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Digital Twins and Predictive Sustainment: Readiness Gains, Inventory Effects, and Performance-Based Logistics Alignment

June 2026

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

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ABSTRACT

What if a Marine squadron commander could predict aircraft failures before deployment, optimize spare-part inventories before shortages occur, and select the right aircraft for the mission based on real-time sustainment forecasts? The U.S. Marine Corps H-1 fleet currently relies on fragmented data systems, reactive maintenance practices, and fleet-wide averages that obscure the unique condition of individual aircraft. This research explores how bureau-number-specific digital twins, powered by predictive analytics and AI-enabled logistics, can transform sustainment from a reactive process into a strategic readiness advantage. Using existing aviation maintenance and readiness data, the study proposes a Minimum Viable Digital Twin framework that integrates aircraft health, maintenance, and supply-chain information to forecast failures, improve mission-capable rates, and strengthen performance-based logistics decisions. The findings outline a practical pathway toward intelligent sustainment ecosystems that could reshape not only H-1 readiness, but the future of Department of Defense aviation logistics as a whole.



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LIST OF ACRONYMS AND ABBREVIATIONS

AAF	Adaptive Acquisition Framework
AAS	Asset Administration Shell
AHMS	Aircraft Health Management System
AMU	aircraft maintenance unit
ASKIT	Aviation Storekeeper Information Tracking
ATO	authorization to operate
BUNO	Bureau Number
cATO	continuous authorization to operate
CBM+	Condition-Based Maintenance Plus
C-FRACAS	common failure reporting, analysis, and corrective action system
CMT	component management tool
CO	commanding officer
DAPML	Deputy Assistant Program Manager for Logistics
DAU	Defense Acquisition University
DECKPLATE	Decision Knowledge Programming for Logistics Analysis and Technical Evaluation
DLIS	Defense Logistics Information System
DoD	Department of Defense
DTU	data transfer unit
EHR	equipment history records
FST	field support team
GAO	Government Accountability Office
HMLA	Marine Light Attack Helicopter Squadron
HUMS	health and usage monitoring system
IMD-HUMS	Integrated Mechanical Diagnostics Health and Usage Monitoring System
IoT	Internet of Things
JDRS	Joint Deficiency Reporting System
JEDMICS	Joint Engineering Data Management Information and Control System



LtCol	lieutenant colonel
MBSE	model-based systems engineering
MPU	maintenance processing unit
MRO	maintenance, repair, overhaul
MSHARP	Marine Corps Sierra Hotel Aviation Reporting Program
NALCOMIS	Naval Aviation Logistics Command Managed Information System
NATO	North Atlantic Treater Organization
NAVAIR	Naval Air System Command
NAVFLIRS	Naval Flight Record Subsystem
NMCS	non-mission capable for supply
NPS	Naval Postgraduate School
NSN	national stock number
OEM	original equipment manufacturer
OOMA	optimized organizational maintenance activity
PBL	performance-based logistics
PCMCIA	Personal Computer Memory Card International Association
PdM	predictive maintenance
PLM	product life cycle management
PMA	Program Office, Aviation
PSM	product support manager
QA	quality assurance
RCM	reliability centered maintenance
SDL	system definition language
SERMIS	Support Equipment Resources Management Information System
SME	subject-matter expert
SysML	Systems Modeling Language



DISCLOSURES

To support the research and writing process for this thesis, we used OpenAI's ChatGPT (GPT-5 and earlier GPT-4-based models) with the permission of our thesis advisors and in accordance with Naval Postgraduate School guidance on the responsible use of generative artificial intelligence. We chose the tool based on our familiarity with it over similar tools as well as accessibility. We used the tool throughout the development of this thesis to refine research questions, improve chapter organization, enhance clarity and concision, identify passive voice, format citations in APA style, and generate conceptual figures illustrating sustainment and digital twin architectures.

Three primary uses:

1. Drafting tool: to review and refine grammar, mechanics, and inconsistencies in writing style, as well as to format references in APA
2. Research tool: to categorize literature for more thorough analysis and evaluation, and to interrogate our hypotheses, ideas, and early drafts
3. Data visualization: to create an infographic

To mitigate the risk of inaccurate information, unsupported claims, or language that did not reflect our intent, we independently verified all factual statements against authoritative sources, including Department of Defense publications, Naval Postgraduate School resources, and peer-reviewed literature. We reviewed and edited all AI-generated suggestions before incorporating them into the thesis and retained sole responsibility for the analysis, findings, conclusions, and recommendations presented in this work. We maintained records of representative prompts and responses and can provide them upon request.



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I. INTRODUCTION

The following introduction is a hypothetical scenario based on our ideal use of the digital twin tool we conceptualize.

March 2029, Camp Pendleton, CA, HMLA-369 is set to deploy in support of Operation Pacific Dawn in six months. The commanding officer (CO), Lieutenant Colonel (LtCol) Peters, and his squadron staff execute pre-deployment milestones. During the squadron's mid-planning conference, the aviation maintenance officer, Major Stone, and her team will present the CO with aircraft by bureau-number (BUNO) for the decision for which BUNOs the squadron will take on deployment.

As LtCol Peters reviews the options, the latest digital twin estimates show a list of critical components across the squadron's aircraft inventory. The digital twin tool highlights five AH-1Z Viper BUNOs that are prime candidates for deployment based on their current maintenance status and the remaining time before failure of their individual components assessed over the planned flight hours up to and through the deployment. The digital twin tool also provides a detailed list of current and planned future stock postures that support those components. This static snapshot of information would have taken hours of careful research and access to disparate information systems before the digital twin tool's creation. Now the tool has been fully integrated to inform and reinforce the commander's decision of aircraft selection. But in this meeting, LtCol Peters throws a curveball at his operations and maintenance teams.

Based on latest intelligence, adversary operations have shifted to a more austere location where extremely fine dust is known to exist. To reach this location, expected flight hours are much higher than initially estimated, and the risk of catastrophic failure of engine components in this environment increases. LtCol Peters now requires an updated depiction of available aircraft based on an increased number of flight hours and engine degradation in the fine dust environment. Major Stone, however, is prepared. The digital twin tool incorporates a sliding scale of usage rates across the inventory that provides the option to increase or decrease flight hours per BUNO. She also is confident the digital twin tool will provide post flight analysis of engine degradation that basically trained pilots can interpret without additional field service support. In real time, the maintenance status and remaining time before component failure is juxtaposed against the overall stock posture of those components with anticipated fleet usage rates and supplier delivery schedules. She adjusts the sliding bar to reveal the ideal four AH-1Zs the squadron will prepare to deploy.



Following the meeting, Major Stone uses the digital twin tool to compile a list of those critical components that will now be ordered in advance of the deployment and prepositioned across the planned supply depots that will support the squadron. With the digital twin tool capability, the necessary materials will be available just-in-time through informed decision-making rather than just-in-case estimates better suited for wholesale supply planning.

A. PROBLEM STATEMENT

The Marine Corps H-1 fleet, now fully fielded and transitioning into a sustainment-focused phase of its life cycle, faces persistent readiness challenges that stem from component-level degradation, obsolescence, and misaligned sustainment resourcing. Although the AH-1Z and UH-1Y were designed for commonality and improved maintainability over their legacy predecessors, in our experience observing aircraft status dashboards, fleet readiness, or operational availability—that is, the total number of aircraft available for use divided by the total number in a partial or full mission capable status—falls well below ideal readiness rates. Obsolescence, diminished manufacturing sources, unaffordable component redesigns, insufficient forecasting tools, and limited visibility into the conditions in which individual aircraft are flown contribute to the low operational availability.

Unlike newer aviation platforms designed with digital engineering from inception, the H-1 program lacks a cohesive digital thread connecting engineering baselines, developmental testing, operational usage data, supply chain performance, and maintenance actions across time. As a result, decision-makers are often forced into reactive approaches to sustainment rather than employing predictive, data-driven strategies. Critical components such as the Mission Computer or Main Rotor Gearbox experience variable reliability across different aircraft, yet the program currently manages them through fleet-wide averages instead of individualized, BUNO-specific, fatigue damage profiles. This limits accuracy when the program estimates sustainment requirements, complicates planning for long-lead procurement of technical data and spare repair parts, and constrains the Marine Corps' capacity to assign aircraft optimally for deployment.



A BUNO-specific digital twin offers a promising pathway to address this gap for the H-1 program. Such models could integrate data from health monitoring systems, maintenance records, supply chain performance, and engineering documentation to create individualized, continuously updated representations of each aircraft and the environment with which it interacts. These digital twins could modulate component usage predictions, customize maintenance planning, and provide historical and predictive inputs for performance-based logistics (PBL) negotiations. While disparate data, models, and simulations exist for Marine Corps aviation light attack platforms, the program has not established and successfully implemented a framework to combine these projects into a digital twin to predict system failures with increasing accuracy, investigate root cause remotely, and provide timely repair procedures.

B. RESEARCH OBJECTIVES

This research seeks to examine how the H-1 program can leverage the Adaptive Acquisition Framework (AAF), modern digital engineering practices, and comprehensive life cycle data integration to develop a viable framework for BUNO-specific digital twins that improves readiness outcomes and informs long-term PBL strategies. The research questions to achieve these objectives are as follows:

1. Primary Research Question

How can the Marine Corps H-1 program develop and implement a framework for BUNO-specific digital twins to model individualized component usage and inform future PBL decisions?

2. Secondary Research Questions

In addition to the primary research question, this paper will explore several secondary research questions.

- What data sources, data structures, and modeling techniques are necessary to create accurate digital twins for H-1 aircraft at the BUNO level?



- How can AAF pathways, such as Middle Tier Acquisition or Software Acquisition, be tailored to support digital twin development and sustainment modernization for a legacy platform?
- What organizational, policy, or data-governance barriers currently prevent the integration of BUNO-specific modeling into H-1 sustainment practices?
- How do subject-matter experts across the U.S. Marine Corps Light/Attack Helicopter Programs Office (PMA-276), the Fleet Support Team (FST), and the broader Naval Air System Command (NAVAIR) enterprise view the feasibility, value, and risks associated with developing individual aircraft digital twins?
- How could digital twin outputs influence material allowance forecasting, long-lead procurement timelines, maintenance prioritization, overhaul standards, new source approvals, trade-offs for engineering design changes, and PBL business case analysis?

C. METHODOLOGY

This research employs a qualitative, exploratory approach using multiple methods to develop a robust understanding of digital twin feasibility within the H-1 sustainment portfolio:

- **Document and Policy Analysis:** Review of AAF guidance (DoDI 5000 series), digital engineering strategies, PMA-276 program documentation, and relevant Government Accountability Office (GAO)/Department of Defense (DoD) sustainment reports.
- **Life Cycle Data Mapping:** Assessment of available datasets, including Naval Aviation Logistics Command Managed Information System (NALCOMIS)/Optimized Organizational Maintenance Activity (OOMA), Decision Knowledge Programming for Logistics Analysis and Technical Evaluation (DECKPLATE), Aircraft Health Management System



(AHMS)/Health and Usage Monitoring System (HUMS), Joint Deficiency Reporting System (JDRS), engineering baselines, and supply catalog records, to determine opportunities and constraints for BUNO-level modeling.

- **Comparative Case Analysis:** Examination of digital engineering or prognostic efforts in other aviation programs in sustainment, production, and development to identify transferable lessons.
- **Subject-Matter Expert (SME) Interviews:** Semi-structured interviews with the H-1 product support manager (PSM), readiness deputy assistant program manager for logistics (DAPML), lead reliability and maintainability analyst, and key Fleet Support Team (FST) predictive sustainment personnel; H-60 PSM; Naval Supply Systems Command PBL Center of Excellence Director.
- **Conceptual Model Development:** Synthesis of findings into a proposed framework that outlines the functions, data flows, sensor locations, and decision points associated with a BUNO-specific digital twin.

Interviews will follow Naval Postgraduate School (NPS) Internal Review Board (IRB) requirements and will be used to validate assumptions, refine the digital twin framework, and provide practitioner insight into operational feasibility.

D. SCOPE AND LIMITATIONS

This study focuses on the U.S. Marine Corps H-1 program during its post-production sustainment phase, emphasizing the potential integration of digital twin technologies into component-level usage modeling and PBL strategy development. The analysis centers on subsystems and sustainment processes developed and managed by PMA-276. Non-developmental items and common equipment developed and managed by external programs are outside the scope of this research. Examples of readiness drivers, such as mission computers or main rotor gearboxes, are used illustratively, not as the exclusive focus of modeling. Limitations include the following:



- Some life cycle data sources may be incomplete, proprietary, or restricted.
- Not all aircraft components have sufficient recorded usage history for immediate modeling but may be recommended for added sensors and usage monitoring.
- Digital twin implementation requires engineering and software resources beyond the scope of this paper; this research focuses on conceptual frameworks rather than prototype development.
- Interview findings reflect the perspectives of available SMEs and may not encompass the full breadth of stakeholders across the naval aviation enterprise.

