# Inter-Agency Working Group on Engineering Complex Systems, Targeted Action Group Report for FY24 – 25

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National Aeronautics and
Space Administration

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Hampton, Virginia 23681-2199

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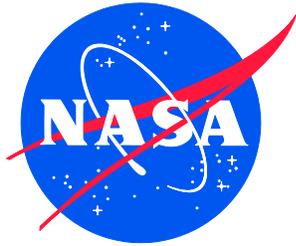
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# 1.0 Interagency Working Group Membership

## 1.1 Current IAWG Participating Agencies (as of August 2025)

- National Science Foundation (NSF)
- Department of Defense (DoD)
- National Aeronautics and Space Administration (NASA)
- National Institutes of Standards and Technology (NIST)
- Department of Energy (DOE)
- Department of Transportation (DoT)
- Department of Homeland Security (DHS)
- Additional agencies are welcome to join

## 1.2 Contributing Members

### 1.2.1 IAWG Leadership

| Name | Title | Organization |
|---|---|---|
| **Executive Committee** | | |
| Duron Shearn | Acting Director, Systems Engineering and Standards Division, DHS S&T | DHS HQ |
| Joseph W. Pellicciotti | Chief Engineer at NASA | NASA |
| KatherineVanhooser | Deputy Chief Engineer at NASA | NASA |
| Dr. Vijay Srinivasan | Senior Advisor, Engineering Laboratory | NIST |
| Kent Jones | Assistant Deputy Administrator for Systems Engineering and Integration | NNSA / DOE |
| **Action Committee** | | |
| Dr. Anna-Maria Rivas McGowan | Senior Technologist for Complex Systems Design | NASA |
| Theodore Johnson | Senior Systems Engineer, Defense Programs Office of SE&I | NNSA / DOE |
| Ken Roof | Systems Engineering Policy and Outreach Lead | DHS HQ, Science and Technology |
| Mark Moody | AST, Engineering Program Management, Office of the Chief Engineer | NASA |

## 1.2.2 TAG Members

| Name | Organization |
|---|---|
| **Targeted Action Groups** | |
| **Additive Manufacturing (AM) Qualification & Certification: Pathways to AM Adoption** | |
| Alison Park, Chair | NASA |
| Dr. Timothy Simpson, Co-Chair | NASA |
| Chris Saldana | DOE |
| Huijuan Dai | DOE |
| Andy Deal | Kansas City National Security Campus |
| Michael Gorelik | FAA |
| Cindy Ashforth | FAA |
| Lori Smith-Mitchell | DLA |
| Brett Conner | DoD (JAMWG) |
| Linkan Bian | NSF |
| Paul Witherell | NIST |
| Austin Young | NRC |
| Tyler LeBrun | Sandia National Lab |
| Dale Cillessen | Sandia National Lab |
| **Digital Twins for Failure Prediction White Paper** | |
| Theodore Johnson, Chair | DOE / NNSA |
| Terry Hill, Co-Chair | NASA |
| Dr. Steven Cornford | The Aerospace Corporation / NASA |
| Mark Adams | DHS |
| Ioana Biloiu | DOE / NNSA |
| Andrew Foote | DoD |
| Dr. Vijay Srinivasan | NIST |
| **Supply Chain Risk Reduction Approaches and Best Practices** | |
| Joseph Moehlmann, Chair | DOE / NNSA |
| Paula George, Co-Chair | DoD / DLA |
| Alma Thomas | DHS, Science and Technology |
| David McQuain | NASA |
| Grant Korte | DHS / USCG |

| Honore Nyuyse | DHS, Science and Technology |
|---|---|
| Chris Hall | DHS / USCG |
| Edward Moshinsky | Office of the Under Secretary of Defense |
| Monique Ofori | Office of the Secretary of Defense |

## 1.3 Acknowledgements

# 2.0 Introduction

To stay well-positioned as an adaptive and leading technical pioneer, the United States (US) must accelerate the advancement and rapidly changing integration of engineering and sociotechnical systems that make up the nation's most complex, large-scale engineered systems such as aerospace, transportation, and national security systems.  Collaborative leadership among thought leaders remains a defining resource for increasing the innovation, efficiency, and impact in defining the path forward.  The Inter-Agency Working Group (IAWG) on Engineering Complex Systems (ECS) is an informal collaboration between agency executive leaders committed to characterizing the way forward for the US Government to achieve essential transformations in the engineering of complex systems. The group addresses effectiveness, affordability, timeliness, and adaptability challenges posed by current and rapidly changing technologically sophisticated integrated systems and practices, through tools and methods, grounded in fundamental natural and social scientific and mathematical principles.

The IAWG on ECS was originally actualized in 2012 and continues today as an informal and efficient means for federal engineering executives to advance the practice and preparedness for engineering's increasingly complex systems and to proactively solve relevant systems problems that impact multiple agencies. The time horizon considered by the working group includes near, mid, and long-term solutions to meet the future needs engineering complex systems.  The functions of the working group include advisory, advocacy, outreach, influence, problem solving and sharing.  Sharing activities occur the most frequently as innumerable lessons learned, findings from programs, strategies, policies, and other insights are shared among the leadership group thus saving considerable resources and duplication of effort and increasing knowledge transfer.  Informal spin-off activities from the IAWG on ECS are common as numerous smaller connections focused on specific topic areas are initiated across the federal sector that yield efficient means of addressing challenges.

More formal "Targeted Action Groups" are also launched as a short-term focused activity after the Executive Committee of the working group identifies, prioritizes and resources multi-agency collaboratives to address specific topic areas.  The current report provides the detailed products of the three Targeted Action Groups that were implemented in fiscal years 24 – 25.  The Targeted Action Groups (TAGs) were:

1. Additive Manufacturing (AM) Qualification & Certification: *Pathways to AM Adoption*
2. Using Digital Twins for Failure Prediction
3. Supply Chain Risk Reduction Approaches and Best Practices

This report begins with background on the IAWG on ECS and an up-to-date summary of the working group today followed by the detailed reports of the three TAGs.

## 2.1 Background

The IAWG on ECS was formed in 2012 by the National Science Foundation (NSF) and the National Aeronautics and Space Administration (NASA) in a response to interest from several agencies in addressing the challenges of engineering increasingly complex systems, particularly those that have large-scale implications in terms of cost, usage, national security, or scientific advancement. The original working group founders produced an article special journal introduction that described the foundational challenges of engineering large-scale complex engineered systems as described in the 2010 position paper *Design of Complex Engineered Systems* (C. Bloebaum, AM. McGowan). Subsequently the working group collectively developed a brief position paper in 2014 that is provided in **Appendix A**.

The working group has been a vehicle for cross-agency communication, coordination and collaboration on initiatives to improve the engineering of complex systems. The group has shared innumerable ideas, strategies, policies, lessons learned, etc., and has spawned countless smaller collaborations on committees and teams across the federal government. Outward facing efforts have included running workshops on special topics, presenting on panels at conferences and advocating for research into the fundamental theories and principles of systems design and engineering.

The *value* derived from the synergistic IAWG collaboration and achieved through the dissemination of the *products* of the TAGs include:

1. Identifying and working towards solving future Engineering Complex Systems needs by:
    1.1. Identify integrated public & private technical needs and approaches
    1.2. Identify shortfalls in technical education and infrastructure, etc.
    1.3. Streamline and update processes
    1.4. Remove bureaucratic impediments
2. Enabling the U.S. Government to be prepared to address Engineering Complex Systems by:
    2.1. Driving strategic directions for R&D and investments
    2.2. Driving strategic directions for future workforces and national infrastructure
3. Getting agency Executives in the same room – provides an executive level network for rapid action as necessary by:
    3.1. Providing a forum for agencies to talk about emerging directions of their organization
    3.2. Informing the Executives members of common issues
    3.3. Improving engineering ecosystem across the federal enterprise for Engineering Complex Systems (e.g., Smart Cities)

## 2.2 Implementation Structure

Organizationally the IAWG on ECS is comprised of an Executive Committee and Action Committee. The Executive Committee, composed of department and agency executives responsible for engineering functions, aims to deliver solutions to meet the future needs of complex systems. Its primary responsibilities include advisory and advocacy efforts, driving strategic directions for research and development investments, workforce planning, and national infrastructure improvements. The committee identifies and prioritizes topic areas and initiates the establishment of TAGs to address them.

The Action Committee, composed of representatives from each agency, plays a critical role in executing the plans and priorities set by the Executive Committee. Its responsibilities include organizing Executive Meetings, overseeing TAGs, monitoring progress, and developing documentation such as white papers and decision summaries for executive review. The committee also works to expand IAWG ECS participation by engaging additional agencies. Artifacts produced by the Action Committee, such as meeting summaries and TAG updates, are shared with the broader community. TAGs are intended to be short termed (from a few months to 2 years), multi-agency teams formed to address specific actions identified by the Executive Committee. These groups are coordinated by the Action Committee, with input from subject matter experts to plan, schedule, and deliver results on defined topics. TAGs may involve resources such as labor, travel funds, and specialized expertise, and can collaborate with industry or external organizations as needed. Their activities include problem-solving workshops, conference presentations, white papers, outreach efforts, training, and personnel exchanges to foster collaboration and advance multi-agency objectives.

Executive Meetings serve as a platform to advance the practice and preparedness for engineering's increasingly complex systems while fostering collaboration among agency executives. These meetings strategically identify and solve future engineering needs and enable agencies to proactively address systems challenges impacting multiple stakeholders. The meetings are designed to encourage open dialogue, address special topics, provide updates on existing TAGs, and identify new areas for action. Regarding the TAG reports provided herein: the insights and recommendations for each of these nation-wide efforts will be distributed to leaders inside and outside of the IAWG on ECS and follow-on actions will be considered by the Executive Committee.

## 2.3 FY 24-25 Targeted Action Groups

As aforementioned, three TAGs were launched in FY24 to address prioritized topic areas identified by the Executive Committee.  The Action Committee worked with each TAG to ensure the goals and deliverables were completed per the guidance of the Executive Committee.  The TAGs were led by two SMEs and staffed with representatives from several agencies.  The TAG leads for the reports provided herein were:

## 2.3.1 Additive Manufacturing (AM) Qualification & Certification: Pathways to AM Adoption

Timothy Simpson, Ph.D.
> Senior Advisor for Advanced Manufacturing & Digital Engineering
> Strategic Partnerships Office | NASA Langley Research Center

Alison Park
> Deputy Tech Fellow
> NASA Engineering and Safety Center

## 2.3.2 Digital Twins for Failure Prediction:

Theodore Johnson
> NNSA/DoE Senior Systems Engineer
> Defense Programs Office of SE&I

Terry Hill
> NASA Digital Engineering Program Manager
> NASA Headquarters, Office of the Chief Engineer

## 2.3.3 Supply Chain Risk Reduction

Joseph Moehlmann
> Logistics Analyst, NNSA/NA-182
> National Nuclear Security Administration

Paula George
> Quality/Technical Analyst
> Department of Defense/Defense Logistics Agency

# 3.0 Targeted Action Group Complete Reports

3.1 Additive Manufacturing (AM) Qualification & Certification: Pathways to AM Adoption



Figure 1: Additive Manufacturing (AM) Qualification & Certification; Pathways to AM Adoption

# 3.1.1 Executive Summary

# Bottom Line Up Front (BLUF)

- We all benefit from *Additive Manufacturing (AM) Adoption*
  - IAWG AM TAG did "deep dive" into AM in aviation, defense, medical, nuclear and space

- AM adoption remains challenging and is expensive
  - Common challenges and themes exist, e.g., balancing risks in design, criticality, production, safety, security, schedule, consequences of failure, etc.

- Goals for IAWG AM TAG:
  - To introduce and connect AM leads across several agencies
  - To identify pathways to AM adoption at the agency level
  - To discuss differences and similar challenges agencies face
  - To recognize duplicate efforts and discover inefficiencies
  - Make recommendations to enable faster AM adoption

  **IAWG AM TAG Deliverable**
  This final presentation which includes active hyperlinks to 150+ AM docs and stds

- Key Finding: Synergies can be improved by communication and coordination

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Figure 2: Bottom Line Up Front (BLUF)

# Committee Members & Significant Contributors

| Committee Members on IAWG AM TAG | |
|---|---|
| NASA | Alison Park, Chair<br>Tim Simpson, Co-Chair |
| DOE | Chris Saldana<br>Huijuan Dai |
| Kansas City National Security Campus | Andy Deal |
| FAA | Michael Gorelik<br>Cindy Ashforth |
| DLA | Lori Smith-Mitchell |
| DoD (JAMWG) | Brett Conner |
| NSF | Linkan Bian |
| NIST | Paul Witherell |
| NRC | Austin Young |
| Sandia National Lab | ~~Tyler LeBrun~~ → Dale Cillessen |

| Special Thanks to Significant Contributors | |
|---|---|
| FDA | Matthew Di Prima<br>Kirstie Snodderly<br>James Coburn |
| Navy | Evan Handler<br>Jenny Semple<br>Justin Rettaliata<br>John Schmelzle |
| Air Force | Adam Hicks<br>Jeff Calcaterra<br>Matt Krug<br>Marybeth Radtke |
| DLA | Jonathan Adkins |

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Figure 3: Committee Members & Significant Contributors

# Why care about Additive Manufacturing (AM)?

- AM offers national strategic value for high-consequence applications (NIST Report 2022)[1]
  - Benefits to personal and public safety
  - Have a profound economic impact
  - Enhance national security and readiness

- AM provides a "Hail Mary" for U.S. manufacturing needs
  - Improve supply chain resilience[2] and reshore manufacturing[3]
  - Address production shortfalls with castings and forgings[4]
  - Provide means for companies to mitigate impact of tariffs[5]

- AM is considered vital to our national security
  - 83% increase in DoD's FY26 budget for AM[6] ($3.3B vs. $1.8B)
  - Enable dual-use factories[7] that can pivot to wartime production



**Rocket Combustion Chamber**

$310,000
18 mo.

with AM:
$125,000
in 5 mo.

Source: Paul Gradl, NASA

**Ex. Making AM Business Case for Space**

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Figure 4: Why care about Additive Manufacturing (AM)?

# What makes AM so challenging and expensive?

- Additive manufacturing creates *process-intensive materials*
  - AM processing conditions, material feedstock, and design geometry all impact the material microstructure, properties, and performance of the part
    - MMPDS Vol. 2[8] defines a new framework for generating/analyzing AM material data (2024)

**Material, process, and part must be qualified/certified when using AM**

Example from *Common Additive Manufacturing Qualification Template*:

- NIST estimates inserting AM into an aviation part factory requires millions of dollars in infrastructure spending and years of material testing
- Vendor qualification is considered proprietary to Lead System Integrators (e.g., Boeing, Lockheed)
- Vendors must "requalify" for each Lead System Integrator, necessitating multimillion dollar investments to be active across aviation supply chain



| | Specimen Count | Cost ($M) | Time (Yrs) |
|---|---|---|---|
| Full-scale article | 2-3 | 100-125 | 4 |
| Components | 10-30 | 10-20 | 3 |
| Sub-components | 25-50 | 10-35 | 3 |
| Elements | 2000-5000 | 10-35 | 3 |
| Coupons | 5000-100,000 | 8-15 | 2 |

Manufacturing Process (foundation)

Project #5550[9]

America Makes — Bill Tredway, ASTRO America, Project #5550

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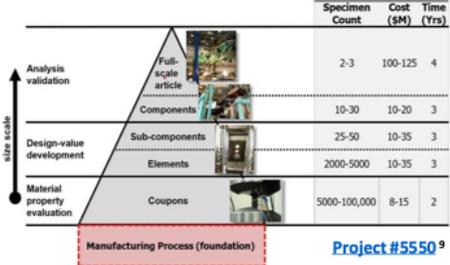
Figure 5: What makes AM so challenging and expensive?

# How does one qualify/certify parts with AM?

- AM qualification/certification is essential for high consequence applications
  - Ensures reliable and repeatable process to produce AM components "fit for service"
- We investigated AM qualification/certification pathways for aviation, defense, medical, nuclear, and space applications:
  - *Regulatory* (e.g., FDA, FAA) vs. *regulator/user/producer* (e.g., NASA, DoD, NNSA)
  - *Performance-based* (e.g., FDA, FAA) vs. *process-focused* (e.g., NASA) approach
  - *Part criticality/classification* and *risk assessment* (e.g., low/med/high vs. flight critical)
  - *Consequences of AM failure*: personal injury (FDA) vs. loss of life (FAA) vs. national security (DoD)
  - Differences in *technical/programmatic authority* across agencies
- Examples of AM part(s) that received approval by an agency
- Hyperlinks to relevant guidance documents, standards, tech pubs, etc.

> **Green box highlights:**
> - AM Value Proposition
> - Making Business Case
> - Failure Consequences

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Figure 6: How does one qualify/certify parts with AM?

## 3.1.3 Use Case Review of AM Qualification and Certification

# FDA | Regulatory Review of AM Medical Devices

- Guidance for AM medical devices published in 2017 (draft 2016)
  - AM device must be *substantially equivalent* to an existing (predicate) device
  - Must validate AM process and material controls, *no AM-specific "qual/cert" event*
- 350+ AM medical devices cleared via 510(k) pathway[10] from 2010-2020

Fig. 1a from [1]
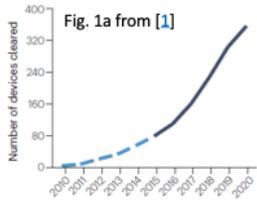
Material:
70% titanium alloy

AM Process:
76% PBF-LB/EB [1]

Fig. 1b from [1] — 2016, 2017, 2018, 2019, 2020

Ankle, Cutting Guide, Resin Only..., Dental, Hip, Shoulder, Knee, Software, Other, Spine cage

Number of devices cleared

Technical Considerations for Additive Manufactured Medical Devices

Guidance for Industry and Food and Drug Administration Staff

FDA AM Guidance Doc [11]
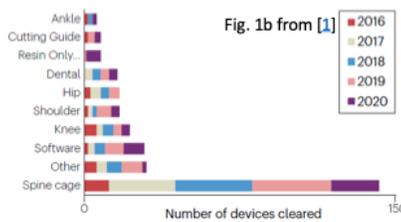
- Regulatory authority is decentralized and delegated to individual FDA centers
  - Center for Devices and Radiological Health (CDRH)[12] reviews and certifies AM medical devices/implants
    - Focus is on end-product while ensuring compliance with AM requirements/standards/regulations
    - Criticality/risk accounted for via product classification in 21 CFR: 3 device classes [13] (majority of AM devices are Class II)
  - CDRH's Additive Manufacturing Working Group reviews practices and policies related to AM
  - Agency-wide Advanced Manufacturing Working Group shares data and information across centers

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Figure 7: FDA | Regulatory Review of AM Medical Devices

# FDA | Validating AM Medical Device Performance

- Performance-based approach used to ensure product quality and process consistency:
  1. Validate the performance of AM device in the worst-case scenario
  2. Validate AM process and materials controls to ensure consistency
- Relies on ASTM and ISO/ASTM standards for medical device conformity [14]

**Ex. (Hypothetical) Spine Cage with Lattice Structure**
- Discrete sizes similar to predicate devices
- Ti6Al4V made with laser powder bed fusion
- Worst-case occurs with 6th powder reuse
- Dimensions validated using printed samples
- Compression and shear testing validate loads

*AM-specific considerations:* removal of residual powder and AM process validation
*Device-specific considerations:* mechanical performance, biocompatibility, and sterilization

Ex. Mechanical testing to validate powder reuse
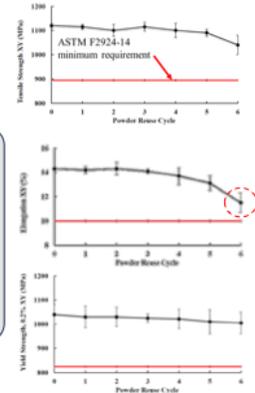
**Value of AM:** Better patient outcomes (e.g., improved osseointegration, faster recovery)
**AM Business Case:** Viable due to high annual demand (e.g., 790,000 knees; 544,000 hips [1])
**Consequences of Failure:** Patient injury, revisions/replacements, recalls

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Figure 8: FDA | Validating AM Medical Device Performance

# NASA | Regulator, Consumer, and Producer of AM

- NASA's agency-wide *AM Requirements for Spaceflight Systems* published in 2021
  - Initial AM standard/specification [15] created by NASA's Marshall Space Flight Center in 2017
  - *Qualify each material on each machine* based on a material specification and a process specification
    - Use of non-NASA specifications/standards is encouraged
  - Certify the design of a system that contains an AM part for a specific mission/spaceflight
- Criticality/risk starts with AM part classification

Part classification defines # of witness coupons/tests

NASA-STD-6030 [16]
(115 requirements)

NASA-STD-6033 [17]
(31 requirements)
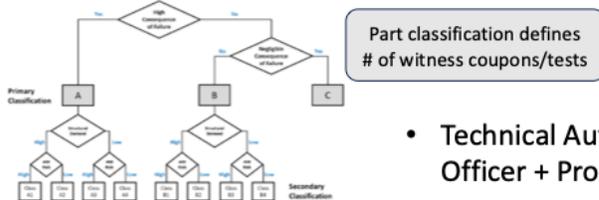
- Technical Authority resides with Chief Engineer + Safety Officer + Program Manager who sign-off at agency level

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Figure 9: NASA | Regulator, Consumer, and Producer of AM

# NASA | Prescriptive Approach to AM Qual/Cert



Workflow to define AM Material Property Suite (MPS), Qualified Material Process (QMP), Design Properties, Part Production Plan (PPP), Qualified Part Process (QPP), AM Production Readiness Review (AMRR)

- Strength, fatigue, and fracture control guidance published for AM spaceflight hardware in 2024

**Top View**

Ex. Lightweight bracket to restrain cable bundle from NASA-HDBK-5026

Flight, spare, and first article made alongside witness and test coupons (19) to comply with NASA-STD-6030 requirements

NASA-HDBK-5026 [18]

**Value of AM:** Save weight, save cost/schedule
**Making AM Business Case:** Viable due to low production volumes and high design complexity
**Failure Consequences:** Loss of payload or crew

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Figure 10: NASA | Prescriptive Approach to AM Qual/Cert

# FAA | Certify Products/Articles that May Use AM

- Advisory Circular for *PBF AM Aircraft Engine Parts* published in 2023
  - 14 CFR §21 [19] defines certification procedures for Products (e.g., aircraft, engine) and Articles (e.g., part, component) as well as for Production Approval
  - Production Approval requires a quality system that ensures product/article confirms to approved design, *no specific AM "qual/cert" event*



**Criticality Level** = Assessed on case-by-case basis

"critical"

"Critical" Parts (e.g. CFR Part 25 → PSEs, CFR Part 33 → LLPs)

"major" effect

"minor" effect

"High Value" Parts

Time

**Value of AM:** Save weight, better performance

**Making AM Business Case:** Difficult due to low production volumes for most aircraft parts

**Failure Consequences:** Component or engine failure, aircraft crashes, loss of life

AC 33.15-3 PBF AM [20]

- FAA Certification Offices located across the country review and approve applications
  - Office manager signs off on approval based on recommendations from technical staff
  - Production Approval is reviewed and approved by Manufacturing Oversight Offices (manager signs)
  - AM focals in FAA Office of Senior Technical Experts (AIR-20) advise on certification approach

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Figure 11: FAA | Certify Products/Articles that May Use AM

Figure 12: FAA | Performance-based Approach for AM Designs



Figure 13: Navy | Regulator, Producer, and Consumer of AM

# NAVSEA Decision Tree for AM Part Adoption

START
2. Requirements
3. Part Performance Requirements
4. Determination of Application Service Condition Level

Severity Level 1-5?
5. Is the component metallic?

6. AM Capability Improvement Desired?
Invoke MSR T9074-AX-GIB-010/100
6. Determine AM Capability Improvements

7. Risk Assessment
8. AM Process and Material Selection (See Figure E-2)
9. Testing and Qualification Requirements
10. Generate Technical Data Package
11. Generating Verification Package for Component Approval
Approval

- NAVSEA's AM Decision Tree and AM Material-Process Selection Flowchart (Ser 05T/2018-024)[34]

8. AM Process and Material Selection - START

Ball Valves (via WAAM)
Fairbanks Morse Defense [35]

Value Manifold (wire DED)
HII Newport News Shipyard [36]

Navy has invested $2.3B since 2018 to shift cost burden for many of these activities to expand industry capacity and defense industrial base (U.S. Naval Institute Proc.) [37]

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Figure 14: NAVSEA Decision Tree for AM Part Adoption

# Navigating AM Part Substitutions in the Air Force

- DoDi5000.93_DAFI63-149 [38]: Air Force Use of Additive Manufacturing
- EZ-SB-13-001 Rev B [39]: Requirements for Substitution of New Material, Product Form, and Processes for Aircraft Metallic Parts (2024)
- EZ-SB-19-01 [40]: Durability and Damage Tolerance Certification for AM Aircraft Structural Metallic Parts (2019)
- MIL-HDBK-516C [41]: Airworthiness Certification Criteria (Rev D coming soon)
- MIL-STD-1587F [42]: Design Criteria Standard - Material and Process Requirements for Aerospace Weapons Systems
- EN-FSB-25-01: Initial Material Qualification Requirements for Metal AM (approved June 2025)
- Risk Assessment Matrix (AWB-150) and AM Reporting Requirements (AWB-120A)

### Courtesy of AFRL
**F-15 Pylon Rib Insertion Success Story**

Issue: -7075 Al Forging, Pylon Rib, Corrosion Fatigue Cracking
-Decision to move to Ti 6-4 forging already made
Long lead time for Ti forging ~1 year

Solution: -Replace with Ti 6Al-4V Additive
-To meet urgent need for aircraft in depot
- Quality issues lessened because of high margin for Ti in this application.

