergent rules based on the behavior of humans using the system. Alternatively, it may use fixed rules established by the system developer. Alternatively, it may be a combination of both. With the advances in Artificial Intelligence (AI), Machine Learning, Data Science, and High Performance Computing (HPC), emergent rules are the emerging practice.
- **Model-Based Engineering (MBE) Methods:** The model-based engineering methods includes any type of engineering digital artifacts used to conceive, design, develop, and build an engineered system or product. The methods includes techniques, processes, and tools to develop and analyze the engineering artifacts. The models may be digital artifacts that include 2-dimensional diagrams, 3-dimensional geometrics, or mathematical and physics-based models. The community for a given digital engineering ecosystem will determine the specific types of tools, techniques, and processes it needs to create, offer, request, and exchange digital artifacts for its platform or domain. As previously stated, the digital engineering ecosystems are heterogeneous and thus unique to the needs of its community. (Howell 2018)

Digital engineering ecosystems are prevalent in various sectors of private industry, driven by the growing importance of digital transformation and innovation. They encompass a range of digital tools, methodologies, technologies, and platforms to facilitate and enhance the engineering and business process. These ecosystems are particularly utilized in sectors like manufacturing, software development, e-commerce, automotive, aerospace, and energy. For example, Amazon, the giant technology company, has gradually built its digital ecosystem since 2000 by interconnecting digital technologies, platforms, tools, and services to maximize value for their business and costumers. It accomplished this by first building giant server infrastructure around the world to serve their e-commerce platform. It then built on that same infrastructure by offering services such as Prime Video, Prime Music, and more. It then integrated their logistics/ fulfillment centers, digital technology solutions, cloud computing, web-services, entertainment services, e-commerce, retail, and healthcare services into one giant ecosystem. This quickly created a network of interconnected services for the company and made their prime users and business customers committed to its platform (Talin 2023).

In the defense industry, DE ecosystems are just beginning to gain momentum. As the Department of Defense (DOD) embraces the paradigm shift towards digital engineering, there is a pressing need for authoritative and comprehensive repositories of digital artifacts associated with its array of military systems. This requirement necessitates that these artifacts not only span across numerous distinct disciplines, but also support the MBSE approach. This need has led to substantial Science and Technology (S&T) investments to develop digital engineering ecosystems dedicated to engineering operations and practices. These ecosystems aim to support the DOD's *Digital Engineering Strategy's* goal # 4 to "establish a supporting infrastructure and environment to perform activities, collaborate, and communicate across stakeholders." This means setting up the infrastructure of high bandwidth and secure networks and databases to manage digital artifacts. The DOD is seeking to develop these ecosystems to enable secure collaboration among all stakeholders, including government, industry, and academia involved in developing military systems (Howell 2018).

D. DIGITAL ENGINEERING AS NAVAL STRATEGY

In recent years, the U.S. Navy has prioritized digital engineering, demonstrating a clear commitment to staying ahead of the technological curve. The establishment of the Digital Warfare Office (DWO) at the OPNAV level is just one example of this investment. Through the utilization of untapped data, the DWO's goal is to improve predictions and enhance decision-making in areas ranging from system acquisition and maintenance to readiness. The DWO, in partnership with the Navy Systems Command (SYSCOMs), have started to drive the migration towards DE by leveraging digital technologies using data science, analytics, and machine learning.

Furthermore, the Secretary of the Navy has issued the recent SECNAV directive 5000.2G, outlining systems engineering guidelines that advocate for the adoption of a model-based approach, digital engineering, and open systems architecture. The directive states the following:

> For all acquisition programs, the PM shall ensure opportunities for application of Digital Systems Engineering approaches, including Model-Based Systems Engineering are identified, applied, resourced, and executed throughout the acquisition life cycle. Programs shall digitally represent the system of interest in a model that describes and defines major system components and interfaces, to the maximum extent practicable, to support integration, interoperability and future upgradeability. (DON 2022a, 64)

To solidify its commitment towards digital engineering, the Navy published its digital engineering strategy in 2020 called *Digital Systems Engineering Transformation Strategy*. This strategy outlines a clear vision for the adoption of digital engineering across the enterprise, while also providing comprehensive guidance for the implementation of processes and tools throughout the entire life cycle of naval systems. The Navy strategy outlines the following transformations objectives, which are closely aligned with the 2018 DOD *Digital Engineering Strategy*:

1. Formalize the development, integration and use of models
2. Provide an enduring authoritative knowledge source
3. Incorporate technological innovation to improve the engineering practice
4. Establish the supporting infrastructure and environments for the Digital Engineering practice
5. Transform the culture of the workforce to adopt and support Digital Engineering across the life cycle. (Bray 2020, 7)

The Navy is fully committed to revolutionizing digital engineering with the creation of the Integrated Modeling Environment (IME), a sophisticated software platform that promises to transform the way naval systems are designed and tested. The IME is a comprehensive simulation environment that seamlessly integrates various systems models and simulations into a unified framework. With its cutting-edge capabilities, the IME will enable naval architects, engineers, and scientists to effortlessly create and analyze digital models of naval platforms and their associated systems. The IME will be equipped with a range of innovative tools, including powerful modeling and simulation capabilities, advanced optimization tools, and state-of-the-art data visualization capabilities. It will leverage on the authoritative source of truth to ensure information is correct, updated, credible, and reliable to all stakeholders. Its most significant advantage, however, is the ability to conduct T&E using live, virtual, and constructing builds, dramatically reducing the time and costs associated with physical testing (Bray 2020, 15). Figure 22 illustrates the Navy's integrated vision for digital engineering via the IME.

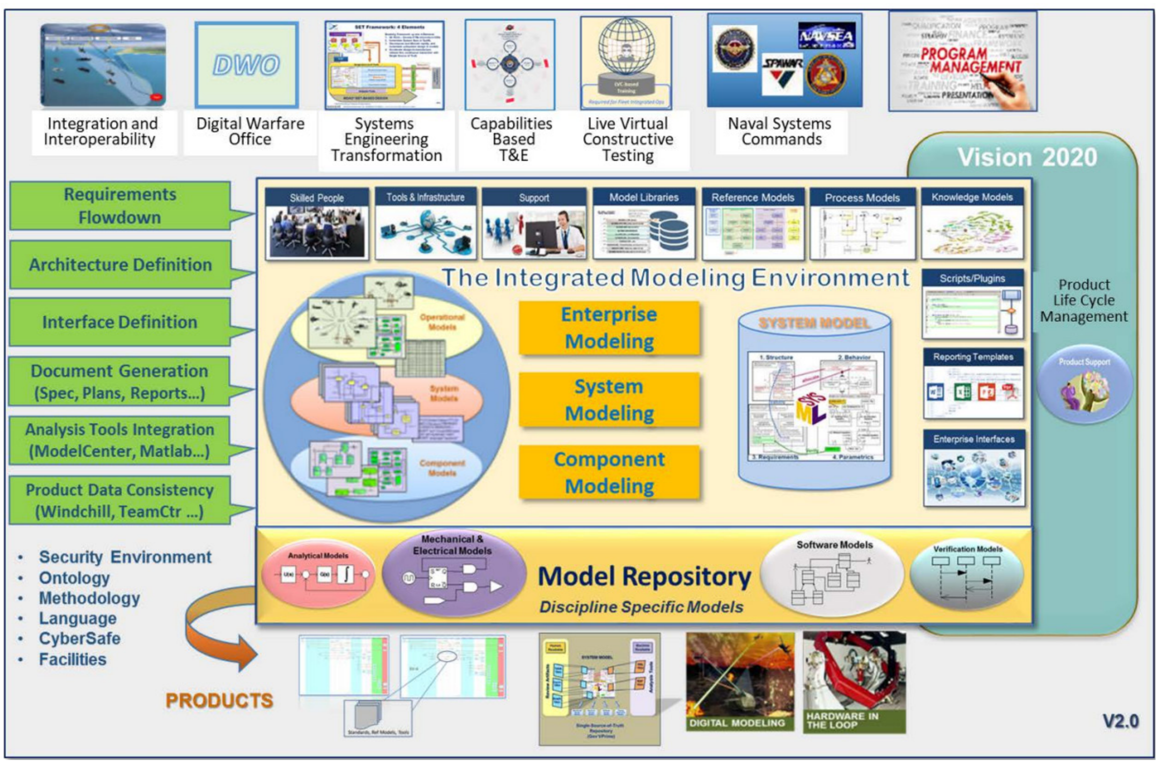

Figure 22. Navy's Integrated Modeling Environment (IME). Source: Bray (2020).

The U.S. Navy is paving the way towards achieving their strategic goals by harnessing the power of advanced digital tools, models, processes, and data through the establishment of the IME. This digital environment has the potential to drive innovation, enhance system performance, and elevate the overall readiness and capability of the fleet.

E. ADOPTION ACROSS INDUSTRY

Digital engineering key tenets such as MBSE, digital twin, digital thread and ASOT are being adopted across various industries, transforming traditional engineering processes by integrating model-based concepts and advanced digital technologies. Below are three case studies that have demonstrated success using digital engineering practices.

1. Case Study: Boeing T-7A Red Hawk

In September 2018, Boeing received the U.S. Air Force (USAF) contract worth $9.2 billion for the construction of 351 advanced trainer aircraft, along with 46 related ground-based training simulators. The goal was to build the next generation of advanced jet trainer to succeed the older T-38C Talon. The new aircraft called the T-7A Red Hawk is a state-of-the-art pilot training system developed for the USAF, aimed at preparing the upcoming wave of fighter and bomber pilots. This supersonic plane, measuring 47 feet in length, was specifically engineered with room for future growth, enhanced supportability, and easy maintenance (Herber and Batchelor 2023).

Boeing shattered traditional paradigms by transitioning from the customary system engineering approach to the application of digital engineering principles, supplemented by Agile software development methodologies and Open architecture. The aircraft's design was thoughtfully crafted employing model-based system engineering, digital, twin, digital thread, and modular design techniques. Further complemented by advanced simulation and virtual testing protocols, it was designed to function as a trainer aircraft with fighter-like performance (Herber and Batchelor 2023).

The outcome of using digital engineering resulted in shortening the time from concept to first flight to 36 months, a significant improvement over past system development efforts. According to Boeing, compared to traditional aircraft development programs, the T-7A experienced (Herber and Batchelor 2023):

- 75% increase improvement in first-time engineering quality
- 80% reduction in assembly hours
- 50% reduction in software development and verification time (Herber and Batchelor 2023).

According to the program manager for the Being T-7 Program, Paul Niewald, "Digital engineering has really been a game changer to this program" (Boeing 2021). Further highlighting that digital engineering not only accelerates the development cycle, but it also aids in pinpointing various issues at the onset of the design process, an occurrence that traditionally would occur years after production (Boeing 2021).

2. Case Study: Submarine Warfare Federated Tactical Systems

In 2011, a two-year effort was launched to implement MBSE within the Navy's Submarine Warfare Federated Tactical Systems (SWFTS). This transition from a document-centric approach to a model-oriented process involved the handling of nearly 2,700 interface requirements. In the case study article *MBSE delivers significant return on investment in evolutionary development of complex SoS*, the SWFTS is "a rapidly evolving combat system-of-systems (SoS) product family. Managing the baseline updates requires processing thousands of baseline change requests, then coordinating and verifying their implementation. The complexity of this effort, which involves well over ten million source-lines-of-code (SLOC) as well as Commercial-Off-the-Shelf (COTS) and military-unique hardware, is compounded by being deployed in ten variants" (Rogers and Mitchell 2021, 385).

Using MBSE, the SWFTS model houses extensive detailed information on subsystems, interfaces, networks, switches, among others, acting as a comprehensive digital blueprint. Abstractly modeling interfaces enable a shared foundation across all data, allowing the model to continuously adapt and evolve to meet SoS engineering challenges. Digital artifacts generated from the model, presented in common formats such as Microsoft Excel, XML, and HTML, spotlight changes for all participants through difference-analysis reports. Furthermore, the model's intricate data relationships make it ideal for creating visuals that promote engineering collaboration. These tailored views provide a detailed snapshot of subsystems and interface diagrams, boosting understanding and cooperation among team members (Zimmerman, Gilbert, and Salvatore 2019, 336).

The shift to MBSE for managing the legacy process demonstrated a significant return on investment. The case study demonstrated an "18.4% reduction in the touch labor required for the interface baseline management process" (Zimmerman, Gilbert, and Salvatore 2019, 336). In addition to cost savings, fewer defects were identified by using MBSE:

- 9% fewer defects introduced during systems [architecture and design] phases
- 18% of defects found in [systems integration and test phase] rather than platform test (Rogers and Mitchell 2021, 404).

Using conservative estimates, this resulted in impressive projected cost savings of approximately $10.6 million over a five-year period as seen in Figure 23. However, the advantages of this transition stretch beyond cost savings or enhanced processes. Notably, it facilitated the automatic creation of consistent interface definition artifacts, specifically customized to support the systems engineering process. This transition further brought the benefits of automated data validation and integrity checks, contributing to the accuracy and reliability of the systems. It promoted design consistency across different submarine classes by identifying inconsistencies and aiding their resolution. Above all, the model has established itself as an authoritative source of truth for the design of the system-of-systems. It has thus improved the ability to manage the complexities inherent in systems engineering, bringing about significant improvements in efficiency and accuracy (Rogers and Mitchell 2021, 405).