E. ORGANIZATION

This study is organized into five chapters.

- Chapter I establishes the foundation of the research by introducing the underlying problems, defining the research objectives and associated research questions, outlining the methodology, and identifying the study's scope and limitations.
- Chapter II provides background on the H-1 platform, sustainment environment, digital engineering concepts, and the rationale for pursuing digital twin capabilities.
- Chapter III reviews academic and defense acquisition literature related to digital engineering, AAF tailoring, sustainment forecasting, and data analytics.
- Chapter IV is the core research and investigation chapter. It analyzes findings derived from policy review, data system mapping, and SME input.



- Chapter V offers recommendations for how the H-1 program can implement a digital twin framework within the constraints of the AAF and Marine Corps aviation sustainment enterprise.



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II. BACKGROUND

During our careers we have observed the Marine Corps H-1 program modernize the legacy AH-1W and UH-1N fleets through development of the AH-1Z Viper and UH-1Y Venom. We believe these aircraft were designed, in part to achieve increased commonality, improved reliability, and enhanced operational capability to better support expeditionary missions over their predecessors. With procurement complete and the final aircraft delivered, the program has shifted into a sustainment-focused phase, wherein readiness, cost efficiency, and component availability have become the dominant management concerns.

Despite improved maintainability over legacy platforms, the maturing H-1 fleet experiences recurring readiness degraders driven by long-lead components, obsolescence in avionics subsystems, and variable wear across different aircraft. Fleet decision-makers frequently must navigate sustainment challenges with limited visibility into how individualized usage patterns affect component health, creating an environment in which supply shortfalls and unexpected failures continue to constrain readiness.

A. SUSTAINMENT ENVIRONMENT AND DATA LANDSCAPE

The Marine Corps operates H-1 aircraft in distributed, maritime, and expeditionary environments characterized by high corrosion exposure, varying operational intensity, and significant logistical constraints. As the fleet ages, sustainment increasingly depends on forecasting tools that can anticipate component failures, optimize maintenance schedules, and inform long-term resource planning.

However, digital integration across sustainment systems remains limited. Data relevant to aircraft health and component performance resides in diverse systems including the following as noted by Naval Aviation Maintenance Program (NAMP, 2024):

- NALCOMIS/OOMA maintenance records and material configuration baseline as installed for each BUNO



- DECKPLATE enterprise readiness and maintenance metrics (periodic maintenance interval cards)
- HUMS flight parameters and mechanical usage data
- Naval Flight Record Subsystem (NAVFLIRS) and Marine Corps Sierra Hotel Aviation Reporting Program (MSHARP) flight activity and hours
- Engineering documentation in Joint Engineering Data Management Information and Control System (JEDMICS) or other repositories
- JDRS engineering investigations, supply discrepancies, product quality deficiency reports, and technical publication discrepancy reports
- The Defense Logistics Information System (DLIS) material provisioning and supply chain performance systems capturing lead times and procurement history
- Support Equipment Resources Management Information System (SERMIS) and the Aviation Storekeeper Information Tracking (ASKIT) system for support equipment and aircrew flight equipment
- Original equipment manufacturer (OEM)–provided reliability data where available

Each system provides valuable information, but they are not fused into a unified dataset capable of driving individualized predictions at the BUNO level. This fragmented landscape complicates sustainment planning, hinders accurate reliability modeling, and prevents PMA-276 from building strong analytical foundations for PBL negotiations.

B. SCHEDULED MAINTENANCE

Scheduled maintenance is defined as the “inspection or servicing of aircraft, equipment, or [support equipment] done on a calendar, mileage, or hour of operation basis” (NAMP, 2024, p. A-83). The time or use driver for this maintenance is derivative of a large series of averages compiled over the course or life of the airframe. Determining the servicing period for a main rotor blade system on an H-1 aircraft, for example, is a



result of a review of thousands of hours of material use, fatigue, and ultimately failure time.

Phase maintenance is a type of scheduled maintenance that is an inspection of the aircraft. This inspection is defined as the examination and testing of aircraft components that include intermediate assemblies, to determine whether they conform to specified requirements. In Marine Corps Aviation, maintenance inspection schedules are determined by NAMP; typically, inspections on the H-1 aircraft occur every 200 flight hours. The average duration of these inspections is fourteen working days and require a minimum of ten Marines to complete. This fact is documented in H-1 technical manuals accessed through the Naval Air Technical Data and Engineering Command website for authorized users (NAMP, 2024, p. A-72).

C. DIGITAL ENGINEERING AND DIGITAL TWINS IN DEFENSE AVIATION

The United States DoD (2024) has directed the services to integrate digital engineering practices throughout system life cycles, emphasizing model-based design, integrated data environments, and digital threads that connect development, testing, fielding, and sustainment. Digital twins, which are dynamic, data-driven virtual representations of physical systems, have emerged as a leading concept for modernizing sustainment planning (Fuller, 2020). In aviation, digital twins can support

- Component-level usage forecasting
- Fleet health monitoring
- Virtual maintenance planning
- Predictive estimates of supply demand
- Simulation of future operational usage impacts
- Recommendations for component design changes

Newer platforms, such as the MV-75, F-35 and CH-53K, have incorporated portions of digital twin architecture from early design phases. For legacy platforms like H-



1 and B-52, however, implementing digital twin capabilities requires retroactive integration of heterogeneous datasets and careful alignment with existing sustainment processes. The Marine Corps currently lacks a formal framework for employing digital twins at either the fleet or BUNO level, representing a gap this research intends to address.

D. PERFORMANCE-BASED LOGISTICS AND COMPONENT USAGE MODELING

PBL strategies rely on accurate predictions of demand, usage, and life cycle cost. For the H-1 fleet, PBL arrangements could offer improvements in supplier responsiveness, material availability, and cost control, but only if the program office can provide data-rich, defensible analyses of anticipated component consumption patterns. Linking the engineering support agency and material support agency could drive reliability improvements in parallel rather than sequencing one component at a time.

Traditional PBL analyses depend on fleet-wide averages, which do not sufficiently account for

- Variability in operational intensity between squadrons
- Environmental impacts such as maritime corrosion
- BUNO-specific histories of component stress and fatigue
- Nonlinear degradation curves caused by flight profiles or mission sets
- Long-lead procurement timelines driven by global supply chain factors

A BUNO-specific digital twin framework would allow PMA-276 to replace generalized estimates with tailored predictions for each aircraft, strengthening future PBL business cases and justifying targeted investments in long-lead components.

E. RESEARCH RATIONALE

The H-1 program is reaching a critical juncture. As procurement ends and sustainment costs increase, PMA-276 must transition from traditional, reactive maintenance planning toward predictive, data-informed approaches. The lack of an established digital twin framework limits the program office's ability to evaluate



component degradation accurately, align resources effectively, or negotiate future PBL arrangements with vendors.

This research is necessary because:

- Readiness is increasingly constrained by component availability and long-lead procurement delays.
- The current data environment does not support BUNO-level visibility into component health or life cycle consumption.
- The AAF encourages tailoring and modern digital engineering approaches, but the H-1 program lacks a roadmap to apply them.
- Digital twin adoption could meaningfully improve forecasting accuracy, resource alignment, and sustainment decision-making.
- Lessons learned from H-1 can inform digital sustainment approaches across other legacy aviation platforms.



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III. LITERATURE REVIEW

The modernization of defense sustainment increasingly depends on the convergence of performance-based contracting, digital engineering, and data-driven maintenance. As platforms age and operational tempo remains high, the DoD continues to face challenges in optimizing readiness, managing rising life cycle costs, and integrating new technologies into legacy sustainment environments. The literature focuses around three domains: PBL, digital twin and digital thread technologies, and predictive analytics. These three domains offer significant potential to improve transparency, forecasting accuracy, and system availability across the weapon system life cycle.

Sanders (2018) tells us that PBL emerges as a long-standing sustainment reform designed to align contractor incentives with warfighter outcomes. Digital twins and digital threads extend this paradigm by enabling continuous, authoritative data flow that improves system understanding, reduces uncertainty, and supports model-based decision-making. Predictive analytics complement these technologies by enabling the forecasting of component degradation, dynamic scheduling of maintenance, and reduction of unscheduled downtime. Together, these themes represent a coherent modernization trajectory for DoD sustainment in which performance outcomes are increasingly driven by integrated data environments, digital representations of physical assets, and algorithmic forecasting.

This chapter synthesizes key findings across these domains to establish a research foundation for analyzing digital twin applications for H-1 sustainment readiness. It reviews academic research, government reports, and international studies to identify trends, gaps, and opportunities relevant to Marine Corps rotary-wing systems. By integrating insights from peer-reviewed articles, official assessments, and defense case studies, this literature review situates the H-1 program within the broader evolution of defense sustainment and highlights areas where digital twin-enabled capabilities may offer significant gains in readiness and affordability.



A. PERFORMANCE BASED LOGISTICS

PBL is a prominent strategy in defense acquisition that emphasizes incentivized outcomes over transactional procurement. As global military logistics confront budgetary constraints and increasing operational demands, PBL has emerged as a key model for aligning industry performance with government readiness goals. The literature broadly agrees on its advantages, improved availability, cost predictability, and efficiency, while also identifying limitations such as inconsistent implementation, limited longitudinal evidence, and challenges related to data access and standardization, particularly in rotary-wing and multinational contexts.

PBL was formally introduced in the Defense Acquisition University's (DAU's) 2005 logistics transformation initiatives and has since been applied to numerous high-value systems (Defense Acquisition University [DAU], 2005). Gansler and Lucyshyn (2006) argued that PBL's success lies in its departure from traditional supply-based contracting by compensating contractors for system readiness or availability rather than discrete parts or services. Gansler and Lucyshyn also assert that over time, PBL has evolved to address the entire product life cycle, with outcomes highly dependent on contract design, performance metrics, and data-sharing mechanisms. Foundational work by the DAU (2005), and Leftwich et al. (2024) collectively establishes the theoretical and policy basis for PBL's continued use in defense programs.

1. Definitions and Concepts

The following defined concepts are foundational to understanding how performance-based logistics contracts are designed.

- **PBL:** A sustainment strategy in which the contractor is compensated based on system outcomes such as availability and reliability rather than individual parts or services (DAU, 2005).
- **System Availability:** The percentage of time a system is fully mission capable (DAU, 2005).



- **Reliability:** “The probability that an item will perform its intended function for a specified interval under stated conditions” (NAMP, 2024, p. A-79).
- **Life Cycle Cost:** The total cost of ownership across acquisition, operation, support, and disposal phases (DAU, 2005).

2. Definition and Evolution of Performance-Based Logistics

Initial guidance on PBL came from DoD reforms such as the 2005 *Performance Based Logistics: A Program Manager’s Product Support Guide* and subsequent DAU handbooks (DAU, 2005). Gansler and Lucyshyn (2006) provided an early academic foundation, advocating contracts that directly incentivize readiness-based performance outcomes. Apte and Rendon (2007) further argued that PBL transforms contractor–government relationships into longer-term partnerships that promote innovation and optimized sustainment.

Prominent case studies, including the F-117, C-17, and F/A-18 programs, demonstrate that PBL can be scaled across services and platforms, with varying levels of success. Ahmed (2019) examined how applying performance-based contracting to an outsourced reliability-centered maintenance program can demonstrate that embedding reliability metrics and performance outcomes directly into contractual arrangements improves maintenance planning discipline, stabilizes cost performance, and enhances operational responsiveness. The case study reinforces broader PBL literature by showing that shared data visibility and clearly aligned incentives are essential for linking contractor behavior to actual system reliability and operational usage across varying demand profiles.

3. Empirical Support and Case Evidence

Several empirical studies document measurable performance gains from PBL adoption. Sanders (2018) observed that PBL arrangements, as implemented in cases such as the C-17 Globemaster III Sustainment Partnership and the F/A-18 Hornet Integrated Readiness Support Teaming, have been credited with improving weapons-system availability and readiness outcomes under integrated performance contracts. Similarly,



Glas (2020) synthesized empirical evidence across multiple PBL implementations and identified statistically significant gains in cost predictability, supplier accountability, and operational readiness. The GAO (2011) likewise reported that PBL programs often outperform traditional logistics models in mission-capable metrics. However, these benefits are contingent on mature data environments and clearly defined, enforceable metrics, conditions that are not yet universal across platforms.