RX Role: -Provided Technical Leadership to Acquisition
-Executed Technology Demonstration Project
-Worked Attachment Issues (bushings, fasteners,etc...)

First structural AM part introduced in 2003

Distribution A: Cleared for Public Release  Case No. 88ABW-2015-2477 19 May 2015

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| USAF Airworthiness Risk Assessment Matrix | | | Severity Category | | | |
|---|---|---|---|---|---|---|
| Probability Level | Probability per FH or Sortie | Freq per 100K FH or 100K Sorties | Catastrophic (1) | Critical (2) | Marginal (3) | Negligible (4) |
| Frequent (A) | $10^{-3} \le$ Prob | $100 \le$ Freq | 1 | 3 | 7 | 13 |
| Probable (B) | $10^{-4} \le$ Prob $< 10^{-3}$ | $10 \le$ Freq $< 100$ | 2 | 5 | 9 | 16 |
| Occasional (C) | $10^{-5} \le$ Prob $< 10^{-4}$ | $1 \le$ Freq $< 10$ | 4 | 6 | 11 | 18 |
| Remote (D) | $10^{-6} \le$ Prob $< 10^{-5}$ | $0.1 \le$ Freq $< 1$ | 8 | 10 | 14 | 19 |
| Improbable (E) | $0 <$ Prob $< 10^{-6}$ | $0 <$ Freq $< 0.1$ | 12 | 15 | 17 | 20 |
| Eliminated (F) | Prob = 0 | Freq = 0 | Eliminated | | | |

Internal AM guidance documents not in public domain:
- TO 34A-1-1: AM Qualifications of Technicians, Machines and Facilities (2021)
- TO 34A-2-1: Metal AM General Procedures and Process Controls (2021)
- TO 34A-3-1: Polymer AM General Procedures and Process Controls (2021)

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Figure 15: Navigating AM Part Substitutions in the Air Force

# Nuclear Applications: National Security Enterprise

- National Nuclear Security Administration (NNSA) maintains the safety, security, and reliability of the nation's nuclear weapons stockpile:
  - NAP 401.1A [43] - Identifies the quality requirements applicable to weapon activities of the NNSA Federal personnel, contractors, and subcontractors
  - SD 452.3-1B [44] - Delivers business requirements and processes for directing, managing, operating, and executing Defense Programs (DP) activities
  - SD 452.3-2A [45] - Provides a common framework to conduct and manage activities for new production and refurbishments of nuclear weapons

Design and production agencies in NSE are all independent NNSA contractors each with different responsibilities

Successful AM adoption requires following the same standards and practices used in conventional manufacturing qualification

FY24 Plan [47]

FY25 Plan [46]

"The W80-4 warhead will be the first program to introduce additively manufacturing metal and polymer components into the stockpile."

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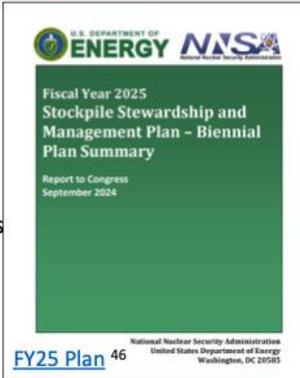
Figure 16: Nuclear Applications: National Security Enterprise

# Nuclear Applications: Nuclear Energy

- Roadmap for Regulatory Acceptance of Advanced Manufacturing Methods in the Nuclear Energy Industry [48] published by Nuclear Energy Institute in 2019

AM Thimble Plugging Device Westinghouse Electric Co [49]

1st AM part installed in a nuclear reactor in 2020 (via NRC §50.59 [50] process)

2020

Westinghouse produces 1000th AM fuel flow plate [51]

AM now being used for serial production

2024

Value of AM: Improve thermal efficiency/performance

Making AM Business Case: Viable due to low production volumes and high design complexity

Failure Consequences: Nuclear meltdown/disaster

AMT-Specific (Initial 5 AMTs) — Generic

Technical — Regulatory Guidelines

Technical Letter Report LPBF ML20351A292 | Technical Assessment LPBF ML20351A292 | Draft Guidelines Document LPBF ML21074A040

Technical Letter Report L-DED ML21301A077 | Technical Assessment L-DED ML21301A077 | Draft Guidelines Document L-DED

Technical Letter Report Cold Spray ML21263A107 | Technical Assessment Cold Spray | Draft Guidelines Document Cold Spray | Subtask 2C Draft AMT Review Guidelines ML21074A037

Technical Letter Report PM-HIP | Technical Assessment PM-HIP | Draft Guidelines Document PM-HIP

Technical Letter Report EBW | Technical Assessment EBW | Draft Guidelines Document EBW

Expected to be developed later after DOE-EPRI demo project

Nuclear Regulatory Commission (NRC) Advanced Manufacturing Technologies [52]

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Figure 17: Nuclear Applications: Nuclear Energy

## 3.1.4 AM Qualification and Certification Considerations

# What hinders AM adoption?

## Cost & Time

- Establishing material controls *and* AM process controls
- Fabricating the AM part
  - Cost of material feedstock
  - Cost of AM equipment
  - Printing time (days to weeks)
  - Post-processing time (2-3x)
- Testing and evaluation
- Inspection/inspectability

## Confidence & Trust

- Trust in the AM process
  - Confidence in relevant AM standards
  - Potential for defects during printing
  - Long-term impact on performance/life
- Organizational culture
  - Risk posture/tolerance
  - Technical/program authority
  - Lack of experience/precedents
- "Psychological readiness" for AM

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Figure 18: What hinders AM adoption?

# Standards/Specs for Material and Process Control

- Catalogued 120 metal AM standards and specifications from 12 different organizations
- Grouped by Category and Application to identify overlaps (e.g., **7 different organizations offer standards to qualify a laser PBF AM machine**)
- At least 3 parallel efforts underway to understand AM standards landscape (NIAR/AFRL, JAMWG SGS, ANSI/America Makes)

| Metal AM Standards & Specifications Organization | Total | Terminology | Data | Design | Feedstocks | Materials | Processes | Post-Processing | Qual/Cert | NDE/NDT | Personnel | Testing | Aerospace | Space | Medical | Automotive | Pressure Vessels |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AIA | 1 | | | | | | | | | | | | 1 | | | | |
| API | 2 | | | | | | | | | | | | | | | | 2 |
| ASME | 4 | | | 2 | | | | | | 1 | | | | | | | 1 |
| ASTM | 35 | | 1 | 3 | 5 | 11 | 1 | 2 | (3) | 2 | | 4 | | | 2 | 1 | |
| AWS | 1 | | | | | | | | (1) | | | | | | | | |
| FAA | 1 | | | | | | | | | | | | (1) | | | | |
| FDA | 1 | | | | | | | | | | | | | | 1 | | |
| ISO | 3 | 2 | 1 | | | | | | | | | | | | | | |
| ISO/ASTM | 29 | 2 | 2 | 4 | 2 | 1 | | 1 | (4) | 1 | 6 | 3 | (2) | | | 1 | |
| NASA | 3 | | | | | | | | | | | | | (3) | | | |
| NIAR | 1 | | | | | | | | (1) | | | | | | | | |
| SAE AME | 39 | | | | 17 | 9 | 6 | | (3) | | | | 4 | | | | |
| | 120 | 4 | 4 | 9 | 24 | 21 | 7 | 3 | 12 | 4 | 6 | 7 | 8 | 3 | 3 | 2 | 3 |

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Figure 19: Standards/Specs for Material and Process Control

# Gaps in AM Standards and Specifications



- Despite all these standards, many gaps still exist
  - Qualification/certification has the most gaps

| Section | High Priority (0-2 years) | Medium Priority (2-5 years) | Low Priority (5+ years) | Total |
|---|---|---|---|---|
| Design | 8 | 11 | 2 | 21 |
| Precursor Materials | 2 | 9 | 8 | 19 |
| Process Control | 2 | 8 | 3 | 13 |
| Post-processing | 1 | 4 | 3 | 8 |
| Finished Material Properties | 9 | 0 | 1 | 10 |
| Qualification & Certification | 13 | 10 | 3 | 26 |
| Nondestructive Evaluation | 5 | 6 | 1 | 12 |
| Maintenance & Repair | 1 | 4 | 2 | 7 |
| Data | 13 | 12 | 0 | 25 |
| Total | 54 | 64 | 23 | 141 |

America Makes & ANSI Standardization Roadmap for Additive Manufacturing (401 pages) [53]
America Makes & ANSI Gaps Progress Report (223 pages) [54]

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Figure 20: Gaps in AM Standards and Specifications

# Accelerating AM Adoption Across Military Services

- Joint Additive Manufacturing Working Group (JAMWG[55]) and DLA are supporting multiple efforts to save cost/time and accelerate adoption of AM in DoD:
  - JAMWG foci: (1) Accelerate qual/cert, (2) data/model sharing, (3) education, (4) integration,



DLA AM Implementation Plan[56] &
JAMA IV IDIQ Pilot Parts Program [57]
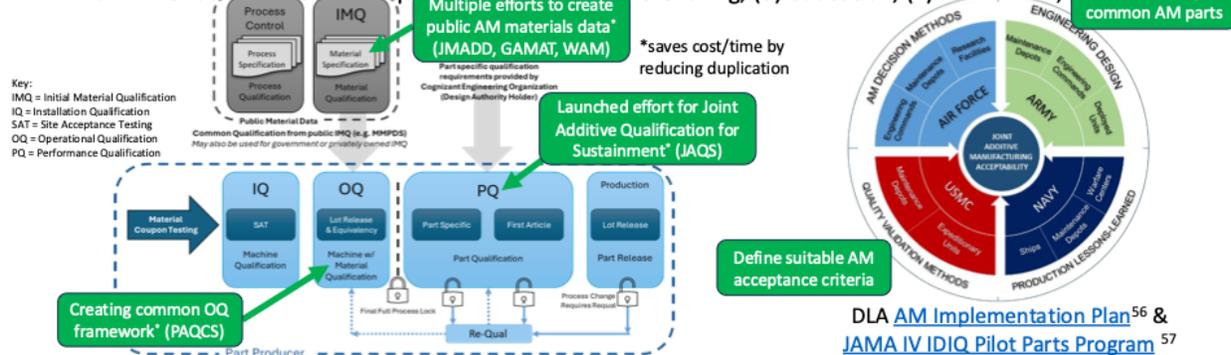
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Figure 21: Accelerating AM Adoption Across Military Services

Figure 22: Accelerating AM Adoption through Sponsored R&D

### 3.1.5 Executive Summary



Figure 23: Executive Summary

## 3.1.6 Recommendations and Suggested Next Steps

# Recommendations and Suggested Next Steps

**Goal: Accelerate AM adoption through improved communication and coordination**

- Strategic
  - Create a permanent *Federal Additive Manufacturing Coordination Council*
    - Designate AM champions at leadership levels in each agency to enable and drive AM adoption efforts
    - Develop a federal AM roadmap with clear milestones and agency-specific implementation paths
  - Create a centralized *federal knowledge repository* for AM best practices, case studies, lessons learned, pedigreed materials databases, qualified AM suppliers, etc.
  - Develop a cross-agency *Integrated Risk Management Strategy* for AM implementation
- Tactical
  - Establish *regular inter-agency technical exchanges* and workshops, following best practices and lessons learned from DoD ManTech initiatives (e.g., JDTMP[59], JAMWG[60])
  - Create *equipment-sharing agreements* between agencies to reduce costs/investments
  - Create *rotational assignments* between agencies to cross-pollinate AM expertise
  - Leverage inter-agency investments in the nation's *Manufacturing Innovation Institutes*

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Figure 24: Recommendations and Suggested Next Steps

## 3.1.7 Further Information and Resources

# Appendix

Links to AM Standards

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Figure 25: Further Information and Resources

The below standards section for Additive Manufacturing (AM) Represents the collected standards of:

- American Petroleum Institute (API)
- American Society of Mechanical Engineers (ASME)
- American Society for Testing and Materials (ASTM)
- American Welding Society (AWS)
- International Organization for Standardization (ISO)
- International Organization for Standardization and American Society for Testing and Materials (ISO/ASTM)
- National Center for Advanced Materials Performance (NCAMP)
- Society of Automotive Engineers (SAE)

# AM Standards: API, ASME, ASTM, and AWS



Figure 26: AM Standards: API, ASME, ASTM, and AWS

# AM Standards: ISO and ISO/ASTM

ISO 17295:2023 Additive Manufacturing — General Principles — Part Positioning, Coordinates, and Orientation
ISO 17296-2-2015 Additive Manufacturing — General Principles — Part 2: Overview of Process Categories and Feedstocks
ISO 23704-3-2023 General requirements for cyber-physically controlled smart machine tool systems (CPSMT) Part 3: Reference architecture of CPSMT for additive manufacturing
ISO 27548 2024 Additive Manufacturing of Plastics — EHS — Test Method for Determination of Particle and Chemical Emission Rates from Desktop Material Extrusion 3D Printers
ISO/ASTM 52900-21 Additive manufacturing — General principles — Fundamentals and vocabulary
ISO/ASTM 52901-16 Standard Guide for Additive Manufacturing – General Principles – Requirements for Purchased AM Parts
ISO/ASTM 52902-23 Additive manufacturing — Test artefacts — Geometric capability assessment of additive manufacturing systems
ISO/ASTM 52903-1-20 Additive manufacturing — Material extrusion-based additive manufacturing of plastic materials — Part 1: Feedstock materials
ISO/ASTM 52903-2-20 Additive manufacturing — Material extrusion-based additive manufacturing of plastic materials — Part 2: Process equipment
ISO/ASTM 52904-24 Additive manufacturing of metals — Process characteristics and performance — Metal powder bed fusion process to meet critical applications
ISO/ASTM 52907-19 Additive manufacturing — Feedstock materials — Methods to characterize metallic powders
ISO/ASTM 52908-23 Additive manufacturing of metals — Finished part properties — Post-processing, inspection and testing of parts produced by powder bed fusion
ISO/ASTM 52909-24 Additive manufacturing of metals — Finished part Properties — Orientation and Location Dependence of Mechanical Properties of Metal Parts
ISO/ASTM 52910-18 Additive manufacturing — Design — Requirements, guidelines and recommendations
ISO/ASTM 52911-1-19 Additive manufacturing — Design — Part 1: Laser-based powder bed fusion of metals
ISO/ASTM 52911-2-19 Additive manufacturing — Design — Part 2: Laser-based powder bed fusion of polymers
ISO/ASTM 52911-3-23 Additive manufacturing — Design — Part 3: PBF-EB of metallic materials
ISO/ASTM 52915-20 Specification for additive manufacturing file format (AMF) Version 1.2
ISO/ASTM 52920-23 Additive manufacturing — Qualification principles — Requirements for industrial additive manufacturing processes and production sites
ISO/ASTM 52921-13(2019) Standard Terminology for Additive Manufacturing—Coordinate Systems and Test Methodologies
ISO/ASTM 52925-22 Additive manufacturing of polymers — Feedstock materials — Qualification of materials for laser-based powder bed fusion of parts
ISO/ASTM 52926-1-23 Additive manufacturing of metals — Qualification principles — Part 1: General qualification of operators
ISO/ASTM 52926-2-23 Additive manufacturing of metals — Qualification principles — Part 2: Qualification of operators for PBF-LB
ISO/ASTM 52926-3-23 Additive manufacturing of metals — Qualification principles — Part 3: Qualification of operators for PBF-EB
ISO/ASTM 52926-4-23 Additive manufacturing of metals — Qualification principles — Part 4: Qualification of operators for DED-LB
ISO/ASTM 52926-5-23 Additive manufacturing of metals — Qualification principles — Part 5: Qualification of operators for DED-Arc
ISO/ASTM 52927-24 Additive manufacturing — General principles — Main characteristics and corresponding test methods
ISO/ASTM 52930-21 Additive manufacturing — Qualification principles — Installation, operation and performance (IQ/OQ/PQ) of PBF-LB equipment
ISO/ASTM 52935-23 Additive manufacturing of metals — Qualification principles — Qualification of coordination personnel
ISO/ASTM 52939-23 Additive manufacturing for construction — Qualification principles — Structural and infrastructure elements
ISO/ASTM 52941-20 Additive manufacturing — System performance and reliability — Acceptance tests for laser metal powder-bed fusion machines for metallic materials for aerospace application
ISO/ASTM 52942-20 Additive manufacturing — Qualification principles — Qualifying machine operators of laser metal powder bed fusion machines and equipment used in aerospace applications
ISO/ASTM 52943-2-24 Additive manufacturing for aerospace — Process characteristics and performance — Part 2: Directed energy deposition using wire and arc
ISO/ASTM 52945-23 Additive manufacturing for automotive — Qualification principles — Generic machine evaluation and specification of key performance indicators for PBF-LB/M processes
ISO/ASTM 52950-21 Additive manufacturing — General principles — Overview of data processing
ISO/ASTM TR 52917-EB Additive Manufacturing — Round Robin Testing — General Guidelines
ISO/ASTM TR52905-EB Additive Manufacturing of Metals — Non-Destructive Testing and Evaluation — Defect Detection in Parts
ISO/ASTM TR52952-EB Additive Manufacturing of Metals — Feedstock Materials — Correlating of Rotating Drum Measurement with Powder Spreadability in PBF-LB Machines

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Figure 27: AM Standards: ISO and ISO/ASTM

# AM Standards: NCAMP and SAE

NCAMP-DRAM ND-ME-001 Std Spec for AM Laser Powder Bed Fusion Operational Qualification
SAE AMS 4999B Titanium Alloy Direct Deposited Products 6Al - 4V Annealed
SAE AMS 5924 Nickel Alloy, Corrosion and Heat-Resistant, 47.5Ni - 22Cr - 1.5Co - 9.0Mo - 0.60W - 18.5Fe Powder for General Applications including Metal Injection Molding and Additive Manufacturing without Special Powder Manufacturing Controls
SAE AMS 5952 Nickel Alloy, Corrosion- and Heat-Resistant, Welding and Additive Manufacturing Wire 57Ni - 20Cr - 10Co - 8.5Mo - 2.1Ti - 1.5Al - 0.005B (2B2) Vacuum Induction Melted and Electroslag or Vacuum Remelted Solution Heat Treated, Cold Worked, Precipitation Heat Treatable
SAE AMS 7000A Laser-Powder Bed Fusion (L-PBF) Produced Parts, Nickel Alloy, Corrosion- and Heat-Resistant, 62Ni - 21.5Cr - 9.0Mo - 3.65Nb Stress Relieved, Hot Isostatic Pressed and Solution Annealed
SAE AMS 7001 Nickel Alloy, Corrosion and Heat-Resistant, Powder for Additive Manufacturing, 62Ni - 21.5Cr - 9.0Mo - 3.65Nb
SAE AMS 7002A Process Requirements for Production of Metal Powder Feedstock for Use in Additive Manufacturing of Aerospace Parts
SAE AMS 7003A Laser Powder Bed Fusion Process
SAE AMS 7004 Titanium Alloy Preforms from Plasma Arc Directed Energy Deposition Additive Manufacturing on Substrate Ti-6Al-4V Stress Relieved
SAE AMS 7005 Wire Fed Plasma Arc Directed Energy Deposition Additive Manufacturing Process
SAE AMS 7006 Nickel Alloy, Corrosion- and Heat-Resistant, Powder for Additive Manufacturing 52.5Ni - 19Cr - 3.0Mo - 5.1Cb (Nb) - 0.90Ti - 0.50Al - 18Fe
SAE AMS 7007 Electron Beam Powder Bed Fusion Process
SAE AMS 7008 Nickel Alloy, Corrosion and Heat-Resistant, Powder for Additive Manufacturing, 47.5Ni - 22Cr - 1.5Co - 9.0Mo - 0.60W - 18.5Fe
SAE AMS 7010A Laser Directed Energy Deposition Additive Manufacturing Process (L-DED)
SAE AMS 7011 Electron Beam-Powder Bed Fusion (EB-PBF) Produced Preforms and Parts Titanium Alloy, 6Al - 4V Hot Isostatically Pressed
SAE AMS 7012 Precipitation Hardenable Steel Alloy, Corrosion and Heat-Resistant Powder for Additive Manufacturing 16.0Cr - 4.0Ni - 4.0Cu - 0.30Nb
SAE AMS 7013 Nickel Alloy, Corrosion and Heat-Resistant, Powder for Additive Manufacturing, 60Ni - 22Cr - 2.0Mo - 14W - 0.35Al - 0.03La
SAE AMS 7014 Titanium Alloy, High Temperature Applications, Powder for Additive Manufacturing, Ti - 6.0Al - 2.0Sn - 4.0Zr - 2.0Mo
SAE AMS 7015 Titanium 6-Aluminum 4-Vanadium Powder for Additive Manufacturing
SAE AMS 7017 Titanium 6 – Aluminum 4 - Vanadium Powder for Additive Manufacturing, Extra Low Interstitial (ELI)
SAE AMS 7018 Aluminum Alloy Powder 10.0Si - 0.35Mg
SAE AMS 7020 Aluminum Alloy Powder 7.0Si - 0.55Mg - 0.12Ti
SAE AMS 7021 Precipitation Hardenable Steel Alloy, Corrosion and Heat Resistant, Powder for Additive Manufacturing, 15.0Cr - 4.5Ni - 3.5Cu - 0.30Nb
SAE AMS 7022 Binder Jet Additive Manufacturing (BJAM) Process
SAE AMS 7023 Gamma Titanium-Aluminide Powder for Additive Manufacturing Ti - 48Al - 2Nb - 2Cr
SAE AMS 7025 Metal Powder Feedstock Size Classifications
SAE AMS 7026 Titanium Ti-5553 (Ti - 5Al - 5Mo - 5V - 3Cr) Powder for Additive Manufacturing
SAE AMS 7027 Electron Beam Directed Energy Deposition-Wire Additive Manufacturing Process (EB-DED-Wire)
SAE AMS 7030 Aluminum Alloy, 10.0Si - 0.35Mg Stress Relieved, Hot Isostatic Pressed (HIP), Solution Treated and Artificially Aged, Produced by Laser Powder Bed Fusion (L-PBF)
SAE AMS 7031 Batch Processing Requirements for the Reuse of Used Powder in Additive Manufacturing of Aerospace Parts
SAE AMS 7032 Machine Qualification for Fusion-Based Metal Additive Manufacturing
SAE AMS 7033 Aluminum Alloy Powder 4.6Cu - 3.4Ti - 1.4B - 0.75Ag - 0.27Mg
SAE AMS 7035 Precipitation Hardenable Steel Alloy, Corrosion and Heat-Resistant, Powder for Binder Jet Additive Manufacturing, 16.0Cr - 4.0Ni - 4.0Cu - 0.30Nb
SAE AMS 7037 Steel, Corrosion and Heat-Resistant, Powder for Additive Manufacturing, 17Cr - 13Ni - 2.5Mo (316L)
SAE AMS 7100 Fused Filament Fabrication, Process Specification for
SAE AMS 7100/1A Fused Filament Fabrication Process- Stratasys Fortus 900mc Plus with Type 1, Class 1, Form 1, Grade 0, Natural Color Material for
SAE AMS 7101A Fused Filament Fabrication, Material for
SAE ARP7042 Recommended Practice: Development Planning for Design of Additive Manufactured Components in an Aircraft System
SAE ARP7043 Recommendations for an Additive Manufacturer Designing/Repairing Aircraft Components
SAE ARP7044 Powder History Metric and Labeling Schema
SAE ARP7064 Machine Requalification Considerations for Fusion-Based Metal Additive Manufacturing

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Figure 28: AM Standards: NCAMP and SAE

The following section provides hyperlinks/URL addresses for resources and references related to the Additive Manufacturing report.