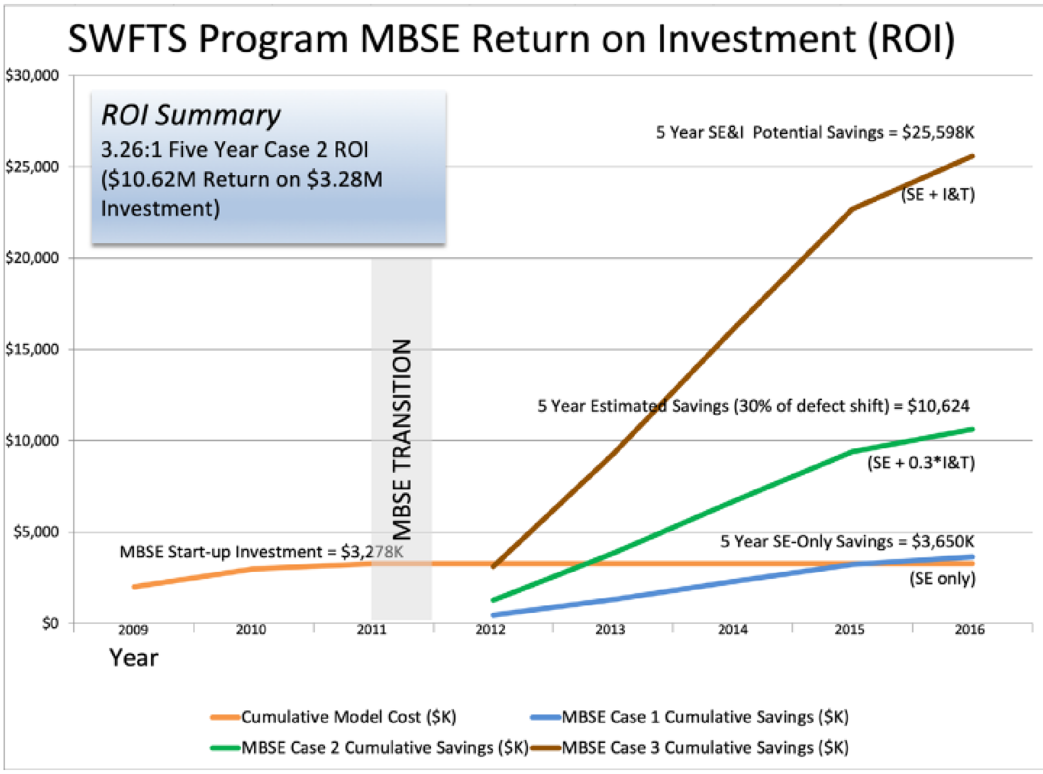

Figure 23. SWFTS Program – MBSE Return on Investment (ROI). Source: Rogers and Mitchell (2021).

3. Case Study: SpaceX

SpaceX has managed to slash the cost of space access by a staggering factor of ten. This notable decrease in cost is driven by investments in digital platforms and specialized software, which are designed to improve process efficiency through superior data management. Utilizing tools such as CAD and finite element analysis software, SpaceX stores crucial data about rocket assemblies in comprehensive databases that are disseminated across diverse teams via a centralized repository, embracing the concept of digital thread and ASOT. The centralized nature of these databases cultivates communication and collaboration among SpaceX's various teams, effectively eliminating informational silos. Using these databases along with digital tools, engineers can rapidly design and modify virtual prototypes, thereby expanding the design process (Carlos 2021).

The company further employs digital twins in its operation, virtual models of physical assets, which harness the power of virtual simulation and real-time data for rapid system evaluation and monitoring. For example, digital twins allow Mission Control operators to access a digital replica of SpaceX's Dragon spacecraft, enabling them to track various aspects such as trajectory, speed, loads, and propulsion systems. This monitoring is made possible through data gathered from the hundreds of sensors embedded in the spacecraft. Ultimately, this information enhances the reliability and safety of SpaceX's spacecraft and other related components (Carlos 2021).

SpaceX heavily depends on data-driven processes to propel the innovation of increasingly complex and advanced systems. Using data analytics reveals the influence of various factors on rocket performance, thereby assisting engineers in making more educated decisions concerning design specifications and limitations. For example, SpaceX shop floor technicians utilize data and models to gain a deeper comprehension of a rocket's intricate mechanisms throughout its manufacturing and assembly process. This is especially advantageous in examining the details of internal systems like electrical wiring and cooling systems, thereby improving efficiency. The intelligent use of an authoritative source of data cultivates an advanced factory environment, where physical and virtual assets work in harmony to boost overall performance (Carlos 2021).

The design of SpaceX's Dragon spacecraft is entirely digital, symbolizing a significant departure from traditional spacecraft design. The days when astronauts grappled with hundreds of switches, knobs, dials, and buttons for spacecraft control are firmly in the past. SpaceX has ushered in an era of digitization, replacing the conventional control system with three touchscreen displays that offer a user-friendly interface, visually appealing aesthetics, and optimized ergonomics to improve the user experience (Chakib 2020). Figure 24 contrasts the spacecraft control system of NASA's Apollo and Shuttle against the digital interface of SpaceX's Dragon.

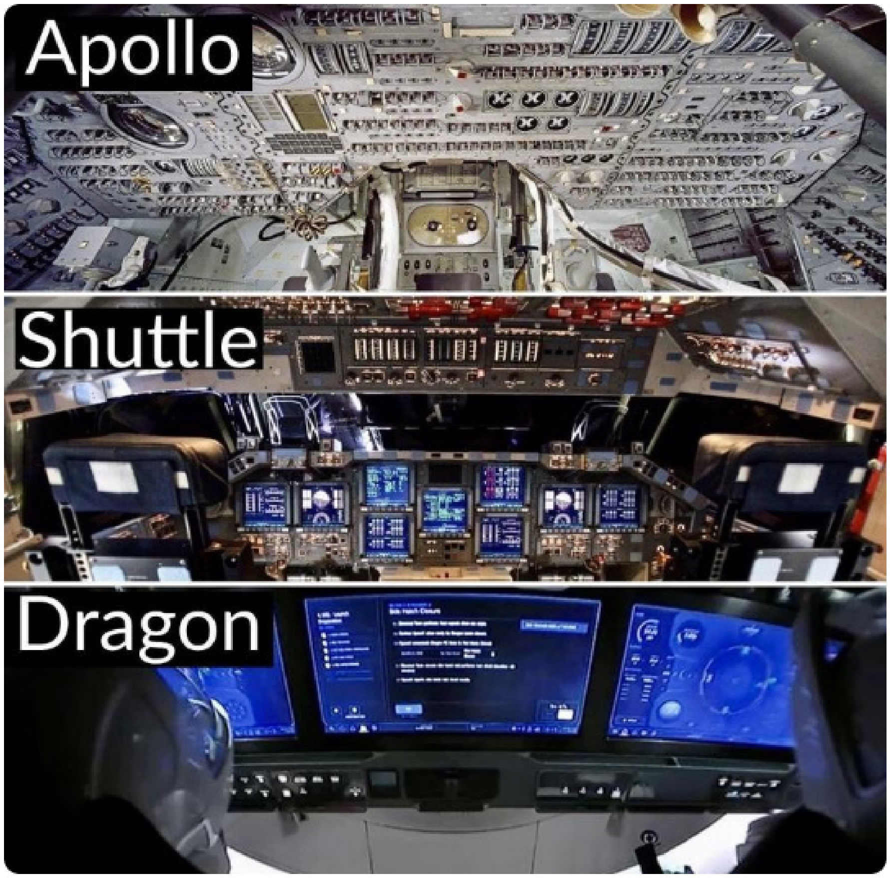

Figure 24. Digital Transformation in SpaceX's Dragon Control Module.
Source: Chakib (2020).

4. Case Study: Formula 1

Formula 1 (F1) is one of the most popular forms of racing around the world, distinguished by its advanced technology and high-intensity competition. Behind each driver is a large team of dedicated professionals working tirelessly around the clock to engineer the fastest vehicle possible. The stakes are high, and competition is intense, with each team pouring significant resources into their vehicle to dominate the race circuit, in most cases by just a fraction of a second (Nguyen, Davis, and Sinclair 2021).

To win the race, there are two principal goals to follow: produce the best racing car and be efficient in operations as a team. Over the years, F1 designers have successfully leveraged digital engineering, especially the concept of digital twin, to achieve these two principal goals. Given the numerous components of a race car that influence its overall performance, each F1 team employs a sophisticated approach without ever building a physical prototype. They develop a digital twin of their vehicle, leveraging the wealth of data gathered from exhaustive testing and actual real-world races. This type of data serves as the authoritative source of truth for the digital model. While the first iteration of the digital twin might not perfectly mirror the physical car, the correlation between real-world performance and the digital model's output enables the team to iteratively refine their design. As this process continues, the precision of the digital twin improves, contributing to gradual enhancements in the physical car's design and performance (Nguyen, Davis, and Sinclair 2021).

Every race car is equipped with approximately 150–200 sensors, each collecting live telemetry data at an incredible rate every millisecond. This data feeds directly from the race circuit to designated technology hubs. At these nerve centers, the digital twin steps into the spotlight, providing crucial assistance in making immediate strategy decisions in a fraction of a second. The digital twin's profound contribution lies in its ability to instantly process live data, conduct simulations, and output reliable predictions. This capability allows each team to adjust their strategy in real-time, enabling their ability to optimize performance and seize the winning edge on the racetrack (Nguyen, Davis, and Sinclair 2021).

Digital twin is also used to help the F1 team prepare and optimize its operation. Drivers are afforded the opportunity to refine their skills and familiarize themselves with driving dynamics using car simulators, effectively the digital twins of their racing vehicles, long before their tires touch the racetrack. To reduce costs, these simulators have grown in importance, providing drivers with a virtual environment to refine their driving skills. Every team leans heavily on their digital twins to forecast and simulate hundreds of potential race scenarios, ensuring they are prepared for a wide array of unexpected occurrences. The fidelity of these simulators plays a vital role in a driver's preparation. The more accurate the simulator, the better drivers can adapt to the unique demands of each circuit. This virtual training proves invaluable, equipping drivers with crucial knowledge and insight, allowing them to approach each race with confidence (Nguyen, Davis, and Sinclair 2021).

Each component of the F1 vehicle has a corresponding digital counterpart. Simulations are performed on these virtual components before the physical parts are manufactured. This cutting-edge approach to design has unlocked the potential to create components that were beyond reach just half a decade ago. Before a part is installed on a car, it undergoes thorough performance and reliability checks within the simulated environment of its digital twin. This process shines a light on the outstanding reliability records of current racing teams despite minimized physical testing time. Essentially, the digital twin methodology is revolutionizing the way teams design, construct, and fine-tune their vehicles. By enabling comprehensive simulated trials of individual components, this technology ensures that only the most robust and efficient parts make it onto the actual vehicle, enhancing the performance and reliability of the car like never before (Nguyen, Davis, and Sinclair 2021).

Figure 25 offers a visual depiction of the digital twin concept as applied in F1. The images on the top quadrant illustrate the 3D digital replica of a racing vehicle. The lower-left image represents the simulation employed for driver training, while the image on the lower-right displays the actual, physical vehicle. This complex interplay between the virtual and physical systems creates an integrated approach aimed at optimizing system performance.

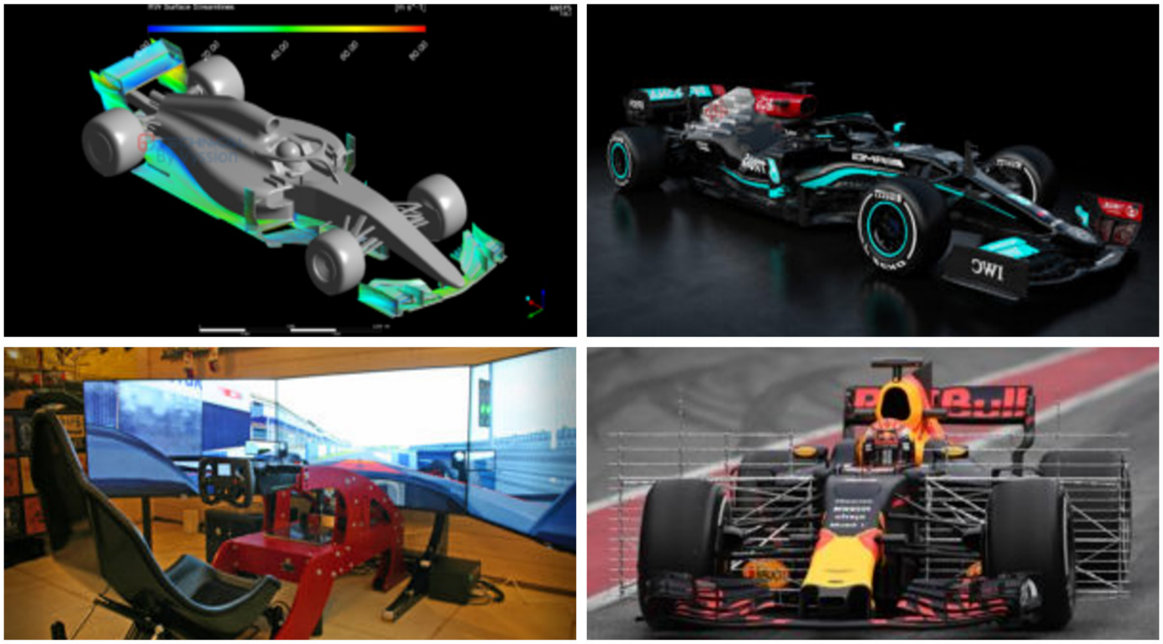

Figure 25. Formula 1 Implementation of Digital Twin. Source: Nguyen, Davis, and Sinclair (2021).