4. Incentives and Contracting Variations

Contract incentives are a critical determinant of PBL effectiveness. Hunter (2015) found that fixed-price incentive (firm-target) contracts tied to availability or mission readiness thresholds tend to align contractor and DoD objectives more effectively than cost-plus arrangements. Hunter (2015) argued that PBL is most effective when contract terms are long enough for contractors to plan, invest, implement process changes, and realize returns; without sufficient duration, contractors have weak incentives to invest in support-infrastructure optimization and continuous improvement. Conversely, poorly designed metrics or limited data transparency can weaken incentives, enable underperformance, or encourage behaviors that do not support long-term readiness.

Boyce and Banghart (2012) highlighted risks associated with overreliance on contractors in long-term logistics support. Their analysis points to moral hazard and the erosion of governmental control over operational decisions when oversight mechanisms and performance metrics are weak. These findings underscore the importance of transparent, outcome-based metrics and continuous government insight, both of which are strengthened when digital thread architectures and data-sharing frameworks are in place.

5. International Applications and Lessons Learned

Internationally, PBL-like arrangements have been adopted under a variety of labels and institutional frameworks. Glas (2020) documented a broad range of international applications in weapon system sustainment, noting that countries such as the United Kingdom have implemented outcome-oriented contracting approaches across both rotary-wing and fixed-wing platforms, with reported improvements in availability, reliability, and logistics performance. North Atlantic Treaty Organization (NATO) partners employ



related constructs, such as Through-Life Capability Management, which similarly seek to align industrial incentives with operational capability outcomes. Importantly, Glas (2020) showed that PBL effectiveness varies significantly across national contexts, with contract design, incentive structures, industrial base characteristics, and institutional environments playing a decisive role. Collectively, these findings suggest that while PBL principles are broadly transferable, their successful execution is highly sensitive to regulatory, organizational, and market conditions rather than amenable to a uniform implementation model.

The literature affirms PBL's value as a sustainment reform mechanism that can improve readiness and cost control when supported by disciplined contract structuring, robust performance measurement, and strong data systems. Yet gaps remain, particularly in longitudinal analyses of rotary-wing platforms and standardized performance metrics across services. As digital sustainment systems mature, future research should examine the intersection of PBL, digital twin architectures, and predictive analytics to expand PBL's impact on platforms such as the H-1 by enabling more precise, data-driven performance management.

B. DIGITAL TWIN AND DIGITAL THREAD TECHNOLOGIES

Digital twin and digital thread technologies have become central to modern engineering and life cycle management, especially in complex aerospace and defense systems. Uhlenkamp et al. (2022) proposed a digital twin maturity model that differentiates implementations based on levels of data integration, model fidelity, and system interoperability, demonstrating that many digital twin applications remain at lower maturity stages due to fragmented data flows and limited integration across life cycle phases. This characterization aligns with Moenck et al.'s (2024) observation that aviation programs frequently remain at the digital shadow stage due to fragmented data flows and limited interoperability.

Across the literature, scholars emphasize that the value of digital twins is inseparable from the digital thread, which is the continuous, authoritative data flow connecting design, production, and operations. Together, these technologies promise



enhanced system understanding, reduced operational risk, and optimized life cycle performance, while also introducing significant challenges in data management, organizational coordination, and technological integration.

Madni et al. (2019) offered a comprehensive conceptual foundation for digital twin technology within Model-Based Systems Engineering (MBSE). They defined digital twins as dynamic, instance-specific virtual representations that are continually updated with real-time sensor, operational, and maintenance data. The digital thread serves as the “connective tissue” linking all life cycle artifacts. Through integration of Internet of Things (IoT) data, simulation models, and machine learning, digital twins enable engineers to analyze system behavior, predict performance outcomes, and support risk-informed decisions.

Madni et al. (2019) argued that embedding digital twins within MBSE environments enhances verification and validation, reduces testing costs, and improves life cycle management. However, they also acknowledged persistent challenges involving data ownership, security, and the absence of standardized frameworks. These issues are echoed throughout the broader digital twin literature.

Moenck et al. (2024) extended this discussion to aircraft production and Maintenance, Repair, and Overhaul (MRO). They described aviation systems as uniquely complex due to long service lives, global supply chains, and stringent regulatory requirements, all of which complicate robust digital thread formation. Data often must transit multiple organizations with differing interoperability standards and levels of willingness to share information. Moenck et al. categorized barriers to digital twin adoption as integrational, organizational, and compliance-related, underscoring the need for improved data standardization and cross-stakeholder coordination.

1. Definitions and Components

The following defined concepts are essential to understanding how digital thread technologies should be understood.

- **MBSE:** A formalized approach to systems engineering that uses digital models as the primary means of information exchange rather than



documents (Owen et al., 2025). MBSE serves as the framework that digital twins integrate with, enabling life cycle connectivity, simulation, and analysis through the digital thread.

- **Digital twin:** A real-time, virtual model of a physical asset used to simulate and monitor performance throughout the life cycle (Madni et al., 2019).
- **Digital Thread:** The integrated, authoritative data backbone linking system artifacts across design, production, and operations, enabling continuous traceability and feedback (Madni et al., 2019).
- **IoT:** A network of connected sensors and devices that gather and transmit data. In the context of this article, IoT provides real-time operational and sensor data that feeds the digital twin, allowing accurate monitoring and updating of the virtual representation (Moenck et al., 2024).
- **Simulation:** The use of computational models to analyze system behavior under different conditions. When combined with the digital twin, simulation enables prediction of performance, failure modes, and system responses using real-world data instead of assumptions (Moenck et al., 2024).
- **Virtual Prototype:** A generic digital model used to represent a system or subsystem for design and testing purposes. In contrast to a digital twin, a virtual prototype does not represent a specific physical instance and is not continuously updated with real-time data (Moenck et al., 2024).
- **MBSE Experimentation Testbed:** A MBSE environment where digital twins, simulations, and system models can be assessed, validated, and refined using operational scenarios. It supports “what-if” analyses and helps integrate digital twins into the MBSE workflow (Moenck et al., 2024).



- **Aircraft:** A complex, safety-critical system composed of many subsystems (engines, avionics, cabin systems, etc.), manufactured and operated over decades, requiring extensive production, maintenance, and life cycle management efforts (Madni et al., 2019).
- **Production:** All processes involved in creating an aircraft or aircraft subsystem including manufacturing, assembly, logistics, and coordination among suppliers (Madni et al., 2019). Aircraft production is characterized by low volumes, high customization, and heavily manual workflows.
- **Manufacturing:** The technology-centric subset of production involving transforming raw materials into aircraft parts or assemblies (Madni et al., 2019). Manufacturing processes must manage large structures, strict tolerances, and many manual steps.
- **Assembly:** The process of integrating components and subsystems into larger structures or completed aircraft (Madni et al., 2019). Due to scale, complexity, and customization, final aircraft assembly is typically performed on-site and is highly manual.
- **MRO:** The life cycle phase focused on keeping an aircraft airworthy and profitable (Madni et al., 2019). It includes scheduled and unscheduled maintenance, repairs, inspections, retrofits, and remanufacturing activities performed throughout an aircraft's long service life.
- **Quality Assurance (QA):** Inspection, measurement, and verification processes ensuring aircraft components meet strict regulatory and safety standards. Digital QA twins support capturing "as-inspected" data, integrating manual and automated inspection, and enabling augmented reality-assisted workflows (Madni et al., 2019).
- **Product Life Cycle Management (PLM):** The coordinated management of all product-related data, processes, and stakeholders throughout an aircraft's Begin-of-Life, Mid-of-Life, and End-of-Life. While data exists,



PLM is hindered by gaps in cross-stakeholder integration and data connectivity (Madni et al., 2019).

2. Integration in Model-Based Systems Engineering

Integrating digital twins into MBSE environments advances system development and sustainment by allowing models to reflect actual operational and maintenance data rather than static design assumptions. Madni et al. (2019) showed that digital twins, when supported by a robust digital thread, enable more accurate simulations, improved performance predictions, and more effective risk assessments throughout the system life cycle. This integration enhances system insight and adaptability and provides a foundation for linking engineering analyses directly to sustainment outcomes, which is an essential capability for platforms like the H-1 facing extended service life and evolving mission demands.

Fuller et al. (2020) emphasized the suitability of digital twins for smart manufacturing, healthcare, and smart city applications, describing digital twins as integrative tools that combine IoT connectivity, data analytics, and machine learning. Their research indicates that these technologies support predictive maintenance, anomaly detection, remote diagnostics, and optimization of complex processes. The authors assert that digital thread infrastructures are identified as critical enablers because they connect data across devices, sensors, models, and operational systems, thereby improving responsiveness and decision quality.

Tuegel et al. (2011) introduced the concept of structural digital twins for aircraft, demonstrating how continuous structural load data can inform service life estimates. Their work is particularly relevant to aging fleets such as the H-1, where structural fatigue and dynamic loading are major sustainment drivers. By linking structural data to digital twins, program managers can refine usage-based life limits and prioritize inspections and retrofits more effectively.

Wu et al. (2023) analyzed digital twins across multiple technological layers, including data collection, model construction, and networked coordination of multiple twins. They described applications in logistics optimization, structural health monitoring,



infrastructure management, and advanced manufacturing workflows. Importantly, they identified multi-twin networks as an emerging area, where digital threads enable reliable data synchronization and cross-twin communication. This system-of-systems perspective is particularly relevant for fleet-level sustainment, where coordinated decisions across multiple aircraft and subsystems are required.

From a defense readiness perspective, the GAO (2022) documented DoD efforts to deploy digital twin-aligned capabilities within predictive maintenance initiatives. Examples include sensor-enabled performance monitoring, automated anomaly detection, and continuous integration of operational data into maintenance planning systems. The GAO (2022) described data flows from equipment sensors to maintenance planners, depots, and operational units that resemble emerging digital thread architectures, enabling condition-based maintenance and estimation of remaining useful life.

3. Implementation Challenges

Despite their potential, digital twin and digital thread implementations face substantial technical, organizational, and compliance-related barriers. Moenck et al. (2024) highlighted integrational challenges such as the absence of standardized data structures, semantic models, and interoperable interfaces across stakeholders. Organizational issues include shortages of qualified personnel, fragmented data ownership, and difficulty coordinating across departments and suppliers. Compliance-related constraints involve stringent data protection requirements, intellectual property concerns, and hesitancy to share high-fidelity models or inspection data, especially for safety-critical components.

The Industrial Digital twin Association's Asset Administration Shell (AAS) framework represents a cross-industry effort to standardize data models and semantics to support interoperability. However, Moenck et al. (2024) observed that adoption remains uneven, with many aviation stakeholders relying on legacy systems and proprietary formats. Incomplete adherence to AAS standards limits the formation of unified digital threads that span product, process, and life cycle data. For defense aviation, these challenges translate into fragmented sustainment data and impede the development of authoritative digital twins for platforms such as the H-1.



The literature demonstrates that digital twin and digital thread technologies can significantly enhance system understanding, predictive capability, and life cycle management when integrated into MBSE frameworks. Madni et al. (2019) highlighted improvements in simulation fidelity and continuous performance assessment; Fuller et al. (2020) and Wu et al. (2023) emphasized benefits in process optimization and multi-twin coordination; Moenck et al. (2024) showed gains in aircraft production and MRO; and GAO (2022) documented early defense applications linked to predictive maintenance and readiness. Collectively, these works show that the main obstacles to broader adoption are data-sharing barriers, lack of standardization, integration complexity, and organizational resistance. Addressing these challenges is essential for leveraging digital twins in support of H-1 sustainment readiness.

C. PREDICTIVE ANALYTICS AND MAINTENANCE

Predictive analytics and predictive maintenance (PdM) are reshaping defense sustainment by enabling data-driven decisions and condition-based interventions. As platforms age and operational demands increase, defense organizations are turning to predictive models to anticipate failures, optimize resource allocation, and sustain readiness. The literature reflects significant progress in this area, particularly where predictive analytics is integrated with digital twins and machine learning. However, persistent barriers remain in data interoperability, algorithm transparency, and cross-platform standardization.

The DoD's transition from reactive to predictive maintenance aligns with broader digital transformation trends. Predictive analytics harness sensor data, machine learning, and statistical modeling to detect early signs of component degradation and forecast failure risks. This transition reduces unplanned downtime, enhances mission-capable rates, and lowers sustainment costs. Enterprise initiatives such as Condition-Based Maintenance Plus (CBM+) and the Air Force's Expeditionary Logistics for the 21st Century (eLog21) institutionalized predictive approaches and laid the groundwork for integrating digital twins and AI tools into military sustainment planning (GAO, 2022; West & Blackburn, 2017).