# Links

1. https://www.nist.gov/publications/strategy-american-leadership-high-consequence-additive-manufacturing

2. https://www.sciencedirect.com/science/article/abs/pii/S0925527321003637

3. https://www.supplychainbrain.com/blogs/1-think-tank/post/40484-how-additive-manufacturing-is-reshaping-us-industries-and-supply-chains

4. https://www.americamakes.us/our-focus/advancing-technology/casting-forging-roadmap/

5. https://www.tctmagazine.com/additive-manufacturing-3d-printing-industry-insights/latest-additive-manufacturing-3d-printing-industry-insights/can-additive-manufacturing-mitigate-the-impact-of-trump-tariffs/

6. https://3dprintingindustry.com/news/analysis-of-u-s-military-budget-shows-increased-commitment-to-additive-manufacturing-241651/#:~:text=The%20U.S.%20Department%20of%20Defense,%3A%20Aerospace%2C%20Space%20%26%20Defense

7. https://3dprintingindustry.com/news/u-s-congress-advances-dual-use-factories-powered-by-ai-and-3d-printing-to-boost-wartime-production-241090/

8. https://www.sae.org/publications/books/content/b-992_volume2/



Figure 29: Links

# Links

9. https://www.americamakes.us/projects/5550-common-additive-manufacturing-qualification-template-cam-qt/

10. https://www.fda.gov/medical-devices/premarket-submissions-sel

11. https://www.fda.gov/regulatory-information/search-fda-guidance-documents/technical-considerations-additive-manufactured-medical-devices

12. https://www.fda.gov/about-fda/fda-organization/center-devices-and-radiological-health

13. https://www.ecfr.gov/current/title-21/chapter-I/subchapter-H

14. https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfstandards/search.cfm

15. https://standards.nasa.gov/standard/MSFC/MSFC-STD-3716

16. https://standards.nasa.gov/standard/NASA/NASA-STD-6030

17. https://standards.nasa.gov/standard/NASA/NASA-STD-6033

18. https://standards.nasa.gov/sites/default/files/standards/NASA/Baseline/0/NASA-HDBK-5026-Final-8-12-2024.pdf

19. https://www.ecfr.gov/current/title-14/chapter-I/subchapter-C/part-21

20. https://www.faa.gov/regulations_policies/advisory_circulars/index.cfm/go/document.information/documentID/1041938

21. https://www.faa.gov/sites/faa.gov/files/licenses_certificates/aircraft_certification/design_approvals/CPI_guide.pdf



Figure 30: Links (cont.)

# Links

22. https://www.aia-aerospace.org/wp-content/uploads/AIA-Additive-Manufacturing-Best-Practices-Report-Final-Feb2020.pdf
23. https://navydigitalsea.com/wp-content/uploads/2024/10/S9074-A2-GIB-010_Requirements-for-AM-PBF-Rev-1.pdf
24. https://navydigitalsea.com/wp-content/uploads/2024/10/S9074-A4-GIB-010_AM-WIRE-DED-Rev-1.pdf
25. https://navydigitalsea.com/wp-content/uploads/2024/12/Ser-05P_24_218_MIL100S_PPD_EXT.pdf
26. https://navydigitalsea.com/wp-content/uploads/2024/10/NAVSEA-Letter-9074_Ser-05P-050-PPDs-for-Metal-AM.pdf
27. https://navydigitalsea.com/wp-content/uploads/2024/12/Distro-A-Ser-05P_24_285_AM_Weldability-PPD_final.pdf
28. https://navydigitalsea.com/wp-content/uploads/2024/10/NAVSEA-Letter-9074_Ser-05Z-223_Guidance-for-Performing-NDT-NDT-PQ-in-support-of-AM.pdf
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33. https://navydigitalsea.com/wp-content/uploads/2024/10/NAVSEA-Letter-9070_Ser-05Z-248_Guidance-on-Identification-Installation-of-Low-Risk-AM-Components.pdf
34. https://ammo.ncms.org/wp-content/uploads/024-4870-Ser-05T-2018-024-20180817.pdf

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Figure 31: Links (cont.)

# Links

35. https://www.linkedin.com/posts/maritimeindustrialbase_advancedmanufacturing-additivemanufacturing-activity-7338536784764510208-WE5h/
36. https://www.naval-technology.com/news/hii-3d-printed-valve-manifold/
37. https://www.usni.org/magazines/proceedings/2025/june/how-technological-innovation-key-shipbuilding-capacity
38. https://static.e-publishing.af.mil/production/1/saf_aq/publication/dodi5000.93_dafi63-149/dodi5000.93_dafi63-149.pdf
39. https://www.daytonaero.com/usaf-structures-bulletins-library
40. https://www.daytonaero.com/_files/ugd/742fa6_f655412ea39b4ab89e7fa86686e6e8f6.pdf
41. https://quicksearch.dla.mil/qsDocDetails.aspx?ident_number=212162
42. https://store.accuristech.com/standards/mil-mil-std-1587f?product_id=2912111&srsltid=AfmBOorQQfCNeBBsElxMoVyN5s7r7AODendk6Ad-MX4GxfZ25Wc9Ycf_
43. https://directives.nnsa.doe.gov/nnsa-policy-documents/nap-0401.001a
44. https://directives.nnsa.doe.gov/news/published-sd-452-3-1b-defense-programs-business-process-system-dpbps
45. https://directives.nnsa.doe.gov/supplemental-directive/sd-0452-0003-2a
46. https://www.energy.gov/nnsa/articles/stockpile-stewardship-and-management-plan-ssmp
47. https://www.energy.gov/sites/default/files/2023-11/FY24SSMP_FINAL_NOVEMBER_2023_0.pdf

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Figure 32: Links (cont.)

# Links

48. https://www.nei.org/CorporateSite/media/filefolder/resources/reports-and-briefs/Report-NEI-Advanced-Manufacturing-Regulatory-Roadmap-Final-2019-05-13.pdf

49. https://www.tctmagazine.com/additive-manufacturing-3d-printing-news/westinghouse-metal-3d-printed-nuclear-component/

50. https://www.nrc.gov/reading-rm/doc-collections/cfr/part050/part050-0059.html

51. https://info.westinghousenuclear.com/news/westinghouse-produces-1000-additive-manufacturing-component-for-vver-440-fuel

52. https://www.nrc.gov/reactors/power/amts.html

53. https://www.ansi.org/standards-coordination/collaboratives-activities/additive-manufacturing-collaborative

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*IAWG on Engineering Complex Systems*

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Figure 33: Links (cont.)

# 3.2 Digital Twins for Failure Prediction White Paper

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## 3.2.1 Executive Summary

The Inter-Agency Working Group (IAWG) established a Targeted Action Group (TAG), comprising subject matter experts from multiple U.S. Government agencies to investigate the application of digital twins for failure prediction in complex systems. This white paper represents the culmination of comprehensive research conducted with the primary purpose of assisting senior and mid-level government leadership in understanding and maximizing digital twin capabilities for failure prediction. The document emphasizes the critical distinction between traditional modeling and simulation, and true digital twin functionality as currently defined by industry, ensuring that leadership can make informed decisions about digital twin investments, manage expectations appropriately, and achieve desired return on investments.

The white paper addresses multiple functional approaches to failure prediction, including reliability analysis, Failure Mode and Effects Analysis/Failure Modes, Effects, and Criticality Analysis (FMEA/FMECA), Fault Tree Analysis (FTA), Physics of Failure (PoF) analysis, Remaining Useful Life (RUL) analysis, Reliability-Centered Maintenance (RCM), Condition-Based Maintenance (CBM), Prognostics and Health Management (PHM), and advanced data

analytics. These methodologies are examined within the context of digital twin applications, providing a comprehensive framework for understanding how digital twin technology can enhance traditional failure prediction approaches, and offer unique capabilities that extend beyond conventional engineering models by providing real-time integration of physical and virtual systems.

Based on research and analysis of specific use cases, the Digital Twin (DT) TAG recommends that organizations develop strategic, needs-based digital twin visions focused on well-defined outcomes such as minimizing equipment failure rates, streamlining operations, increasing efficiency, and enhancing product development capabilities. The DT TAG particularly emphasizes the importance of expanding digital twin scope beyond individual components to encompass entire systems or missions, which provides comprehensive visibility across all operational levels, important interfaces with the system of primary interest, and enables real-time, actionable insight for decision-makers. This strategic approach is especially effective for low-volume, highly configured products where substantial system investments are required, and detailed information is needed to effectively respond to quickly changing conditions.

## 3.2.2 Introduction

The Inter-Agency Working Group (IAWG) Senior Executives identified their respective internal Subject Matter Experts (SME) to participate in the Targeted Action Group (TAG), investigating the application of Digital Twins (DT) for failure prediction in complex systems. A TAG is a multi-agency group that addresses specific actions identified by the IAWG Senior Executives. This report is the culmination of the research by the Digital Twin for Failure Prediction TAG (DT TAG).

**Purpose**

This document will assist Senior and Mid-level leadership within the Agencies of the U.S. Government in maximizing digital twin unique capabilities for failure prediction with the following intent:

Agency Senior Execs – to provide high-level understanding of digital twins, describing what they are and are not as well as potential value provided; as many occurrences of the term 'digital twin' in use today are nothing more than what have been traditionally referred to as 'modeling and simulation' within the engineering domain. It is important that senior leadership understand the difference between traditional modeling and simulation, and the functional capabilities of digital twins. This understanding will provide insight into questions which need to be asked during scope definition, as well as inform current and future decisions, associated expectation management, and desired return on investments.

Mid-level leadership – to highlight digital twin program management and systems engineering value, inform of the risks and constraints of digital twins, present technical considerations in

scoping of work, illustrate operational use cases and expected outcomes, ensure scope of work is appropriate, and identify needed resources available to be successful to inform tactical planning and execution.

The document can serve other purposes, such as guiding the formulation of consensus among several user requirements groups, developers, engineers, and resourcing organizations regarding the development of the system, expected costs, and final end-state functional capabilities very early in the lifecycle.

**Scope**

IAWG Original DT TAG Guidance: Digital twin models are indistinguishable from actual or intended real-world systems or processes, and allow for systems testing, monitoring, integration, maintenance, etc. How can this technology be utilized to identify system faults and predict failures?

IAWG Original TAG Deliverables:

- Summarize existing agency work on digital twins for failure prediction and,

- Identify potential use-cases, both inside and outside the IAWG agencies, to demonstrate the value and challenges for using digital twins to predict system failures, along with identifying lessons learned.

DT TAG refined the scope to increase the ability to execute based upon final recommendations, via standard systems engineering system capability decomposition, while maintaining the intent of the IAWG Senior Executives to the following:

Need Statement: Provide guidance to Federal agencies exploiting digital twin approaches to predict and manage critical system and component failure rates to lower operations and sustainment costs, and optimize mission performance through improved system reliability, supportability, and survivability via informing future decision planning of proactive repair/replacement, and to inform needed supply chain processes and infrastructure.

Goal Statement: Provide a standard approach and/or recommendations for Agencies as they approach developing digital twins for the purpose of failure prediction, leveraging best practices, and lessons learned from both contributing organizations and external industry professional organizations.

**Methodology**

Initial DT TAG project scoping efforts provided the revised Needs Statement and Goals, where team members applied their engineering and logistics experience from varied backgrounds to map out the following plan:
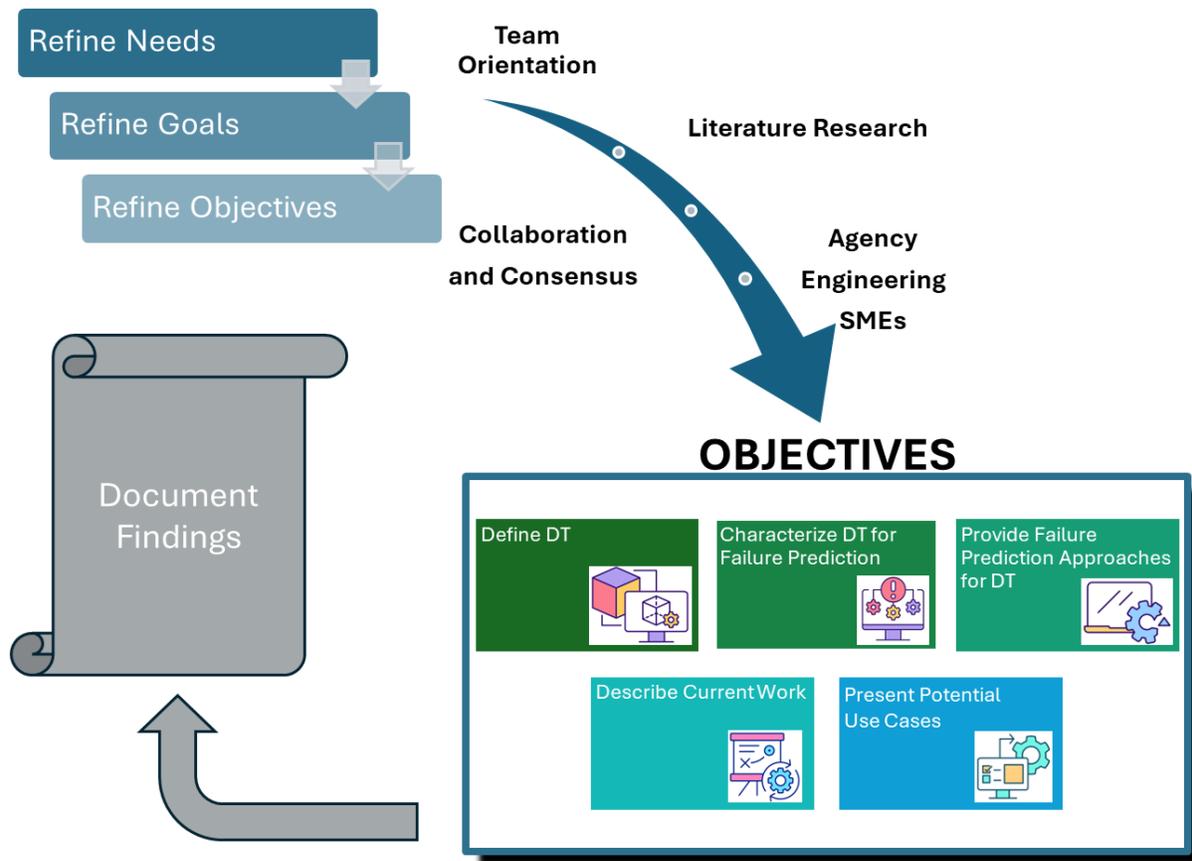
Figure 34: Digital Twin TAG Methodology

Objectives:

- Provide a mutually agreed upon definition of digital twins.

- Provide general digital twin characteristics and capabilities and identify considerations when designing a digital twin to support the needed failure prediction of critical systems of interest.

- Provide definition of approaches for failure prediction and applicability to digital twin implementation.

- Summarize existing agency work on digital twins for failure prediction and,

- Identify potential use-cases, both inside and outside the IAWG agencies, to demonstrate the value and challenges for using digital twins to predict system failures, along with identifying lessons learned.

Literature research included publications from Government, industry, and academia on the topics of digital twins, logistics, Models-Based Systems Engineering (MBSE), and standards. The DT TAG also conducted reach-back within home organizations for information on current and potential use cases of digital twin failure prediction projects (Figure 1).

### 3.2.3 Functional Description of Digital Twins - DT TAG Objective 1

The idea of a 'digital twin' was born at NASA in the 1960s as a virtualization of the Apollo mission, in conjunction with physical assets. In response to the Apollo 13 oxygen tank explosion and subsequent damage to the main engine, NASA employed multiple software simulators to evaluate the failure and extended a physical model of the vehicle to include avionics components. This 'digital twin' was the first of its kind, allowing for a continuous ingestion of data to model the events leading to up to the accident for forensic analysis and exploration of next steps. Fast forward half a century and NASA, along with others in the aerospace community, continue to develop and utilize high-fidelity digital models of physical systems and components, as well as the extreme environments in which they operate [1].

However, the term 'digital twin' is relatively new to the broader engineering domain, although many characteristics of how digital twins are currently defined have existed throughout industry for the last few decades but have not been specifically labeled as such. Additionally, since the term 'digital twin' has been widely used across several industries over the last few years, without a common definition of what a digital twin is and is not, has led to multiple interpretations of the definition of a digital twin; some are accurate (for example they are something different than traditional high-fidelity simulations and have bi-direction flow of information to real-world assets), but many describe high-fidelity models and simulations as digital twins due to being new to the world of engineering and using the term incorrectly out of ignorance or self-serving purposes. Therefore, it was of utmost importance the DT TAG came to an agreement regarding the definition of a digital twin to set the foundation and common understanding of what a digital twin for failure prediction could be, in addition to associated characteristics.

**Digital Twin Definitions**

The following are the definitions of digital twins used by the DT TAG to determine the generally accepted modern definition of a digital twin, and some high-level characteristics. The reader will notice the underlined text per source as the general description and functional characteristics of a digital twin, with the *italicized* text identifying the directionality of information flow between the system in the physical world and the virtualized portion of the twin.

**DoDI 5000.97:** "A digital twin is a virtual representation of a product, system, or process that *uses the* best available models, sensor information, *data collected from the physical system*, and input data to mirror and predict system activities and performance over the life of its corresponding physical twin and inform system design changes over time. There can be multiple

digital twins of a system, but all digital twins should be based on authoritative sources of information and have clearly defined uses and scopes. Digital twins may vary in fidelity, based on the use case."

**Digital Twin Consortium (DTC) 2022 Summary:** "A digital twin is a <u>virtual representation of real-world entities and processes</u>, *synchronized at a specified frequency and fidelity*."

https://www.digitaltwinconsortium.org/hot-topics/the-definition-of-a-digital-twin.htm

***Digital Twin: Definition & Value* – AIAA and AIA, December 2020:** "A set of <u>virtual information constructs that mimics the structure, context and behavior of an individual / unique physical asset</u>, or a group of physical assets, is *dynamically updated with data from its physical twin throughout its life cycle* and informs decisions that realize value."

https://aiaa.org/wp-content/uploads/2024/12/digital-twin-institute-position-paper-december-2020.pdf

**IBM *How does a digital twin work?*:** "A digital twin is a <u>virtual model designed to accurately reflect a physical object</u>. The object being studied — for example, a wind turbine — is outfitted with various sensors related to vital areas of functionality. These sensors produce data about different aspects of the physical object's performance, such as energy output, temperature, weather conditions and more. *This data is then relayed to a processing system and applied to the digital copy*."

https://www.ibm.com/topics/what-is-a-digital-twin

**NNSA:** A digital twin is a set of <u>virtual information constructs that mimics the structure, context and behavior of an individual / unique physical asset, or a group of physical assets</u>, is *dynamically updated with data from its physical twin* throughout its life cycle and informs decisions that realize value.

- Essential elements of a digital twin:

    - a virtual representation (digital model)

    - a physical realization (asset)

    - a transfer of data / information (connected) between the two

- A digital twin encompasses the entire product lifecycle of a physical asset, i.e. the design and engineering phase ("As Designed"), the manufacturing phase ("As Built"), and the operational/sustainment phase ("As Used" and "As Maintained"), whenever a physical asset is employed.

**National Academies, Sciences Engineering Medicine**, *Foundational Research Gaps and Future Direction for Digital Twins, Dec. 2023:* "A digital twin is a set of <u>virtual information</u>

constructs that mimics the structure, context, and behavior of a natural, engineered, or social system (or system-of-systems), is *dynamically updated with data from its physical twin,* has a predictive capability, and informs decisions that realize value. The bidirectional interaction between the virtual and the physical is central to the digital twin.

DT TAG Assessment:

Utilizing the aforementioned digital twin definitions and common themes for the general characteristics (including information exchange with the representative system in the physical world) of digital twins, the following were identified as highly probable characteristics across most uses of digital twins for failure prediction and a good starting point of refinement and have been summarized as the following:

- A virtual representation of a product/object, system, process/behavior of something in the physical/natural world

- Data is exchanged between virtual and physical system(s)

It was the decision of the DT TAG to use the definition of the Digital Twin Consortium (DTC) (2022), given it is a cross-industry working group established for the sole purpose of creating a common understanding of digital twins are or are not.

Digital Twin Consortium (DTC), 2022 – Detailed Definition:

https://www.digitaltwinconsortium.org/hot-topics/the-definition-of-a-digital-twin.htm

- A digital twin is a virtual representation of real-world entities and processes, synchronized at a specified frequency and fidelity

- Digital twin systems transform business by accelerating holistic understanding, optimal decision-making, and effective action

- Digital twins use real-time and historical data to represent the past and present and simulate predicted futures

- Digital twins are motivated by outcomes, tailored to use cases, powered by integration, built on data, guided by domain knowledge, and implemented in IT/OT systems

To build upon the DTC definition, the following diagram adds some additional contextual contributions to a digital twin (Figure 35).
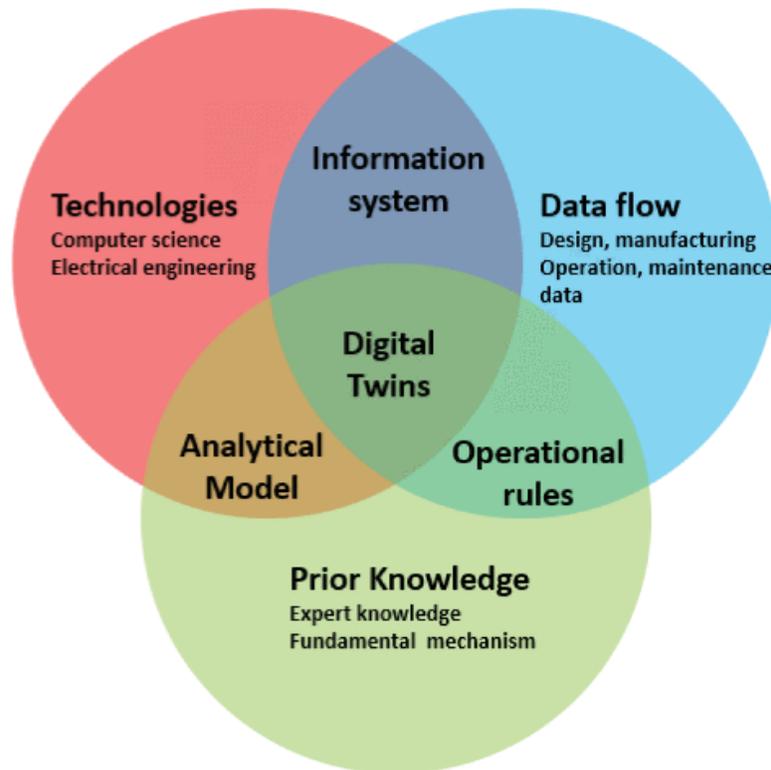
Figure 35: Contributions to the Digital Twin [2]

Additionally, the DTC is made up at the time of writing of 196 government, corporate and academia members with Steering Committee Members (for example BP, Dell, Microsoft, and Sev1Tech).

Implications of the definition:

A digital twin is a virtual representation of real-world entities and processes, synchronized at a specified frequency and fidelity:

- Virtual representation: Digital twins are virtual entities, and both they and their elements exist in cyberspace, not real space (real-world).

- Real-world entities and processes: Digital twins are the virtualization what they represent in the real, tangible world. Digital twins may include any, or all, of the real-world elements (for example parts, system elements, environments, etc.) and may include any, or all, of the real-world processes these entities experience (for example definition, design, fabrication, integration, operation, etc.).

- Bi-directional: Digital twins are not stand-alone; they are representations of real-world elements and thus need bi-directional flow of information to ensure they are "twins" for the desired functionality.

- Specified frequency and fidelity: This bi-directional flow is critical and must be often enough to avoid inconsistencies. The fidelity required and thus specified for the digital twin application determines the synchronization requirements.

- Purpose and expected functionality: One additional critical area of consideration of a digital twin is its purpose, which will be discussed in later sections. This purpose will help define the digital twin elements and associated functionality. There are a variety of purposes, and a well-conceived digital twin may achieve several. The purpose of a digital twin will help bind and constrain the scope of the digital twin development and maintenance activities.

## 3.2.4 Functional Approaches to Failure Prediction

Failure prediction is the process of using data to forecast **if** an item or system is likely to fail. Typically, with failure prediction there is interest in **how** (failure mode) the item/system will fail, **when** (time to failure and/or remaining useful life) the item/system will fail, and **why** (failure mechanism/cause) the item/system will fail. Additionally, it should not go without addressing each of these in context of the typical three states of life: infant mortality (early failure), nominal (random failure), and wear out (wear out failure) [3].

There are a variety of supporting and foundational analyses for failure prediction including:

- Reliability Estimate

- Failure Modes and Effects Analysis (FMEA) or Failure Modes, Effects, and Criticality Analysis (FMECA)

- Fault Tree Analysis (FTA)

- Physics of Failure (PoF)

- Remaining Useful Life (RUL)

- Reliability Centered Maintenance (RCM)

- Condition-Based Maintenance (CBM)

- Prognostics and Health Management (PHM)

- Data Analytics

For predictions about **how** a system will fail, typically there is an initial identification phase in which potential contributing factors are captured. FTAs, Hazard Analysis Probability of Failure (PoF) and Data Analytics [4] can be particularly useful here. Following this identification phase, one begins to architect/construct the scope of the analysis. Some of the correlated needs are obvious, but others may require SME insight. For example, frictional wear-out is affected by vibrations, heat, cycles, and lubrication (among others). A SME might also suggest that coatings, corrosion and an external dirt environment could contribute as well. Thus, for a digital twin to accurately predict a frictional failure, it will need to account for all the above factors. Some may contribute more than others, and various methods (including Design of Experiments [5]) can be employed to help efficiently include the critical contributors and exclude the weaker, statistically less likely, contributors. The focus is on finding and mitigating the driving causes.