F. IMPLEMENTATION CHALLENGES

Despite the obvious advantages and ongoing enhancements of digital tools and model-based practices, several engineers remain hesitant to fully adopt them, frequently defaulting to traditional system engineering methodologies. Though some have begun integrating these innovative concepts, there is still a widespread mix of traditional and model-based practices across different organizations. Such inconsistencies pose considerable obstacles for those organizations striving to leverage the transformative potential of digital engineering.

According to a 2020 study the Systems Engineering Research Center (SERC) on digital engineering (DE)/ MBSE adoption across the Enterprise (McDermott et al. 2020), the top three roadblocks to adoption in technical management are noted below and illustrated in Figure 26:

- Methods and Processes
- Organizational Culture
- Communicating success stories and best practices

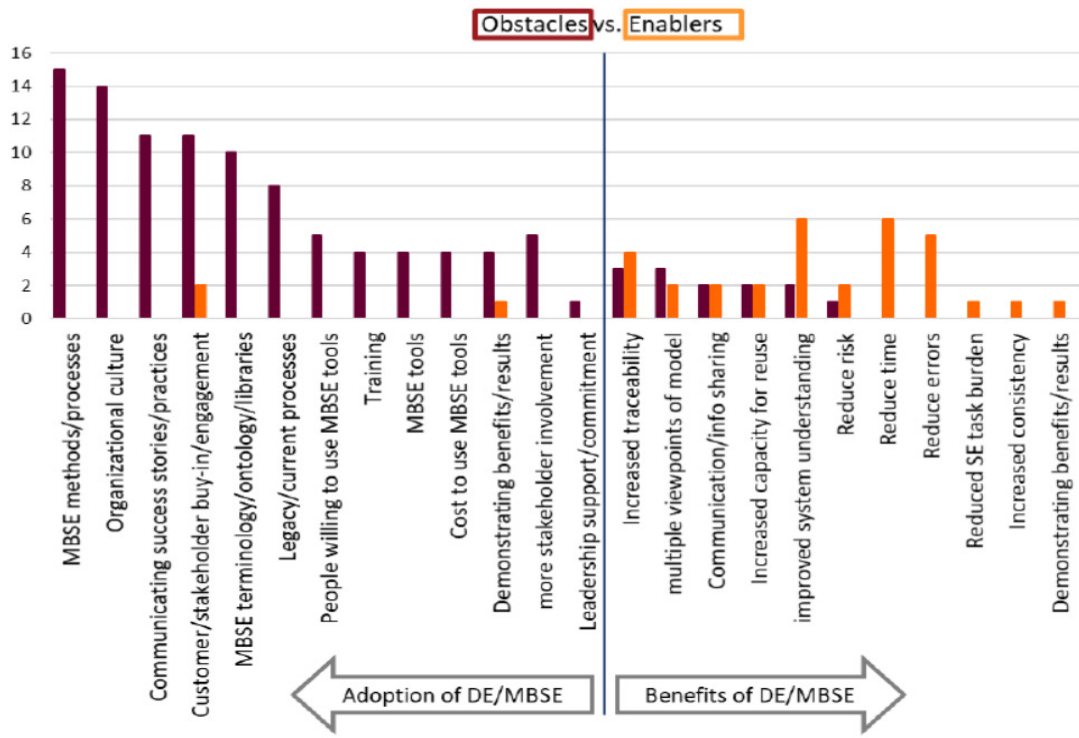

Figure 26. Technical Review MBSE/DE Obstacles and Enablers. Source: McDermott et al. (2020).

Other key findings on the adoption of DE/ MBSE from the same SERC technical report are listed below (McDermott et al. 2020):

- "Benefits at this point are more perceived than measured. Organizations appear to be searching for guidance on measuring the value and benefits of DE/MBSE usage" (McDermott et al. 2020, 62).
- Participants in the survey "disagree or strongly disagree that enterprise capabilities for managing, using, and validating data and models are mature" (McDermott et al. 2020, 62). This indicates a lack of trust in the management of models.
- Smaller organizations tend to do a better job at adopting DE over larger organizations. This could be due to cultural barriers that are easier to overcome in smaller organizations (McDermott et al. 2020, 62).

- Participants in the survey agreed that DE tools and processes are reaching a more mature state than before (McDermott et al. 2020, 62).
- Participants strongly disagree on the availability of personnel to conduct DE/MBSE. This means that organizations do not have enough people to fulfill these roles (McDermott et al. 2020, 62).
- The most frequently reported obstacles to adoption were "organizational culture, workforce knowledge/skills, leadership support/commitment, awareness of MBSE benefits and value, MBSE tools, and change management process design" (McDermott et al. 2020, 67).
- The most frequently reported enablers to adoption included "leadership support/commitment and workforce knowledge/skills, as well as people willing to use MBSE tools, champions, people in systems engineering roles, training, and demonstrating benefits and results" (McDermott et al. 2020, 67).
- "DE/MBSE [is] just an extension of existing systems engineering roles and skills. In other words, mature SE capabilities are essential to DE/MBSE success" (McDermott et al. 2020, 68).
- "The most critical skills for DE/MBSE favored system architecture and systems thinking, along with requirements engineering, domain knowledge, and SE process skills. Added to these were 'digital skills' relating to modeling, data science, simulation, data/tools environment, and model governance" (McDermott et al. 2020, 68).

According to Booz Allen Hamilton, common obstacles in the adoption of DE in the defense industry include the following (Silvas and Brownlow n.d.):

- **Resistance to Digital Tools** – A segment of system engineers, especially those without formal training, are uneasy with the tools required for digital modeling. In digital engineering's infancy, these tools were often complex and challenging to master, leading many to question their practicality despite recognizing their theoretical value. These engineers are convinced that digital methods, due to their complexity, are time-consuming, if not more so, than traditional paper-based approaches.

- **Inconsistent Lexicons and Taxonomies** –An additional frequent issue is the inconsistent method applied to the information utilized by the model. Variations in data presentation, lexicon, or taxonomy by different system architects can cause confusion, errors, and redundancies, including dual capture of the same information or mixed units of measurements. Thus, uniform lexicons and taxonomies are essential to ensure everyone is in alignment.

- **Mature Use Case Strategy** – Many system engineers hesitate to use digital tools, and architects apply them inconsistently, primarily due to unclear usage of digital models. Engineers uncertain about necessary data and architects lacking a consensus on model design can result in unstructured methods. Hence, the initial step should be defining how digital models will align with organizational goals and the mission.

- **Mature Tool Strategy** – With the growth of digital engineering, the array of tools has expanded, making it challenging for system architects and engineers to utilize them correctly. Organizations often employ incompatible tools, leading to laborious manual data exchanges, or use overly complex tools, increasing the burden on engineers. However, a well-developed tool strategy can ensure consistent and effective use of digital tools for all involved (Silvas and Brownlow n.d.).

One of the biggest hurdles to digital engineering adoption lies in its execution within organizations. As technology management expert Paul Leonardi from the University of California Santa Barbara suggests, successful implementation hinges more on the ground-level usage of new digital tools than strategic vision. In his insightful article, *The Nuts and Bolts of Digital Transformation*, published in the MIT Sloan Management Review, Leonardi (2020) underscores a significant issue. He reveals that many senior leaders and managers, lacking a ground-level perspective, often fail to set their teams up for success. This shortcoming leads to digital transformations not achieving their intended impact. To avoid this failure, leaders should understand how their organization will use digital tools and how these new processes will add value to their employees. This implies planning the transformation in reverse from the bottom-up rather than the top-down approach. Without employees recognizing the benefits of digital transformation and proper training, they will not utilize the necessary digital tools required to make the change. Leonardi emphasizes that success depends not on grand promises by leaders, but on decisions made by the front-line employees (Leonardi 2020). A recommended planning approach to digital transformation is shown in Figure 27.

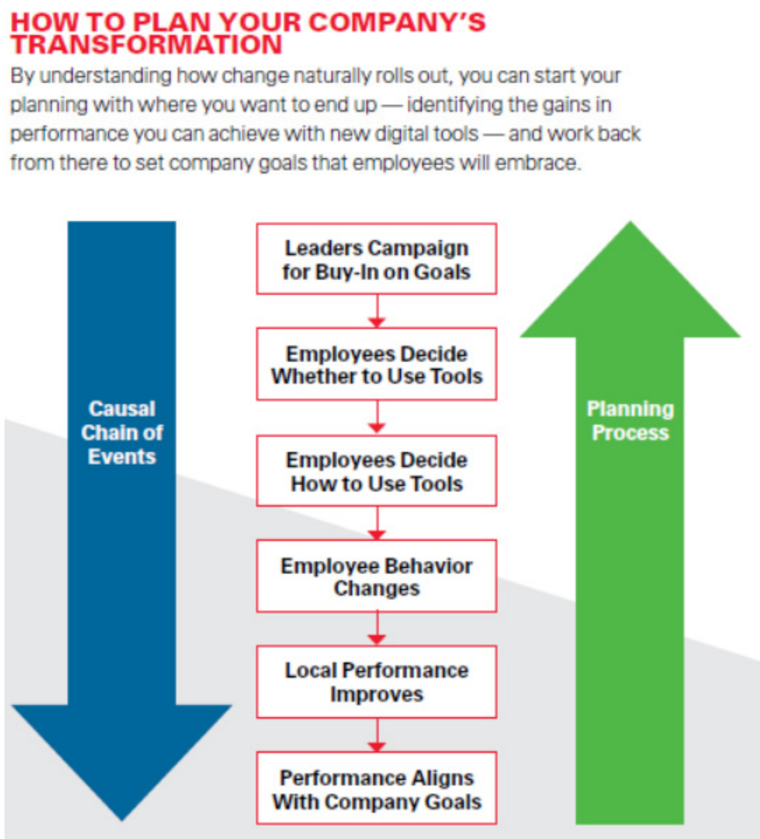

Figure 27. Recommended Roll-Out Approach to Digital Transformation. Source: Leonardi (2020, 2).

IV. ADVANCING T&E THROUGH DIGITAL ENGINEERING

With a deeper understanding of the Naval Acquisition Test & Evaluation process and its existing challenges, coupled with a comprehensive knowledge of Digital Engineering and its principal tenets, the stage is set to explore the intersection of these two domains. This chapter focuses on the potential applications of Digital Engineering to enhance the Naval Acquisition T&E process, thereby striving to address the primary research question.

A. T&E AS A CONTINUUM

The Department of Defense Developmental Test, Evaluation, and Assessment (DTE&A) organization is leading the effort in transforming the practice of Test & Evaluation by sponsoring multiple initiatives aimed at incorporating digital engineering concepts and best practices. DTE&A is responsible for providing guidance on Systems Engineering and Development Test to the military services in support of acquisition programs. DTE&A's current goal is to transform T&E to better support capability delivery to the warfighter and maintain advantage over potential adversaries. DTE&A plans to make this change with a new paradigm in which:

- T&E provides focused and relevant information supporting decision-making continually throughout capability development.
- T&E informs from the earliest stages of Mission Engineering through Operations and Sustainment. (Collins 2023)

The proposed approach, introduced in 2023, transforms the traditional, isolated conduct of Test & Evaluation and unifies it with Systems Engineering and Mission Engineering (ME). ME involves the strategic planning, comprehensive analysis, and seamless incorporation of current and emerging operational and system capabilities, with the overarching objective of achieving the desired outcomes in warfighting missions (DAU n.d.d). Instead of operating as standalone actions, these elements converge in an innovative, integrative framework termed T&E as a continuum. This progressive paradigm has key attributes and enablers critical in the conduct of T&E as a continuum and delivery of capability at the speed of need. Executing T&E as a continuum requires the integration of ME, SE, and T&E into parallel, collaborative, and combined efforts through a dynamic, connected new model-based SE "V" environment. By leveraging this model-based environment along with digital engineering concepts, DOD can shift towards an iterative "model-test-validate-design-test" process (Collins 2023). This process proactively facilitates the consistent availability of mission capability insights. It allows for an early understanding of potential outcomes and maintains an ongoing flow of valuable information, paving the way for efficient mission planning and execution. This new vision of T&E as a continuum is illustrated in Figure 28.

T&E as Continuum is made up of attributes and enablers that integrate and align to current DOT&E strategic pillars documented in the DOT&E Strategy Implementation Plan of 2023 as well as the DOD Digital Engineering Strategy goals. Table 4 provides a description of each attribute and enabler depicted Figure 28.