1. Definitions and Concepts

The following defined concepts are helpful for predictive analytics understanding.

- **PdM:** A maintenance approach that forecasts equipment failure and recommends servicing actions before issues impact mission performance (GAO, 2022).
- **Condition-Based Maintenance (CBM):** Maintenance conducted when indicators suggest potential or imminent failure (Verhagen, 2023).
- **Machine Learning:** “a subfield of AI that has evolved from pattern recognition to analyzing data structures and integrating them into models that users can understand and regenerate.” (Achouch et al., 2022, p. 8, para 3.2.7).

2. Empirical Evaluations in Military Contexts

Empirical studies consistently show strong evidence for the efficacy of predictive maintenance. The GAO (2022) reported reductions in unscheduled maintenance events across tracked vehicle fleets and Air Force aircraft following the deployment of predictive models. These systems integrate sensor networks, failure histories, and operational profiles to produce predictive dashboards supporting maintenance planning. The GAO (2022) also reported that the military services have acknowledged examples of predictive maintenance contributing to improved maintenance outcomes, such as earlier fault detection and reduced costs, although systematic metrics and quantification of readiness effects remain limited.

Taoufyq et al. (2025) argued that effective predictive maintenance depends not only on analytical algorithms but also on the quality and integration of data, organizational knowledge, and physics-based understanding, forming a hybrid framework that supports improved diagnostics and prognostics performance within maintenance operations. Their work reinforces the need for DoD-wide data governance standards to ensure that predictive analytics can be scaled and sustained across platforms, including rotary-wing aircraft like the H-1.



3. Algorithms and Optimization Models

Advanced algorithms form the core of predictive analytics. O’Neil et al. (2025) demonstrated that Bayesian networks and supervised learning approaches provide more precise failure probability estimates than traditional rule-based diagnostics. Achouch et al. (2022) synthesized Industry 4.0 predictive maintenance research and highlighted that PdM effectiveness depends on end-to-end data integration (i.e., platforms that enable continuous, “fluid” communication of life cycle equipment data), an integration gap that many digital-thread and PBL data ecosystems still struggle to close.

Wu et al. (2023) and Fuller et al. (2020) showed how hybrid machine learning models that combine regression, neural networks, and decision trees can improve scheduling, inventory management, and anomaly detection. Uçar et al. (2024) reviewed state-of-the-art AI-based predictive maintenance techniques and concluded that while artificial intelligence and machine learning significantly enhance performance and prediction accuracy in PdM, their effectiveness depends on robust data analytics, real-time anomaly detection, and the ability to address “transparency, explainability, system integration,” and validation challenges in real-world maintenance systems.

4. Impact on Readiness and Cost Avoidance

Predictive analytics directly contributes to operational readiness and cost avoidance. The GAO (2022) found that early fault detection and dynamic maintenance scheduling reduce depot workloads and improve sortie generation. Platforms such as the F/A-18E/F Super Hornet and the Army’s Bradley Fighting Vehicle have realized tangible benefits through predictive diagnostics, including decreased maintenance labor hours and more predictable spare-part consumption (GAO, 2022). These results suggest that when supported by appropriate data infrastructure and governance, predictive analytics can reduce life cycle costs while improving mission performance, outcomes directly relevant to the H-1 fleet.

The literature confirms that predictive maintenance enhances readiness, reduces costs, and supports proactive sustainment decision-making. Nonetheless, research gaps persist in algorithm standardization, cross-platform evaluation, and integration with



existing maintenance systems. To realize enterprise-level benefits, future efforts must focus on unified data governance, algorithm transparency, and scalable implementation frameworks across the services. For the H-1 platform, the convergence of predictive analytics with digital twins and PBL has promise for addressing rotorcraft-specific failure modes and dynamic operating environments.

D. INTEGRATION OF DIGITAL TECHNOLOGIES IN ACQUISITION

Despite the challenges outlined above, the literature provides several examples of digital twins, digital threads, and MBSE being integrated into defense acquisition to modernize life cycle management and improve decision-making. Donovan (2022) examined the adoption of digital engineering tools such as GENESYS and MagicDraw to strengthen traceability, systems modeling, and data continuity. West and Blackburn (2017) argued that digital thread and digital twin technologies are becoming essential for managing system complexity, accelerating fielding, and reducing long-term sustainment burdens. The GAO (2022) further reinforced that digital technologies are increasingly necessary for predictive maintenance and readiness outcomes across multiple weapon system portfolios. Collectively, these works frame digital transformation as a central acquisition priority, characterized by significant potential benefits and substantial technical, organizational, and policy challenges.

The shift toward digital engineering is rooted in long-standing acquisition inefficiencies, including fragmented documentation, disconnected data systems, and slow feedback loops. Donovan (2022) explained that digital engineering environments enable program offices to maintain authoritative system models that replace static documents and foster early integration across engineering disciplines. West and Blackburn (2017) contended that digital twins and digital threads enable continuous data flow from design through manufacturing to operations and sustainment, signaling a transition from linear to integrated acquisition processes. The GAO (2022) showed that the DoD's predictive maintenance initiatives rely on similar principles, centralized data, continuous monitoring, and digital representations of fielded assets. Together, these sources emphasize that digital



acquisition is not merely technological modernization, but a structural reconfiguration of how defense systems are developed, fielded, and supported.

1. Model Conversion and Digital Engineering

One core challenge in digital engineering is achieving interoperability among modeling tools used across the acquisition life cycle. Donovan (2022) assessed model conversion from GENESYS, which uses the System Definition Language (SDL), to MagicDraw, which uses Systems Modeling Language (SysML). The study finds that only 34% of entities and 9% of relationships transferred correctly, revealing substantial semantic mismatches and the absence of shared ontologies. This lack of interoperability inhibits digital thread formation, limits model reuse, and forces time-intensive manual remediation. These findings underscore the need for standardized data models, translation mechanisms, and policy guidance to support tool interoperability.

Moreover, digital engineering success depends on maintaining authoritative models as programs progress through life cycle phases. Donovan (2022) noted that many current modeling ecosystems rely on ad hoc exports and tool-specific connectors, disrupting continuity and undermining confidence in model fidelity. West and Blackburn (2017) similarly argued that digital twins only deliver strategic value if the underlying digital thread preserves data integrity from design through sustainment. Without reliable model-transfer mechanisms, programs risk eroding engineering knowledge, duplicating effort, and weakening the basis for future digital twin development. These risks are especially acute for long-lived platforms such as H-1.

2. Affordability and Technical Debt

Affordability is a central concern in the adoption of digital thread and digital twin technologies. West and Blackburn (2017) conducted a systemic evaluation of whether digital twins are economically viable for the Air Force and concluded that affordability depends on platform maturity, data environments, and life cycle length. They introduced the concept of technical debt in digital engineering: insufficient early investment in data structures, model quality, and integration leads to escalating sustainment costs and constrains future modernization options.



The GAO (2022) echoed these concerns, noting that predictive maintenance initiatives often face affordability challenges when programs lack foundational data architectures or sensor integration. In such cases, digital technologies yield limited returns and require costly retrofits. Both the GAO (2022) and West and Blackburn (2017) indicated that affordability is inseparable from early, disciplined digital engineering practices that minimize technical debt across the acquisition life cycle. For the H-1 program, this suggests that future digital twin investments must be aligned with clear data strategies and life cycle planning to be cost-effective.

3. Policy and Organizational Barriers

Policy and organizational factors significantly affect digital twin and digital thread adoption. Donovan (2022) identified the absence of unified modeling standards and DoD-wide ontologies as a major obstacle to interoperability and model reuse. The GAO (2022) similarly reported that services lack consistent policies for data sharing, predictive maintenance implementation, and platform-agnostic digital frameworks. These policy gaps hinder the formation of stable digital threads and slow the adoption of common engineering practices across programs.

Organizationally, West and Blackburn (2017) highlighted cultural resistance, misaligned stakeholder incentives, and limited digital literacy as impediments to digital transformation. Donovan (2022) likewise observed that manual remediation during model conversion often stems from organizational structures that do not support integrated tooling or shared data governance. The GAO (2022) noted parallel issues in maintenance communities, where inconsistent leadership support and uneven resourcing slow predictive maintenance implementation. These findings indicate that successful digital transformation requires sustained leadership attention, workforce development, and cross-functional alignment. These conditions must be actively cultivated for H-1 digital twin initiatives.

Digital twin and digital thread technologies offer substantial potential to transform acquisition by supporting continuous data flow, predictive maintenance, and integrated life cycle management. However, their success depends on resolving tool interoperability challenges, establishing robust digital engineering infrastructures, and managing technical



debt from the outset of a program. Policy gaps and organizational resistance further slow digital adoption, underscoring the need for standardized modeling guidance and strengthened data-governance structures. When addressed, these issues enable digital engineering to improve readiness, interoperability, and life cycle cost outcomes. They are strategic objectives that are directly aligned with enhancing H-1 sustainment readiness.

E. RELEVANCE TO H-1

The H-1 platform, consisting of the AH-1Z Viper and UH-1Y Venom, presents a compelling case for integrating PBL, digital twins, and predictive analytics due to its operational tempo, fleet age, and sustainment complexity. H-1 aircraft operate in high-vibration, high-temperature, and corrosive environments and perform diverse mission profiles that drive accelerated wear and complicate life prediction. Current sustainment practices rely heavily on manual inspections, time-based maintenance intervals, and fragmented data systems that limit life cycle visibility and constrain proactive decision-making.

Digital twin technologies offer a pathway to integrate real-time flight data, maintenance histories, avionics health data, and structural load information into a unified framework capable of continuously modeling system health. Aligning digital thread architectures with existing and future H-1 MBSE baselines would allow program managers to improve part life forecasting, reduce supply chain uncertainty, and inform PBL negotiations with quantitative evidence of usage and degradation patterns. Predictive analytics would further enhance this capability by identifying early-stage degradation and supporting condition-based maintenance, thereby reducing unscheduled removals, and improving sortie generation.

As the Marine Corps seeks to extend H-1 service life beyond original estimates, the convergence of PBL, digital twins, and predictive maintenance becomes essential. The literature reviewed suggests that an integrated approach could improve mission readiness, reduce life cycle costs, and increase operational agility. This makes the H-1 platform a suitable and strategically important testbed for investigating how digital twin-enabled



sustainment can be practically implemented within existing acquisition and logistics structures.

F. IDENTIFIED GAPS AND OPPORTUNITIES FOR FUTURE RESEARCH

Although PBL has demonstrated success across numerous fixed-wing and ground platforms, its application to rotary-wing aircraft remains underexplored. Rotorcraft present distinct sustainment challenges due to high vibration, complex dynamic loading, and diverse mission profiles. Few longitudinal studies rigorously track PBL implementation and its impact on readiness, cost, and risk in rotorcraft fleets. Future research should therefore examine whether PBL outcomes documented in fixed-wing programs translate to platforms like H-1 and how PBL can be tailored to rotorcraft-specific failure modes and operational demands.

1. Need for Unified Standards in Digital Twin Implementations

The literature strongly supports the potential value of digital twins, but implementation remains fragmented and often platform-specific. Differing modeling standards, data structures, and integration approaches result in siloed digital twin solutions with limited scalability. Unified standards and shared ontologies are needed to ensure interoperability across platforms, life cycle phases, and stakeholder organizations. For H-1, this raises questions about which standards and architectures would best enable an extensible digital twin capability that can align with broader naval aviation and joint digital engineering efforts.

2. Challenges in Data Interoperability and Institutional Adoption

Interoperability challenges are pervasive in both predictive maintenance and PBL environments. Legacy systems often lack modern sensor suites and open interfaces, complicating real-time data exchange and integration. As Verhagen et al. (2023) noted, even when new sensors or analytic tools are available, the absence of standardized data models and harmonized data architectures across original equipment manufacturers, operators, and maintenance organizations severely constrains condition-based maintenance implementation, creating persistent barriers to scaling digital capabilities across platforms.



Institutional resistance to change, fragmented data-governance policies, and insufficient workforce training further impede adoption of digital technologies. These issues are particularly salient for H-1, which relies on legacy sustainment infrastructure and distributed maintenance organizations. Future research should explore change-management strategies, data-governance frameworks, and cost–benefit trade-offs associated with overcoming technical debt in H-1 sustainment.