These contributors are typically accounted for in one of three ways:

- Explicit inclusion (e.g. Physics of Failure frictional degradation models, Failure Analysis of Interfaces)

- Historical inclusion (e.g. Statistical Probabilities, Sample distributions)

- Combination of the above

**GAO-23-105556,** "Actions Needed to Further Implement Predictive Maintenance on Weapon Systems" indicates that the DoD spends nearly $90B annually on weapon system maintenance. To improve weapon system readiness and availability, the DoD is implementing predictive maintenance, which relies on condition-monitoring technology and data analytics to schedule maintenance based on evidence of need [6].

For predictions about **when** a system will fail, the focus is on capturing the entire system that is at risk. Failures can be both internal and external; many systems have failures related to loss of external interfaces.

- Infant mortality, duration, *and* wear out – all can change under stress, and presence of weak links

- Mean Time Between Failure (MTBF)

- Operational Scenarios, Off-Nominal studies

For predictions about **why** a System will fail, the focus is on determining root causes and driving factors for those causes. Physics of Failure, FMECAs and historical data will be key to this. Failure Analysis of current or past failures used to update models will enable better 'in family' predictions.

- Root cause

- Physics of Failure

- FTA and FMECA

**Reliability Analysis**

A reliability analysis (including an estimate or prediction) is a forecast that involves analysis of system characteristics and use the environment to estimate the reliability of a system prior to the item being developed, built or deployed for operations. The Office of the Under Secretary of Defense (OUSD) for Research and Engineering (R&E) Office of Systems Engineering and Architecture (SE&A) released "Best Practices to Achieve Better Reliability and Maintainability Estimates for DoD Systems" guidance in February 2025 [7]. Reliability estimates are needed because they are used for many purposes, including:

- Assessing progress in meeting the specifications, and ultimately the user needs

- Quantifying the effect of corrective actions that are based on root cause analysis

- Estimating repair and restoration times in the event of a system failure

- As a factor in estimating availability

- As a factor in determining fleet sizing

- As a factor in forecasting spares requirements

- As a factor in determining personnel requirements (manning of maintenance organizations)

Digital Twin Considerations:

- What: Identification of driving root causes

- How: Causal chains of off-nominal events

- When: MTBF, Repair and Restoration times

**Failure Mode and Effects [Criticality] Analysis (FMEA/FMECA)**

As specified in DI-SESS-81495C, "The FMECA identifies independent single item failures and the resulting potential impact on mission success, performance, safety, and maintainability. The FMECA promotes corrective actions by identifying potential failure risk and maintainability issues in order that appropriate corrective actions may be taken early to eliminate or control high risk items to improve operational readiness and reduce life cycle cost. The FMECA also establishes baseline engineering information to identify and eliminate or control all failure modes throughout the system's life cycle. The FMECA analytics establish the basis for fault detection, fault isolation, operator and maintainer failure recognition, depot test parameters and lay-in repair parts." [8]

Key parameters from the FMEA/FMECA that are required to support failure prediction include:

- **Function:** A concise statement regarding the item's purpose or role within the system

- **Failure Mode and Cause:** A description of how the item can fail with their root cause(s)

- **Mission Phase / Operational Mode:** Description of the mission phase, operational mode, and system Concept of Operations (ConOps) requirements that failure occurs

- **Failure Effects:** Explanation of what happens if a failure mode occurs. Often described in terms of local, next higher assembly, and end effects

- **Failure Detection Method:** A description of the methods by which the occurrence of the failure mode is detected by the operator or maintainer at the system level

- **Fault Isolation:** Describes the most direct procedure that allows a maintainer to isolate the malfunction or failure

- **Compensating Provisions:** Design provisions or operator actions that can circumvent or mitigate the effect of the failure

- **Severity Classification:** A classification of the severity of the failure effect as defined by MIL-STD-882D from Category I – Catastrophic, Category II – Critical, Category III – Marginal, and Category IV – Minor

On its own, the FMEA aids in:

- Determining the effect of each failure mode on performance

- Root cause identification and development of corrective actions

- Investigation of the design of alternatives

- Development of test methods and troubleshooting techniques

- Qualitative reliability and maintainability analyses

- Locating single point failures

- Providing data for developing the Reliability Block Diagram

- Qualitative safety and supportability analyses

- Ranking failure according to severity classification

- Estimating system critical failure rates

- Identifying reliability and safety critical components

Digital Twin Considerations:

- What: Identification of driving failure modes, severity ranking, Single Point failure

- How: Causal chains of off-nominal events

**Fault Tree Analysis (FTA)**

FTA is a method to analyze the potential for failure(s) by graphically and mathematically representing the system. FTA is a top-down approach that shows how a failure moves through a system by creating a graphical model of how component failures lead to system-wide failures. An FTA diagram (Figure 36) helps to convey how one or more small failure events could lead to a catastrophic failure.

An FMEA/ FMECA is considered a 'bottoms-up' analysis, whereas an FTA is considered a 'top-down' analysis. FMECAs and FTAs are compatible methods of risk analysis, with the choice of method dependent on the nature of the risk to be evaluated. Since FTA is a top-down analysis, there is a higher probability of misinterpretation at the lowest level. On the other hand, with the FMEA/FMECA starting at the lowest level, it will probably result in a better method of risk analysis (assuming lowest level data is available). Also, the FMEA/FMECA considers only single failures while FTA considers multiple failures which will impact accuracy.
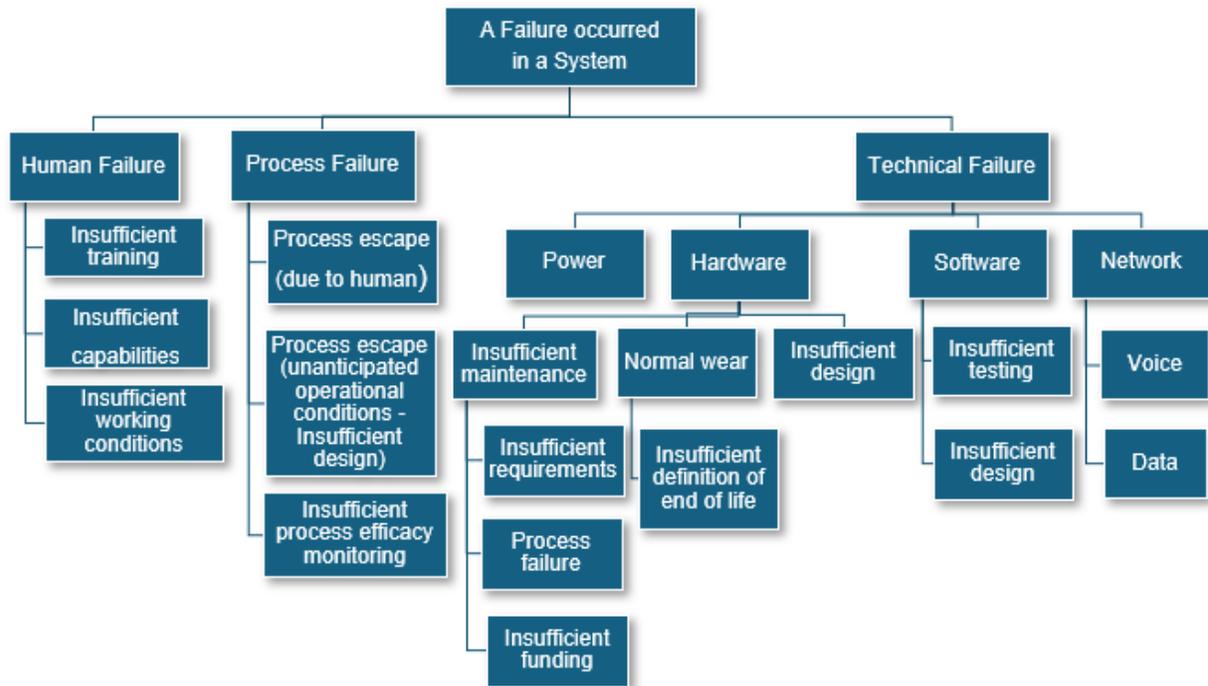


Figure 36: Example Areas of Failure for Consideration with FTA Diagramming

FTA is particularly useful in providing insight into the following supportability analysis areas:

- Functional analysis of highly complex systems

- Observation of combined effects of simultaneous, non-critical events at the highest-level event

- Evaluation of safety requirements and specifications

- Evaluation of system reliability

- Evaluation of human interfaces

- Evaluations of software interfaces

- Identification of potential design defects and safety hazards

- Evaluation of corrective actions

- Identification and simplification of maintenance requirements and troubleshooting procedures

- Elimination of causes of observed failures

Digital Twin Considerations:

- What: Identification of driving failure causes, identification of vulnerabilities, inclusion of off-nominal scenarios

- How: Causal chains of consequential events

**Physics of Failure (PoF) Analysis**

PoF is the modeling and simulation of the root causes of failure, including fatigue, fracture, wear, and corrosion. PoF is used to design reliability into a product, perform reliability assessments, and focus reliability tests where they will be most effective. NASA/SP-202300004376 "NASA Methodology for Physics of Failure-Based Reliability Assessments Handbook" provides more details, including empirical and deterministic methods [9].

Empirical methods leverage past component failure data from field studies, warranty claims, and lab tests to predict the reliability of systems. Empirical PoF methods include five fundamental statistical models of Exponential, Weibull, Normal, Lognormal, and Binomial distributions, and the more-advanced parametric modeling approach of Bayesian Inference.

Deterministic methods include degradation (due to accumulated damage from stress), erosion, diffusion, and corrosion phenomenon leading to sudden or eventual failure. Deterministic models incorporate component load profiles, material specifications, and environmental stresses to

recreate the life conditions a component or system experiences, to predict reliability. Deterministic methods discussed in the NASA PoF Handbook include:

- Electromigration in Electrical and Electronic Components

- Thermal PoF

- Fluid (for example pipe flow)

- Electromagnetics (for example wave optics, ray optics, AC/DC)

- Structural Analysis Modeling

- Acoustics

- Chemical (for example batteries and fuel cells, electrodeposition, chemical reactions)

- Radiation PoF in Semiconductors

The NASA PoF Handbook also has a section on digital twins, which states:

> "Recent literature and NASA studies suggest that creating predictive digital twins can be accomplished by leveraging model-based or interpretable machine learning methods to couple sensor data with physics-based models of the system. […] In addition, digital twins can be infused with development-cycle data (e.g., CAD, finite element analysis, life test data, availability), so knowledge is shared across various discipline and mission teams uniformly. This encourages rapid iterations of virtual prototypes that promote common communication platforms across the organization. These digital twins can also be utilized to virtually simulate in-situ-system conditions by using real-time data ingestion from diagnostic system-level prognostics and on-board sensors. This will enable rapid health evaluation, anomaly investigation, and evolving monitoring strategies. Alternatively, these same digital twins can be used with simulated data to analyze 'what-if' scenarios and to train operations teams. For example, Digital twins can evolve, or be trained if AI/ML enabled, with monitoring data and new failure signatures knowledge to enable analyst-agnostic, accurate, and efficient reliability predictions and system-performance risk identification. Therefore, continued advancement of digital twin capabilities is needed."

Digital Twin Considerations:

- Constraints: Detailed knowledge of materials, interfaces, fields and operational attributes

- What: Identification of driving failure categories/kinds to enable relevant physics to be incorporated, identification of critical interactions between elements of the system, environment and operational activities.

- How: Insight into the mechanisms driving failure (degradation, friction, ablation, etc.)

- When: Insight into relevant time scales and operational scenarios under which failures occur

**Remaining Useful Life (RUL) Analysis**

The key to RUL is having representative and quality data for the system(s) of interest over a sufficient time frame of which the RUL calculation considers these data sources to the maximum extent possible.

RUL determination requires multiple data sources. These data sources include:

- Engineering and PoF analysis results

- Field removal and failure data

- Field and depot observations of systemic issues

- Historical system life data

- Obsolescence data

- Repair cost data

Engineering and PoF analysis results help to quantify expected durability/life of components, subsystems, and structures. Sound engineering models and modeling techniques exist for many failure mechanisms. The engineering analysis results can identify life-limited components and, in many cases, estimate projected component life. These analyses can also identify test methods for quantifying expected life. In some cases, accelerated testing approaches can be used.

Field removal from operations, and failure data from representative components, subsystems, or structures provide insight into aging trends. In many cases, complex systems do not show aging in the way that individuals might expect. In some cases, because of the nature of the repair, a given system may be a collection of components with various ages and states of repair. These systems may show little system-level aging and more of a component-level steady state failure rate, depending on the service maintenance practices and specific initiatives.

Field and depot observations of systemic issues can identify factors or concerns that will influence RUL estimates. Field team assessments, combined with data (depot and field) analysis, can identify trends or concerns that could alter initial estimates for RUL.

Historical surrogate system life data can greatly inform RUL decisions. By assessing the life cycles of actual comparable systems, the feasibility of RUL values can be assessed. In many cases, systems are replaced more for new capability and less for end of useful life considerations. Many military systems provide needed capabilities for decades.

Obsolescence data will help determine when part cost and availability will begin to influence the economic useful life, and such data are typically available to inform supply chain risk assessments. Repair cost data will provide needed information to assess the impact of field level and depot programs on the overall optimum RUL value.

Digital Twin Considerations:

- Constraints: Requires representative and field data over sufficient time periods, physics of failure analyses

- What: Identification of driving failure categories/kinds to enable relevant physics to be incorporated, identification critical interactions, between elements of the system, environment and operational activities

- How: Insight into the mechanisms driving failure (degradation, friction, ablation, etc.)

- When: Insight into relevant time scales and operational scenarios under which failures occur

**Reliability-Centered Maintenance (RCM)**

Per DoDM 4151.22-M, "RCM is used to determine what failure management strategies should be applied to ensure a system achieves the desired levels of safety, reliability, environmental soundness, and operational readiness in the most cost-effective manner. In the context of RCM, this can mean identifying various maintenance actions. For example, one of the most useful products of an RCM analysis is the identification of technically defensible proactive maintenance tasks such as on-condition, scheduled restoration, and scheduled discard tasks. RCM can yield other results that also contribute significantly to the safe and reliable operation of assets. These can include design modifications, changes to a training program, identification of new operating and emergency procedures, or modifications to technical manuals." [10]

RCM is based on the following precepts:

- The objective of maintenance is to preserve an item's function. RCM seeks to preserve the desired level of system or equipment functionality.

- RCM is a life-cycle management tool and should be applied from design through disposal.

- RCM seeks to manage the consequences of failure, not prevent all failures.

- RCM identifies the most applicable and effective maintenance task or other logical action.

- RCM is driven by (in order of importance) safety or a similar critical consideration such as environmental law, the ability to complete the mission, and economics.

- RCM acknowledges design limitations and the operating context. At best, maintenance can sustain an inherent level of reliability within the operating context over the life of an item.

- RCM is a continuous process that requires sustainment throughout the life cycle. RCM uses design, operations, maintenance, engineering, logistics, and cost data to improve operating capability, design, and maintenance.

Digital Twin Considerations:

- Constraints: Insight into historical failures and maintenance effectiveness

- What: Identification of failure modes

- How: Prioritized Failures

- When: Most effective maintenance actions prior to failure, estimates of resultant lifetime

**Condition-Based Maintenance (CBM)**

DoDI 4151.22-I defines CBM as "a maintenance practice based on monitoring the condition of equipment to assess whether it will fail during some future period to take appropriate action to avoid the consequences of that failure. Condition based maintenance employs real-time or approximate real-time assessments of data obtained from the equipment or external tests and measurements using either test equipment or actual inspection. The objective of CBM is to perform maintenance based on the evidence of need while ensuring safety, reliability, availability, and reduced life-cycle cost." [11]

DoDI 4151.22-I further defines Condition-Based Maintenance Plus (CBM+) as "a collaborative DoD readiness initiative focused on the development and implementation of data analysis and sustainment technology capabilities to improve weapon system availability and achieve optimum costs across the enterprise. CBM+ is the application and integration of appropriate processes, technologies, and knowledge-based capabilities to improve the reliability and maintenance effectiveness of DoD systems and components. At its core, CBM+ is maintenance performed based on evidence of need. CBM+ is built upon RCM and CBM to enhance safety, increase maintenance efficiency, improve availability, and ensure environmental integrity. CBM+ diminishes life-cycle costs by reducing unscheduled maintenance and enabling predictive maintenance. CBM+ turns rich data into information about component, weapon system, and fleet conditions to more accurately forecast maintenance requirements and future weapon system readiness to drive process cost efficiencies and enterprise activity outcomes."

The OUSD Acquisition and Sustainment (A&S) Office of the Deputy Assistant Secretary of Defense for Material Readiness published the CBM+ Guidebook in August 2024, which outlines a need for greater accuracy in failure prediction. The CBM+ Guidebook states, "To achieve greater integration, CBM+ suggests tying together various data sources, or at the very least,

interfacing data sources and analytical systems using common standard protocols. Modern CBM+ analytic software should offer integrated condition monitoring and analysis capability, which permits the effective integration of different forms of analysis and other condition data into combined management information reports. Statistical analysis tools and Continuous Process Improvement (CPI) should be considered." [12]

Digital Twin Considerations:

- Constraints: Requires real-time data, requires historical data, upfront data analysis to predict failures and life

- What: Identification of Failure Modes

- How: Causal failure chains and issues that lead to failures

- When: Most effective maintenance actions prior to failure, estimates of resultant downtime

**Prognostics and Health Management (PHM)**
PHM is an advanced approach to minimize maintenance costs, while maximizing operational availability and utilization of critical systems. PHM seeks to develop sensor hardware and algorithms to detect anomalies, diagnose problems that cause the anomalies, and compute a probability distribution of time to failure. Given this distribution, along with operational constraints and objectives for the system, maintenance activities can be scheduled to achieve the optimal cost and utilization. The PHM is the essential functionality of the system to monitor its own health, collect all related parameters, and report out failures and other maintenance-related issues to the maintainer and/or operator for proper awareness of the system's functionality, as well as corrective and preventive maintenance. PHM includes, but is not limited to, all Built-In-Test (BIT) faults, mechanical diagnostics, exceedances, and other health management state parameters to assess the health of the system.

PHM is intertwined with other maintainability and testability approaches, such as diagnostics and BIT faults:

- Diagnostics: The determination of the current condition of a component or system and the process to isolate one or more root causes of faults to the point where corrective action can be taken

- BIT: A test approach using built-in test equipment or self-test hardware and software that is internally designed into a systems, subsystem, or equipment to test all or part of that system, subsystem, or equipment

- Prognostics: The process of monitoring the health of a product and predicting its RUL by assessing the extent of deviation or degradation from its expected state of health in its expected usage conditions

- Health Management: Uses prognostic information to make decisions related to safety, condition-based maintenance, ensuring adequate inventory, and product life extension

- PHM: Permits the evaluation of a system's reliability in its actual life-cycle conditions

Digital Twin Considerations:

- Constraints: Requires real-time and/or historical data and upfront data analysis to predict failures and life

- What: Identification of failure modes

- How: Embedded in predictive model

- When: Estimation of remaining life

**Data Analytics**

Sustaining the readiness of systems is critical for their security, thus necessitating efficient and effective maintenance approaches. Historically, maintenance approaches relied on either reactive or scheduled maintenance, which contributed to greater-than-necessary downtime and higher sustainment costs. Leveraging artificial intelligence / machine learning (AI/ML) technology within a predictive maintenance approach enables systems to shift from a reactive to a proactive, preventative maintenance approach. Data analytics offer insights to forecast potential issues before they become critical based on data trending and *a priori* component/system knowledge, while concurrently optimizing system performance and reducing downtime and resources.

AI/ML are the foundation of predictive maintenance and perform tasks typically requiring human intelligence. While ML focuses on enabling learning from data that improves performance over time, data analytics use AI/ML to analyze large, complex sets of data and identify patterns that human analysts might miss, or the time required to complete would be untenable.

AI/ML effectiveness in predictive maintenance relies on the quality and quantity of data. High-quality data enables more accurate predictions, while a large dataset provides the breadth needed for the models to learn effectively and make accurate failure predictions. Data sources for systems include equipment sensors, historical maintenance records and environmental conditions.

The following are some examples of industry approaches to failure prediction, to set the stage for later digital twin-identified characteristics for failure prediction.

"Failure prediction is essential for predictive maintenance due to its ability to prevent failure occurrences and maintenance costs. At present, mathematical and statistical modeling are the prominent approaches used for failure predictions. These are based on equipment degradation, physical models and machine learning methods, respectively. None of these approaches ensure failure predictions well before their occurrence to provide sufficient time to treat potential causes proactively. Therefore, in this paper, we present a Bayesian based methodology to learn and associate failure signatures with potential failure occurrences." [13]

"Failure prediction is the task of forecasting whether a material system of interest will fail at a specific point of time in the future. This task attains significance for strategies of industrial maintenance, such as predictive maintenance. For solving the prediction task, machine learning (ML) technology is increasingly being used, and the literature provides evidence for the effectiveness of ML-based prediction models. However, the state of recent research and the lessons learned are not well documented. Therefore, the objective of this review is to assess the adoption of ML technology for failure prediction in industrial maintenance and synthesize the reported results. We conducted a systematic search for experimental studies in peer-reviewed outlets published from 2012 to 2020." [14]

Time-based models

One type of model is a time-based model called a regression model. This kind of model allows a predictive maintenance (PdM) system to predict the number of days (or other metrics, like cycles, months, or products made) that are left before the system fails. This model collects some historical data and uses that data to look over every machine failure, building a model based off the timing of failures regarding current maintenance practice. It will then make a prediction for a date or specified time interval for failure. [15]

Irregular behavior models

Perhaps a more common model, some failure prediction models look at so-called "anomalous" or non-normal behavior in an asset and use that behavior to predict failures. For example, let's say a facility has a robot gripper arm that usually moves to Point A, picks up a part, and moves the part to Point B. However, when the machine is close to failure, the machine arm starts to take longer when it moves to Point B, freezing in place with the part in its arm. We can point to this irregular behavior and understand it as a failure marker, using it as a way of diagnosing how close the asset is to failure. [15]

Survival model

Survival failure prediction models ask the question: "How does the failure risk of an asset change over a period of time if we look at X number of characteristics?" [15]

## 3.2.5 Proposed Guidance for Digital Twin Outcomes for Failure Prediction

Building on the previous discussion on approaches to failure prediction it is important to then fully explore many of the defined facets and design considerations which will impact the scope and success of an operational digital twin for failure prediction. As shown in Figure 37, there are many high-level constituent sources of information to be integrated as part of a digital twin and generic capabilities desired of most digital twins for failure prediction.
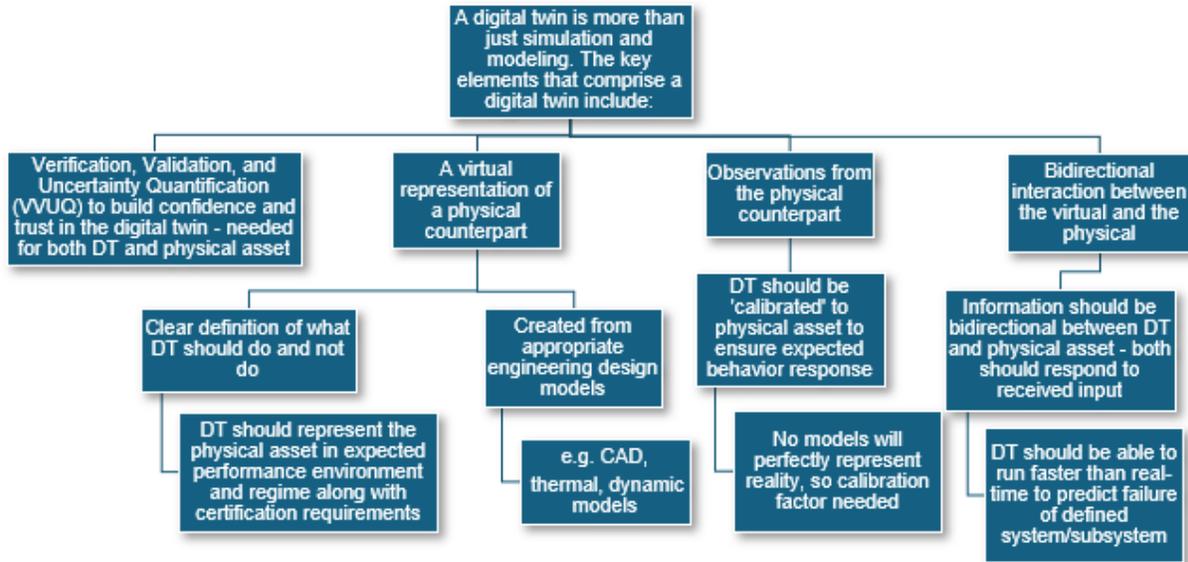


Figure 37: Digital Twin High-Level Capabilities Along with Constituent Sources of Models Common for Digital Twin for Failure Prediction

At this point, the prospect of efficiently designing, building, and utilizing a digital twin may appear daunting; indeed, it does not come for free, or without substantive effort. Furthermore, trying to 'model the universe' in order not to miss anything will be expensive, and ultimately lead to a recursive 'digital twin of the digital twin' cycle.