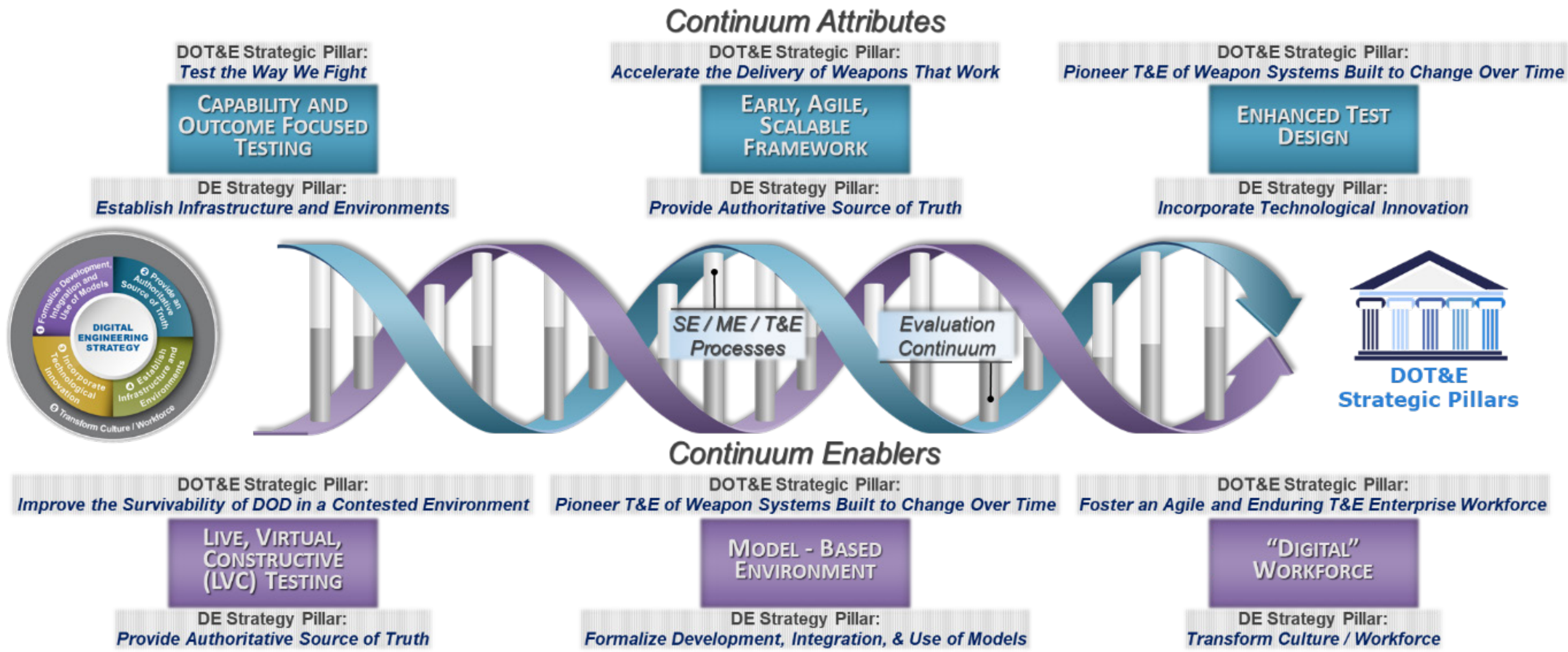

Figure 28. T&E as a Continuum. Source: Collins (2023).

Table 4. T&E Continuum Attributes and Enablers. Source: Collins (2023).

T&E Continuum	DOT&E Strategic Pillar	DE Strategic Pillar
Attributes		
"Capability and Outcome Focused Testing: Often called 'mission-focused testing' – focus as early as possible on the performance of the military capability when fielded. 'Test like we fight' – ensure early Contractor Test & DT engineering and tech verification testing provides information that directly supports evaluation of performance and risk in a mission context culminating in OT. Supports future evolution of discrete KPPs & Knowledge, Skills and Abilities to "system behaviors" enabling rapid evaluation against those desired system behaviors within the context of the model-based environment. Focus Cyber contribution on cyber survivability vs. selective vulnerability mitigation."	"Test the Way We Fight"	"Establish Infrastructure and Environment"
"Early Agile, Scalable Framework: Informs decisions across the capability life cycle – develop the foundational and holistic framework before program initiation. Framework is adaptable and scalable across the six AAF pathways – tailorable to pre-Program of Record S&T, P&E efforts, and integrated across DT & OT. Holistic framework underpins a consistent 'informed risk management' methodology with knowledge gained from operational and technical capability evaluation."	"Accelerate the Delivery of Weapons that Work"	"Provide Authoritative Source of Truth"
"Enhanced Test Design (ETD): Expands recent efforts to improve Integrated Testing and better supports early evaluation of performance in a mission context. ETD incorporates VV&A across the whole of	"Pioneer T&E of Weapon Systems Built to Change Overtime Time"	"Incorporate Technological Innovation"

T&E Continuum	DOT&E Strategic Pillar	DE Strategic Pillar
capability evolution to provide initial data informing whether desired capability outcomes can be achieved. ETD uses a comprehensive 'design-test-validate' approach assessing evolving 'system behaviors' enabling capability developers to adapt designs driven by changing operational environments. Incorporates appropriate Scientific Test and Analysis (STAT) techniques to gain efficiencies and help enable rigorous evaluation of test results."		
Enablers		
"Live, Virtual, Constructive (LVC) Testing: Increased use of M&S and other constructive approaches, spanning the spectrum of threats and operational environments, is essential to obtaining a comprehensive understanding of systems' performance. Implement a model validation level (MVL) metric using simulation results and corresponding referent data to understand model trustworthiness. LVC approaches enable Systems-of-Systems (SoS) testing – an essential requirement supporting evaluation of emerging concepts and improved capability validation. Requires continued evolution of test ranges and facilities to incorporate combined LVC capabilities – this evolution will entail a 'shared' infrastructure within the DE environment."	"Improve the Survivability of DOD in a Contested Environment"	"Provide Authoritative Source of Truth"
"Model- Based Environment: The most critical enabler of a continuum of testing • Require a digital backbone and model-based approaches to manage the continuum of T&E activities. • Integrates T&E activities with ME and SE	"Pioneer T&E of Weapon Systems Built to Change Over Time"	"Formalize Development, Integration, Use of Models"

T&E Continuum	DOT&E Strategic Pillar	DE Strategic Pillar
activities conducted in parallel. • Manages, curates, and analyzes data generated for all ME, SE, and T&E activities. Incorporates the agile, scalable evaluation framework and helps assure consistency with the full range of ME, SE, and T&E activities. Uses 'digital threads' displaying progress in modeling system performance beginning early in ME through the potential development of high-fidelity 'digital twins'."		
" 'Digital' Workforce: Underpinning adoption of the model-based environment requires a 'digital' workforce that is savvy with the processes and tools associated with MBSE, Model-Based T&E (MBTE), and other model-based processes. Digital Engineering for T&E is the only DE credential planned by the T&E Functional Area..."	"Foster an Agile and Enduring T&E Enterprise Workforce"	"Transform Culture/ Workforce"

This new T&E paradigm seeks alignment with the Digital Engineering strategic goals, as well as strategic initiatives from both the DT and OT perspectives. However, it falls short in offering comprehensive process steps to actualize the T&E transformation. The concept of T&E as a continuum is primarily intended to provide overarching guidance on the department's T&E direction rather than detailed execution plans. Herein lies an opportunity for military services, such as the Navy, to devise the 'how' via a roadmap, to effectively integrate digital engineering in a way that elevates T&E practices. Importantly, this roadmap should aim to address not just the strategic objectives, but also devise solutions to tackle existing T&E challenges and limitations.

B. USING DE TO OVERCOME CURRENT T&E CHALLENGES

Digital engineering holds transformative potential for addressing the complex challenges and limitations currently faced in the T&E community. By leveraging the power of key tenets such as digital twin, digital thread, MBSE, ASOT, and digital tools and technologies, DE provides an innovative pathway to streamline the T&E process, improve resource allocation, and mitigate existing issues. This necessitates shifting the challenges from the limitations of the physical environment to the boundless opportunities within the digital domain. For example, digital engineering enables the creation of digital twins that can significantly reduce the dependency on physical testing, thus overcoming geographical and resource constraints. It allows for the digitization of T&E artifacts improving the collaboration and sharing of information among teams, and it leverages on digitalization, which leads to significant change in how organizations operate and deliver value. In essence, the application of DE can result in more efficient, reliable, and robust T&E processes, revolutionizing the traditional methods of executing these activities. The subsequent list outlines how the application of DE can address and resolve current T&E challenges covered in Chapter 2.

a. Inadequate Infrastructure

Digital twin can substantially decrease reliance on physical infrastructure. By harnessing the power of virtual environments and digital twins, it is possible to drastically minimize the necessity for physical testing facilities. This approach is beneficial in situations where the existing infrastructure is not available or insufficient to support test requirements. This method could eventually lead to the establishment of a virtual test range, designed to mimic the conditions and scenarios of a physical test range as closely as possible. For instance, such a virtual range could be employed to simulate flight conditions for a missile, thereby assessing its performance under varying weather conditions, altitudes, and operational scenarios. Such an approach generates crucial data and understanding, guiding the development, refining the design, and preemptively addressing potential risks before even embarking on the creation of a physical prototype. It is worth noting that despite the substantial value that virtual testing brings to the table, it is not meant to completely substitute physical testing as this is necessary to validate and verify the performance of a system in the real world.

Much like digital twins, MBSE can be used to develop robust modeling and simulation capabilities. By developing models of complex systems and simulating different scenarios, MBSE techniques can help identify interactions and limitations, providing a more holistic view of the system and its infrastructure requirements. The use of models in MBSE allows for quick and easy adjustments to system designs. If a potential issue is identified, changes can be made quickly in the model before costly changes to the physical system or infrastructure are required.

b. Limited Test Space

To evaluate advanced systems like hypersonic and long-range weapons, the Navy faces two options: expand existing test ranges or harness digital twin technology to test within a virtual environment. Given that hypersonic technology is new, gathering data for model validation becomes challenging. Constructing a robust model could benefit from employing modeling and simulation techniques, sensitivity analysis, digital tools, historical data from related, previously deployed technologies, and using similar models. Virtual testing using modeling and simulation also mitigates potential encroachment issues such as interference with consumer electromagnetic spectrums, including 5G, and environmental disruption.

c. Evolving Threats and Scenarios

Addressing evolving threats and scenarios presents a significant challenge for the Navy, primarily due to the uncertain timeline of intelligence gathering. Nevertheless, digital engineering can offer a solution by enabling a shared platform for threat models and scenarios across multiple programs. The implementation of a model repository or ecosystem, like the Navy's proposed Integrated Model Environment, could provide greater opportunities for acquisition programs and organizations to leverage this information, thereby enhancing their individual T&E efforts. The reliance on authoritative sources of truth is critical to maintain up-to-date threat models and scenarios. This allows teams to collaborate and operate more efficiently, without the need to spend time searching for data or verifying its accuracy. Moreover, the incorporation of a digital thread can also facilitate access to historical data from previous threat models, together with associated test results, offering insights that can guide current and future T&E efforts. Lastly, to counter the challenge of limited test targets, sharing threat model data with design agents and target providers could expedite the production of physical prototypes, ensuring their prompt availability for testing purposes.

d. Test Integration

The optimal approach to addressing the challenge of testing multiple naval systems across multiple domains at a force level is by using all components of DE. Digital twins can be used to replicate test ranges, enabling tests to be performed in a virtual environment. This mitigates the need to physically combine multiple test ranges into a single complex "range of ranges," thereby reducing both costs and logistical difficulties. Digital thread can be used to track, manage, and share system data across a multi-domain environment. MBSE can be used to create models of naval systems and integrate them to both virtual and physical systems. ASOT can be used to ensure the validity and accuracy of all data, while maintaining it within a unified repository. Additionally, digital tools can construct virtual models of naval systems and integrate them with virtual reality technology to enable operators in the loop. Through the utilization of advanced modeling, simulation tools, and 3-D game engines, and analytics software, a variety of operational scenarios can be simulated to evaluate the performance of systems of systems. Lastly, the establishment of a DE ecosystem where all digital artifacts, models, and tools reside would enable various naval programs to participate and connect their system models. This would give rise to a purely digital environment where all naval systems are replicated via models and connected to simulate a real-world scenario. A similar concept, known as Live, Virtual and Constructive (LVC) is already being implemented across the services. This test framework, composed of differing simulation types, is currently being used by the Navy primarily for fleet training but could be repurposed to support system development and T&E at both the unit and force level.

e. T&E Spending

Despite the Navy's T&E budget experiencing a 23% reduction from fiscal year 2021 to 2023, the urgency for testing new and emerging naval systems has not just persisted but surged. It is now more critical than ever for the Navy to insist that design agents and contractors integrate digital models into the technical data packages they deliver. These models, once available to the Navy, can be interconnected via a digital thread infrastructure, such as the proposed Integrated Model Environment (IME). This environment not only incorporates ASOT, but also enables the application of digital tools, providing a cost-effective virtual testbed. According to Jay Stefany, the Navy's acting acquisition chief who spoke on the necessity of naval system models during a 2021 acquisition symposium at NPS,

> In an ideal world, a single digital model would be employed for the program's requirements definition phase, the 3D design phase, and seamlessly transition into the digital production phase. This same model and data would then be harnessed for developmental and operational testing. The goal is not to reinvent the wheel, if an Original Equipment Manufacturer (OEM) already possesses a model, or they are in the process of developing one, we [the Navy] should be fully involved in that process. (Serbu 2021)

Thus, leveraging these system models for T&E purposes can yield substantial cost savings, which in turn results in a more efficient allocation of the existing T&E budget. To bring this concept to fruition, it's vital for the Navy to foster close collaboration among design agents, OEMs, and the wider industry. This partnership will ensure the models are protected, developed, thoroughly tested, and validated to support test requirements and operational needs.

f. T&E Cost Perception

While DE may not necessarily solve the perception of excessive T&E costs, it can help track and manage these expenses more effectively across the system's life cycle. Given the historical challenge of managing T&E costs accurately, the U.S Navy is driving an initiative to digitize the T&E resource requirements of the Test and Evaluation Master Plan (TEMP). This digital transition, known as TEMP Part Four (TP4), aims to replace the current document-centric approach with a more modern web-based tool for resource tracking. The TP4 tool enhances the efficiency of T&E practitioners and Program Managers by facilitating the search, coordination, and identification of T&E resource requirements. The initiative is not only designed to streamline the resource management of T&E, but also to compare actual T&E expenses against their budgeted allocation throughout a program's life cycle (Said 2019). It will additionally empower OPNAV to validate a program's T&E resources before granting TEMP approval. The TP4 tool is on track to become a mandatory requirement for all Department of Navy testing programs in the foreseeable future. As illustrated in Figure 29, the TP4 tool holds great potential in aiding the tracking of T&E expenditures.