3. Opportunities for Incentive Alignment and Data Capture

Existing PBL arrangements highlight opportunities to align user incentives with data-capture requirements. For example, the V-22 AE1107 “power-by-the-hour” PBL contract with Rolls-Royce has experienced challenges in collecting real-time engine usage and health data; the integrator must rely on end users to upload data post-flight rather than receiving it automatically. Similar dynamics are likely in any future H-1 digital twin or PdM construct. One opportunity is to structure incentives so that aircrew and maintainers receive credit for flight hours or maintenance actions only when health-monitoring data are correctly uploaded and reconciled with systems such as the NAVFLIRS. Such mechanisms mitigate over or underreporting of usage and simultaneously encourage timely data submission to PBL contractors and program offices.

For H-1, this suggests research questions related to how PBL and digital twin architectures can be codesigned to streamline data collection, ensure data quality, and reward timely reporting. Exploring these mechanisms could yield practical recommendations for making digital twin–enabled sustainment both technically feasible and behaviorally sustainable in a fleet context.



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IV. RESEARCH ANALYSIS

This chapter presents a proposed digital twin enabled sustainment architecture for the H-1 platform. The intent is to move from reactive, interval-based maintenance toward predictive sustainment. Building on the challenges identified in earlier chapters, this section focuses on defining what is required to enable predictive sustainment at the forward deployed level.

Current H-1 sustainment practices rely heavily on scheduled maintenance intervals and historical averages. Maintenance decisions are often made after failures occur rather than before. Logistics planning is also largely reactive, which creates delays in part availability and increases aircraft downtime. In addition, decision makers have limited visibility into the condition of individual aircraft or even squadrons of aircraft operating in confined environments. Aircraft assigned to a fleet replacement squadron with a rigid syllabus of training flights operate within a much smaller flight envelope than light attack and utility aircraft in extreme maritime, mountain, or desert environments. Neither do they exercise survivability equipment like those in combat. These aircraft, however, are subject to the same maintenance intervals as the entire population of aircraft in the Fleet. These factors contribute to reduced operational availability and inefficient sustainment planning.

Although large amounts of data exist across aircraft systems and maintenance databases, these data sources are not connected. Furthermore, much of this data is subject to human subjectivity where the aircraft operator or maintainer can troubleshoot system failures by trial and error or feel rather than a systematic built in test or instrumented measurement. Engineering documentation, logistics data, and aircraft usage information are stored in separate systems. As a result, decision makers struggle to combine the disparate data and develop a complete picture of aircraft health or forecast sustainment requirements. Attempts to overlay operational data on failure modes for specific components are the exception often requiring excessive lab analysis and engineering investigation labor hours. These investigations and component failure analysis may yield revelations specific to a particular environment but the corrective action is usually rolled-up into Fleet wide averages. Scheduled maintenance practices such as 200-hour phase



inspections further reinforce this reactive model by applying fleet-wide assumptions instead of aircraft specific condition data.

Subject matter expert interviews reinforced these challenges. Participants described difficulty accessing relevant data and validating predictive analytics. They also highlighted sustainment contract structures that emphasize execution of repairs rather than predict failures. Several stakeholders noted that predictive capability must support decision making at the forward deployed level, where aircraft selection and maintenance prioritization directly affect readiness.

This chapter establishes forward deployed predictive sustainment capability as the desired operational outcome. However, achieving this capability requires foundational changes. Data from disparate information systems must be integrated into a single evaluative autonomic system. The system will also have self-contained analytics to minimize electronic emissions and for forward deployed environments while prioritizing mission essential component information and total processing power or compute. This chapter therefore focuses on defining these enabling requirements rather than proposing a fully developed digital twin solution.

The architecture presented in this chapter introduces a unified data environment that integrates aircraft generated data with maintenance and logistics data from information systems currently in use. This architecture supports predictive modeling at the bureau number level. It is designed for human decision makers to anticipate component degradation and extend component life limits in real time. Logistics requirements including spare parts, component repairs, structural inspection, and support equipment can be optimized using objective aircraft programmed data and improve forecast accuracy of sustainment requirements.

The proposed architecture supports decision makers at multiple stakeholder levels. Enterprise stakeholders can use aggregated fleet data to inform sustainment planning. Program offices can use predictive analytics to support reliability analysis and procurement forecasting. Depot and intermediate maintenance activities can adjust workload standards for phased inspection. Organizational level maintenance activities and forward deploying



units can use digital twin outputs to support aircraft selection for deployment and better schedule phases for maintenance work loads.

This chapter also discusses implementation challenges. These include data trust, integration limitations, and contracting alignment. A phased implementation strategy is then proposed to transition from the current sustainment environment toward predictive sustainment enabled by digital twin capability.

A. CURRENT H-1 SUSTAINMENT DATA ENVIRONMENT

The H-1 sustainment environment contains large amounts of operational and maintenance data. Every flight hour is manually tracked in one system, but engine operating hours are machine tracked in another system. Maintenance actions, supply requisitions, component operating time are all tracked in separate information systems. Despite the availability of the data, sustainment decisions are still largely reactive. The primary reason is that data exists across multiple systems that are not integrated. Decision makers must manually gather information from different sources, which makes predictive planning dependent on integration assumptions.

Aircraft generated data for the H-1 platform is primarily collected through the Integrated Mechanical Diagnostics Health and Usage Monitoring System (IMD-HUMS). This system captures vibration data, aircraft electronic fault codes, and component performance information. Data is stored in the aircraft maintenance processing unit (MPU) and transferred using the data transfer unit (DTU) to the personal computer memory card international association (PCMCIA). Maintainers then review the data on ground-based systems and determine if maintenance action is required.

Fleet maintainers can access a portion of this data. However, the original equipment manufacturer retains intellectual property rights to additional data fields. Bell can therefore conduct deeper analysis than what is available to fleet maintainers or program office personnel. This creates a limitation for government-led predictive analytics and digital twin development.



The H-1 aircraft maintenance unit (AMU) also provides additional maintenance data. This information is useful but not integrated with HUMS outputs. As a result, aircraft condition data remains distributed across separate systems. Maintainers must manually combine information to develop an overall understanding of aircraft health.

Maintenance data is primarily captured using NALCOMIS OOMA and transferred to DECKPLATE. NALCOMIS OOMA is used daily to track discrepancies, document maintenance actions, and record component removals and installations. Component removals are also tracked separately with paper log sets and equipment history records (EHR) although much of the same information is captured electronically in the component management tool (CMT) with data sourced from NALCOMIS. Maintenance Action Forms generated in OOMA provide a detailed history of aircraft maintenance activity.

DECKPLATE serves as the standard maintenance data repository across Department of the Navy aviation platforms. However, data quality depends heavily on manual entry. Aircraft generated data is not automatically transferred into maintenance systems but relies on technicians to interpret the data and feedback from aircrew to load the presumed faults into OOMA. The manual entry is limited to pre-selected work unit codes tied to a baseline of part numbers specific to each unique aircraft BUNO. Frequently, loaded baselines lag the actual aircraft configuration, technicians estimate incorrectly, or interface mismatch occurs during OOMA to NALCOMIS to DECKPLATE interface. These three opportunities for data inconsistency result in at least one error for every maintenance action manually recorded. Data accuracy will also vary across squadrons depending on experience, workload, and data entry practices.

Reliability analysis for the H-1 platform is conducted primarily at the component level. The Reliability and Maintainability team within PMA-276 assesses component performance using the common failure reporting, analysis, and corrective action system (C-FRACAS) tool. This provides insight into fleet level reliability trends. However, analysis is not typically performed at the aircraft specific level due to volume of components and sub-systems. This limits the ability to track degradation patterns for individual aircraft.



Phase maintenance for the H-1 platform is conducted every 200 flight hours with a tolerance of plus or minus ten percent. The phase structure consists of four inspection periods labeled A, B, C, and D. Each phase includes a different set of inspections. This spreads maintenance across time rather than requiring a full aircraft teardown during a single event. Even with this approach, phase maintenance remains interval based and averaged across aircraft. Aircraft operating conditions and usage differences are not fully considered. These inspections typically require ten to fourteen days to complete for a well-functioning squadron. This results in significant aircraft downtime and careful monitoring of aircraft flight hours to sequence aircraft and minimize multiple aircraft in phase simultaneously.

Replaceable parts for the H-1 platform are tracked primarily using national stock numbers (NSN) which have manufacturer part numbers tied to them. Components are removed following scheduled or unscheduled maintenance events. Replacement components are then ordered or repaired. Once available, the component is installed on an aircraft. These events are generally treated independently. There is limited linkage between logistics data and aircraft specific degradation patterns.

Long lead procurement further complicates sustainment planning. Many components have known lead times. However, demand signals are not always forecasted accurately. Some components require carcass turn in before replacement components are issued. This creates delays when failures occur unexpectedly. By the time a component fails and a carcass becomes available, the aircraft may already be downed due to supply. This condition is categorized as non-mission capable for supply (NMCS).

Engineering data for the H-1 platform is also fragmented. Intellectual property restrictions limit access to certain original equipment manufacturer data. Access to engineering baselines varies depending on contract structure and component ownership.

Aircraft selection for deployment further illustrates the limitations of the current sustainment environment. The squadron commander makes the final decision. That decision is informed by the Maintenance Material Control Officer, Maintenance Control Chief, Maintenance Chief, and Aviation Maintenance Officer. These leaders review

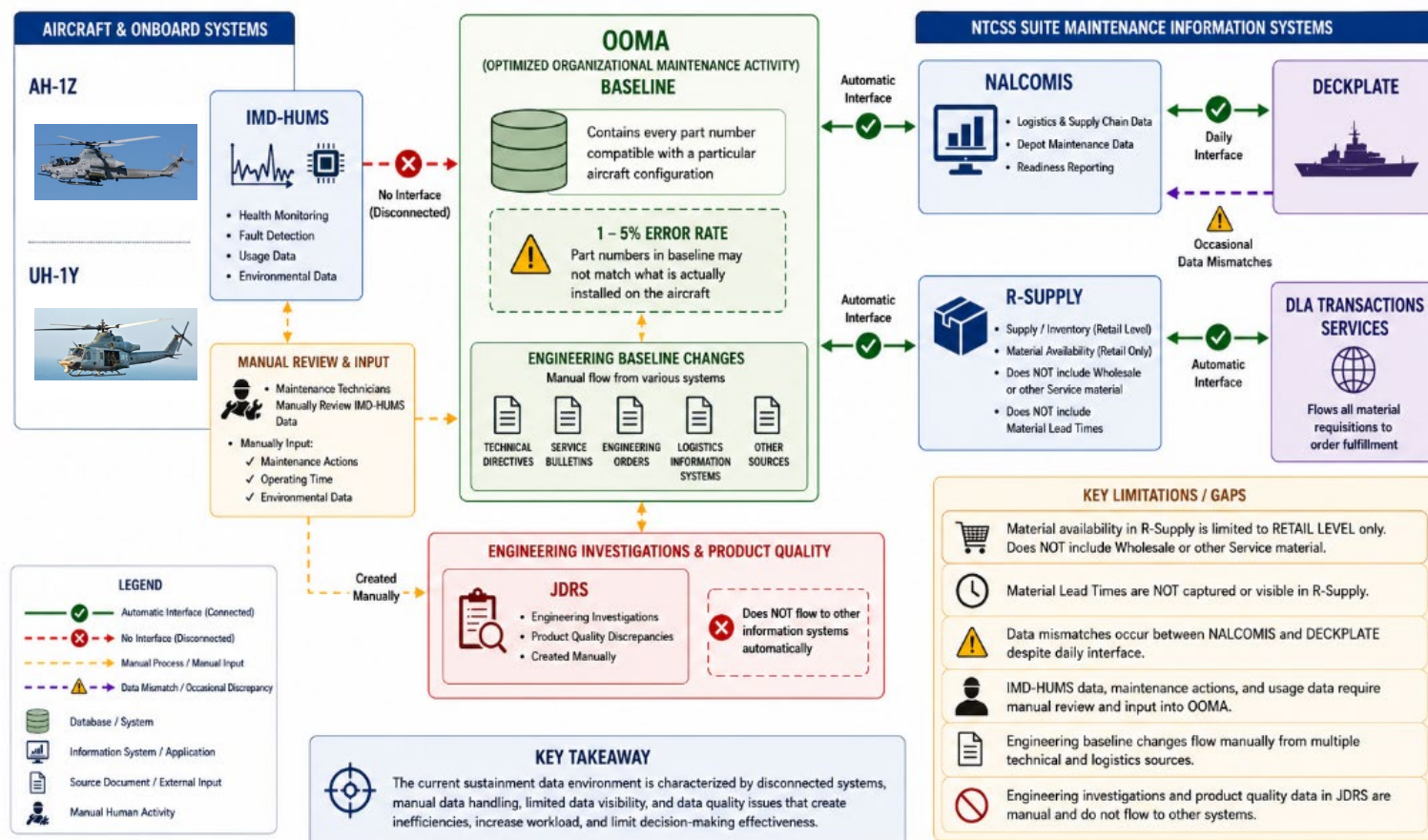


available maintenance data and apply operational experience. This process is largely manual and based on intuition. Predictive tools with better accuracy than a maintenance chief with 18 years of operational experience are not currently available to support this decision.