As shown in Figure 38, success with a digital twin begins with establishing clear objectives. Do we want to know What, How, or When it fails? What kinds of failures? What kinds of operations? What sets/subsets of the system?
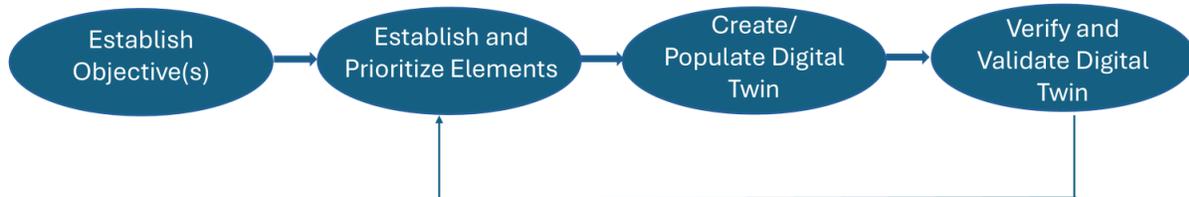


Figure 38: Digital Twin for Failures Strategy Implementation

Clearly articulated objectives enable SMEs and engineers to begin to explore what is and what is not relevant (important to understand) for the digital twin. This process of identification, categorization, and rank/prioritization of elements is at the heart of a successful digital twin. Note that nearly all the various Reliability and Maintainability analyses utilize this high-level thinking: how to win now the near-infinite domain of possible contributors down to those that really contribute.

Various ranking and prioritization techniques can be used depending on availability of data both design and historical. Some examples of these techniques can include: estimation of impact using 5 bins (aka NASA 5x5 risk matrix), utilization of Design-of-Experiments and quantitative identification of risk/uncertainty contributors and their contribution, and identification of the factors that are indistinguishable from noise (for example, factors which can be ignored) to plan the development of the digital twin and a core part of the associated uncertainty quantification.

While there are a wide variety of characteristics and groupings, the important goal is to have a complete collection. Brainstorming, data mining, and other identification techniques should be used to flesh these out. Figure 6 was created within NASA's Digital Engineering Program to communicate to senior leadership how the digital twin should evolve from the standard engineering model's development in an integrated Digital Engineering product lifecycle framework.

It should also be strongly noted that digital twins should naturally evolve out of models/simulations created as part-standard development efforts. An eye is given to digital twin usage as part of Ops and Sustainment, and they are more than just static CAD models or high-fidelity simulations (Figure 39).
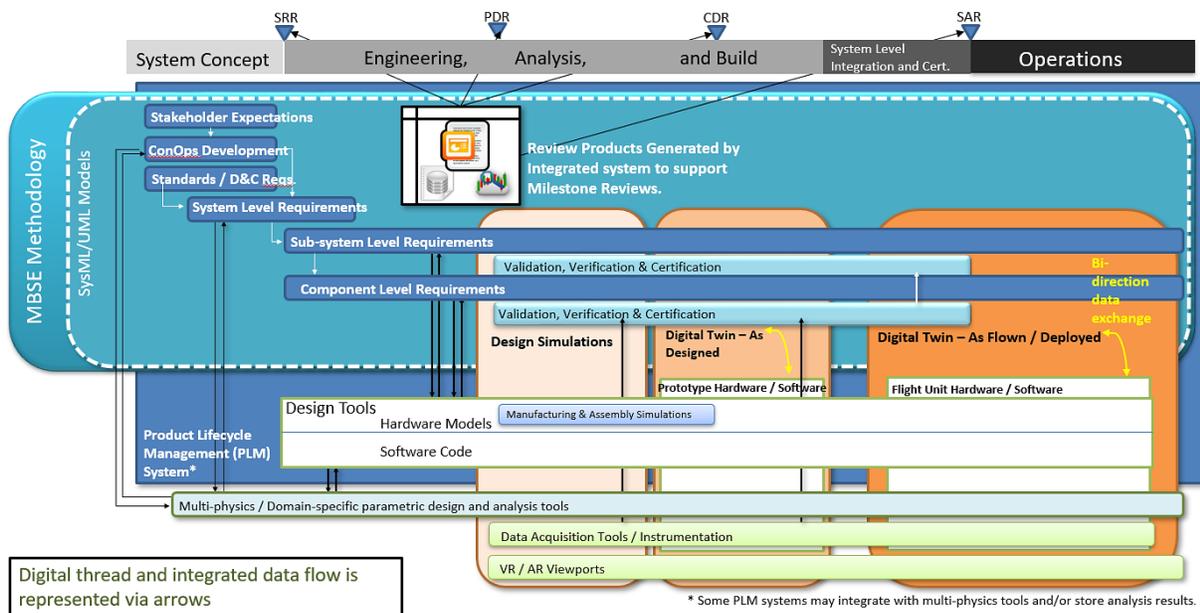


Figure 39: Digital Twin Evolution from the Standard Engineering Models Development in an Integrated Digital Engineering Product Lifecycle Framework

## Description of Recommended Considerations and General Capabilities of a Digital Twin for Failure Prediction

This section describes the recommended capabilities of user needs, mission, objectives, environment, interface, personnel, or other factors that require a digital twin for failure prediction. Description of recommended digital twin capabilities are consistent with the description of the approaches to failure prediction provided in Section 3.2.3.

## Level I Characteristics

The following Level I and Level II Digital Twin Characteristics are summarized in Figures 40 and 41. Before undertaking the development of a digital twin, the most important characteristics of digital twins needing identification are the phases of the system lifecycle should the digital twin virtualize, and these should be agreed upon. Not coming to an agreement and understanding of the associated boundary conditions will result in a digital twin which performs somewhere between sub-par, and failure to achieve the desired outcomes. As with lifecycle phases of the physical systems, similar duration of the digital twin's existence, operation, and desired functionality should be representative in the creation and/or the planned digital twin evolution from one phase to the next.
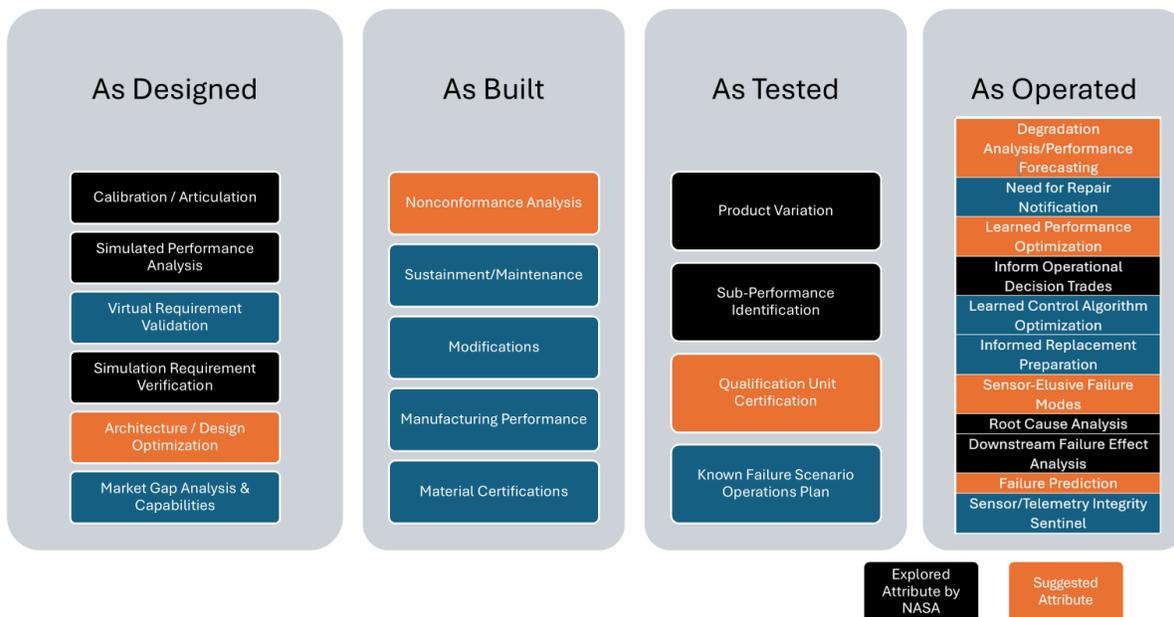


Figure 40: Level I Digital Twin Characteristics Regarding Operational State of Physical Representation Used by NASA

It should be noted that it is critical that the digital twin and the physical system stay synchronized in form and function, such that virtual and physical assets are respectively one half of a digital twin. This synchronization can be ensured to happen via configuration and changing managed

processes, which should be considered a cornerstone of systems engineering and the standard practice within industry. The primary lifecycle digital twin virtualizations are:

<u>As Designed</u>

In this phase, the digital twin doesn't truly meet the definition of a digital twin mentioned previously and should more accurately be considered what it is: a potentially sophisticated assemblage of simulations and models which represent everything known about the as-designed system to date. This is an important stage to verify, at least virtually, that the representation has all the components, measurable/observable characteristics, and functionality as defined before the development of the digital twin.

<u>As Built</u>

The as-built digital twin will reflect the system which has been 'manufactured' (hardware, software, system workflow, or operational structure, as a digital twin doesn't just have to be a vehicle or system of hardware and software). Often there are limitations with the design during the initial manufacturing phase, where limitations and constraints which were not sufficiently defined during the conceptual phase of the system are realized, and the design must be modified. The digital twin must be changed to keep in sync with these changes and keeping the digital twin and physical system changes should be incorporated as part of the project configuration management processes and discipline.

<u>As Tested</u>

Once the physical system has been manufactured, it must be verified, certified, and cleared for operations prior to any operational changes are realized. A key element to note is that during the process of verification, certification, and clearance for operations, there is a non-zero chance there will be errors, defects, and missed functionality realized during these processes, and the digital twin must be modified along with the physical system through these phases. Ultimately, the digital twin must be certified to be a virtualization of the physical system to an agreed upon range of accuracy and uncertainty.

<u>As Operated</u>

The final (for digital twins evolving from previous lifecycle incarnations) and likely the most long-lived digital twin is associated with system operations support. Within the government sphere, it is not uncommon for deployed systems to operate for decades, and such the real-world system will go through periodic and possibly constant changes and evolution and will need to be updated due to new edge use cases identified, changes in constituent technologies, or the operational environment itself. And with every change made to the real-world system, the representative change must also be made to the digital twin and then verified against the physical system. Failure to keep the synchronization will lead to false trust in the digital twin, or all out

lack of desired functionality, and likely a significant loss of return on the non-trial investment made. More discussion on digital twin operational considerations is made in Section 3.2.4.

**Level II Characteristics**

The Level II characteristics illustrated in Figure 41, while not a comprehensive list of considerations when performing the more detailed planning and design for the digital twin, does provide a set of characteristics which will encompasses or facilitate the discussions for the majority aspects to consider and make deliberate digital twin design decisions.

A detailed discussion of each of the sub-characteristics will not be provided here, as it would be considerably outside the scope of this white paper but should be evident enough for the discussions which need to be undertaken. However, the higher-level considerations follow.
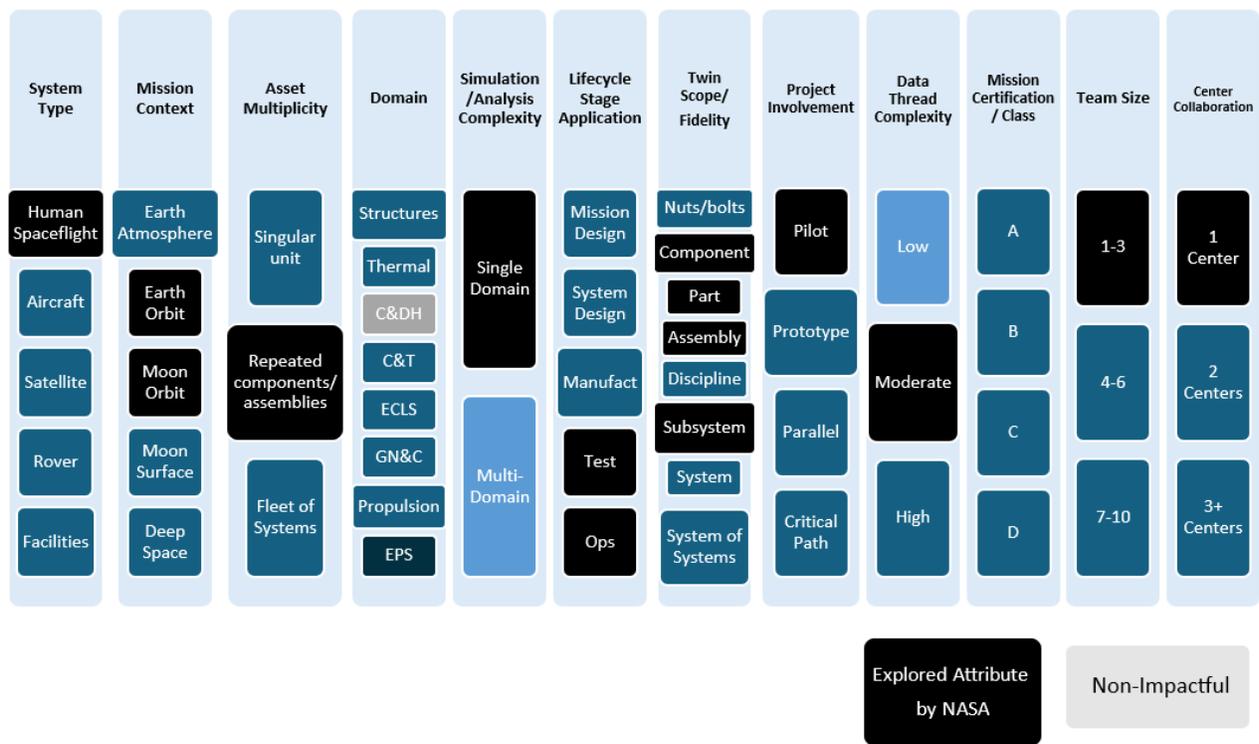


Figure 41: Level II Digital Twin Characteristics Regarding Operational State of Physical Representation Used by NASA as of End of Year 2024

## System Type

The system type is one of the more obvious regarding how the characteristics will play into the planning and development of the digital twin. Each system type will have different behaviors, designs, and methods of gathering information on the system, all of which will dramatically change the nature of the digital twin and how it interacts with its physical counterpart.

### Mission Context

This is synonymous with Operational Context such that the performing organizations can find the relevant mission context/environment of which the operational physical asset is measured or modeled in the operational context of the digital twin.

### Asset Multiplicity

Asset multiplicity is an important consideration, specifically if the number of deployed physical systems will need to interact or communicate with each other. This interaction of the multiple physical systems must be replicated intentionally to ensure the desired level of 'twininess' of the digital twin.

### Domain

Much like the system type, this sub-characteristic is self-evident but a foundational part of the construction and capability of digital twin.

### Simulation / Analysis Complexity

This sub-characteristic will drive much of the digital twin computational requirements and needed resources, tool integrations and corresponding complexity, and the primary driver for understanding and managing uncertainty quantification.

### Lifecycle Stage Application

This sub-characteristic can be considered redundant to the Level I characteristics discussed previously. It is reflected at this level not only as a reminder, but it does facilitate some of the finer nuances needed in connection with many of the other sub-characteristic decisions needed at this level.

### Twin Scope / Fidelity

The desired virtualization of the physical counterpart is foundational to the digital twin planning. Decisions in this area will drive the scope, accepted fidelity, and approach to managing uncertainty. This area will also drive the associated complexity and overall scope and will be the main factor for development and certification budgetary needs.

### Project Involvement

This sub-characteristic would appear to be largely redundant to Lifecycle Stage Application, there finer nuances in this area will help define associated risk to the program/project and criticality of the development effort, associated certification rigor, budgetary resources, and overall schedule.

<u>Data / Digital Thread Complexity</u>

Digital twins exist only because of the associated data / digital thread, and thus, understanding and mapping out the breadth, complexity, and flow of needed information is critical.

<u>Mission Certification Class</u>

The examples provided in Figure 8 are NASA-specific, but analogous mission certification classifications are found in DoD, DoE, DHS, and other federal agencies, and are in turn levied on contracted support from the aerospace and defense industry. These associated sub-characteristics form the basis of final certification and readiness for operations and should be factored into the fidelity of digital twin.

<u>Team Size</u>

The values presented in Figure 8 are largely arbitrary but are presented to force consideration of the scale of the workforce which will be interacting with the digital twin to drive considerations such as deployment approach, communication, digital thread, latency of data, under interface, training, and security, to name only a few.

<u>Center Collaboration</u>

This sub-characteristic has some overlap with Team Size but also speaks to the needs of the other organizational stakeholders. What do they want out of this system, what is their role, what resources will they contribute to the development, certification, and operations of the digital twin?

**Operational Systems and Impacts to Associated Digital Twins**

Identification of the interfaces of the real-world system and that of the digital twin with infrastructure, data systems, tools, processes, and organizations as a system-of-systems is important, as it will ultimately impact the proposed digital twin system. Ideally, this information will be collected by standard systems engineering efforts. The concept of a digital twin is relatively new and systems engineering principles need to be used as part of the digital twin formulation and scoping, which includes identifying all needed interfaces. This information can be useful to personnel involved with system development, whether it be users, buyers, or developers, should they want to know if a certain change or feature was considered, and if so, why it was not included. The information in this section helps to place bounds on the expectations for the proposed digital twin.

The following should be considered when initially scoping the digital twin as part of developing the concept of operations, but also in terms of vigilance in the operational phase and further emphasizing the necessity of baseline management of the digital twin. The same configuration/change management processes and workflows should be used for the approved changes in the physical system *and* the digital twin.

### System Processing Changes

Change in the way in which a system is operationally managed, and the associated processes will impact the utilization of a digital twin for failure prediction. Such changes which will result in changes to the typical system's behavior, data, and thus the way the system ages and in turn fails. Depending on the resiliency of the respective part parts of the system, in some cases extremely minor changes in operations and maintenance can manifest in dramatic changes in the MTBF and should be understood well and reflected in the digital twin.

### Technology Changes

Changes to technology in the real-world or digital twin systems will impact the ability of failure prediction capabilities and insight into the physical system, and the operational need to do so should be considered for the proposed system.

### Interface Changes

Changes in the system at the primary interfaces, and subsequent secondary and tertiary interface changes can cause changes in the system and associated failure prediction. However, even if it doesn't drive a change in failure prediction, it is a best practice to make needed changes in the digital twin (see previous comments regarding synching of digital twin and physical system baselines).

### Personnel Changes

Anticipated or unanticipated changes in personnel caused by the new mission requirements, changes in user classes, or both can be factors in the real-world system which might impact the system failure characteristics and should be considered within the digital twin.

### Environment Changes

Changes in the operational environment can cause changes in the system functions, process, interfaces, or personnel behavior, and associated system failure response and must be appropriately reflected in the digital twin environment modeling.

### Operational Changes

Changes to the physical system's operational policies, procedures, methods, or daily work routines, which could be caused by the above changes or unmentioned external factors, can result in the failure modes and probabilities, and should be planned for in the digital twin planning and reflected in the digital twin operations and sustaining.

### Sustaining Support Changes

Changes in the support of the real-world system resulting from intended (e.g. budget reductions) or unintended (e.g. organization apathy) actions will reflect in the level of real-world system

sustainment. Further, these changes affect failure modes and probabilities. Periodic digital twin-to-real-world reverification ensures the two remain at the levels of desired replication.

**Proposed Development Methodology by Implementing Organizations**

The proposed methodological approach to using digital twins for failure prediction, which will result from the approaches specified in previous sections, is presented here and contains a major portion of the description of the proposed methodology. Methods of description used, and the level of detail provided, will depend on the situation. The level of detail will be sufficient to explain how the proposed methodology will satisfy user's needs and buyer's expectations but will not be decomposed to the levels reflective of the implementing organizations.

It is important to keep in mind the early digital twin ConOps must be written in the user's language. In most cases, this means avoidance of terminology specific to domain SMEs; for example, computer "jargon" should be avoided since ConOps documents should be understandable by several different system user groups, and such, graphical representations should be used wherever possible. Useful graphics could include, but are not limited to, work breakdown structures, $N^2$ charts, functional block diagrams, structure charts, allocation charts, data flow diagrams, object diagrams, context diagrams, timing diagrams, storyboards, and entity-relationship diagrams, which capture many of the Level I and II digital twin characteristics. Usage of MBSE methodologies and associated SysML models will dramatically aid in capturing and communicating said information, particularly as the system of interest becomes increasingly complex.

The resultant digital twin design plan describes the proposed digital twin virtualization in a high-level manner, indicating the operational features that are to be provided *without specifying design details of the proposed system*. It will not contain digital twin design specifications but will contain some examples of typical design strategies and use cases for the purpose of clarifying operational details of the proposed digital twin system. In some cases, users and/or the stakeholders may impose design constraints on the proposed system (e.g., must use specified hardware items, security sensitivities, and software preferred packages); while not ideal from a design and engineering perspective, they are often a reality and should be recognized and captured as early in the digital twin lifecycle as possible.

<u>Operational Description of the Proposed System</u>

The operational description of the proposed digital twin system should include operational features and capabilities, the operational environment of the proposed system, operational policies and constraints, modes of operations, user classes, other involved personnel, and the envisioned support environment for the proposed system which align with the Level I Characteristics defined in Section 4.2.

<u>Digital/Virtual Features and Capabilities</u>

Features and lower-level characteristics and capabilities of the proposed digital twin system that will be largely defined the scope of the system, and additionally be visible to users of the system, should be itemized and summarized in this digital twin definition. Operational Digital/Virtual features should be listed in priority order in accordance with the priorities established in previous digital twin definition.

<u>Logical Environment</u>

A logical environment refers to the functional or conceptual layout of a system, focusing on what it does and how it interacts, rather than its physical implementation. This digital twin definition should describe the logical interfaces with other systems. A context diagram (for example, SysML model) illustrating the physical system environment, boundaries, and known and/or anticipated interfaces of the proposed system is strongly recommended to ensure proper digital twin interface definition and integrating of needed information per the digital thread.

<u>Physical Environment</u>

A physical environment describes the tangible aspects of a system, including its hardware, infrastructure, and physical connections. This digital twin definition should describe the direct physical interfaces with other systems. A context diagram (for example, SysML model) illustrating the physical system environment, boundaries, and known and/or anticipated interfaces of the proposed system is strongly recommended. This ensures proper digital twin interface definition, interoperability standards, and data communication and data rates (to mention only a few important factors of design consideration) are factored into the digital twin detailed design.

<u>Use Classes for the Proposed System</u>

A user class is distinguished by the patterns of interaction between user and system. Factors that distinguish a user class include responsibilities, skill level, work activities, and system modes exercised by the user. Different user classes may have distinct operational scenarios for their interactions with the digital twin system. In this context, a user is anyone who will interact with the proposed system, including operational users, data entry personnel, system operators, operational support personnel, software maintainers, and trainers.

This is an aggregation of the Level II characteristic definition involving, but not limited to, sub-characteristics formerly mentioned: Domain, Project Involvement, Mission Certification Class, Team Size, and Center Collaboration.

**Operational Failure Prediction Digital Twins**

This digital twin definition describes the various planned modes of operation for the digital twin system, which might include normal, degraded, maintenance, training, emergency, alternate-site, peacetime, wartime, ground-based, flight, active, and/or idle modes, and how all of those relate

to how the digital twin will be used in relation to the real-world counterpart. Important modes to include are backup and emergency modes, if such exist. This is especially true if these modes involve different geographical sites and equipment that have significant impacts on the system.

## 3.2.6 Use Cases

The following DT TAG membership agencies have provided, deployed, or hypothetical relevant use cases for their Agency to be used to spur creative consideration in the future within their Agency or others.

**NASA**

**Artemis I Orion Electrical Power System Digital Twin** [16]:

In 2015, it was recognized by NASA's Orion Chief Engineer that NASA's design insight into the Orion subsystems for Artemis I was not sufficient to provide standard engineering support to flight operations. To address these concerns, and to provide an opportunity to apply emerging model-based systems engineering and digital twin methodologies, as well as provide opportunities for employees across NASA to get hands-on training, an Orion Digital Twin pilot project was initiated in 2020 as part of the Agency's Digital Transformation initiative.

With the increase in complexities of spacecraft, as well as decreased time to make decisions during missions in critical or emergency situations, digital modeling and integration of design can reduce the time to answer questions by days, and the required human resources by an order of magnitude over conventional approaches. Additionally, it has been identified as a critical capability for NASA's future.

The project sought to enhance human interface with data to increase decision velocity and accuracy. Additionally, the project enables real-time mission support, decision making, and anomaly resolution with digital search via an intelligent application. This has never been available via paper or PDF documents or drawings. Development of a robust SysML model and digital twin also provides an opportunity for the Orion Program, Engineering support, and flight operations communities to engage, and provide interface integration opportunities to Gateway, space suits, and international partner elements (Service Module, HTV-XG, etc.).