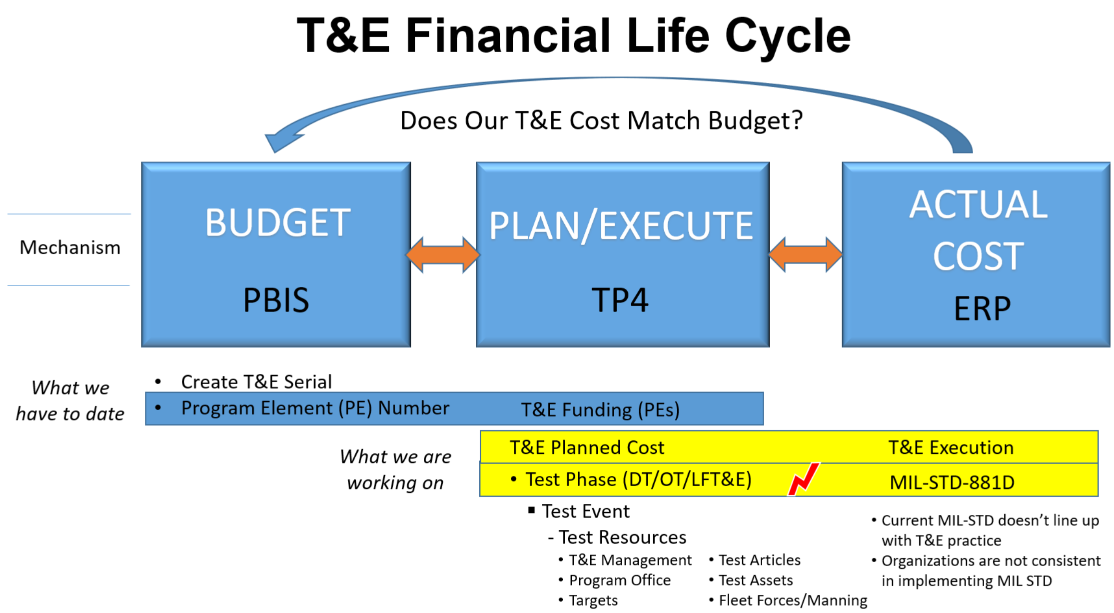

Figure 29. T&E Financial Life Cycle using TP4. Source: Said (2019).

While the potential benefits are considerable, this effort could be significantly amplified, if not already considered, by incorporating digital thread and ASOT. Digital thread serves as an integrative framework that connects and centralizes data flows, including those relating to T&E costs such as labor, targets, test articles, assets, fleet manning, administrative costs, laboratory support, and test range. The relationship between digital thread and ASOT provides real-time cost tracking and analysis, which enhances the visibility of T&E expenses and expedites data-driven decision making. ASOT, in turn, guarantees the accuracy and reliability of this data. It helps to maintain a consistent, unambiguous perspective on T&E costs, minimizing discrepancies and errors while improving cost tracking and reporting precision.

To counter the perception of inflated T&E budgets, decision-makers need to have real-time access to actual T&E financial data for a given program. Costs tracked via digital thread and stored in a common repository enable decision makers and T&E stakeholders to gauge actual T&E expenditures at any given point, determine resource demands, and forecast potential resource conflict and financial constraints. This clear, up-to-date visibility of a program's financial records can greatly facilitate informed decision-making and enable a more accurate understanding of T&E costs across the community.

g. Schedule Delays

Upon a thorough examination of the 2014 DOT&E report concerning program delays, it becomes evident that Navy programs have a statistically higher likelihood of encountering difficulties during test execution. The report revealed that about 37.2% of Navy programs, or 16 out of 43, dealt with test execution challenges. Most of these issues were largely attributed to unavailability of necessary resources such as ships, system under test, test ranges, and targets during the test execution phase. Further test execution obstacles emerged due to unsuitable test instrumentation and inadequate test procedures.

Moreover, approximately 75% of all programs in the DOT&E study encountered delays owing to issues discovered either during either DT or OT phases. The T&E community generally supports the discovery of system issues during DT or OT, as this validates the efficacy of the T&E process in preemptively identifying potential problems prior to system deployment. However, an unusually high number of quality or performance issues may indicate underlying problems such as inadequate pre-testing analysis conducted by the design agent, intrinsic system complexity, or flawed system design. A further breakdown of the issues causing program delays is found in Figure 7.

To mitigate program delays identified during test execution, either in DT or OT phases, the following digital engineering strategies can be employed:

- Resource Allocation via Digital Thread – The integration of a digital thread and ASOT allows for real-time resource monitoring, enhancing allocation efficiency and mitigating both overuse and underuse. This fusion facilitates data-driven resource distribution decisions, grounded in reliable and up-to-date information. In addition, the continuous data stream from the digital thread supports predictive analytics, assisting in forecasting future resource requirements. By applying these digital engineering concepts, the Navy can considerably minimize the likelihood of resource unavailability during test execution.

- Advanced Test Instrumentation – Presently, most Navy ships necessitate telemetry instrumentation for live fire tests, a process that involves prior scheduling and funding for engineering personnel, equipment, and onsite staffing. Working capital organizations like the Naval Surface Warfare Center (NSWC) typically provide these services for most T&E events, with additional telemetry support requested from appropriate test range facilities for improved coverage flight coverage area. However, the use of advanced technologies such as Artificial Intelligence, alongside automatic tracking telemetry systems, can streamline telemetry configuration and installation, and minimize the need for onsite staffing. While this approach could mitigate the risk of telemetry malfunctions, the initial investment in procuring and integrating these advanced systems may lead to an upfront increase in T&E costs.

- Improved Test Procedures –Traditional methods of documenting test procedures through spreadsheets or word documents often lead to reuse of these procedures without customization to fit the specific system under test or test scenario. Such oversight can result in inappropriate test procedures, ultimately failing to meet test objectives. To address this issue, the integration of MBSE, digital thread, and ASOT can be highly beneficial. MBSE allows for test procedures to be modeled and simulated in advance of actual testing, facilitating early identification and correction of potential issues. This process results in robust, tailored test procedures, thereby reducing multiple iterations and rework. In addition, the digital thread and ASOT offers an effective means to track and manage all test procedure revisions. This ensures that all stakeholders involved in the T&E process are working with the most current and accurate procedures, minimizing errors, and promoting efficiency.

- Quality Improvement – To reduce the excessive identification of system issues during physical testing, which often results in substantial schedule delays, the incorporation of MBSE, digital twin, and digital thread should be considered. MBSE empowers design agents and engineers to construct detailed, digital prototypes of the systems in development. These digital representations can undergo rigorous analysis and testing in virtual environments, thereby identifying, and correcting potential defects early in the design phase. This leads to superior and high-quality designs exhibiting fewer defects, which ultimately reduces the necessity for extensive physical modifications and testing in subsequent development stages. Moreover, the utilization of a digital twin for real-time simulations and analysis, coupled with a digital thread for tracking system changes and modifications, provides comprehensive visibility into the system's performance and evolution over time. Together these two DE tenets provide continuous visibility into the system's performance and history. They can be used to identify patterns and trends that may indicate potential quality issues, allowing for proactive corrections and improvement prior to physical testing.

h. Data Strategy

It is vital to formulate a robust data strategy for T&E during the initial stages of system development. This proactive approach not only ensures that the program can comprehensively assess all its development and operational testing requirements, but it also strengthens the potential for streamlined execution and ultimate success of the program. Below are some methods on how digital engineering can be used to improve the challenges associated with test data.

- Data Integration – Most test data is gathered from various sources during test execution, such as the system under test, instrumentation equipment, targets, aircraft, test ranges, etc. To overcome the challenge of disparate datasets, the first step should focus on making all test data available in one single repository using ASOT. This would necessitate that design agents and contractors engage in a continuous exchange of their systems' most recent data dictionaries with the Navy. After consolidating all data, including data dictionaries, into a common repository, the next stage involves leveraging digital tools like artificial intelligence and machine learning to automate the data processing and cleaning step. This transformation converts raw data into a format ready for analysis, reducing time and effort and minimizing potential errors. Coupled with the power of cloud computing and advanced analytics tools, this approach could enable near real-time data analysis capabilities, ensuring that stakeholders and decision-makers are equipped with the most current information.

- Data Storage and Security – In order to overcome the challenges of substantial data storage and ensure optimal security, it's essential that the T&E community fully integrate digital tools and technologies, primarily focusing on cloud-based solutions. The DOD has already paved the way in this regard, forming collaborations and issuing contracts with major cloud-service providers, such as Amazon Web Services (AWS) and Microsoft Azure. For example, in a move to harness the potential of these digital capabilities, the Navy has initiated actions to make use of services such as AWS GovCloud and AWS Secret Region. These provide a secure and robust environment conducive to the pursuit of modern software development methodologies such as DevSecOps. AWS has not only solved the issue with data storage, but has met the Navy's highest security protocol, impact level six (IL-6), which ensures the secure handling of classified information (Martin 2021). Sophisticated cloud-based platforms allow organizations to seamlessly scale storage capacity in accordance with their evolving data requirements. This effectively mitigates the need for substantial investments in physical infrastructure and associated maintenance costs. Furthermore, these platforms fortify data security, leveraging stringent encryption protocols and robust access controls. Cloud-based services are equipped with dedicated security teams who provide around-the-clock surveillance and promptly respond to any potential threats. These services also prioritize the ongoing maintenance and updates of their infrastructure, thus guaranteeing that the storage systems are continuously up to date with the most recent security patches. In addition, the migration of T&E data to the cloud significantly propels the collaboration capabilities among various teams, including design agents and industry partners, by enabling data accessibility through established secure networks like SIPRNET or SDREN. Thus, the transition to cloud-based solutions not only enhances data security and storage capacity but also fosters efficient collaboration within the T&E community.

- Data Quality – Refining data and preparing it up for analysis can frequently be a demanding undertaking. Nonetheless, with the deployment of sophisticated data visualization tools, such as Tableau Prep or Python scripting, it is possible to establish an automated workflow specifically designed for data cleaning. The creation of such a digital workflow has been made considerably less complicated, thanks to modern digital tools and algorithms. This sequential workflow scrutinizes and modifies the data file at each step, ultimately producing a refined file free from errors and ready for data analysis. This approach, when paired with Machine Learning techniques, can empower data analysts or engineers to progressively train an algorithm to detect anomalies, errors, data corruption, and redundancies in test data. This fusion of cutting-edge technology and digital tools redefines and optimizes the existing process, thereby assuring superior data quality.

- Data Infrastructure – To tackle data infrastructure challenges, it is imperative for the Navy to transition from local server hubs or file-sharing infrastructure to robust cloud-based solutions. Despite the existing technology and DOD's partnership and contracts with major corporations for data hosting, across both unclassified and classified spectrum, the T&E community has yet to fully embrace these technological advancements. This hesitation may stem from concerns of data spillage, potential data loss, mistrust in emerging technology, or, as is often the case, a lack of awareness about the resources readily accessible to the T&E community.

- Data Sharing – In October 2020, the DOD unveiled its data strategy, detailing its blueprint to ensure data visibility, accessibility, connectiveness, trustworthiness, interoperability, and security. This strategy, which the Navy supports and plans to implement, also advocates enhancing data sharing and collaboration to enable more informed decision-making (DOD 2020b, 6-9). However, today's T&E data often exists in isolated silos, scattered across multiple servers in various organizations, frequently duplicated, and generally overlooked following test events. This valuable data typically gets archived to media or servers in secure buildings, seldom to be accessed again. Dissemination of such information often necessitates approval from the respective program office or the program's T&E Chief Developmental Tester. Historically, these approvals have been in place to protect data from unauthorized access, ensure need-to-know, and to prevent misinterpretation of data that could lead to wrong conclusions. An effective resolution to the data sharing challenge could be found in the establishment of a Digital Engineering Ecosystem, one that utilizes digital thread and ASOT. This kind of ecosystem could provide all T&E stakeholders with access to the same data from a consolidated repository. Leveraging the digital thread, programs could have the ability to trace, monitor, and document all system test data from its origin, registering user access, data modifications, and downloads, thereby ensuring full system traceability from inception to disposal. Such a system offers significant advantages by enabling rapid and effortless retrieval and access to both current and historical test data. This streamlined access facilitates data analyses, including trend analysis, which helps in determining system performance over time, and enables continuous enhancement of future system improvements. To maintain the principle of 'need-to-know', this ecosystem can incorporate sophisticated access controls to diverse data categories, thereby enabling the respective program offices to retain rights of approval regarding data access. This balances the openness of the digital ecosystem with the need for security and confidentiality.

i. Testing AI and ML

The Navy needs to develop a robust T&E process or ecosystem that can support development, operation, and sustainment of AI-enabled systems. While the DOD has made a commitment to pioneer approaches for AI T&E and Verification and Validation, those plans have yet to materialize. The problem with testing non-deterministic systems is the nature of the unknown output or response. This makes it harder to determine the conditions under which these systems might fail and what steps could correct system behavior. In the publication on *Building Trust Through Testing*, the author suggests that the goal of the solution should build trust with fleet operators (Flournoy 2020). For the fleet to trust the AI-enabled system, they need assurance that the technology has been fully tested under stressful and relevant conditions with high performance results before they can delegate tasks and use it for decision-making.