The current sustainment environment for the H-1 platform contains substantial data. However, this data remains fragmented across multiple systems. Authorizations to Operate (ATO) and cyber security manifest as the largest barriers in terms of time and money to connect these disparate information systems. Decision makers must manually combine information to support sustainment planning. This limits predictive capability and reinforces reactive maintenance practices.



CURRENT SUSTAINMENT DATA ENVIRONMENT FOR MARINE CORPS ATTACK AND UTILITY HELICOPTERS



Note. Image generated using OpenAI ChatGPT (2026) with the initial prompt: “Conceptual schematic illustrating the fragmented sustainment data architecture supporting Marine Corps attack and utility helicopters, including maintenance, engineering, and supply systems with limited interoperability and manual data exchanges.”

Figure 1. Current Sustainment Data Environment



B. SUSTAINMENT DECISION-MAKING LIMITATIONS

The current H-1 sustainment environment limits predictive decision making. Maintenance and logistics actions are often based on current aircraft status rather than future risk. Decision makers rely heavily on experience and manual review of available information. This makes it difficult to anticipate failures before they occur.

One limitation is the inability to adjust maintenance timing based on aircraft condition. Phase inspections are governed by the Naval Aviation Maintenance Program. Squadrons are required to follow these intervals. Changes to maintenance timing require a waiver. These waivers must be routed through the chain of command. Most requests are ultimately routed to the Type Commander. This process takes time and discourages adjustments based on aircraft condition.

This limitation affects deployment planning. Squadrons typically operate on an eighteen-to-twenty-four-month deployment cycle. Units usually know their next deployment window well in advance. During periods of increased operational tempo, this timeline may shrink to six months to one year. Despite these known timelines, maintenance planning does not account for projected aircraft degradation. Aircraft may be selected for deployment without understanding their future reliability.

Logistics planning presents another limitation. H-1 maintenance plans are designed off reliability centered maintenance (RCM) where critical components are given conservative life expectancies and removals are scheduled. Despite this conservative design, unscheduled removals predominantly diminish operational availability. Supply chains rarely sustain stocking levels for scheduled maintenance and may disintegrate for years for components that are removed ahead of their scheduled intervals. When supply chains break, squadrons resort to sourcing material from other aircraft internal to their squadron which increases maintenance labor hours and operational planners require two or three aircraft to reliably complete one sortie.

Component allocation policies also affect repair timelines. Critical components below planned stocking levels are sometimes source controlled by the operational commander instead of the typical material commander. That is, to optimize priority,



Commander, Naval Air Forces fills requisitions rather than the Commander, Naval Supply Systems Command. H-1 Mission computers have historically been one example of high-demand components subject to these controls. When component reliability falls short of fleet averages and its supply chain disintegrates, additional labor resources must be flowed to manage operational availability.

The environmental conditions and missions assigned create additional variability that does not complement reliability centered maintenance. Aircraft operating in maritime environments may experience increased corrosion over Fleet wide averages. Aircraft operating in fine sand will degrade engine performance more quickly than fleet averages. Different altitudes, temperatures, humidity, loads, and missile threats continue to an aircraft's unique performance. These factors are not currently incorporated into sustainment planning.

Shipboard operations provide a clear example. Saltwater exposure increases corrosion risk. Squadrons conduct additional washdowns as a preventative measure. Labor intensive aircraft and engine washes mandated broadly rather than to a specific aircraft, erodes human trust in the efficacy of the procedure. When maintenance decisions are not based on measured aircraft condition, human system integration suffers as well.

These limitations reduce the effectiveness of sustainment planning. Maintenance timing remains fixed. Logistics actions occur after failures. Deployment planning relies on manual assessment. These factors highlight the need for predictive sustainment capability to support forward deployed decision making.

C. SUBJECT MATTER EXPERT FINDINGS AND PRACTITIONER INSIGHTS

Subject matter expert interviews were conducted with personnel across the H-1 program and related aviation sustainment organizations. Participants included fleet support personnel, program office leadership, reliability engineers, logistics planners, and product support managers. Additional insight was gathered from the H-60 program to provide comparison with an established performance-based logistics environment. These



discussions identified several consistent themes related to predictive sustainment and forward deployed decision making.

1. Data Access and Integration Challenges

Interview participants consistently indicated that large amounts of data already exist within the H-1 sustainment environment. However, this data is not easily accessible in a unified format. Users must manually review multiple systems to understand aircraft condition.

Fleet support personnel emphasized that the challenge is not data collection, but data integration. As one participant noted: “It’s not creating a brand new thing... it’s refining the data infrastructure that allows us to review all of the information that we’re already collecting in one framework.” (Horney, 2026)

Reliability personnel also described challenges connecting maintenance data with operational usage data. Component-level reliability data exists, but aircraft-level modeling remains limited. This prevents forecasting degradation for individual aircraft.

Program office personnel also noted that additional aircraft data exists at the original equipment manufacturer level. Access to this information is limited by intellectual property restrictions. This further complicates integration and predictive analytics development. These challenges create barriers to predictive sustainment capability. Decision makers must manually interpret data rather than relying on automated analysis.

To overcome the sifting, integration, and intellectual property barriers, we propose creating a digital architecture that tunnels and prioritizes the most relevant information and partners with equipment manufactures to share valuable operational data that can lead to increased insight into designing for reliability.

2. Predictive Maintenance Limitations

Subject matter experts indicated that current maintenance planning remains interval based. Maintenance actions are scheduled using flight hours rather than aircraft condition.



Fleet support personnel noted that environmental conditions are not incorporated into predictive maintenance planning. These factors are typically addressed after failures occur. One participant described this limitation in operational terms: “We know when the aircraft is going to need these things... but we don’t have the ability to project forward based on usage rates and environment.” (Horney, 2026)

Reliability personnel also described challenges with predictive modeling. Predictive analytics require consistent data inputs. Variability in maintenance reporting reduces confidence in predictive outputs.

3. Logistics and Supply Chain Constraints

Logistics personnel described challenges in forecasting demand for high failure components. While lead times can be determined for material at constant production rates, procurement is based on average historical demand with limited forecasting. Dynamic components like the main gearbox have material properties with known life based on load cycles. When the engineering analysis of an individual aircraft load cycles can reliably be tracked and overlayed with production lead times, the supply chain will galvanize. The airworthiness of a component can be extended based on conditions unique to that aircraft rather than Fleet wide averages.

Program office personnel also described limited visibility into vendor pipelines. Fleet users typically do not have immediate insight into component availability timelines. For example, a maintenance technician deciding whether to replace a broken piece part or the next higher assembly of a component would need to call a supply requisition manager. If the component availability were available on demand, the technician could immediately place the optimum replacement part on order aligned with the squadron’s maintenance and operations plan.

No-functioning components or carcass turn-in requirements were also identified as a constraint. Component carcasses typically retrograde for repair and sit in storage warehouses until a repair contract is ready. This wait time increases the necessary buffer stock of functioning components needed to keep a Fleet of aircraft operationally available. These component carcasses will have varying levels of fatigue damage or reasons for



removal but cannot be tracked by serial number or electronically linked to the equipment history. Logging the operational information that caused the removal and providing to the repair site would enable swift prioritization of which components to induct first and what would need to be replaced to return the component to acceptable level of functionality.

One participant summarized this challenge: “By the time a component has broken for there to be a carcass, it’s already too late... the aircraft is already down.” (Kelley et al., 2026) These logistics constraints reinforce reactive sustainment planning.

4. Contracting and Performance-Based Logistics Alignment

Product support managers emphasized the importance of aligning predictive maintenance with performance-based logistics contracts. Current sustainment structures often incentivize reactive repair rather than predictive planning.

The H-60 program was identified as a useful comparison. Product support personnel described how performance-based logistics improved readiness outcomes: “Our readiness rates have done nothing but climb... and we attribute that to the responsiveness of our lead integrator and the way the contract is structured.” (Berry, 2026)

To optimize contract structure, the engineering support activity and material support activities must collaborate. Key performance indicators like operational availability or increased mission capability rates depends on numerous variables including engineering specification tolerances, levels of repair authorized, and authorization to competitively source manufacturing. The various support activities are given different budget authorities from Congress to reinforce the tension designed between airworthiness and operational availability. Outcome based performance contracts structured to accept funds from engineering, material, and operational support activities will enable predictive sustainment and safely improve readiness.

Program office personnel indicated that predictive analytics combined with component tracking by serial number could enable similar improvements for the H-1 platform as seen on the H-60 platform.



5. Forward-Deployed Decision Requirements

Interview participants emphasized the need for predictive capability at the forward deployed level. Squadron leadership must select aircraft for deployment and plan sustainment actions based on expected usage.

Fleet support personnel described how this capability could support operational decision making: “Give me four of your best aircraft... based on how many hours they’re going to fly and what components are likely to fail.” (Kelley et al., 2026)

Participants also emphasized the need for disconnected capability. Forward deployed units may not have consistent connectivity. Predictive tools must therefore function at the forward node level keeping smaller packets of information available to make decisions. When connectivity is available to transfer data to the spoke or hub, it must be tailored for rapid transfer. These requirements reinforce the need for digital twin capability designed for operational use.

6. Summary of Subject Matter Expert Findings

Subject matter expert interviews identified several common themes. Data exists but is too dispersed and disintegrated to make rapid decisions. Predictive maintenance capability remains limited. Logistics planning is reactive. Contracting structures are not aligned with predictive sustainment. Forward deployed decision makers lack predictive tools. These findings support the development of a digital twin enabled sustainment architecture designed to support predictive decision making at the forward deployed level.

D. POLICY AND ADAPTIVE ACQUISITION FRAMEWORK PATHWAYS ANALYSIS

The development of a digital twin enabled sustainment capability for the H-1 platform must align with existing Department of War acquisition policy. The Adaptive Acquisition Framework provides multiple pathways that can support the development and fielding of this capability. However, the nature of the proposed system requires a tailored approach that combines rapid prototyping with iterative software development.



The desired capability is not a single system. It is a combination of a data architecture, predictive analytics, and a forward deployed decision support tool. The threshold requirement is a tool that can operate at the forward node and support squadron-level decision making. This requirement drives both the acquisition strategy and system design.

The Software Acquisition Pathway provides the most appropriate long-term framework for this capability. This pathway is designed for systems that require continuous development, frequent updates, and integration of new data sources. The digital twin concept relies on iterative refinement of models and analytics. As more data becomes available, the system must adapt. This is in alignment with the intent of the Software Acquisition Pathway, which emphasizes rapid delivery and continuous improvement. The pathway also supports modular development, which is necessary for integrating data from multiple existing systems.

However, the Software Acquisition Pathway alone does not address the need for rapid initial development. The Middle Tier of Acquisition pathway provides a mechanism to prototype the capability. This pathway allows programs to develop and demonstrate new capabilities within a short timeframe. It reduces the time required to move from concept to fielded capability. This is critical for testing predictive sustainment concepts in an operational environment.

A combined approach is then required. The Middle Tier of Acquisition pathway should be used to develop and demonstrate an initial prototype. This prototype should focus on integrating existing data sources and delivering a basic decision support tool to a forward deployed unit. Once the capability is demonstrated, the program should transition to the Software Acquisition Pathway for continued development and scaling. This will also build trust in the capability by the end user.

Organizational alignment is also required for successful implementation. Although the H-1 program is the initial focus, the capability has broader applicability across the Naval Aviation Enterprise. The lead acquisition authority must therefore be positioned at a level that can support cross-platform integration. A Naval Aviation Enterprise level



approach enables standardization of data architecture and reduces duplication of effort across programs. The H-1 program can serve as a pilot effort, but the long-term objective should be enterprise adoption.

Data ownership and access represent a critical policy consideration. Current sustainment data is distributed across government and original equipment manufacturer systems. In some cases, access to detailed aircraft data is restricted by intellectual property agreements. This limits the ability of the government to develop independent predictive analytics capability. To enable digital twin development, the government must establish ownership of the data architecture. This does not eliminate the need for original equipment manufacturer data. Instead, it requires integration of that data into a government-managed system. This approach reduces vendor lock and allows the system to expand across multiple platforms with different manufacturers.