The Orion digital twin received actual vehicle mission telemetry data to be used for faster-than-real time simulation. In addition, the digital twin enabled visibility to propagated trending to simulate unplanned performance or possible failure, as well as various scenarios to gauge vehicle performance and recommended actions. However, based upon the most recent definition of digital twins, the current lack of information flowing directly from the digital twin to the flight vehicle places it slightly lower on the digital twin 'twininess' spectrum.

**Digital Twins of Mars Rovers:**

NASA created the OPTIMISM (Operational Perseverance Twin for Integration of Mechanisms and Instruments Sent to Mars), a full-scale engineering model that functions as a digital twin of the Perseverance rover currently operating on Mars. This Earth-based twin provides critical failure prediction capabilities through several key methods. OPTIMISM 'digital twin' system is comprised of the following physical components on Earth, digital representations and models, and connected systems:

Physical Hardware Components

- Full-Scale Rover Body - Physically identical to Perseverance (though with thicker wheels to accommodate Earth's gravity)

- Robotic Arm - Equipped with a coring drill for sample collection

- Adaptive Caching Assembly - System responsible for storing collected rock and sediment samples

- Mobility System - Wheels and drive mechanisms that allow traverse testing

- Sample Collection System - Complete end-to-end drilling and storage mechanisms

Software Components

- Autonomous Navigation System (AutoNav) - Software that creates 3D maps from terrain images and plans driving routes

- Flight Software - Identical or similar software to what runs on the Mars rover

- Command Processing Systems - Software that validates and tests commands before they're sent to Mars

Testing Environment

- Mars Yard - A dedicated testing ground (described as "about as long as a doubles tennis court and twice as wide")

  - Varied Terrain Features - Different slopes, obstacles, and hazards for navigation testing

  - Diverse Rock Collection - Various rock types to test drilling capabilities across different materials

- Integration Systems

  - Command Validation Framework - Systems to ensure commands sent to Mars can be safely executed

- Problem Simulation Infrastructure - Capability to reproduce and diagnose issues encountered on Mars

- Environmental Adaptation Systems - Components to account for Earth vs. Mars environmental differences (temperature, gravity, etc.)

The OPTIMISM system integrates these components to provide a comprehensive digital twin capability that supports preventative testing, problem diagnosis, and solution development for the Perseverance Mars mission.

**NNSA**

**Digital Twin for Weapons Aging and Lifetimes** [17]

Within NNSA, a successful digital twin representation within advanced manufacturing and surveillance settings has the potential to transform weapons Aging & Lifetimes (A&L). A&L Digital Twins require integration of a unique set of data streams from historical data, as well as modernizing the workflows using automated scripts. These data streams are more often distinct in their nomenclature and formats, which makes integration unintuitive. A parallel effort is the modernization of workflows, which enables lab-developed data analytics to be applied in simulated parameter sweeps of unprecedented scale. The approach for introducing digital twins involves connecting experimental data and simulation data through an integrated database, as shown in Figure 42.

In this approach, insights obtained from experimental data (both historical and current datasets) can be stored into a centralized database and can be used as input parameters for a simulation. This database will always update as new data, models, and insights are introduced, making it a living database. Updated workflows can then take advantage of the system by querying parameters of interest, as well as output analyses, in an automated manner. This vision for digital twins is focused on creating fast, streamlined workflow from data acquisition, and high-fidelity modeling for advanced manufacturing and weapons surveillance.

Exercised case studies towards realizing A&L Digital Twins show new capabilities development and their benefits:

- **Modernizing software workflows** for decreased computational expense, simulation of massive parameter sweeps, and training machine learning based surrogate models to aid in part design.

- **Instantiating A&L Digital Twin models that extend traditional physics-based modeling approaches** to enable optimal utilization of available information, such as data-informed physical modeling (DIPM) and/or physics-informed ML/AI, alongside traditional pure physical models.

- **Digital Twin platforms that manage and perform analytics on relevant data streams** for outputting models directly from a database as a necessary step in realizing data-driven digital twins.
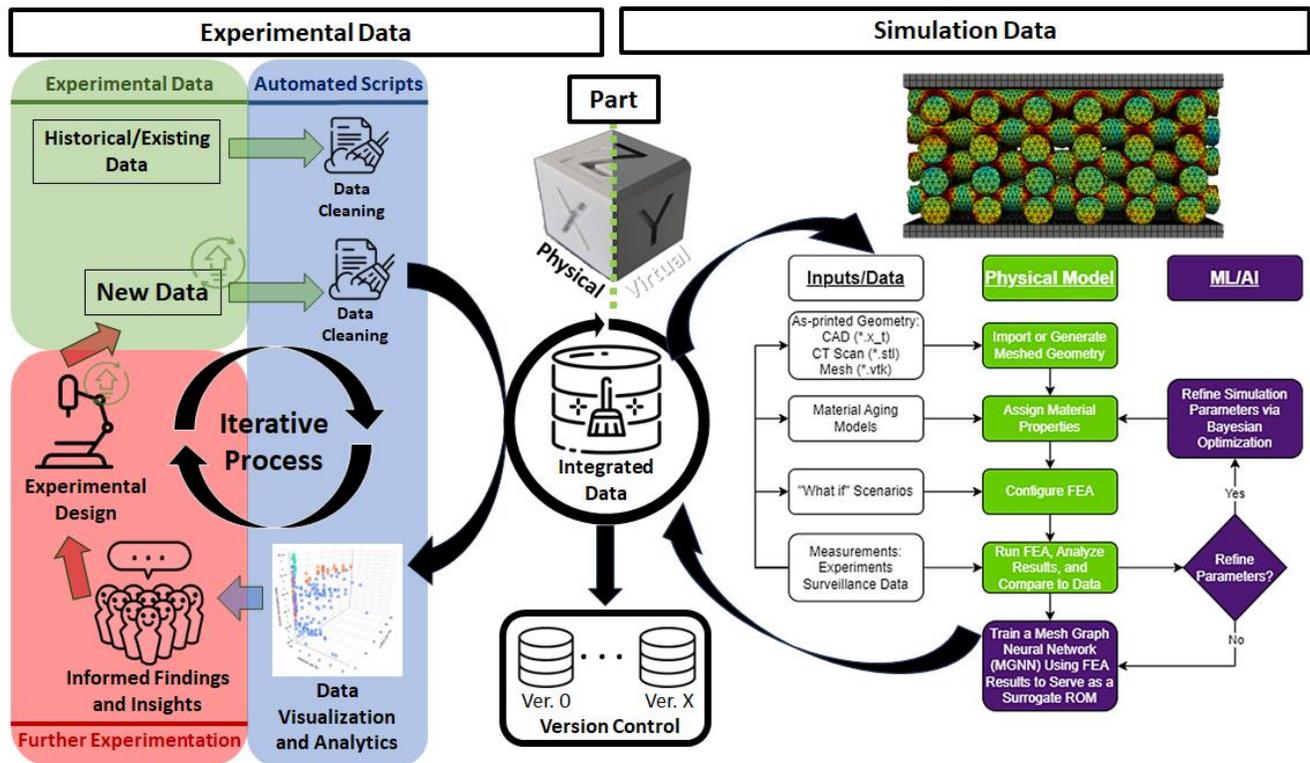


Figure 42: Future Outlook for Weapons Aging and Lifetimes in Which Experimental and Simulation Data Streams are Integrated, Tracked, and Leveraged to Realize Digital Twins

**Digital Twin for Predictive Manufacturing Maintenance & Efficient Production Operations** [18]

Using digital twins to investigate the internal workings of complex devices, manufacturers can predict when issues will occur and attend to maintenance concerns before they disrupt the entire production. Examples from NNSA Production Agency, which use high-fidelity modeling and simulations and digital twins for smart manufacturing and efficient production are presented below:

- **Integrating real-time sensor data** (for example, vibration, temperature, current) with simulation results to predict failures in advance. These systems automatically alert the appropriate personnel directly (if defined) or can submit automated tickets into the maintenance system.

- **Exercising manufacturing process simulation tools** in targeted fashion to justify large capital expenditures by using historical manufacturing data and upcoming demand. This

determines the impact of capacity increases on areas that cannot otherwise meet demand, which could be considered a different type of 'failure'.

- **Associating a variety of production data to the physical asset** to provide a more comprehensive view of tools/gages used, calibration standards, environmental conditions observed, test data/dimensional scans, and machine data. Important information from the manufacturing process used to improve the timeliness of containment activities if an issue is identified, and the collection steps allowing for error proofing to ensure the process accuracy will not proceed if expected conditions are not met (e.g.: prevent need for containment after the fact – again a different type of 'failure').

- **Using physics-based simulations (e.g. FEA, CFD, EM, materials) to address manufacturing challenges**. Physics-based simulations are used in response to a failure and the models can be calibrated against test data, generally involving some level of Verification, Validation and Uncertainty Quantification (VVUQ), and used to virtually test changes to the design, fixturing, test conditions, etc. to define a proposed path forward. There is an urge to leverage simulations of the manufacturing or testing processes across all products before manufacturing, but there are challenges.

- **Leveraging the lessons learned through simulation to generate 'Design for Manufacturing' or 'Design for Testing' rules that are visible to Design Agencies during definition creation (again, avoid the 'failure').**

**OUSD**

The Office of the Under Secretary of Defense (OUSD) Research and Engineering (R&E) Systems Engineering and Architecture (SE&A) Specialty Engineering (SpE) manages the Department of Defense (DoD) – Industry Reliability and Maintainability (R&M) Engineering Roundtable. This roundtable prioritizes and addresses R&M challenges (pain points) within Government, DoD, and Industry, and presents results at the Annual Reliability and Maintainability Symposium (RAMS). One of the current pain points that meets biweekly is focused on instantiating Digital Engineering (DE) into R&M engineering activities. The following are use cases under development in support of instantiating DE into R&M.

**Product Support Feedback Loop Use Case**

This use case aims to enhance R&M in DoD product support activities. It offers a model-based framework to effectively manage a product support feedback loop use case.

Model-Based Systems Engineering (MBSE) is important for the following reasons: complexity management, improved communication, enhanced quality, increased productivity, improved decision making, documentation/traceability, facilitation of reuse, and support for systems thinking. MBSE is important because it provides a comprehensive framework for dealing with

the challenges of modern systems engineering, leading to better-designed systems, more efficient development processes, and ultimately, more successful project results.

MBSE uses formalized modeling techniques, like Digital Twins, to represent and analyze systems, allowing engineers to anticipate and mitigate potential reliability issues early in the design process. By creating a comprehensive and coherent digital twin, MBSE facilitates a thorough understanding of complex interactions and dependencies, which is crucial for identifying and addressing potential failure points.

Digital Engineering (DE), on the other hand, leverages advanced computational tools and virtual environments to simulate and assess the performance and sustainment of systems over their lifecycle. This digital twin representation enables engineers to predict wear and tear, maintenance needs, and operational challenges, ensuring that systems are designed not only for optimal performance but also for long-term reliability and ease of maintenance.

The digital thread of data is used and shared across various digital twins/models and plays a role in the interchange of maintenance and design for reliability data. A digital thread is a bidirectional, dependable and trustworthy interconnected information system that links multiple dimensions, including structure, behavior, space, time, and lifecycle stages.

Together, MBSE, DE, digital twins, and the resultant digital thread provide a framework for integrating reliability and sustainment considerations into the system development lifecycle, leading to long-term and cost-effective solutions.

The use case SysML diagram in Figure 43 shows the actors and interactions with various tasks involved in the product support feedback of the digital twin.

Figure 44 shows the digital twin with the flow of engineering data to product support analyses (for example logistics, sustainment, etc.) with a feedback loop for feeding back R&M improvements to the design models. It encompasses data between MBSE and Model-Based Product Support (MBPS) [19], including flow of Reliability Block Diagram (RBD), Fault Tree Analysis (FTA), Identification of mission essential functions, and Failure Modes, Effects, and Criticality Analysis (FMECA) data to Maintenance Task Analysis (MTA), Level of Repair Analysis (LORA), and Reliability Centered Maintenance (RCM)/Conditioned Based Maintenance + (CBM+). It also includes the flow of reliability data for readiness-based spares.
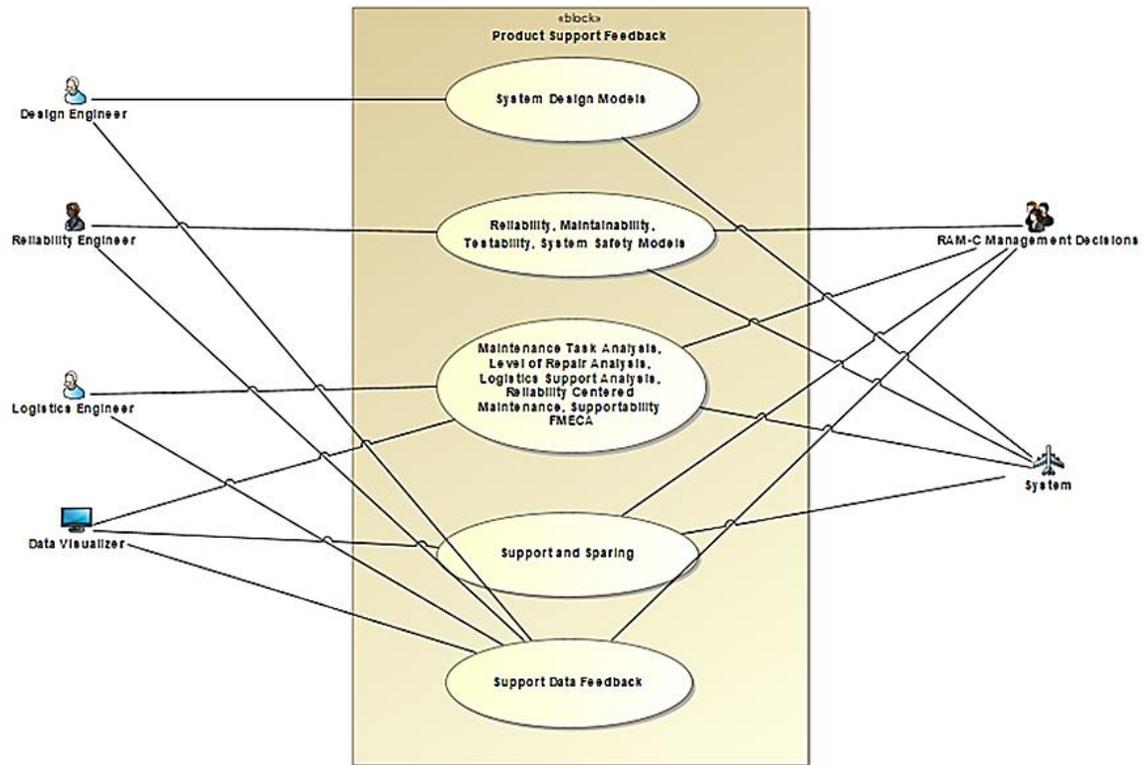
Figure 43: Product Support Feedback Loop Use Case
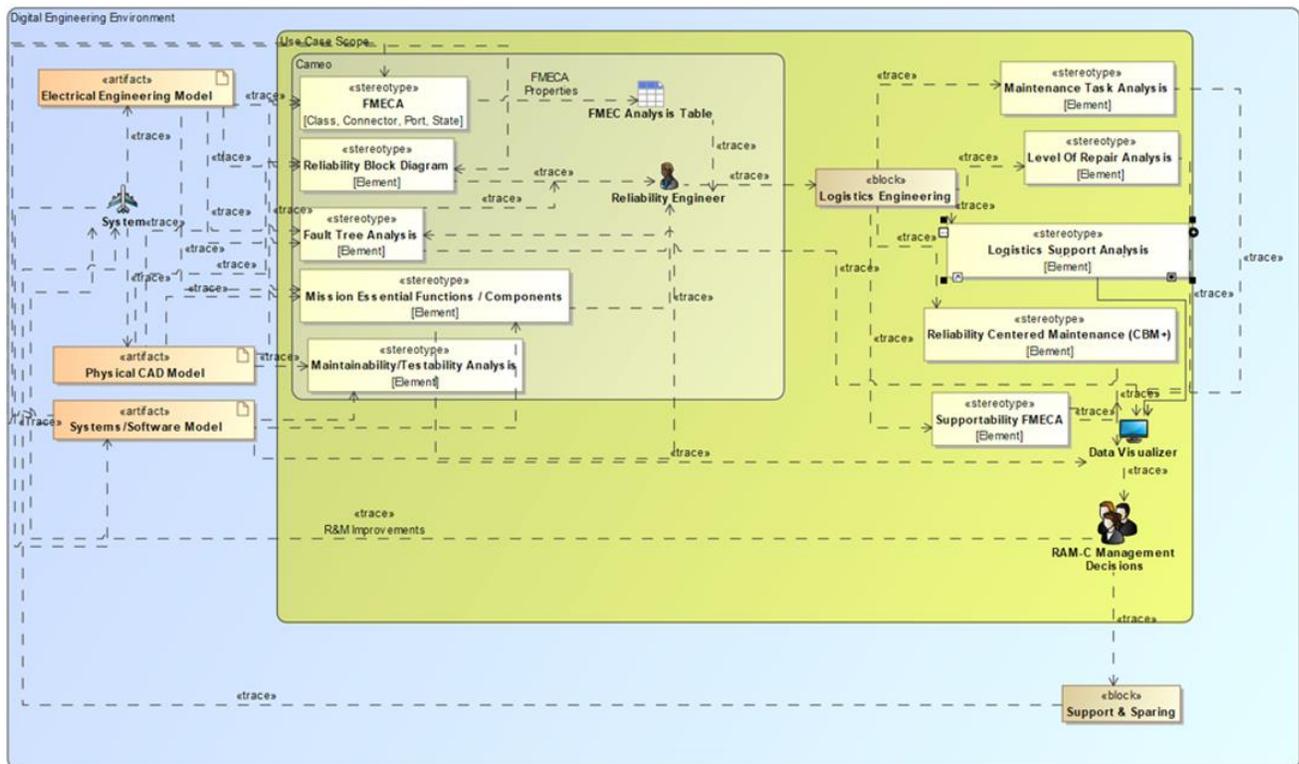


Figure 44: Product Support Feedback Digital Environment

**Type of Use Case:** An abstract use case was used to represent the Product Support Feedback Loop. This high-level use case is not directly elaborated but is used as a basis for other use cases. It represents common interactions that can be generalized across multiple use cases.

**Components of Use Case:** Traditional processes are represented in MBE through diagrams that depict key elements (actors) of the traditional process. The overall goal of the use case is stated up front. In this case, it is to outline the connections across the various analyses and actors in Product Support, and how they link to design analyses. Additional components of a digital twin use case are represented with the following:

- **Goal or Objective:** Goal of optimizing Product Support; primary actors of the reliability engineer and RAM-C management are using the system to achieve a goal of R&M improvement

- **Preconditions:** All external systems (represent as SysML blocks) and actors must be available and usable

- **Postconditions:** Applicable Data efficiently exchanged across all elements

- **Trigger:** All use cases (ovals within the use case diagram) can be triggered by an anomaly, failure, design change or analysis that changes data for any relevant element in the system of interest

- **Business Rules:** Governmental and data policies must be adhered to; information and data security is paramount; and configuration management processes are in place

- **Assumptions:** Applicable elements are available, and data / communication transmission can occur

- **Stakeholders:** R&M / IPS / Program Leadership, Warfighters, Maintainers, and other users

- **Success Criteria:** The use case is successful when all elements are fully integrated, and data flows through the use case for stakeholders to properly assess for inputs and impacts to sustainment

- **Elements**: Actors and blocks included in Use Case

- **Meta Data** and specific data elements are not represented in the Use Case but can be added into additional digital twins/model diagrams based on the scenario

- **Element Relationships:** Trace relationships are used throughout the Use Case. The relationships created between actors and use cases represent communication that occurs between those elements

**Model-Based Engineering (MBE) / DE and Mission Assurance of Complex NASA Systems with Federated Modeling**

Mission assurance engineering at NASA/Goddard Space Flight Center (GSFC) is a framework of digital twins, methodologies, analyses, tools, and processes that ensure each system's safety, reliability, maintainability, and availability (RMA); quality, and software robustness via risk assessments and analyses to assess and manage mission 'lifetime' engineering risks and impacts of hazards/failures, mitigations, corrective actions, and recovery strategies.
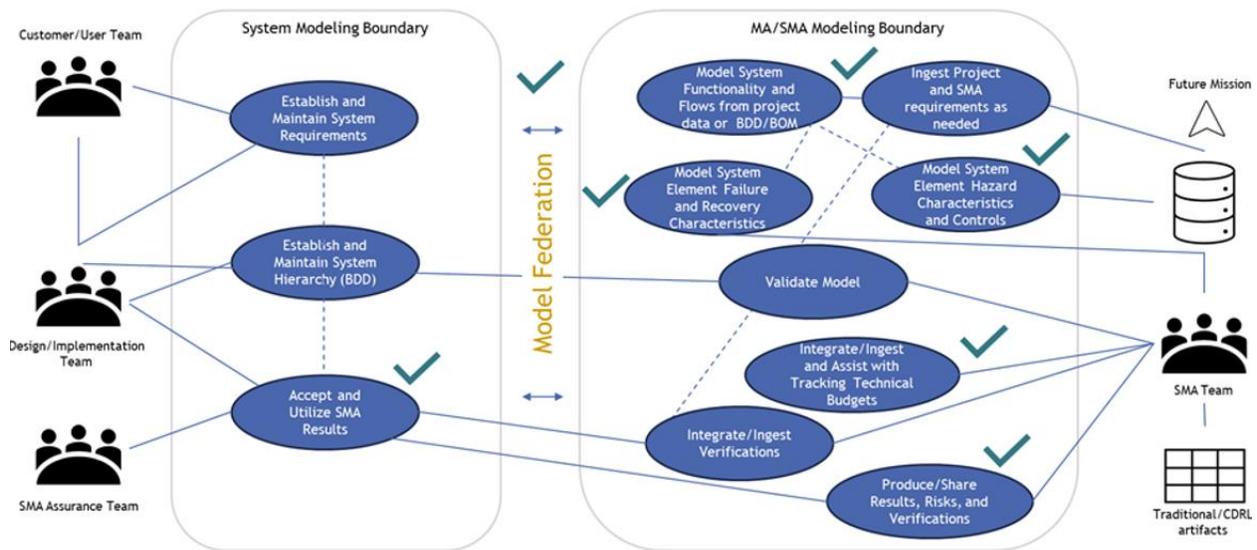


Figure 45: Model Based Safety and Mission Assurance (MBSMA) Use Case

The Use Case shown in Figure 45 is based on Modeling processes and controls into a digital twin based on recommendations from the following studies:

- Establish a multi-discipline modeling team (Systems Engineering (SE) and Safety and Mission Assurance (SMA) at a minimum).

- Establish modeling responsibilities (for example: Systems Engineers model requirements and system configuration hierarchy within digital twin via Block Definition Diagrams (BDDs); Reliability Engineers (REs) model and codify failure behaviors, characteristics, and controls; the design and systems teams conduct configuration element-functionality and interface/flow details within Functional Block/Wire Diagrams; Safety Engineers model hazards).

- Complete SMA-modeling, based on importing/ receiving modeling elements and data from the system model, by:

  - Creating a Bill of Materials (BOM) in the system model and exporting that to Excel.

  - Importing the exported BOM into the SMA model.

- Performing SMA modeling.

- Produce SMA artifacts and share resulting data between digital twin/modeling elements by:

  - Exporting SMA artifacts and artifact-data items in Excel.

  - Ingesting/emulating those artifacts in the system model in tables and attachments.

  - Validate and refine modeling (and designs) until a final and acceptable result is achieved.

  - Share modeling with future missions.

  - GSFC used three mission test cases and two tools to evaluate the ability of DT/MBE to support Probability Analysis (PA), Failure Mode Effects and Criticality Analysis (FMECA), Fault Tree Analysis (FTA), Limited Life Analysis (LLA), Availability, and Maintainability.

  - DT/MBE is found to be valid and useable for NASA Mission Assurance if adequate modeling processes and environments are established.

  - Model-Based Organizations, including NASA, must decide for themselves how to implement DT/MBE in a way that makes sense for all their engineering, assurance, operational, and production elements. Therefore, it is essential to engage subject matter experts from each element as early as possible.

- Leveraging SysML Engineering Design Models (MBSE) for R&M Engineering Analysis

  - This Use Case is based on the NASA Johnson Space Center (JSC) decision to develop an approach to facilitate the integration of System Design and Reliability and Safety Analysis activities.

  - Figure 46 shows how the Model-Based Fault Management Engineering (MBFME) is applied structurally within meta-model.

  - Figure 47 shows how the MBFME Use Case's behaviors are applied within the meta-model.

Using this MBSE Toolchain and Methodology:

- Mission assurance and reliability engineering can be incorporated early in the design cycle.

- Safety and reliability analysis can be conducted in conjunction with other systems engineering processes.