While digital engineering might not offer a specific solution to the solve the problem with testing AI-enabled systems, it can offer ways to make the process more efficient by addressing its inherent challenges:

- Infrastructure not suitable for testing – The development of AI-enabled systems necessitates a sophisticated test infrastructure, encompassing dedicated test beds, extensive test ranges, and advanced modeling and simulation capabilities to facilitate iterative testing. Traditional testing methodologies, constrained to single physical locations, must evolve towards more flexible, digital environments. Harnessing the power of cloud-based resources and ASOT enables rapid access to digital tools and data, thereby enhancing automated testing procedures and accelerating overall system development.

- Large representative data sets – Employing key principles of digital engineering, such as ASOT and digital thread, contained within a Digital Ecosystem, will allow effective management of the extensive test data associated with AI-enabled systems. These systems will further necessitate scenario-specific data from various other test events for meaningful learning and system refinement. The utilization of a common enterprise infrastructure, such as the Navy's IME, could offer a platform for AI/ML developers and T&E practitioners to harness and benefit from the data collected from other programs, enabling data sharing, and thus facilitating thorough and comprehensive testing of their own systems.

- Integration into System-of-Systems – Integrating AI into existing or new systems requires taking a system architecture approach when conducting T&E. To properly test these AI-enabled systems in a force level environment, testing components or individual systems separately will not work. AI/ML system respond very differently from traditional systems, as their behavior is a result of a combination of different factors such as its components, computational algorithms, training data, scenarios, training framework, virtual and physical environments, and human interaction. All these factors will ultimately affect system performance. However, with the use of MBSE, the complex architecture of these integrated systems can be conceptualized, developed, and managed in a structured digital environment. Furthermore, applying system-of-systems level testing allows for comprehensive evaluation of algorithms, beyond just element or unit level. This broader scope not only provides a more holistic assessment of system performance but also ensures that the integrated AI/ML components function seamlessly within the larger system construct. The challenge with predicting system performance for these AI-enabled systems becomes once the testing parameters widen to account for operator interaction and unexpected scenario conditions.

- Traceability and Interpretability – The use of a digital twin and digital thread could aid in addressing the traceability and interpretability challenges of AI-enabled systems. Unlike traditional computer or weapon systems, AI/ML systems often make decisions that are difficult to trace, which can present a unique set of challenges for the T&E community. A digital twin could be used to simulate the behavior of the system under various scenarios. By observing the system's behavior in the digital twin, one can gain insights into the decision-making process of the AI/ML systems. This offers the potential for understanding the reason behind its decisions and can help provide some level of interpretability. Alongside, digital thread can provide crucial data points to help analyze the system's decision-making process. The digital thread would record and maintain the data that feeds into the system, the system's responses, and the resulting outcomes, forming a cohesive narrative that gives context to the AI's decision-making process. By utilizing digital twin and digital thread, the T&E community could enhance their understanding of AI/ML decisions and relationships to the requirements, which can help build trust and confidence in these systems.

Table 5 summarizes this section by using a comprehensive matrix, mapping how key tenets and components of Digital Engineering can be effectively utilized as potential solutions to address current naval T&E challenges.

Table 5. Digital Engineering Tenets Mapped to Current T&E Challenges

	Digital Engineering					
T&E Challenges & Limitations	**Digital Twin**	**Digital Thead**	**MBSE**	**ASOT**	**Digital Tools & Technologies**	**DE Ecosystem**
1. Inadequate Infrastructure	X		X			
2. Limited Test Space	X		X		X	
3. Evolving Threats and Scenarios		X		X		X
4. Test Integration	X	X	X	X	X	X
5. T&E Spending	X	X	X	X		X
6. T&E Cost Perception		X		X		
7. Schedule Delays						
A. Resource Allocation		X		X		
B. Test Instrumentation					X	
C. Test Procedures		X	X	X		
C. Quality Improvement	X	X	X			
8. Data Strategy						
A. Data Integration		X		X	X	
B. Data Storage and Security					X	
C. Data Quality					X	
D. Data Infrastructure					X	
E. Data Sharing		X		X		X
9. Testing AI and ML						
A. Testing Infrastructure				X	X	
B. Representative data sets	X			X		X
C. Integration into SoS			X			
D. Tracebility and Interpretability	X	X				

C. ROADMAP FOR THE FUTURE: DIGITAL T&E

1. Opportunity for Improvement

As the Navy sails into the fourth industrial revolution, the integration of digital engineering and T&E becomes crucial. The harmonization of these disciplines is not merely beneficial but essential, as it forms the backbone for validating system models, providing a robust foundation for acquisition life cycle management. The conventional T&E approach, largely document-centric, relies heavily on the insight and judgment of T&E practitioners. It is a process mired in manual documentation and subjective judgment, which, while valuable, can sometimes be a bottleneck in fast-paced and agile system developmental cycles. In contrast, digital engineering signifies a paradigm shift. It embraces a model-based approach that leverages digital twins and simulation, constructing systems using an authoritative source of truth. The digital engineering approach creates transparency, collaboration, and accuracy, making it possible to assess and test systems in virtual environments before they're built, therefore reducing potential risks, schedule, and costs.

Digital engineering is not just a theoretical proposition. Its potential has been presented through a comprehensive literature review and analyses conducted in the earlier sections of this thesis. The four case studies presented in the literature review provide proof that digital engineering works at reducing cost, improving system performance, and enabling rapid system development. From this research, DE tenets have been proposed to directly address the current naval T&E challenges. The insights derived and the solutions proposed are not end goals but stepping stones that pave the way for the next stage of evolution, Digital T&E.

This section provides a forward-looking roadmap of digital T&E that not just outlines the steps required to make this transformation but also envisions a future where T&E is infused into digital engineering, creating a feedback loop of continuous testing, assessment, improvement, and validation. Utilizing concepts from the case studies on digital engineering, it becomes evident that the digital twin tenet is central to digital transformation. Without this critical element, digitalization of the current system development process remains unachievable.

To revolutionize and enhance the current document-centric approach in T&E, recognizing its weaknesses is essential. In addition to the challenges identified in the literature review, the existing process is static and difficult to alter. This difficulty stems from its alignment with the current acquisition process, which relies on serial process steps and multiple program reviews, creating barriers to changing requirements after the detailed design phase. Consequently, the T&E process remains inflexible and fails to adapt to evolving threats. For example, once the TEMP document is finalized and resources are allocated, shifting strategy becomes nearly impossible. The introduction of new system requirements to counter new threats can critically endanger the program or escalate costs to unsustainable levels. In addition, decisions concerning system improvements usually occur after the completion of critical test milestones in both DT and OT. This timing is often too late for implementing substantial modifications to the system. Moreover, it may take years for an acquisition program to reach the DT phase and even more to reach OT, especially for new system development, effectively eliminating opportunities to adjust system requirements once testing has begun. This lack of flexibility and adaptability in the process not only constrains timely response to emerging threats but also may extend the timeline and increase the costs of implementing necessary changes. To address this challenge with digital engineering, it is important to examine how private industry has overcome this problem.

2. Advancements in Industry through DE

In the Formula 1 case study, system modifications and fine tuning are made at an incredible speed thanks to the use of a digital twin. F1 vehicles are not trivial to design and are often considered highly complex systems. They represent the pinnacle of automotive engineering and technology, involving an intricate interplay of various components and subsystems. Even with this level of complexity, F1 designers and engineers can rapidly build a new vehicle with improved performance based on data collected from the physical vehicle. This constant feedback loop of test-model-analyze is what allows them to produce advanced vehicles without ever having to build a prototype. Their T&E process is fast thanks to their digital twin's profound ability to instantly process live data, conduct simulations, and make reliable predictions. This capability allows F1 engineers to constantly adjust their strategy, make vehicle modifications, and retest to gain an advantage over their competitors.

Drawing parallels with the methodology used in Formula 1, in the Boeing case study, the company applied digital engineering, specifically digital twin, MBSE, and digital thread in the development of the T-7A aircraft. The use of these digital engineering tenets allowed the company to achieve a remarkable feat by taking the development of the T-7A from concept to first flight in under 36 months. This set new records, making it one of the fastest aircraft developments of its kind. In contrast to the traditional aircraft development process, Boeing's innovative approach resulted in a "75% increase improvement in first-time engineering quality, 80% reduction in assembly hours, and a 50% reduction in software development and verification time" (Herber and Batchelor 2023).

SpaceX's advancement in the design of the Dragon spacecraft can be attributed to the innovative application of digital twins. Using this concept, SpaceX was able to create a digital replica of the Dragon spacecraft, enabling operators in Mission Control to monitor intricate details of its status, such as trajectory, loads, speed, propulsion systems, and other subsystems. This real-time mirroring is achieved by utilizing data received from the hundreds of sensors seamlessly integrated into the spacecraft. From a digital engineering perspective, the use of digital twins has redefined the traditional design and development process. Through detailed modeling, simulation, and analysis, SpaceX engineers have optimized the spacecraft's subsystems, gaining an in-depth understanding of how individual components interact under diverse conditions. This knowledge has guided informed design decisions, leading to a spacecraft meticulously crafted to meet specific mission objectives, thereby elevating both performance and efficiency.

From a Test & Evaluation standpoint, digital twin is a robust framework for continuous monitoring, test, and assessment. Through its use, SpaceX, Boeing, and Formula 1 can conduct extensive virtual testing of their systems under simulated real-world conditions, thereby uncovering potential design flaws or areas for improvement without the risks associated with physical testing. This method not only accelerates the T&E process but also facilitates rapid identification of issues. This contributes to a continuous cycle of enhancement, optimizing performance and system refinement.

3. Digital T&E

While the term 'Digital T&E' may not be found in existing literature, this thesis defines it as the application of digital engineering methods to the test and evaluation phase of systems engineering. Achieving this improvement necessitates a shift in perspective. Instead of persisting with the conventional design-build-test approach, there must be a transition to a more sophisticated model-simulate-analyze-build-validate iterative methodology. While this may appear to expand the approach at first, it does not. Rather, it offers a more precise and clearly defined framework, revealing a path toward greater efficiency and accuracy in system development. The steps in this innovative approach are detailed below:

1. **Model** – The process commences with the creation of a model that accurately represents the physical system. Ideally, a digital twin is constructed to offer higher fidelity, capturing intricate details of the system and its individual components.
2. **Simulate** – Once the model is developed, it's crucial to simulate it within a context that closely mirrors its expected physical environment. This step may require the creation or utilization of a virtual operational environment to accurately reflect real-world conditions.
3. **Analyze** – Upon completing the simulation, a thorough data analysis is initiated. In this phase, metrics or Technical Performance Measures (TPMs), serve to evaluate system performance and promptly identify any issues. By harnessing advanced digital technologies, including artificial intelligence and machine learning, simple processes can be automated, resulting in heightened efficiencies. Analysis results are carefully evaluated to ensure system requirements are satisfied, and necessary model adjustments are made if any discrepancies are detected. The adjusted model is then simulated and analyzed again, and this

iterative process continues until the model consistently produces the desired outcomes.

4. **Build** –After the model has been thoroughly simulated and has successfully met the system requirements and desired outcomes, the next stage is to transition from the virtual environment to the construction of the actual physical system.
5. **Validate** – After building and testing the physical system in its intended operational environment, the following stage involves validating the system model. This validation is conducted using the data generated from the physical test as the authoritative source of truth, ensuring that the virtual model faithfully represents the real-world system.

This iterative methodology underscores a dynamic and continuous relationship between the virtual models and their physical counterparts. By constantly updating and validating the models with data generated from the real-world system, a cohesive and accurate representation is maintained. Such an approach mirrors the integration of digital engineering within system development paradigms, as demonstrated by industry leaders such as SpaceX, Boeing, and Formula 1.

Applying this approach to the current naval acquisition T&E process, an innovative methodology for executing digital T&E emerges, as illustrated in Figure 30. This cutting-edge digital T&E approach for naval systems revolutionizes the existing process by incorporating digital engineering principles. It moves beyond the traditional, sequential, and document-centric phases of planning, preparation, execution, analysis, evaluation, and reporting. Instead, it enables a more dynamic, flexible, and iterative approach, emphasizing continuous feedback and system enhancement. All test data generated from this process, considered as an authoritative source of truth, serves to validate the system models, and promote constant precision and refinement. This transformation represents more than a simple reorganization of the existing T&E process; it signifies a profound shift in the way we conduct naval acquisition system development.