Contracting strategy must also evolve to support predictive sustainment. The development of the digital twin capability should be executed under a dedicated contract focused on data integration and analytics development. This contract should include requirements for data standardization, system interoperability, and the forward deployed capability.

Once the capability is established, its outputs must be integrated into existing performance-based logistics contracts. Current contracts are structured to respond to failures rather than predict them. For example, performance based contracts from material support activities like NAVSUP and DLA use supply response time and material availability as key performance metrics. The manufacturers contracted with don't have manufacturing rights to the entire aircraft making it difficult to use availability metrics at the aircraft level. Predictive outputs from the digital twin must be incorporated into demand forecasting and supply planning processes. This will require modification of contract metrics and incentives. Contractors must be incentivized to support predictive demand rather than reactive repair.

The requirement for forward deployed capability further shapes the acquisition approach. The system must function in environments with limited connectivity. This



requires edge-based processing and local data storage. The capability must be deployable at the squadron level and operate without continuous reach-back to centralized systems. This requirement aligns with operational concepts such as the Marine Corps' distributed aviation operations concept that emphasizes the need for decision support at the point of execution.

Integration with existing systems is another key consideration. Current maintenance and logistics systems are deeply embedded in naval aviation processes. Replacing these systems is not feasible in the near term for affordability reasons and implementation. The digital twin capability must therefore integrate with existing systems rather than replace them. This approach reduces implementation risk and supports user adoption. Over time, the data architecture may evolve, but initial implementation must work within the current system environment.

The Adaptive Acquisition Framework provides a viable pathway for developing this capability. However, successful implementation requires alignment between acquisition strategy and sustainment contracting. A specific focus on data ownership must remain throughout both. A phased approach that begins with prototyping and transitions to continuous software development provides the most effective path forward.

E. PROPOSED DIGITAL TWIN SUSTAINMENT ARCHITECTURE

This section presents a digital twin enabled sustainment architecture designed to support predictive decision making at the forward deployed level. The architecture is structured to operate within the constraints of existing naval aviation systems while enabling integration of aircraft, maintenance, and logistics data into a unified decision support capability.

The primary objective of this architecture is to provide a decision support tool at the forward deployed node. This tool allows squadron-level leadership to assess aircraft condition, anticipate component failures, and make informed sustainment decisions prior to mission execution. Achieving this capability requires a supporting data architecture that integrates multiple data sources and enables predictive analytics across the sustainment enterprise.



1. Architecture Overview

The proposed architecture is based on a hub, spoke, node model. This structure reflects how naval aviation operates and supports decision making at different levels of the organization.

The node represents the forward deployed unit. In aviation, this is typically a squadron or detachment operating with limited resources. The node contains a local instance of the digital twin model along with sufficient data storage to support predictive analysis. This capability must operate independently when connectivity is limited.

The spoke represents an intermediate level, typically located at the Marine Aircraft Group. This level provides additional computational support, expanded model storage, and access to subject matter experts such as Fleet Support Teams. The spoke also functions as a staging point for logistics support and resupply.

The hub represents the enterprise-level data environment. This includes program office resources, centralized data storage, and software development teams. The hub is responsible for refining digital twin models, integrating new data inputs, and validating updates before distribution to lower levels.

This structure enables distributed decision making while maintaining centralized model development and data integration. It also reduces processing power needed at the forward deployed nodes.

2. Data Flow and Model Management

Data within the architecture flows in both directions between the hub, spoke, node. Aircraft data collected at the node is uploaded to higher-level systems when connectivity is available. This data includes maintenance records, aircraft usage information, and environmental conditions.

At the hub level, this data is incorporated into the broader data environment. Models are refined using updated inputs and validated by engineering and software teams. Once updated, the refined model is distributed back down to the spoke and node levels.



At the node, the system operates using the most recently downloaded model. The model does not update locally while disconnected. Instead, it provides predictive outputs based on existing data. When connectivity is restored, updated models are downloaded and replace the previous version.

This approach allows forward deployed units to maintain predictive capability without requiring continuous connectivity.

3. Unified Data Layer

The architecture relies on a unified data layer that integrates information from existing systems. This layer does not replace current systems such as NALCOMIS or logistics databases. Instead, it aggregates data from these systems into a common structure that supports analysis.

Inputs to the unified data layer include aircraft generated data, maintenance records, logistics data, and environmental conditions. Aircraft data includes vibration information, fault codes, and performance metrics. Maintenance data includes component removals, repairs, and inspections. Logistics data includes inventory levels, demand history, and supply timelines. Environmental data captures operating conditions such as temperature, altitude, and location to extrapolate soil type and corrosive elements.

By combining these data sources, the system can assess aircraft condition in a more complete context while leaving decisions to continue operating the aircraft or replace components up to the humans conducting the mission. This enables more accurate predictive modeling and supports decision making at all levels of architecture.

4. Predictive Analysis and Decision Support

The digital twin uses integrated data to generate predictive outputs that support sustainment decisions. The system evaluates component performance and estimates the likelihood of future failures. It also considers the operational impact of those failures.

The primary output is a decision support report tailored to the user. This report identifies components that are likely to require maintenance or replacement within a



specified timeframe. It also provides an assessment of the severity of potential failures if no action is taken.

The system evaluates maintenance actions based on available resources. For example, the model can compare the effort required to repair a component with the availability of material to replace it. This assessment accounts for available manpower and time constraints defined by the user.

The output is not a directive. It is a recommendation. A human-in-the-loop reviews the assessment and determines the appropriate course of action. This ensures that operational priorities and mission requirements are considered alongside predictive analytics.

5. Forward-Deployed Capability

The forward deployed node is the threshold requirement for this architecture. The system must function at this level without reliance on continuous connectivity. This reflects the operational environment of Marine aviation, where units must make decisions with limited external support.

At the node, the digital twin provides the ability to evaluate aircraft readiness prior to mission execution. Squadron leadership can use the system to select aircraft for deployment based on projected reliability. The system can also identify components that should be repaired or replaced before deployment. This optimizes building maintenance phase trees to build continuity as decision makers move to new units or end active service. Increased visibility to decision makers at the CNAF level facilitates rapid prioritization when facing material constraints.

This capability supports more effective planning and reduces the risk of aircraft becoming unavailable during operations. It also enables more informed logistics decisions by identifying required parts before failures occur.



6. Integration with Sustainment Processes

The architecture is designed to integrate with existing sustainment processes rather than replace them. Maintenance systems and logistics systems remain in place. The digital twin provides an additional layer of analysis that supports decision making.

Predictive outputs can be used to inform logistics planning and supply actions. Components can be ordered in advance based on projected demand rather than waiting for failures to occur. This supports a shift from reactive sustainment to predictive sustainment.

Phase maintenance is also affected by this approach. Existing inspection intervals remain in place. However, predictive analytics can be used to adjust maintenance actions based on aircraft condition. This allows maintenance to be tailored to individual aircraft rather than relying solely on fleet-wide averages.

7. Implementation Considerations and Risks

The primary challenge associated with this architecture is trust. Predictive systems require users to rely on model outputs rather than traditional experience-based decision making. If users do not trust the system, it will not be used effectively. Keeping the software agile for end users to make custom data fields to see what is most relevant to them gives more ownership and utility of the system.

Data quality also affects system performance. Inconsistent or incomplete data can reduce the accuracy of predictive models. This reinforces the need for improved data integration and standardization.

Contracting alignment is another consideration. Predictive sustainment requires changes to how logistics support is structured. Existing contracts must be adjusted to incorporate predictive demand and incentivize proactive support.

Despite these challenges, the architecture provides a feasible approach to enabling predictive sustainment. It aligns with existing operational structures and leverages available data while introducing new analytical capability.



F. IMPLEMENTATION PHASING STRATEGY

This section outlines a phased approach to develop and field a digital twin enabled sustainment capability for the H-1 platform. The strategy aligns with the Adaptive Acquisition Framework and supports gradual integration into existing sustainment processes. The approach prioritizes early operational testing, iterative development, and eventual integration with logistics and contracting structures.

1. Implementation Timeline and Approach

The proposed implementation follows a five-year timeline aligned with the Middle Tier of Acquisition pathway. This timeline allows for rapid prototyping while maintaining sufficient time for refinement and scaling. Initial capability can be demonstrated within the first two to three years through limited operational testing.

The strategy is structured in phases that build upon each other. Early phases focus on data integration and prototype development. Later phases expand capability and integrate predictive outputs into sustainment processes.

2. Phase I: Data Integration and Prototype Development

The first phase focuses on establishing the data foundation required to support predictive analytics. This includes integrating aircraft generated data from IMD-HUMS with maintenance data from NALCOMIS OOMA. These data sources provide the baseline required to begin modeling aircraft condition and component performance.

This phase is led by PMA-276 with support from NAVAIR digital engineering resources. Development is executed under a dedicated prototype contract aligned with the Middle Tier of Acquisition pathway. The objective is to produce a minimum viable capability that can support limited decision making.

Initial development focuses on a single use case. The system is designed to support aircraft selection for a detachment. This use case provides a measurable application for predictive analytics while limiting operational risk.



3. Phase II: Operational Prototype and Parallel Testing

The second phase introduces the prototype into an operational environment. A single HMLA squadron is selected to conduct testing. This provides a realistic environment without introducing unnecessary variability associated with test units that operate under non-standard conditions.

The Marine Corps Service Level Training Exercise at Twentynine Palms provides an ideal test scenario. During this exercise, the selected squadron must determine which aircraft will deploy as part of a detachment for approximately thirty-five days. The digital twin tool is used to generate a recommended set of aircraft based on projected reliability and component performance.

Testing is conducted in parallel with existing decision processes. Squadron leadership continues to select aircraft using current methods. The digital twin generates a separate recommendation that is not used to influence the decision. Aircraft performance is then monitored throughout the exercise to assess the accuracy of the model.

This approach allows validation of predictive outputs without introducing operational risk. It also supports user familiarization with the system and begins to build trust in the capability.

4. Phase III: Model Refinement and Software Sustainment

The third phase focuses on refining the digital twin model based on data collected during operational testing. Inputs from aircraft performance, maintenance actions, and user feedback are incorporated into the model. This phase transitions from prototype development to sustained software development under the Software Acquisition Pathway.

A software sustainment contract is established to support continuous updates to the digital twin. This includes incorporating new data sources, refining predictive algorithms, and improving user interfaces. The system continues to operate within existing maintenance and logistics frameworks.



During this phase, the capability expands beyond the initial use case. Additional decision support functions can be introduced, including maintenance planning and identification of future component requirements.

5. Phase IV: Integration with Logistics and Contracting

The final phase integrates predictive outputs into sustainment processes and contracting structures. This phase represents a shift from reactive logistics to predictive support.

Outputs from the digital twin are used to inform demand forecasting and supply planning. Components can be ordered in advance based on projected need rather than waiting for failures. This supports improved aircraft availability and reduces downtime. Integration with performance-based logistics contracts is required to fully realize this capability. Existing contracts must be modified to incorporate predictive demand signals. Incentives should be aligned to support proactive component delivery rather than reactive repair.

This phase will require coordination with original equipment manufacturers, NAVSUP, and other stakeholders. It represents the most complex aspect of implementation due to existing contractual structures and organizational boundaries.

Metrics for Success

The effectiveness of the digital twin capability is measured through operational outcomes. One key metric is the reduction in Non Mission Capable rates. This includes both supply-related and maintenance-related downtime. A decrease in these rates indicates improved sustainment performance.

Another metric is the accuracy of failure predictions. The system must demonstrate the ability to correctly identify components that require maintenance within a defined timeframe. This metric is critical for building trust in the system and validating its predictive capability.

These metrics will allow for an accurate evaluation of system performance during testing and after implementation.



G. CHAPTER SUMMARY

This chapter presented a digital twin enabled sustainment architecture designed to support predictive decision making for the H-1 platform. The analysis began with a review of the current sustainment data environment and identified limitations in how maintenance and logistics decisions are made. Although large amounts of data exist across aircraft systems and sustainment processes, this data is not integrated in a way that supports forward-looking decision making.

Subject matter expert interviews reinforced these findings. Participants described challenges with data access, limitations in predictive maintenance capability, and constraints within current logistics and contracting structures. These insights highlighted the need for a system that can integrate available data and provide actionable outputs to decision makers at the operational level.

The chapter then examined how existing acquisition policy can support the development of this capability. The Adaptive Acquisition Framework provides a viable pathway through a combination of rapid prototyping and continuous software development. A phased approach using the Middle Tier of Acquisition pathway followed by transition to the Software Acquisition Pathway allows the capability to be developed, tested, and refined in an operational environment.