- Incorporating failure and reliability data into the system model allows for continuous and proactive safety and reliability assessments.

- This approach adds value to the design process by enabling these analyses to occur both early in the development process, and as frequently as necessary, enhancing the ability to identify and address potential issues promptly.
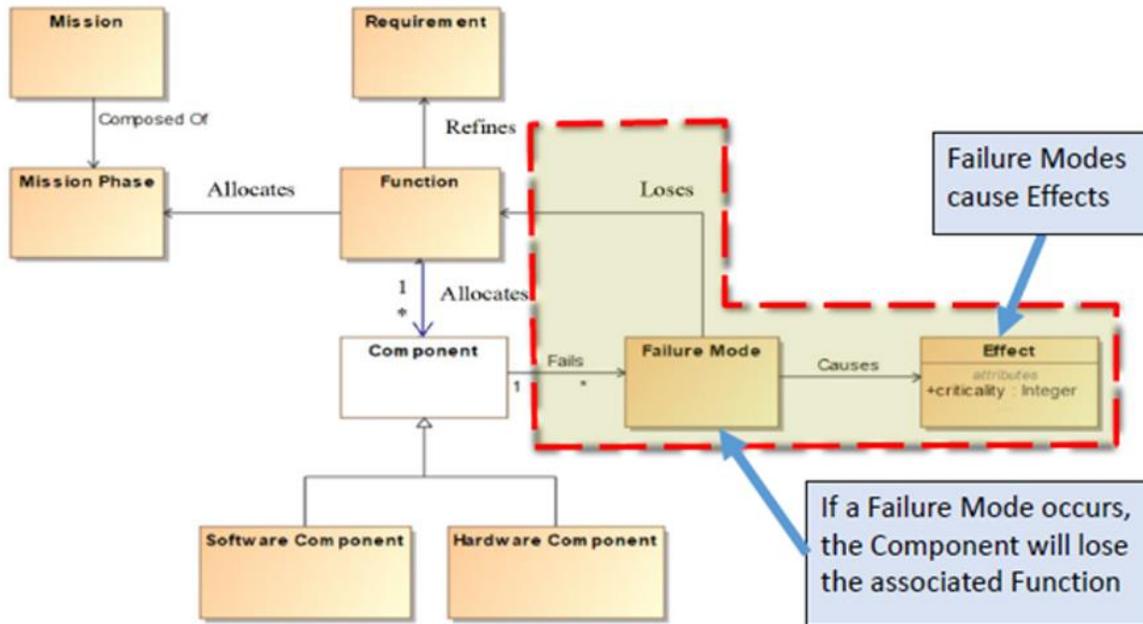


Figure 46: MBFME Meta-Model – Structural
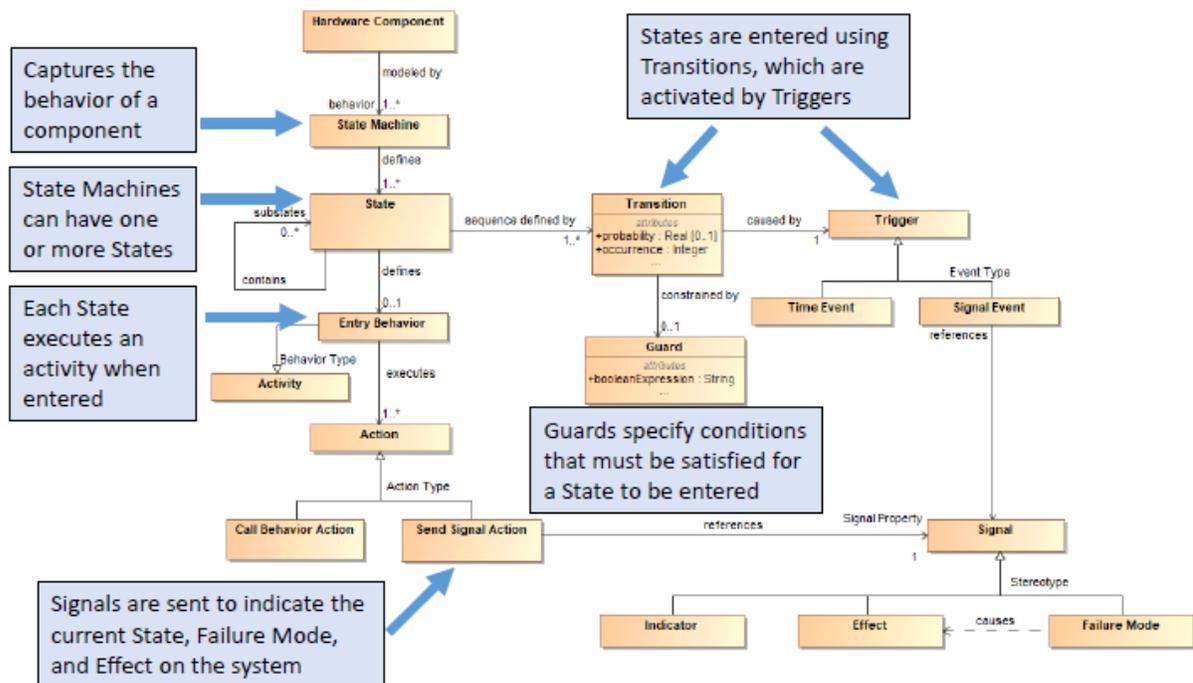


Figure 47: MBFME Meta-Model - Behavior

# 3.2.7 Challenges

As demonstrated in the previous sections, integrating Digital Twin systems with failure prediction methodologies involves detailed attention to data, real-time communications, and the physical environment. Additionally, other considerations must be addressed for successful implementation.

**Technology**

Digital Engineering technologies, tools, and approaches are rapidly evolving and proliferating. Industry has developed solutions to most of the technical challenges of digital twin computational complexity and speed, data storage and access, and human-machine interfaces. However, an individual Agency or Organization may struggle to keep pace with the rapidly expanding availability and capability of digital tools. One mitigation to help offset the changing technical environment is for Agencies to maximize the modularity of their tool portfolio to ease the burden of updating, improving, and re-certification of digital twins. This modularity would include the attention to enterprise DE architecture, selection of tools and information management repositories which are compliant with industry interoperability formats and standards and avoiding vendor lock with systems which store information in proprietary data formats, or limitations for future data export to other vendor solutions.

**Culture**

Cultural understanding of what a digital twin is and is not, is still in flux. The term 'digital twin' is often erroneously used as a synonym for a simulation or model. Having a clear and repeatable definition that is in alignment with larger industry-wide working groups helps Agencies interface with the private sector and coordinate Federal efforts. DT TAG recommends the definition published by the Digital Twin Consortium (See Section 3.2.2).

Though a digital twin is specifically designed and built to match a unique real-world system or system-of-systems, many methods, tools, and lessons learned should be shared among Agencies. Participation in consortia such as the Federal Digital Engineering Forum help alleviate parochial shielding of one organization's work.

The complexity involved with creating a digital twin also requires senior leadership to understand its purpose and value. The digital transformation of systems engineering and acquisition is not merely the procurement of more software tools, but a dedication to developing new approaches, gaining new skills, and governing data through authenticated sources of truth, and federation thereof across government-to-industry contractual boundaries. The commitment increases as emerging practices of AI/ML enhance digital twin performance and value.

**Incremental Development**

A common approach to developing digital twins mirrors the systems engineering developmental cycle (Figure 48). During the operational concept phase, where the needs demanded of the system are formulated, the requirements of the digital twin are simultaneously generated. As

engineers decompose these needs to functions assigned to assemblies in the physical system, engineers begin to develop models corresponding to their real counterparts. Similarly, as engineers integrate and test assemblies into larger and more functional parts of the system, they evolve the models into sophisticated simulations.
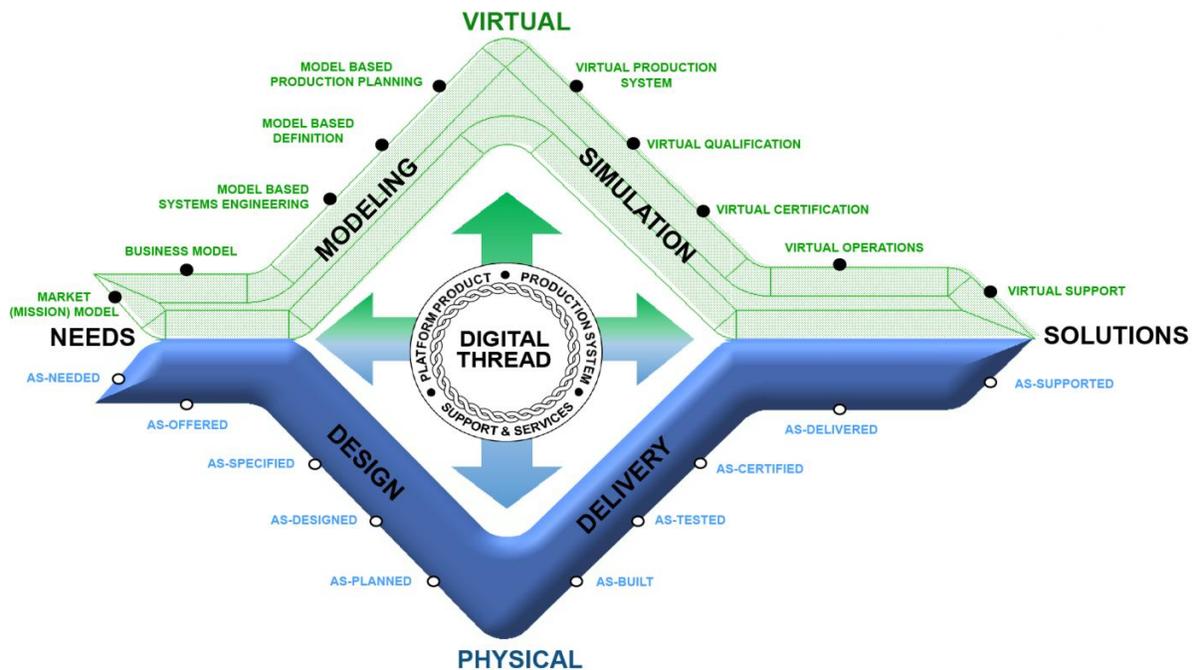


Figure 48: Systems - Digital Twins Development [20]

This parallel development of the system and its digital twin provides mutual support for both efforts. The intent is to avoid reworking and retrofitting if the real-world system and digital twin were developed separately. However, the engineers may choose to more fully leverage the virtual element to help more rapidly mature the development of the real-world asset during their earlier phases of a program lifecycle. The teams, too, can iterate previous work when requirements and other deign impacts change. The two teams' coordination leads to effective methods for completing the bi-directional flow of data between the real-world system and its digital twin. Throughout the effort, this two-prong development provides several opportunities to confirm that the digital twin can send, receive, and process real-time data from the system with sufficient speed and volume to be a benefit for the prediction of system behavior.

**Return on Investment**

An Agency must recognize that the cost and schedule in developing a digital twin is not trivial. Performing a cost-benefit analysis will help drive the scope and fidelity (both cost drivers) before beginning the endeavor. Industry can provide benchmarks for cost, time, and resources, but an Agency can apply analogous approaches to the probable costs when comparing the resources

required to create a low fidelity simulation versus a high-fidelity simulation (including the considerable configuration management, testing, and accreditation processes and documentation).

## 3.2.8 Conclusions

Digital Twins for failure prediction TAG efforts found there is strong interest in digital twins for specific applications, but not all digital twins are equal, and these nuances are important for organization leadership to understand. An agency-specific, strategic-approach use of digital twins can be distinct in terms of sophistication, lifecycle phase to which they applied and used, and the associated measurable benefits. There is not one best method or one single-use of a digital twin for predicting failures of systems, processes, etc. An organization's end goal for the digital twin determines its best method and use for failure prediction. For some digital twin applications, the testing "what-if" scenarios are the primary driver; for others, emulation may be the key use (for example when checking for configuration errors, or when training operators); and for others still, maintenance prediction is the key use (for example when estimating future performance).

The DT TAG adopted the Digital Twin Consortium definition for a digital twin as a "virtual representation of real-world entities and processes, synchronized at a specified frequency and fidelity", and considered connecting the currently applied failure analysis methods to the digital twin. Due to its unique applicability to each of the participating federal agencies, each digital twin use case represents a needed solution to specific problems, not necessarily failure avoidances related.

Measuring the success of applicability of the digital twins for predicting failures depends on the scope, need, priority of solving problems, added value and required efficiency for each program across Agencies. Small successes at NNSA are related to the deployment of digital twins to reduce or mitigate weapon systems design and production failures and have more operational flexibility and efficiency. Notable large successes at NASA are related to the enhancement of the flight mission operation efficiency by employing the digital twins for preventative testing, problem diagnosis, and mission solution development. At OUSD, digital twins are deployed for complex systems reliability and sustainment to anticipate and mitigate potential reliability issues early in the design process; to predict wear and tear, maintenance and product support needs, and operational challenges; to ensure that systems are designed not only for optimal performance, but also for long-term reliability; and for ease of sustainment.

Ultimately it is important for senior leadership to first define the strategic advantage of a digital twin for failure prediction (or any other functionality), what a successful end state looks like, and then understand the required additional resources to evolve standard engineering models and simulations into the desired digital twin functionality prior to committing to such a path.

**Actionable Recommendations**

Based on comprehensive research and particular use cases studied, DT TAG proposes the following actionable recommendations for analysis and consideration:

- Develop an organization-specific digital twin strategic needs-based and solution-effective vision which focuses on desired analytical outcomes, guidelines for reuse, shareability, and knowledge transfer that enables desired organization outcomes and follows a mission-based adoption.

- For example, specific digital twin strategic goals (desired analytical outcomes) could minimize equipment failure rates, streamline factory operations and processes, increase operational efficiency, and perform enhanced product development. Digital twins could be most effective when applied to low-volume, highly configured products where substantial system investments have been made, and detailed information is needed to quickly respond to changing conditions, particularly for areas such as asset optimization and preventive maintenance.

- Another effective approach is to expand the scope of the digital twin strategy from a single object or piece of equipment, to building a digital twin of the entire system of interest or mission. This allows complete visibility across all levels of the system operations and processes all the way down to how individual systems and people interconnect in real time. The combination of this information permits organizational-specific and actionable information.

- Develop repositories (ex. reliability, maintainability, and supportability) within the federal government and create a digital twin/failure prediction capability matrix connecting the digital twin and failure prediction domains. There are limited publicly available resources (for example Failure Mode/Mechanisms Distribution 2016) that outline historical failure modes and mechanisms that would be a valuable foundation for failure prediction activities. NASA Goddard Space Flight Center is currently developing a failure mode dictionary that could be adopted as part of digital engineering to support digital twin for failure prediction activities. The application of AI and ML to summarize maintenance data collection or Failure Reporting, Analysis, and Corrective Action System (FRACAS) data from the Government and industry offers opportunities to develop future repositories to support digital twin for failure prediction. Identifying other repositories that could support failure prediction techniques like FMEA, RCM, CBM, and PHM enables faster adoption and results from applying digital twin techniques.

- Expand industry-government partnerships activities utilizing digital twins for increased collaboration and predicting failures, along with lessons learned applied to operations, design and production, and processes.

- Integration with overarching Government Digital Engineering (DE) forums (for example Federal (FED) Digital Engineering Forum Emerging Technologies Working Group or similar), or creating a new panel focused on the digital twin for predicting failures across the federal government can help communicate the findings of this study, share lessons learned for future applications, and deep dive into customable, reusable approaches to inform the users and decision makers about the potential of digital twin applicability for predicting breakdowns before they occur. An example of a resource which could be shared is the DI-SESS-82483 Digital Twin Description Data Item Description (DID). As part of the DID, the Data Requirement Deliverable (DRD) describes the design and context of a digital twin to be delivered on contract. Agencies could use the DRD as a template to request similar or consistent digital twin deliveries. [21]

- A joint relationship with the Digital Twin Consortium needs to be established to expose the results of this study for a mutually beneficial collaboration.

- Presenting the work at specialized Digital Engineering conferences is a must to develop and grow relationships with industry. Encouraging adoption of digital twins for failure predictions with their business models. This ensures the respective investment in digital twin and failure prediction technology and best practices are aligned between government and industry.

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## 3.2.10 Acronyms and Abbreviations

| Acronym or Abbreviation | Definition |
| --- | --- |
| A&L | Aging & Lifetimes |
| AIA | American Institute of Architects |
| AIAA | American Institute of Aeronautics and Astronautics |
| AI/ML | Artificial Intelligence / Machine Learning |
| BDD | Block Definition Diagram |
| BIT | Built-In-Test |
| BOM | Bill of Materials |
| CAD | Computer Aided Design |
| CBM | Condition-Based Maintenance |
| CBM+ | Condition-Based Maintenance Plus |
| CFD | Computational Fluid Dynamics |
| ConOps | Concept of Operations |
| CPI | Continuous Process Improvement |
| DE | Digital Engineering |
| DHS | Department of Homeland Security |
| DIPM | Data-Informed Physical Modeling |
| DoD | Department of Defense |
| DoDI | Department of Defense Instruction |
| DoE | Department of Energy |
| DRD | Data Requirement Deliverable |
| DT | Digital Twin |
| DTC | Digital Twin Consortium |
| EM | Electromagnetic |

| | |
|---|---|
| FEA | Finite Element Analysis |
| FED | Federal |
| FMEA | Failure Modes and Effects Analysis |
| FMECA | Failure Modes, Effects, and Criticality Analysis |
| FRACAS | Failure Reporting, Analysis, and Corrective Action System |
| FTA | Fault Tree Analysis |
| GSFC | Goddard Space Flight Center |
| IAWG | Inter-Agency Working Group |
| JSC | Johnson Space Center |
| LLA | Limited Life Analysis |
| LORA | Level of Repair Analysis |
| MBE | Model-Based Engineering |
| MBFME | Model-Based Fault Management Engineering |
| MBPS | Model-Based Product Support |
| MBSE | Models-Based Systems Engineering |
| MTA | Maintenance Task Analysis |
| MTBF | Mean Time Between Failure |
| NASA | National Aeronautics and Space Administration |
| NNSA | National Nuclear Security Administration |
| NIST | National Institute of Standards and Technology |
| OPTIMISM | Operational Perseverance Twin for Integration of Mechanisms and Instruments Sent to Mars |
| OUSD | Office of the Under Secretary of Defense |
| PA | Probability Assessment |
| PdM | Predictive Maintenance |
| PHM | Prognostics and Health Management |
| PoF | Physics of Failure |

| | |
|---|---|
| R&E | Research and Engineering |
| RAMS | Reliability and Maintainability Symposium |
| RBD | Reliability Block Diagram |
| RCM | Reliability Centered Maintenance |
| RE | Reliability Engineer |
| RMA | Reliability, Maintainability, and Availability |
| RUL | Remaining Useful Life |
| SE | Systems Engineering |
| SE&A | Systems Engineering and Architecture |
| SE&I | Systems Engineering and Integration |
| SMA | Safety and Mission Assurance |
| SME | Subject Matter Expert |
| SpE | Specialty Engineering |
| SysML | Systems Engineering Modeling Language |
| TAG | Targeted Action Group |
| USDR&E | Under Secretary of Defense for Research and Engineering |
| VVUQ | Verification, Validation and Uncertainty Quantification |

## 3.3 Supply Chain Risk Reduction Approaches and Best Practices

**An Interagency Working Group of Engineering Complex Systems White Paper**

### 3.3.1 Executive Summary

In the summer of 2024, the Interagency Working Group on Engineering Complex Systems chartered a Targeted Action Group (TAG) to examine and report back on the subject of supply chain risk reduction. Supply chain management is critical to the success of federal agencies, enabling procurement of goods and services, management of inventory, and distribution. Over the course of the next year, the team leveraged its membership across five agencies to gather the best of breed of approaches and best practices for supply chain risk reduction across the whole of government. The effort culminated in a Technical Interchange hosted by the TAG with key supply chain subject matter experts from seven Federal government agencies each sharing both their common and unique supply chain risk reduction efforts.

In addition to conventional supply chain risk management techniques focused on efficiency, production performance, and transportation, some approaches and best practices gathered involved leveraging commercial-off-the-shelf (COTS) software suites for analysis of vendors for inherent risks associated with financials, cyber security, lower tier suppliers, non-U.S. Labor, and foreign investment/ownership.

It was widely accepted and understood that not all approaches will work for all agencies as their mission sets and organizational constructs drive different priorities and leadership decisions. However, because of those differences, it is truly beneficial to see potential supply chain risk reduction solutions through others' eyes to be aware of different approaches an agency had not considered or was unaware of.

### 3.3.2 Introduction

The Interagency Working Group (IAWG) on Engineering Complex Systems provides an informal and efficient forum for federal engineering Executives to advance the practice and preparedness for engineering increasingly complex systems and to proactively solve relevant systems problems that impact multiple agencies. Participants are Department/Agency Executives who have the primary responsibility for engineering functions for their agencies. The group's intent is to identify and recommend the near, mid, and long-term solutions necessary to meet the future needs of complex systems by identifying, prioritizing, and resourcing areas for collaboration among government, industry, and academia.

The IAWG membership includes: the Department of Energy National Nuclear Security Administration (NNSA), the National Science Foundation, the National Aeronautics and Space Administration (NASA), the Department of Defense (DOD), the Department of Transportation's (DOT) Federal Highway Administration, the National Oceanic and Atmospheric Administration (NOAA), the Department of Homeland Security (DHS), and the National Institute of Standards and Technology (NIST). Each organization contributes a Department/Agency Executive level participant to the IAWG's Executive Committee.

In the summer of 2024, the IAWG's Executive Committee chartered a TAG to examine and report back on the subject of supply chain risk reduction approaches for the benefit of all participating agencies. The goal of this TAG is to share information about existing approaches, processes, references, etc., to reduce supply chain risk during the acquisition process via a technical interchange meeting/workshop so that agencies can learn from each other and share best practices or lessons learned and summarize the findings in a document to be shared and distributed through the IAWG Executive Committee.

### 3.3.3 Background

Agencies across the Government are in the process of independently updating their processes and procedures related to reducing supply chain risk. For example: counterfeit parts that satisfy fit and form but will not function are difficult to detect. Supply chain risk management is critical to the success of federal agencies, enabling efficient and cost-effective procurement of goods and services, management of inventory/obsolescence, and distribution. Within government agencies, disruptions in the supply chain create inefficiency, impede cost-effectiveness, delay schedules, cause mission failure, and sometimes result in injury and/or loss of life.

To address and correct such disruptions often requires additional government resources (unbudgeted/un-forecasted) at the expense of other needs and obligations. Subversion and counterfeit/nonconforming item infiltration can lead to system failures, injuries, and sometimes loss of life. Finally, inefficient stewardship of taxpayer dollars undermines public trust and confidence creating other barriers to mission accomplishment.

Reducing supply chain risk supports on time and on budget programs (in any agency) that in turn build public trust in the agency's use of limited tax dollars. It enables the potential for budget savings or cost avoidance, reallocation of resources to other priorities, and possibly schedule acceleration for a program. Successful supply chain risk management helps build long lasting trust and strategic relationships between government and the industrial base in a time of diminishing sources of manufacturing and supply and a return to great power competition.

It is important to note that each government agency has a different mission set and funding line each with specific requirements and expectations. This has sometimes resulted in siloed solutions/processes or even different solutions not just between agencies but also sometimes within a single agency. Some activities are more results-focused versus efficiency-focused which drives different priorities and tolerances for efficiency versus performance. As a result, each agency manages their supply chain differently based on their mission, organizational structure, and leadership's focus.

Not all risk reduction techniques are executable in every agency. However, this paper seeks to provide a menu of recommended approaches to supply chain risk reduction based on the sharing of best practices across different agencies. It is not meant to be an "all inclusive" list of supply chain risk reduction techniques, but a focused list based on each agency's lessons learned and successes in their own perspective efforts supporting their missions.


## 3.3.4 Supply Chain Risk Reduction Recommended Approaches

Below is a list of various inputs and recommendations from the participating agencies in no particular order. This paper does not attribute them to any specific agency as multiple agencies contributed similar inputs. However, if there is a specific tool, guide, or service available from an agency, that is noted with contact information to request it or a web address to access it.

**Standardization and Clarity**

While flexibility is important in the adoption of a supply chain risk management (SCRM) program, standardization and visibility are essential for flow-down of requirements, risk assessments, definitions, supplier scorecards and SCRM best practices. Measuring supply chain risks should be approached in a consistent and standardized manner to allow true apples-to-apples scoring and comparison of risks for prioritization and appropriate handling strategies. Use a standardized risk management process to include a risk register and risk management governance process for handling and reporting risk to leadership. The DOD has developed a standardized DOD Supply Chain Risk Taxonomy which outlines 12 risk categories, each with several subcategories. For a copy, please contact the Office of the Secretary of Defense (OSD) Office of the Undersecretary of Defense Acquisition and Sustainment (OUSD(A&S)) at jared.m.andrews6.ctr@mail.mil or steven.j.delazaro.ctr@mail.mil.