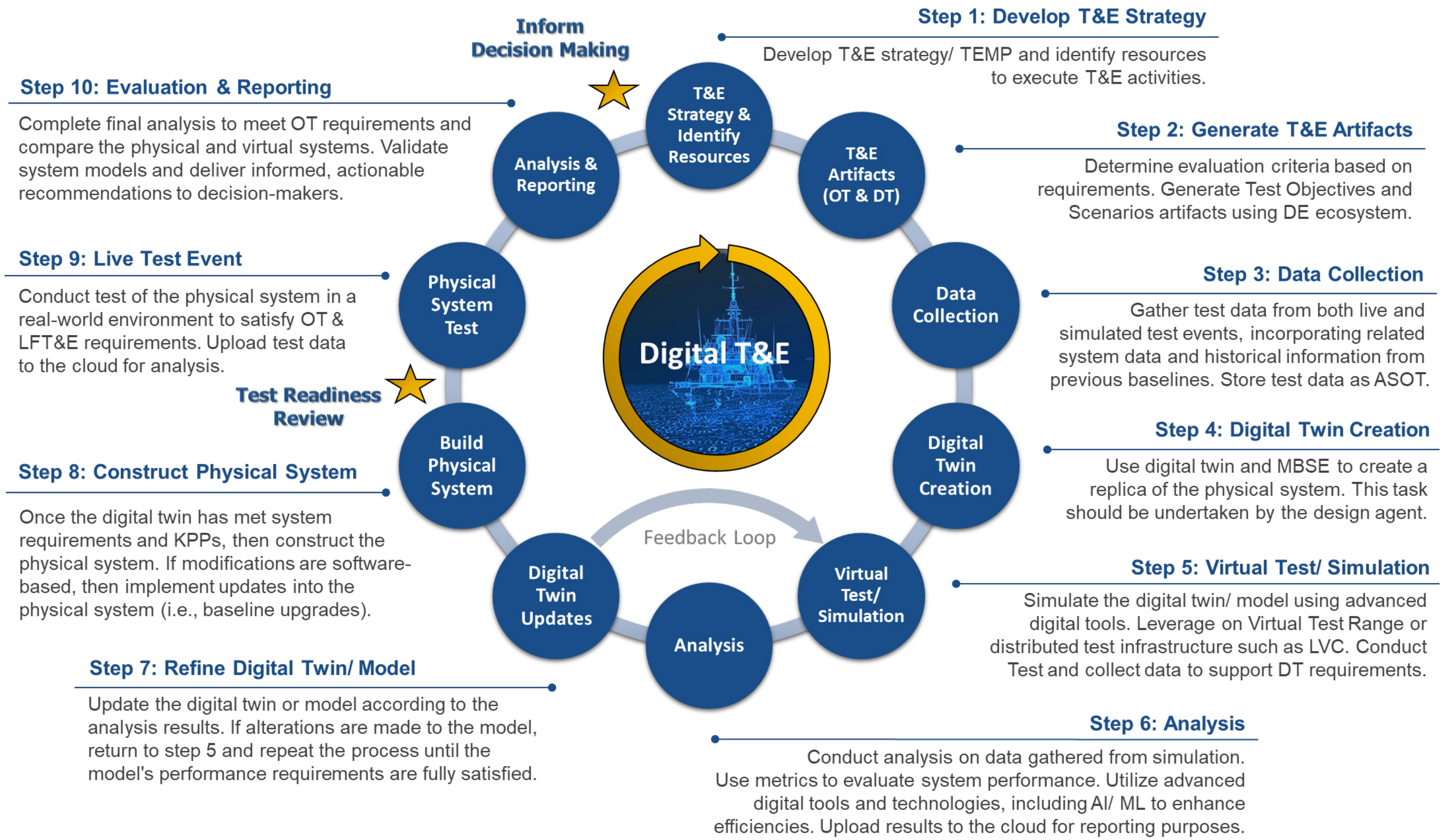

Figure 30. Digital T&E Roadmap for Naval Systems

Digital T&E for naval systems consists of ten overarching process steps aimed at improving the existing process by incorporating digital engineering tenets as defined in the literature review. The process steps are as follow:

1. **Develop T&E strategy** – Crafting a robust strategy remains vital in the envisioned future state to guarantee that operational requirements, system capabilities, and technological risks are meticulously assessed. Rather than focusing on the physical system, the strategy is redirected toward testing, evaluating, and validating the system's models. Emphasis must be given to scrutinizing these models within virtual test ranges that accurately mimic real-world scenarios. With this strategy in place, the establishment of test resources can be significantly expedited, leveraging ongoing initiatives like TP4 and utilizing a digital engineering ecosystem such as the Navy's IME. Once the resources are planned, it is essential to charter the T&E WIPT structure. This ensures that personnel at various warfare centers, naval commands, and industry partners are properly identified and financially supported to facilitate T&E activities throughout the entirety of the system's acquisition process.
2. **Generate T&E artifacts** – This process step revolutionizes the current preparation phase by fully embracing the capabilities of a digital engineering ecosystem. Rather than relying on isolated spreadsheets and files locked away on individual computers, this innovative approach mandates the utilization of a cloud-based digital ecosystem, such as the Navy's IME or another naval enterprise system. Within this ecosystem, test information, including test objectives, scenarios, evaluation criteria, and analysis plans, are created and managed as digital artifacts. This shift unlocks a more efficient and transparent process, no longer constrained by traditional limitations. Leveraging the principles of ASOT and the digital thread, this new methodology ensures a unified and coherent flow of information. Every piece of data is interconnected, enabling instant reflections of changes across the entire process, enhancing traceability, and improving decision-making within the T&E process. The digital engineering ecosystem also enables rapid cross-organizational collaboration,

eliminating the inefficient and error-prone practice of sharing files via email or shared folders. Test planning data now resides in the cloud, granting stakeholders real-time access to the latest information. Moreover, this new method enables collaboration among different programs, promoting the reuse of models, test objectives, scenarios, evaluation criteria, and analysis plans. This not only reduces the effort required in developing plans in isolation but also enhances consistency and alignment across various initiatives.

3. **Data Collection** – In this stage, close collaboration with the system's prime contractor or design agent is essential to secure and share relevant test data. This information will fuel the development of the system model, utilizing data gathered from simulated and actual live T&E events. If the system is of a new design, component testing data or information from related models or baselines must be provided to the design team. Such data acts as the authoritative source of truth, forming the foundation of the system model.

4. **Digital Twin Creation** – This stage of the process mandates the creation of the system model, harnessing the principles of both digital twin and MBSE. As evidenced by successful case studies, the fidelity of the model is directly correlated with its ability to accurately mirror the real system. Therefore, it is advised for the Navy to employ a digital twin to create a precise replica of the physical system. This task is complex and demands expertise, and therefore, it should be entrusted to the defense contractors or design agents, who have the industry's best minds for this development. This approach signifies a substantial transformation from the traditional method, where T&E is grounded in the physical system, to a more progressive mindset where the models themselves become the foundational basis for T&E. This also leads to a future state where contracts for most major systems are awarded based on system models or digital twins, not physical prototypes. In this future state, the contractor assumes the responsibility of delivering a detailed system model or digital twin to the Navy, shifting the practice of T&E from the physical world to a virtual environment.

5. **Virtual Test/ Simulation** – Upon receiving the digital twin or system model, the T&E WIPT must be prepared to embark on virtual testing, simulating the system model within its intended operational environment. This process demands the creation of a virtual test range, a responsibility assigned to the Navy, to guarantee the accurate replication of environmental conditions. This responsibility eliminates any potential conflict of interest with the model developer, ensuring an unbiased testing environment. Additionally, if the test scenarios demand complex system-of-system testing, such as force-level interoperability, the Navy has the option to utilize existing distributed test beds like the LVC test environment to facilitate these simulations. This approach to conducting virtual test events is more than a mere technological advancement, it represents a strategic shift in the development test phase of the traditional T&E process. The virtual testing not only serves to validate the system model but also allows for timely identification of design flaws and performance issues long before the physical system is built.
6. **Analysis** – At this stage, specialized T&E analysis organizations will embark on data analytics, focusing on the information collected from simulations. Following the completion of a virtual test event, the relevant data will be rapidly uploaded to the cloud-based DE ecosystem. This automated process eliminates the cumbersome need for manual data distribution methods, or shipping of test data, thereby streamlining accessibility for analysts. Moreover, advanced techniques such as machine learning and digital tools will be employed to automate data reduction and validation steps, significantly reducing the analysis timeline. By utilizing performance metrics or TPMs, the analysis team can promptly pinpoint system issues, reporting them via a digital dashboard housed within the DE ecosystem. This innovative approach contrasts sharply with the traditional T&E process, where report documents are discarded post-testing. In this new process, all information is meticulously retained, stored, and made easily accessible through a digital thread within the ecosystem. Serving as an authoritative source of truth (ASOT), this data informs insightful decisions and enables subsequent

design modifications, facilitating the continuous monitoring of performance trends throughout the system's development life cycle.

7. **Digital Twin/ Model Refinement** – In this stage, the analysis results become critical in guiding the defense contractor or design agent to make necessary improvements or modifications to the system model or digital twin. Upon implementing those adjustments, the prime contractor then provides the Navy with an updated version of the system model, signaling a return to the previous step 5, virtual testing/ simulation. This iterative process is essential to ensure that all system issues are meticulously addressed before the physical system's construction commences. Characterized by a constant feedback loop, this methodology enables a seamless and efficient mechanism that ensures both accuracy and agility in the system design process.

8. **Construct Physical System** – Once the system model or digital twin has successfully met its Key Performance Parameters and other specified requirements through a rigorous cycle of testing, analysis, and iterative model refinement, the process then advances to the manufacturing stage of the physical system. Leveraging the precision and insights learned from the digital environment, the manufacturing of the physical system can proceed with confidence and efficiency. The insights and validation achieved through the virtual testing not only guide the production process but also ensure that potential issues have been addressed proactively. By grounding the construction phase based on a well-tested digital twin, the risks, costs, and uncertainties traditionally associated with building a complex naval system are significantly reduced. After the construction of the physical system, a Test Readiness Review is conducted to ensure proper preparations are in place to conduct T&E on the physical system.

9. **Live Test Event** – After the construction of the physical system, the T&E community is given the opportunity to test the physical system in a real-world environment for two primary reasons. The first reason is to satisfy the OT and LFT&E requirements. These assessments rigorously evaluate the system's performance, resilience, and effectiveness under authentic operational conditions.

Through a combination of live scenarios, the T&E community gains insights into how the system responds to actual challenges, demands, and stressors that it will encounter in its intended environment. The second reason is to is to validate the system model or digital twin. This is an essential step to ensure a closed-loop connection between the physical and digital systems, creating a seamless integration of data, behavior, and performance characteristics. By meticulously comparing the real-world responses of the physical system to the predictions and behaviors exhibited by the digital twin, any discrepancies can be identified, documented, and mitigated. This iterative validation strengthens the confidence in the system model and enhances its predictive capabilities for future developments.

10. **Evaluation & Reporting** – This phase is a critical junction in the digital T&E process where data and observations from live test events are analyzed, compared to its system model or digital twin, and translated into valuable insights. By performing a detailed comparative analysis between the physical system and its digital twin, the process allows for the identification of essential correlations, discrepancies, and differences. This information stored in the DE ecosystem is assessed and then distilled into actionable recommendations, providing decision-makers with clear insights and pathways for future system enhancements or modifications.

V. CONCLUSION AND FUTURE WORK

A. RESEARCH SUMMARY

This thesis embarked on an exploration to determine how digital engineering could improve the current T&E process for naval systems. By conducting an exhaustive literature review into both T&E methodologies and the emerging field of Digital Engineering, and by examining four distinct case studies that shed light on the application of digital engineering across various industries, this study uncovered a robust potential for the integration of digital engineering tenets to address and potentially resolve existing challenges within T&E. This research led to the development of a forward-looking roadmap, proposing a future state for the seamless integration of T&E with digital engineering, an approach appropriately termed digital T&E. This roadmap advocates for a transformational fusion between these two disciplines through a modern model-simulate-analyze-build-validate methodology. Central to this approach is the creation of a digital twin or system model, serving as a virtual replica of the physical naval system. By harnessing this digital model, engineers can thoroughly test and evaluate systems within controlled virtual environments.

This roadmap represents a strategic shift in the practice of T&E, moving the focus away from the physical domain into a virtual environment. The process emphasizes system model simulation using realistic operational scenarios and conditions. By utilizing advanced digital tools for in-depth analysis, it allows for the uncovering of profound insights into potential system behavior, interactions, and performance limitations. This understanding not only dramatically reduces the risks, unexpected complications, and delays typical of traditional methods but also enables rapid system development and significant cost savings. Characterized by a cyclical and adaptive approach, the new process promotes continuous improvement and precise fine-tuning. Through model validation using T&E data as ASOT and digital thread to link information from across the system life cycle, this method ensures that the physical system is optimized for peak performance prior to construction.

These findings not only provide profound insights into how digital engineering might streamline and optimize the T&E process but also pave the way for a more modernized naval acquisition framework. By weaving digital engineering into the very fabric of T&E, this research illustrates a pathway towards greater efficiency, precision, and adaptability. It signifies a bold step forward into a new era of innovation and advancement, reshaping the landscape of naval system development and potentially serving as a blueprint for broader applications within the defense industry.

Secondary research questions were also considered in this thesis, but with less emphasis than the primary research question. These include the following:

- What specific digital engineering methods will be most effective for improving the naval T&E process and how can each be used?

In the four case studies examined in this thesis, a consistent and important theme emerged, the role of digital twins or system models as a core component in the shift towards digital engineering. This concept is not just an enhancement but a fundamental necessity without which a comprehensive digital transformation remains unattainable. For a profound overhaul of intricate system development processes, such as naval acquisition, there needs to be a deliberate shift in focus. Rather than revolving T&E around the physical system, the emphasis must gravitate towards a thoroughly conceived digital model, preferably a digital twin that is refined, validated, and perfected by T&E. This transition is vital for realizing the full potential of digital engineering, laying the groundwork for innovation, efficiency, and precision in the development of complex systems.

- What is the recommended roadmap for a future naval T&E process that leverages digital engineering?

The recommended roadmap outlines a new concept called digital T&E, defined as the application of digital engineering methods to the test and evaluation phase of systems engineering. The concept and its underlying process steps are illustrated in Figure 30.

- Will the roadmap support T&E for most naval systems or will it have to be significantly tailored for distinct types of naval systems?