A digital twin architecture was proposed to address the identified limitations. The architecture is based on a hub, spoke, node model that reflects the structure of naval aviation operations. The forward deployed node serves as the focal point for decision making and represents the threshold requirement for the system. A unified data layer integrates inputs from aircraft systems, maintenance records, logistics data, and environmental conditions. Predictive analytics generate outputs that support aircraft selection, maintenance planning, and component forecasting. A human-in-the-loop approach ensures that recommendations are evaluated within the context of operational requirements.

A detailed implementation strategy was also presented. The approach begins with data integration and prototype development, followed by operational testing at the



squadron level. The Marine Corps Service Level Training Exercise was identified as a realistic environment for initial validation. Subsequent phases focus on model refinement, software sustainment, and integration with logistics and contracting structures. Success is measured through reductions in Non-Mission Capable rates and improved accuracy of failure predictions.

The findings of this chapter support the primary research objective of this thesis. The Adaptive Acquisition Framework provides a viable pathway for developing digital twin capability, but successful implementation requires alignment across data architecture, acquisition strategy, and sustainment processes. The proposed approach enables predictive sustainment at the forward deployed level while remaining compatible with existing systems and organizational structures.

This chapter establishes the foundation for implementing digital twin capability within the H-1 program and provides a framework that can be extended across the Naval Aviation Enterprise.



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V. CONCLUSION AND FURTHER RESEARCH

This research examined how the Marine Corps H-1 program can develop and implement a framework for BUNO-specific digital twins to support predictive sustainment and improve readiness outcomes. The analysis identified that current sustainment practices rely heavily on reactive maintenance, fragmented data systems, and fleet-wide averages that do not account for the variability in aircraft usage and operating environments. These limitations reduce the effectiveness of maintenance planning, delay logistics response, and constrain the ability of decision makers to optimize aircraft selection for deployment.

A. RESEARCH FOCUS

The primary research question focused on whether digital twins could improve sustainment decision-making by enabling aircraft specific modeling of component degradation, maintenance and supply forecasting, and readiness risk. Additionally, the research examined how these predictive capabilities could refine current performance-based logistics contracting strategies. The study ultimately investigated how a digital twin-enabled sustainment architecture could transition the H-1 enterprise from reactive maintenance practices to a more predictive, condition-informed, and operationally responsive sustainment model.

1. Today's Barriers to Sustaining the H-1 Aircraft

Scheduled maintenance intervals refined only by fleet-wide averages and manual interpretation of disconnected data systems limit sustainment of the H-1 aircraft today. Without a unified information ecosystem, decision makers at the operational leading edge lack timely visibility of the condition of the individual aircraft available for the mission at hand. Maintenance planners expend labor hours and replace material with usable life remaining yet react to unscheduled failures on other systems not monitored. Supply planners struggle to manage working capital funds obligated to chase last year's demand spikes with little to fund current unfilled orders. Inability to integrate BUNO level operational context such as environmental exposure, mission profile, and component specific usage limits effectiveness of current sustainment planning methods.



2. Framework Used to Address These Barriers

The framework proposed in this study is a digital twin-enabled sustainment architecture designed to integrate operational, maintenance, engineering, and supply-chain data into a unified decision-support environment. As discussed in Chapters II through IV, the framework combines three complementary concepts: digital twins, predictive analytics, and performance-based logistics (PBL). At its core, the framework establishes an aircraft-specific digital representation of each H-1 bureau number (BUNO) that continuously incorporates data from systems such as IMD-HUMS, NALCOMIS/OOMA, DECKPLATE, engineering repositories, and logistics databases. These digital twins use predictive models to estimate component degradation, remaining useful life, maintenance requirements, and future materiel demand. The resulting outputs support decisions at multiple levels, including aircraft selection for deployment, maintenance scheduling, spare-part forecasting, and long-term product support strategy. By linking technical condition data with logistics and contractual decision-making, the framework provides a structured means to transition the H-1 enterprise from reactive, interval-based sustainment to a predictive, condition-informed approach aligned with readiness outcomes and future PBL arrangements.

This framework addresses the barriers identified throughout the research by establishing the foundational elements necessary for predictive sustainment. The framework first creates a unified data environment that overcomes the fragmentation of operational, maintenance, engineering, and supply data. It incorporates predictive analytics that transform raw data into actionable forecasts of component degradation and readiness risk. It provides a common analytical basis that can be used by program managers, logisticians, maintainers, and contracting personnel to make more informed decisions. Finally, the framework supports a phased implementation strategy consistent with the Adaptive Acquisition Framework, enabling incremental development while managing technical, organizational, and policy risks. These elements together offer a practical and scalable approach for overcoming existing barriers and establishing a digital foundation for more responsive and cost-effective H-1 sustainment.



3. Predicted Barriers as New Sustainment Framework is Implemented

Although the proposed framework offers substantial potential benefits, the research also identified significant barriers that will complicate implementation. The largest obstacles involve data integration, cybersecurity requirements, intellectual property restrictions, and organizational resistance to changing existing sustainment practices. Implementing the framework will require development of a unified digital environment that connects existing aircraft, maintenance, engineering, and logistics information systems into a common data architecture. This environment would aggregate data from sources such as IMD-HUMS, NALCOMIS/OOMA, DECKPLATE, engineering repositories, and supply databases, allowing predictive models to analyze aircraft-specific conditions and generate decision-support outputs. Establishing this integrated data environment will require extensive coordination among stakeholders, development of secure interfaces between systems, and completion of Authorizations to Operate (ATOs) and other cybersecurity approvals before operational use. Organizationally, the transition from experience-based sustainment decision-making toward algorithm-supported predictive sustainment may also encounter resistance from personnel accustomed to traditional maintenance processes. Successful implementation will require not only technical modernization but also governance reform, workforce development, policy alignment, and long-term institutional commitment.

4. How the Proposed Framework Can Be Generalized

While this study focused specifically on the Marine Corps H-1 platform, the proposed framework has broader applicability. Many military aviation platforms operate under the same disconnected data sources and interval-based maintenance practices. The findings suggest that digital twin enabled sustainment architectures can serve as scalable models for integrating operational, engineering, and logistics data across multiple weapons systems. The framework may therefore provide value for other aviation platforms through digital twin architecture under the adaptive acquisition framework. Furthermore, the integration of predictive analytics with performance-based logistics strategies may offer a



replicable approach for improving sustainment affordability and operational responsiveness across the broader sustainment enterprise.

5. Proposed Sustainment Framework

This research concludes that the Marine Corps H-1 program can develop a viable framework for BUNO-specific digital twins by integrating existing operational, maintenance, engineering, and logistics data into a unified predictive sustainment architecture aligned with modern digital engineering principles and Adaptive Acquisition Framework pathways. Although substantial organizational and policy barriers remain, the research demonstrates that foundational data sources and enabling technologies necessary to support predictive sustainment already exist within the H-1 enterprise. This study does not propose the development of an entirely new system. Instead, it recommends the more effective integration and use of existing aircraft, maintenance, engineering, and logistics data. With disciplined data governance, secure system interfaces, and coordinated implementation, these existing resources can be combined to enable a practical and scalable digital twin capability that improves sustainment decision-making and readiness outcomes. A digital twin enabled sustainment framework could significantly improve operational availability, maintenance and supply planning and performance-based logistics contract strategies to transition the H-1 program from reactive sustainment toward a predictive and operationally responsive sustainment model.

6. Decision-Support Applications of Digital Twin Outputs

The findings of this research indicate that the value of a digital twin extends well beyond improved visibility into aircraft condition. By replacing fleet-wide averages with aircraft-specific predictions of component degradation, remaining useful life, and future demand, a digital twin-enabled framework could materially improve many of the H-1 program's most important sustainment decisions. More accurate forecasts would strengthen material allowance calculations, support earlier initiation of long-lead procurements, and reduce the likelihood of non-mission capable for supply conditions. Maintenance planners could better prioritize inspections and repairs based on projected readiness risk rather than fixed intervals alone, while engineers could use the same analyses



to evaluate overhaul standards, compare alternate sources of repair, and quantify the expected return on design changes intended to improve reliability. These predictive outputs would also provide a more rigorous analytical foundation for performance-based logistics business case analyses by enabling PMA-276 to estimate component demand, readiness outcomes, and contractor performance metrics with greater confidence. Together, these capabilities would allow the H-1 program to make more informed technical, logistical, and contractual decisions and provide a practical path toward a predictive, condition-informed, and operationally responsive sustainment model.

B. FURTHER RESEARCH

While this research outlines a framework for digital twin enabled sustainment, several areas require additional study before the capability can be implemented at scale across Naval Aviation. These areas reflect practical challenges that emerged during the analysis but could not be fully addressed within this study.

Cybersecurity is one of the first issues that needs further examination. The proposed system depends on frequent software updates, data exchange across multiple levels, and the ability to operate at the forward deployed node. Current Risk Management Framework processes are not well suited for systems that evolve continuously. Future research should focus on how continuous authorization to operate (cATO) can support a digital twin system. This includes how updates are approved, how data is protected, and how the system continues to function when connectivity is limited.

Standardization is another area that requires attention. Digital twin capability will not scale unless there is some level of consistency across platforms. At the same time, each aircraft has unique characteristics that must be accounted for. This balance is not well defined today. Research should examine how Naval Aviation can establish common standards for data structure and system integration without limiting flexibility. This effort should not begin late in the life cycle of a platform. It must be considered during development, when instrumentation and built-in tests are first designed. Without that early planning, predictive capability will always be limited by the quality of available data.



Refinement of the data architecture also requires further study. While this research proposes a unified data layer, it does not fully define how different data streams should be structured and combined. Aircraft systems, maintenance records, and logistics databases were developed independently and do not align in format or purpose. As a result, combining these data sources into a single usable model remains a challenge. Future research should examine how to design a data architecture that can ingest and organize these inputs in a consistent way. This includes determining how data is normalized, how discrepancies are resolved, and how information is presented to support predictive analysis. Without a more refined approach to data architecture, the effectiveness of digital twin capability will remain limited regardless of the quality of the underlying models.

Ownership across the life cycle remains unclear. Aircraft programs in operations and sustainment often do not have the funding or authority to develop new capabilities. Programs in development are focused on delivering aircraft and managing configuration. As a result, digital twin capability falls into a gap between phases. Future research should examine how responsibility for this type of capability is assigned. This includes identifying who leads development, who funds it, and how it is sustained over time.

Data governance is closely tied to this issue. While this study addressed data access, it did not fully define how data should be managed. Questions remain about who is responsible for validating data and resolving inconsistencies between systems. There is also a need to define how data flows between node, spoke, and hub levels without creating conflicting versions of the same information. Research should focus on governance models that establish clear authority while still allowing data to be shared across the enterprise.

Model validation is another area that requires deeper study. Predictive systems are only useful if users trust the output. That trust depends on consistent performance over time. Future research should focus on how to measure model accuracy in an operational environment. It should also examine how uncertainty is presented to users. Maintainers need to understand what the system is telling them and how much confidence to place in that information.



Cost and return on investment should also be explored in more detail. This study identified potential improvements in readiness, but it did not quantify the financial impact. Decision makers will need to understand whether the benefits justify the cost of development and sustainment. Future research should examine how predictive maintenance affects inventory levels, repair timelines, and overall operating costs. This will help determine how the capability should be prioritized across platforms.

Contracting presents another challenge. The current structure of performance-based logistics is built around responding to failures. A predictive approach changes that relationship. Parts may be ordered before failure occurs, and maintenance actions may shift based on model outputs. Future research should examine how contracts can be adjusted to support this approach. This includes how incentives are structured and how data is shared between the government and industry partners.

Environmental effects are not well captured in current sustainment practices and need further study. Aircraft operating conditions have a direct impact on how components degrade. These factors are often addressed after the fact rather than built into planning. Research should focus on how environmental data can be incorporated into predictive models in a meaningful way. This will improve the accuracy of the system and better reflect real operating conditions.

Training is another critical area. Maintainers are the primary users of digital twin systems and need to understand how to use them for digital twins to have a positive impact on readiness. Future research should examine how training can be integrated into existing maintenance pipelines. This includes how to present information in a way that supports decision making rather than adding complexity.

Finally, scalability across platforms must be addressed. The H-1 program is a useful starting point, but the value of this capability increases when it is applied across Naval Aviation. Future research should examine how this framework can be adapted to other platforms without requiring a complete redesign. This includes identifying what can be standardized and what must remain platform specific.



These areas reflect the work that remains from a pilot capability to an enterprise solution. Addressing them will be necessary to ensure that digital twin enabled sustainment can be implemented in a way that is effective, sustainable, and trusted by the users who rely on it.



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