**Supply Chain Risk Management Training**

Organization-wide awareness and training further embed the SCRM practices with senior stakeholders and empowers decision makers to manage, mitigate and respond to supply chain risks from a common understanding of supply chain risk. Additionally, it empowers/enables everyone (from senior leader to a shipping dock worker) to be a sensor, (e.g. recognition of tampered packaging, counterfeiting, etc.). A shared understanding of risk management practices facilitates risk identification and appropriate handling strategy execution. Consider establishing levels of certification. Agencies can leverage the Defense Acquisition University's (DAU) online classes at www.dau.edu for a recently developed supply chain risk management credentialing program or just for individual training classes.

**Data Access and Integration**

The ability to integrate supply chain data across multiple activities (procurement, quality, vendor performance, inventory, strategic sourcing, etc.) facilitates enterprise visibility. Using SCRM tools assists organizations to be predictive versus reactive. Data integration allows an organization to execute an efficient make-to-stock acquisition approach versus an inefficient make-to-order approach. Sharing vendor data across the organization, including performance metrics, capabilities, and partnership levels, can further streamline procurement processes.

A critical precursor to data integration is having clean data. There are several COTS software suites that offer data cleansing or data wrangling services to help agencies clean their data to facilitate easier and more accurate data integration. Data access and integration can also mean sharing vendor data across an organization's various procurement activities. One of the production sites within NNSA posts all vendor data to include what they make, performance, capacity, level of partnership, etc. to a website accessible by the other NNSA sites to save time in vendor sourcing by having a ready list of approved vendors from which to choose from, saving time and strengthening the supply chain. The Government-Industry Data Exchange Program (GIDEP) can be used to identify issues with vendors or certain National Stock Number (NSNs).

The System of Award Management (SAM) should also be used to determine if vendors are suspended, proposed for debarment, or debarred prior to procuring from them. Another resource for information on parts availability and specifications/standards is Information Handling Service (IHS) Global Haystack. In addition to COTS SCRM tools, there are also several effective DOD Agencies SCRM tools, such as the Defense Logistics Agency's (DLA) Business Decision Analytics (BDA) Decision Support Tool. BDA uses predictive modeling, data engineering, and machine learning, and multiple data sources (government, DOD, DLA, and commercial) to identify supply chain risk in multiple areas. The risk assessments are presented in dashboards, risk reports and visualization tools.

**Contract Requirements**

Begin incorporating SCRM expectations into the terms and conditions of procurement contracts with suppliers. These requirements might include NIST 800-171 requirements; lower tier

transparency; disclosure and notification of Foreign Ownership, Control, or Influence (FOCI); periodic financial reports; etc. If there is a potential introduction of foreign ownership during execution, ensure it is in compliance with The Committee on Foreign Investment in the United States (CFIUS). CFIUS is an interagency committee that reviews certain transactions involving foreign investment in the U.S. to assess their potential impact on national security. In some situations, the U.S. government may deny the change of ownership to take place or only allow it under certain conditions. More information on CFIUS can be found at https://home.treasury.gov/policy-issues/international/the-committee-on-foreign-investment-in-the-united-states-cfius. There are Federal Acquisition Regulation (FAR) and Defense Federal Acquisition Regulation Supplement (DFARS) requirements for procuring certain items/materials from U.S. sources; procurement/contracting activities must be aware of those requirements and follow them.

**Manufacturing Extension Partnership (MEP)**

When there is a vendor that is having trouble in quality, quantity, and/or efficiency, the MEP is there to help them improve and meet their contractual obligations to the government. The NNSA's Savannah River Site has leveraged the MEP for years to help its vendor base. Established in 1988, the MEP is a unique public/private partnership model which makes MEP services affordable for U.S. small and medium-sized manufacturers. It is a cost-share program, with financial contribution from federal, state, and local governments. MEP industry experts work side-by-side with manufacturers to reduce costs, improve efficiencies, develop the next generation workforce, create new products, and more. The MEP's mission is to strengthen U.S. manufacturing. The program is available in every state. There is a two-minute video that provides an overview of the MEP at https://www.youtube.com/watch?v=pZWeW0t oc8. More information can be found on the MEP website https://www.nist.gov/mep.

**Due Diligence**

Require procurement/contracting activities to incorporate a standardized supply chain risk analysis into the supplier vetting process before the contract is awarded. NNSA's Defense Programs suggests these eight areas/lenses through which to evaluate a vendor pre-award: cybersecurity indicators, financial health, risk events (e.g. judgements, penalties, violations, etc.), past performance, counterfeit indicators, foreign corporate linkages, non-U.S. labor, and lower tier supply chain network. Also require annual re-evaluations to reduce or head off vendor risk if a company develops concerns you would have otherwise been unaware of until it was too late (e.g. financial decline resulting in default without another source).


**Vendor Management**

A key lesson from the COVID pandemic is to qualify multiple vendors early on. Consider awarding 80/20 split between two sources to preserve resiliency in key supply chains. Consider establishing formal long-term/strategic partnerships with vendors. If possible, provide outyear

forecasting of current needs as well as potential requirements in the future. Look for opportunities to modify or be flexible on requirements to better suit a vendor's existing capabilities (e.g. does it have to be red, or could it be blue and still functional because the vendor is set up to make blue not red).

**General Supply**

Consider approaching the supply chain using the product support management concept. The DOD does this. NASA is restructuring to take advantage of this concept. NNSA is just beginning to explore it from a life cycle logistics point of view. For more information on this, the Product Support Manager (PSM) Guidebook can be found on the DAU website at https://www.dau.edu/tools/product-support-manager-psm-guidebook.

Utilize the Defense Priorities Allocations System (DPAS). It is used to prioritize national defense-related contracts/orders throughout the U.S. supply chain to support military, energy, homeland security, emergency preparedness, and critical infrastructure requirements. More information on DPAS can be found at https://www.acquisition.gov/far/subpart-11.6. Additionally, consider in-house/organic manufacturing, consolidated, or centralized production for support of mission critical areas – establish a standardized process for make versus buy decisions.

**Inventory**

Consider use of safety stock as needed to maintain/preserve schedule disruptions especially for unique items or single/sole source vendors. Conversely, while you save money by not having to store inventory, you also increase supply chain disruption risk using the just-in-time inventory model as experienced worldwide during the COVID pandemic.

Consider how you dispose of excess/obsolete inventory. The DOD and NASA both use reclamation sales to get rid of inventory and generate additional revenue. NASA does this in partnership with GSA to get proceeds back to their programs and projects. This can be for large end items as well.

Also consider the risk of improperly disposing of excess/obsolete inventory, or where that inventory is being sent. The majority of all counterfeit electronic components infiltrating world-wide resulted from countries (included the U.S.) shipping e-waste to China, who then harvested used components from the e-waste, refurbished/remarked those components, and sold them as new.

**Technology**

Leverage COTS supply chain risk software suites (e.g. Exiger, Interos, Deloitte, Dunn & Bradstreet, etc.). Some of these tools are already available on the GSA schedule. However, this paper recommends each agency evaluate multiple platforms to ensure the tool meets the needs of the organization versus the cheapest/easiest to use. Success may require a combination of tools as each has an area of specialty. NNSA's Defense Programs NA-182 developed a guide to help select the correct supply chain risk software suite. The NA-182 Supply Chain Risk Tool Selection Guide can be requested by contacting joseph.moehlmann@nnsa.doe.gov.

Additionally, OSD has been working on a list of all the government owned software tools out there as well that might be leveraged. To learn more about this effort and its progress in OUSD(A&S), contact jared.m.andrews6.ctr@mail.mil or steven.j.delazaro.ctr@mail.mil.

**Subversion**

Establish strategies that address Suspect/Counterfeit (S/C), Nonconforming (NC), and Fraudulent Item concerns. The DOD uses the Product Data Reporting and Evaluation Program (PDREP) and the Joint Deficiency Reporting System (JDRS), both administered by the Navy. They can be accessed at https://www.pdrep.csd.disa.mil/ or https://www.jdrs.mil/, however, much of the data is only available to .mil addresses. Information on Suspect/Counterfeit (S/C), Nonconforming (NC), and Fraudulent Items is also available from the GIDEP which can be accessed through membership at https://www.gidep.org. Another source for information on S/C, NC, and fraudulent Electrical/Electronic/Electromechanical (EEE) items is the Electronic Resellers Association International (ERAI). Another result from the COVID pandemic was manufacturers procuring materials and components without proper providence/traceability to keep their production lines operating which resulted in a number of COTS assemblies and subassemblies containing S/C and NC items being sold to the government.

1. Ways to reduce risk of S/C and NC items:
2. Improve procurement practices – less focus on price and more focus on quality.
3. Use of other mechanisms to surveil contractors – i.e., Remote Surveillance, more effective use of Defense Contracting Management Agency (DCMA). DLA is currently working with the Aerospace Industries Association (AIA) on National Aerospace Standard (NAS) 413 "Remote Surveillance Standard" will be balloted in the summer of 2025. DOD Adoption is planned for this document. NASA, DCMA, and the Navy are also involved with this effort.
4. Add traceability requirements and enforce them.
5. Strengthening procurement policy to prevent S/C or NC.
6. Participate in the development of industry counterfeit prevention standards and ensure the standards are used in contracts.
7. Require a counterfeit prevention or NC plan from the vendor.
8. More balanced focus on all types of counterfeiting: EEE, mechanical, and material.
9. Mandate the use of reporting systems: PDREP, GIDEP, DOD's Supplier Performance Risk System (SPRS), and Electronic Resellers Association International (ERAI), before and after contract award. Most of the government is not following the OMB Office of Federal Procurement Policy OFPP 91-3 which mandates the use of GIDEP by Federal Agencies to report NC and S/C material to other Federal Agencies
10. Improve or increase testing to detect S/C & NC materials.
11. Look for opportunities for your organization/personnel to work with government, industry and academia on the SAE G-32 Committee (Cyber Physical Systems), the G-19 Committee (Counterfeit Prevention for EEE Parts), G-19A Committee (Test Laboratory Standard to

Detect Counterfeit EEE Parts), and the G-21 Committee (Counterfeit Prevention for Non-EEE Parts and Materials).

### 3.3.5 Disposal Concerns

**Environmental and Sustainability Concerns**

Include environmental and sustainability concerns into the supply chain risk calculus. Monitor potential storms, flooding, drought, pandemics, earthquakes, riots, political unrest in production locations, etc. and their effect on production and suppliers both in initial acquisition and during contract execution. As an example, Amazon Web Services monitors and advises clients on their distribution networks based on environmental events.

**Quality**

Don't let speed or price overrule quality—is Procurement evaluated on awards to unsatisfactory vendors or just gross volume of awards? Ensure vendors and sub-tier vendors are properly qualified and follow a QA Plan. Involve Subject Matter Experts (SME), often an engineer, in vendor selection/auditing. Be cautious of generating quality requirements that are specific to your organization if an industry standard (e.g. AS9100, AS9120, AS9003, ISO 9001, etc.) will suffice. Make use of the industry standards for counterfeit prevention, (e.g. AS5553, AS6174, AS6081, AS6496, AS6886, AS6832, AS6934, & AS6171, etc.). Known qualified vendors have been driven away by NNSA specific quality standards that were too uniquely exacting when an industry standard that the vendor understands would have been acceptable.

**Partnering/Collaboration**

The DCMA has been partnering with DLA and the Department of Commerce to leverage combined resources and expertise to secure domestic sources for critical minerals. Because of their combined efforts, they have been successful in garnering Congressional and White House attention, acknowledgement, and help.

Addressing Diminishing Manufacturing Sources and Material Shortages (DMSMS) requires a concerted effort to break down data silos and foster greater resource collaboration. Siloed data and a lack of communication often result in redundant engineering efforts to overcome component obsolescence or material shortages, leading to increased costs and delays. By promoting data sharing and collaborative workflows, we can significantly reduce unnecessary rework and improve the efficiency of DMSMS mitigation strategies.

To achieve this, leveraging common enterprise platform tools like Microsoft Power BI is crucial. The development of visual, interactive dashboards shared across the DOD, DHS, and other critical supply chain partners fosters enhanced collaboration and shared situational awareness. This unified view of DMSMS data enables proactive identification of vulnerabilities, promotes cross-agency information sharing, and drives data-driven decision-making. As an example, the recent partnership between the Coast Guard and Air Force C-130J program has the potential to reduce mission-critical system downtime through collaborative practices, highlighting the potential

benefits of this approach. Integrating Power BI with other software platforms creates a secure environment for real-time communication, standardized reporting, and effective DMSMS mitigation. This type of integration can ultimately improve supply chain resilience and reduce operational costs.

**Additional Resources**

Broadly, the DOD has been tasked to stand up a DOD SCRM Integration Center to create a broad forum for discussing SCRM. As of the writing of this paper, it is still in its infancy but soon taking shape. Its long-term intent is to partner/involve other agencies. To learn more about this effort and its progress in OUSD(A&S), contact jared.m.andrews6.ctr@mail.mil or steven.j.delazaro.ctr@mail.mil.

Currently, there is a bi-weekly Interagency SCRM Working Group hosted by the DOT. To join or find out more information, please reach out to patricia.hu@dot.gov.

Additionally, DLA hosts a bi-weekly DOD SCRM Forum this is also attended by other agencies. For information on that forum, please contact zainab.baa@dla.mil in DLA Logistics Operations.

For information on tackling Diminishing Manufacturing Sources and Material Shortages (DMSMS), OSD shared that the SD-22 DMSMS Guidebook is filled with best practices for implementing a DMSMS program. It is used not just by the U.S., but also by 13 other countries as well. It can be found on the DAU website at https://www.dau.edu/cop/dmsms/documents/sd-22-dmsms-guidebook-march-2024. OSD has been hosting monthly webinars on this subject for the last two years. For information on how to take part, contact Robin Brown, the DMSMS Program Manager and Parts, Materials, & Processes (PM&P) Program Manager in OUSD(R&E) Systems Engineering & Architecture, Defense Standardization Program Office (DSPO) at robin.brown@dla.mil. Additionally, the GIDEP is the official DOD repository for DMSMS information.

## 3.3.6 Conclusion

Within the resident expertise of the TAG, a good number of supply chain risk reduction approaches were shared and discussed. During the technical interchange, each TAG member invited other subject matter experts to share their knowledge and efforts. Additionally, several supply chain professionals were invited from other agencies and offices to contribute. While the TAG's efforts have clearly compiled a strong collection of supply chain risk reduction approaches and best practices to be shared and utilized across the interagency activities, it is noteworthy to acknowledge how much effort and work in the different agencies has taken place in recent years on this subject.

As referenced in the paper, there are several existing and growing forums for supply chain risk management and their willingness to share and collaborate across the interagency. The DOD has stepped out boldly in this discipline leading the charge in many ways but always seeking to include others and their willingness to contribute to supply chain risk management. The TAG hopes readers across the IAWG will take advantage of some or all the recommendations in this paper and choose one or two of the forums to participate in to contribute as well as stay abreast of the latest and most successful supply chain risk reduction practices.

## 3.3.7 TAG Membership

- Alma Thomas, Department of Homeland Security, Science and Technology

- David McQuain, National Aeronautics and Space Administration

- Grant Korte, CWO-3, Department of Homeland Security, U.S. Coast Guard

- Honore Nyuyse, Department of Homeland Security, Science and Technology

- Chris Hall, Department of Homeland Security, U.S. Coast Guard

- Joseph Moehlmann, National Nuclear Security Administration

- Edward Moshinsky, Office of the Under Secretary of Defense

- Monique Ofori, Office of the Secretary of Defense

- Paula George, Department of Defense, Defense Logistics Agency

## 3.3.7 Additional Technical Interchange Participants

- Andrew Foote, Office of the Under Secretary of Defense, Research and Engineering

- Arthur Beauchamp, Department of Defense, Defense Logistics Agency

- Chris DeLuca, Office of the Under Secretary of Defense, Research and Engineering

- Eric Hoover, Department of Defense, Army Joint Munitions Center

- Jared Andrews, Office of the Under Secretary of Defense, Acquisition and Sustainment

- Kelly Alexander, Office of the Under Secretary of Defense, Research and Engineering

- Michael Spletzer, Department of Defense, Defense Contract Management Agency

- Miranda Hendrix, Department of Homeland Security

- Nadine Geier, Office of the Under Secretary of Defense, Research and Engineering

- Robin Brown, Office of the Under Secretary of Defense, Research and Engineering

- Steve de Lazaro, Office of the Assistant Secretary of Defense for Sustainment (Logistics)

- Zainab Baa, Department of Defense, Defense Logistics Agency

## 3.3.9 External Sources

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# 4.0 Appendix: Position Paper of the IAWG for ECS, 2014

**Transforming the Practice of Engineering for Large Complex Systems**

**Inter-Agency Working Group on the Engineering of Complex Systems**

**Executive Summary**: The complexity of engineered systems has swelled in the last several decades, and this trend is likely to continue for the foreseeable future. While projects are becoming more complex, current engineering practice has largely evolved from a top-down approach that is the legacy of past successes. A fundamental rethinking of engineering methodologies is urgently needed if our nation is to ensure that the large complex systems critical to our national security, economy, and quality of life are resilient in the face of natural disasters, creative adversaries, and an unforeseeable future. In June 2012, an Inter-Agency Working Group (IAWG) on Engineering Complex Systems convened to explore these issues from the perspectives of several government agencies that represent diverse missions. The IAWG seeks to stimulate a dialogue that will help usher the engineering community toward the next generation of research and practice.

**55 million without power, 11 deaths, and an estimated cost of $6 billion**. The biggest blackout in American history began without warning. August 14, 2003 was a typically hot summer day in the northeastern United States, with millions of homes and businesses relying on air conditioning to meet critical cooling needs. The demand for electric power was high. The Cleveland-Akron area of Ohio had been hot for days, and two local power generation units were offline for routine repairs and maintenance. Shortly after noon, a software tool that provides situational awareness of the system went offline for nearly four hours due to a combination of bad data and human error. During those hot, sunny hours, several high-voltage power transmission lines sagged and came into contact with overgrown trees, causing short circuits. With an incomplete understanding of what was taking place across the system, utility operators were unable to respond effectively to these and other real-time conditions, including the loss of another power generation unit and a software bug at a utility company. The failures in Ohio began to ripple throughout the system, and within a 15-minute period shortly after 4 o'clock the problem cascaded through Michigan, Pennsylvania, New York, Ontario, and New Jersey. The result was 55 million people without power, 11 deaths, an estimated cost of $6 billion, and disruptions affecting small and large business from hospitals to military facilities.

**The complexity of engineered systems has swelled in the last several decades**. All indications point toward this trend continuing for the foreseeable future. As a result of the revolution in information technology and the adoption of new models for partnerships, governance, and financing, systems in areas such as defense, aerospace, health care, and civil infrastructure (transportation, electric power, and water supply systems, for example) have escalated dramatically in scale and interconnectivity. As with the Northeast blackout, these systems all have mechanical, cyber, and human dimensions. The interactions of these dimensions present challenges ranging from sheer size to interoperability across multiple engineered systems and organizational boundaries.

These interactions have led to increasing complexity. A system may be considered complex if it is not mathematically predictable within reasonable constraints of time, computational power, and existing modeling tools. The interactions that can take place within a complex system cannot be fully imagined or defined based on an understanding of its constituent elements. This makes it impossible to fully test such a system in a traditional manner. Beyond the unpredictable behaviors of these systems, the inability to fully understand and envision them during their design phase usually leads to significant cost and schedule overruns in the development and operation phases.

The difficulty of anticipating these interactions is further complicated because systems often face changing requirements throughout their life cycles. The F/A-18 aircraft, which had its first flight in 1978, was initially designed to serve the U.S. Navy on aircraft carriers for sorties averaging 90 minutes. Its useful life was to be roughly 15 years, including 3000 flight hours. When Switzerland decided to purchase the aircraft in the mid-1990s, its requirements were different. The Swiss F/A-18 was to be a land-based interceptor that would fly sorties averaging 40 minutes. The aircraft's useful life was extended to 30 years, including 5000 flight hours. These new requirements for greater durability demanded a significant redesign effort. In order to address the increased fatigue to the airframe that would result from 2000 additional flight hours, the Swiss redesign called for building the center barrel of the aircraft from titanium rather than aluminum. Because of the complexity of the F/A-18, this relatively small change had the unintended consequences of increasing the weight of the aircraft and shifting the center of gravity. This required changes to the flight control software and manufacturing processes, raising the cost per aircraft by roughly $10 million.

As governments around the world seek to stretch constrained resources through collaboration on complex systems such as the International Space Station (ISS), there is an increasing need to address these types of challenges. In the case of the ISS, the partners have had to adapt to a more ambitious operational model than its designers envisioned, a greater variety of spacecraft docking with the station, and a more difficult orbital debris environment than existed when it was designed. None of the partner governments could have afforded the full investment alone, and none could have kept the station continuously manned over more than a decade.

**While projects are becoming more complex, current engineering practice has evolved from a top-down approach** that enabled the development of our entire present-day physical infrastructure, ground and air transportation systems, and telecommunication networks. This approach, involves reducing a system to its constituent components and computing the performance capabilities and material properties of each component using existing knowledge or scientific theories. The behavior of the entire system is then inferred from the behavior of, and the interactions among, its components. This process can be useful for analyzing large systems such as computers, but it is inadequate and potentially even counter-productive for highly networked systems affected by variables such as the number of decision-makers, culture, and organizational practice, which fall outside traditional engineering concerns. The success of this "components-first, interactions-later" approach can encourage many engineers to focus exclusively on a single component or technical discipline of a system, and to marginalize both nonlinear, unpredictable technical interactions such as those experienced with the F/A-18 and complex social interactions such as incentives and governance.

A fundamental rethinking of engineering methodologies is urgently needed if our nation is to ensure that the large complex systems critical to our national security, economy and quality of life are resilient in the face of natural disasters, creative adversaries, and an unforeseeable future. This transformation of

engineering calls for not only a deeper understanding of systems and the scenarios in which they operate, but also for capitalizing on knowledge from interdependent fields such as the social sciences and humanities. A reexamination and reconstruction of engineering practices from the roots upward—from initial research to system disposal—will yield important discoveries that are often found only at the intersection of existing disciplines. Bridging the gap between the natural and social sciences and synthesizing the knowledge and practices of both is essential, as is taking advantage of the rapid advances in computing power available. Today is a watershed moment for engineering that calls for a fundamental transformation of its practice.

**In June 2012, an Inter-Agency Working Group (IAWG) on Engineering Complex Systems convened to explore these issues** from the perspectives of several government agencies that represent diverse missions. The National Science Foundation has identified needed research on designing complex engineered systems and pioneered funding research and workshops toward this end for over two decades. The National Aeronautics and Space Administration (NASA) found it necessary to advance and adopt new model-based systems methodologies for recent missions to Mars. In April 2011, the U.S. Secretary of Defense announced seven science and technology priorities essential to the future of the nation, one of which was Engineered Resilient Systems aimed at transforming engineering environments so that warfighting systems are more resilient and affordable across the acquisition lifecycle. At the National Institute of Standards and Technology, benchmark studies on immense complexities in cyber-physical systems were recently completed. And the Department of Energy is making significant investments in advanced simulation to address a wide range of complex problems, including new modeling capabilities to understand nuclear weapon performance, innovative nuclear reactor design, and performance of a smart energy grid. Through NextGen, the FAA is in the midst of a widespread, transformative change to the complex national airspace and the way we fly. Similarly, the advent of connected vehicles and infrastructure provides an opportunity to transform surface transportation on the nation's highways.

Looking at these challenges through a common lens, the IAWG envisions a future in which large, technologically path-breaking engineering projects are undertaken regularly, are almost always successful, and are routinely accomplished on time and within budget. There is an urgency to achieve this vision because our society increasingly relies on complex systems, and their number is on the rise. They are heavily influenced by factors such as environmental sustainability, highly networked cyber systems, and other drivers of organizational complexity such as project teams distributed across multiple continents and time zones, divergent interests among numerous stakeholders, and geostrategic concerns that can affect international partnerships.

**The IAWG seeks to stimulate a dialogue that will help usher the engineering community toward the next generation of research and practice**. The path forward will redefine how engineers approach both the technical and social challenges of researching, designing, developing, and delivering systems, making it possible to reframe the engineering of complex system in ways that significantly enhance value and effectiveness. The needed transformations must address effectiveness, affordability, timeliness, and adaptability challenges posed by current and future technologically sophisticated systems, through tools and approaches grounded in fundamental scientific and mathematical principles.

Long-term success will require engaging the diverse research communities across all relevant fields (e.g., engineering, social science, business, and law); working with private industry to transform that research into new, transformational advances in engineering practice; and collaborating with the educational

community on the development of innovative training techniques to enable a new generation of engineering practitioners and educators. By initiating this crucial interdisciplinary discussion, the IAWG seeks to draw on the collective wisdom of all stakeholders across the engineering enterprise. We believe this transformation represents more than a small step for professional practice—it is a giant leap forward for our future.

**Inter-agency Working Group Meeting Participants, 2014:**

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