This question was not addressed in this thesis. However, its underlying concept of digitalizing the physical system into a digital model still applies regardless of the type of naval system. However, it is worth noting that while the foundational principles of digital engineering and T&E fusion may be broadly applicable, there could be unique characteristics or requirements specific to different types of naval systems. These may necessitate some degree of customization or adaptation within the proposed model-simulate-analyze-build-validate methodology.

B. RESEARCH LIMITATIONS

Given the integration of digital engineering within T&E is a relatively new concept, the existing literature provides very limited data and specific case studies that examine these two domains together. As a result, the case studies featured in this thesis were drawn from publicly available information, demonstrating how digital engineering has been successfully applied to enhance system development processes across various industries. Rather than focusing solely on the intersection of T&E and digital engineering, this research extended its scope to these broader applications to extract best practices, efficiencies, and insightful trends. Through a synthesis of these case studies, along with recent defense and naval digital engineering strategies, and an exhaustive review of the literature in both disciplines, a comprehensive and innovative roadmap for digital T&E was developed.

This limitation underscores the need for ongoing research, publication, collaboration, and adaptation of digital engineering across T&E. Such efforts will pave the way for the effective integration of these two domains, not only within the Navy but also across the defense industry.

C. RECOMMENDATIONS

As this research has demonstrated, the integration of digital engineering within the T&E process is possible and holds immense potential for transforming the current methodologies used in naval system development. Based on these findings, it is recommended that the U.S Navy prioritize investments in digital infrastructure such as cloud-based platforms, DE ecosystems, establishment of digital threads and ASOT, digital tools, and most importantly, the development of digital twins. The first step to realize the digital T&E roadmap as laid out in this thesis requires a comprehensive upgrade of the existing naval information technology infrastructure to enable and harness the transformative power of digital engineering across the enterprise.

Another vital recommendation entails a thorough reassessment of the Navy's strategy for implementing digital engineering. At present, the Navy's strategy for this transformation operates on a top-down approach, often without understanding the needs and perspectives of the workforce. This approach overlooks the importance of ensuring that the transformation resonates with those who will be directly affected by it. As Leonardi (2020) insightfully observed in his article, *The Nuts and Bolts of Digital Transformation*, leaders must comprehend how their organizations will leverage digital tools and how this innovation will bring tangible value to the workforce. This observation suggests a fundamental shift in planning, from a top-down to a more responsive bottom-up approach. Such a change involves recognizing the unique needs, concerns, and values of the workforce, coupled with appropriate training. Without this alignment, there's a risk that the newly introduced tools, technologies, and processes might be met with resistance. This could lead to an ineffective transformation of organizational culture and a disappointing deployment strategy. Therefore, engaging with and learning from the ground-level workforce must be a central tenet of the Navy's digital transformation efforts, ensuring a strategy that's not only visionary but also practical and sustainable.

It is also strongly recommended that the U.S. Navy develop and implement new policies and contracts with OEMs, design agents, or defense contractors to secure rights to the technical data packages and digital models of acquisition systems. In many instances, these contractors are already creating digital models but are not sharing them with the government. Addressing this challenge may necessitate congressional involvement to draft new legislation that mandates defense contractors to provide these system models while safeguarding intellectual property rights. This complex issue should support a fair and transparent playing field between the Navy and defense contractors. It needs to ensure a careful balancing of rights and responsibilities. Defense contractors must be permitted to not only deliver the digital model but also have the flexibility to utilize its design for other defense contracts. This involves being granted the rights to address and rectify issues that are identified during the digital T&E process. On the other hand, the Navy should be responsible for leading and conducting T&E on the digital models and allowing its continued reuse to support other purposes such as fleet training, distributed force level exercises, and other mission requirements.

This leads us to increased collaborations between the T&E community, academia, industry, and defense contractors are highly recommended to share knowledge and insights, alignment of best practices, and drive the evolution of digital engineering within T&E. The adoption of digital twins and the model-simulate-analyze-build-validate methodology is not just a future roadmap, it represents a paradigm shift that requires cultural acceptance, strong collaboration, updates to T&E acquisition policies, and investment in digital infrastructure.

D. FUTURE WORK

While this research laid the foundation for integrating digital engineering and T&E through a comprehensive roadmap, it did not cover several promising avenues due to the time constraints of this master's thesis. These unexplored areas present opportunities to refine and expand the proposed future-state roadmap. Some key areas worthy of further investigation include:

1. **Ontology** – An in-depth investigation into the role of Ontology could reveal innovative methods to enhance the management of ASOT. Within this environment, test data and analysis findings take on a special significance as an ASOT. Thus, exploring how ontology may be employed to streamline the storage, labeling, access, and reuse of such vital data could play a critical role in forming a robust digital thread. By comprehending and strategically leveraging Ontology concepts, engineers and designers may create an integrated environment where data and information flow seamlessly across various stages of system

development, testing, and evaluation. This understanding could not only increase efficiency and consistency within the process but also open new avenues for collaboration and innovation within the field of T&E.

2. **“Digital” Workforce** – Identified as a critical enabler in the concept for T&E as a continuum by DTE&A, this topic merits further exploration. Further research into this specific area would provide valuable insights into the precise abilities, knowledge, and skills essential for enabling and supporting the practice of digital T&E. Understanding these elements is vital not only for effective implementation but also for developing training programs, creating new roles, and establishing guidelines that align with the evolving digital environment.

3. **Mission Engineering** – Another component of the T&E as a continuum, Mission Engineering in the context of simulating multiple system models, each mirroring a specific tactical Naval system, requires further investigation. This future research could explore how these digital twins could be simulated in a distributed environment to enhance warfighting mission scenarios. By analyzing the opportunities, challenges, and best practices of this integration, the study could provide essential insights. These insights could enhance T&E practice within a virtual environment, optimizing force level interoperability performance for complex naval operations.

4. **Organizational Structure** – While mentioned in the literature review, the topic of optimal organizational structure to support digital T&E requires a comprehensive investigation. The current WIPT T&E organizational structure, relatively unchanged over the past two decades, may no longer be adequately suited to facilitate the rapidly evolving practice of T&E within a digital environment. Assessing and reshaping this structure, keeping pace with technological advancements and modern methodologies, could play a crucial role in fully realizing the potential of digital T&E. Future research could focus on identifying the challenges, opportunities, and requirements for this transformation, ensuring the proposed organizational framework is agile, responsive, and optimized to meet the demands of digital T&E.

APPENDIX. GENERAL T&E PHASES AND ACTIVITIES

Table 6. General T&E Phases and Activities. Source: DOD (2022a).

T&E Phase	T&E Activities
Planning	Support the development of system requirements and acquisition contracts (Not found in T&E competency model. Inserted for the purposes of T&E guidance only. • Identify T&E risk factors based on likelihood and consequence of occurrence to test strategy/approach and impact on the overall program plan and schedule through participation in all program risk management processes. • Develop risk mitigation recommendations for T&E risk factors in accordance with the processes and procedures found in the DoD Risk, Issue, and Opportunity Management Guide to cover system risk elements throughout the acquisition cycle and during the test program. • Support Program Management Office's development of a risk management plan with T&E-relevant risks and mitigation plans that enable a balanced plan for a program. • Translate requirements documents to identify evaluation criteria to support T&E planning. • Determine whether the capability requirements are sufficiently defined to assess testability and that they are relevant to the operational mission. Understand how flexible requirements in agile developments could affect T&E. • Determine data requirements to assess evaluation criteria for assessing the system performance requirements and evaluation of Critical Operational Issues, Key Performance Parameters, and Key System Attributes. • Determine necessary T&E infrastructure requirements and identify shortfalls that will require investments to meet T&E infrastructure sufficiency, and if and how the Digital Engineering Ecosystem is being used for the program. • Apply all T&E policies, practices, and procedures to develop a T&E Strategy that supports the program's Acquisition Strategy for the applicable Adaptive Acquisition Pathway. Incorporate IT at the earliest opportunity and identify how the following components fit together during systems development: CT, DT, OT, and LFT. For T&E aspects, identify where interoperability, cybersecurity, Scientific Test and Analysis Techniques (STAT), environmental mitigation, safety, and mission-level testing, etc., fit into system development. Determine the appropriate criteria for evaluating OT parameters (Effectiveness and Suitability) and LFT&E parameters (Lethality and Survivability). • Document the T&E Strategy that integrates policy, program requirements, cost and resource estimates, evaluation framework, and the T&E schedule to accomplish program goals. Use appropriate contracting strategies to maximize the efficient use of human capital and other resources. • Identify all organizations and activities with roles and responsibilities in providing for or overseeing the T&E Strategy that supports a program's acquisition life cycle or a system of systems' acquisition life cycle. • Identify and organize the T&E management forum (e.g., T&E WIPT, Integrated Test Team, Combined Test Team) necessary to address all T&E issues and documentation to support the T&E Strategy, approach, and overall program plan. • Translate the T&E Strategy into the appropriate test planning documentation (e.g., Developmental Test Plans, Operational Test Plans, and Live-Fire Test Plans) including identification of all the required resources to ensure the strategy is executable and supports the Systems Engineering Plan and overall Acquisition Strategy.

T&E Phase	T&E Activities
	• Provide financial cost estimates for T&E support to ensure resources are available and mapped against the schedule to ensure availability during development and production of the system life cycle. Ensure all test costs are fully captured in budget requests and TEMP resource tables, or other test strategy documentation.
Preparation	• Interact with all organizations/activities that require information/activity exchange to successfully complete the test planning as enumerated in the T&E Strategy. • Continually coordinate and monitor availability of required test and/or evaluation resources to identify any potential resource problem to ensure effective completion of test events. • Execute tasking orders and funding streams to commit resources as requested, when and where required to complete T&E activities/events. Ensure accounting of all applicable T&E resources. • Verify readiness of resources for T&E program execution. • Ensure all required resources are deployed to the test site(s) as required and in sufficient time to provide for pre-test rehearsal(s), communications, and instrumentation checks. • Comply with and implement policies and procedures (e.g., safety, security, environmental) required to successfully conduct test activity/event. • Investigate specific policies, procedures, and operational constraints for applicable test ranges to ensure compatibility during test operations. • Assess all T&E related factors to determine system/test article readiness before starting the test. Ensure adequate personnel are assigned to allow continual coverage for overlapping test events. • Plan, conduct, and report on Test Readiness Reviews.
Execution	• Manage test execution/risk mitigation factors by adapting to real-time changes/challenges to advise Test Director to optimize test opportunity and coverage of key parameters/factors/conditions that have significant effect(s) on operational performance. • Confirm data collection tools are valid, operators and maintainers are trained, M&S/Live Virtual Constructive hardware and software tools are properly integrated, and system under test is configured as required to execute the test events/activities and collect required data. • Confirm and monitor security and safety compliance (such as people and item/system under test) and environmental requirements/constraints to protect resources and comply with established policies. • Develop, validate, rehearse, and execute tests in an organized fashion to facilitate identification of completed data suitable in form and format for analysis and evaluation. Ensure data required for STAT analysis are suitable. • Control the test schedule to ensure timely execution of critical tasks, assigned resources, and project milestones to optimize collection of data in support of evaluation objectives. • Verify all required and expected raw test data to ensure completeness of data to support a system evaluation.

T&E Phase	T&E Activities
	• Ensure validity of collected test data to meet test objectives in support of planned analysis and evaluation. Determine how cybersecurity will be used to protect the integrity of test data. • Distribute data per the data management plan for analysis of test results in support of the evaluation.
Analysis	• Translate outputs from test instrumentation systems, data acquisition system methods and formats, software tools/logs, capabilities, and operation to verify and validate test data set. • Identify gaps and variances in raw test data to determine data voids or outliers that may degrade analysis and evaluation. • Reduce, translate, and analyze raw test data into organized and meaningful data products to support planned analysis of STAT-based design, evaluation, and reporting. • Conduct data scoring to refine demonstrated test results to establish a complete data set of system, to include software performance. • Align data to specific test objectives in support of the planned analysis and the overall evaluation.
Evaluation	• Confirm that the tests conducted support the stated test objectives to ensure adequacy of the planned analysis and evaluation. Determine appropriate analysis and evaluation techniques to be incorporated in a system evaluation or a system of systems' evaluation (e.g., STAT, design of experiments, or similar). • Confirm that M&S met test objectives to augment test data and ensure adequacy of evaluation. Identify how accredited M&S (including the validate and verify process) should be used to supplement live test data. • Determine whether the collected data are sufficient to accurately and completely support established measurability metrics. • Determine whether the data collected via M&S tools are sufficient to adequately supplement data collected during live T&E to facilitate a credible evaluation of the system's (or system of systems') realistic survivability and lethality under combat conditions. • Confirm that the collected test data can sufficiently and accurately support the evaluation framework in the approved TEMP or other test strategy documentation. • Relate test results and evaluation conclusions to performance specification and performance results to report on operational significance. • Assess how hardware/software components are brought together to function properly as required in capability documents and what their performance brings to the larger system of systems designed to achieve required capability.
Reporting	• Determine and provide T&E input to all technical and programmatic reviews to support acquisition decision-making. • Assess, document, apply, and/or adapt lessons learned on conduct of test data collection, analysis, and evaluation processes to ensure constant improvement of methods and processes. • Provide the required programmatic T&E reports and/or presentation (quick-look analysis, test reports, analysis reports, software sprint reports, and evaluation reports) to capture test background, methodology, limitations, results, evaluation, and recommendations to support acquisition decision making and user needs (e.g., development of TTPs, etc). • Archive the data throughout the T&E planning, preparation, T&E execution, analysis, and evaluation phases to support future T&E efforts.

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