Digital Twin-Digital Thread Solution Evaluation Benchmark

Report of Findings
General Availability Edition

Release 1.2

February 2026

AEROSPACE & DEFENSE PLM ACTION GROUP

Participating Solution Providers

Ansys part of SYNOPSYS

Capgemini

Cortona3D

eQ Technologic

HEXAGON

Infosys

PROSTEP integrate the future

Abstract

An Aerospace & Defense PLM Action Group (AD PAG)-sponsored project team undertook the challenge of advancing industry's awareness and understanding of the current practical value potential of digital twin-digital thread (Dtw-Dth) investment. They did this by benchmarking use cases using commercially available Dtw-Dth solutions, including software and services. Domain experts from AD PAG member companies partnered with four industry organizations and engaged with seven leading solution providers to execute the benchmarks. Results were consolidated, analyzed, and conclusions were drawn. For this general availability edition, results were neutralized to mask specific solution performance.

This report documents 1) a set of use cases representative of Dtw-Dth value opportunities across all lifecycle stages for aerospace original equipment manufacturers (OEMs) and their supply chain, and 2) the findings and conclusions from evaluating the capability of commercially-available solutions to perform those use cases.

Recognizing the topic's breadth and state of maturity, the Dtw-Dth Benchmark inquiry was not focused solely on "measuring how well it is done" but more broadly on "understanding *how* it is done, *what* is real today, and *where* it is going." The report describes an evolving landscape of highly capable commercial solutions offering varied approaches and a clear set of technological and organizational challenges that must be addressed to unlock the full potential of this paradigm. It concludes that the current practical value potential of Dtw-Dth investment is real and substantial, as verified by demonstration of very powerful Dtw-Dth solutions provided to industry today.

Preface

This document is intended to convey the findings and conclusions from an extensive benchmark study on the topic of digital twin and digital thread (Dtw-Dth) to a broad audience of Product Lifecycle Management (PLM) professionals from industry, academia, government, and the solution provider community. The study was a collaborative exploration of solution strategies, implementation approaches, current value delivery capabilities, and future visions of commercial Dtw-Dth solution providers. The findings reported are the result of work commissioned and conducted by the Aerospace & Defense PLM Action Group (AD PAG) with contributions from four industry organizations and in collaboration with seven solution providers who share a passionate commitment to realizing the value of Dtw-Dth. We encourage you to contact any AD PAG member, partnering industry organization, participating solution provider, or CIMdata to share your thoughts on this report and the important Dtw-Dth topic.

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Revision Record

Revision	Date	Description
1.0	December 2025	Initial Release
1.1	January 2026	Copy edits for clarification and removal of an inaccuracy in comments following Figure 13
1.2	February 2026	Organization name corrections, addition of feedback request and survey links

Digital Twin-Digital Thread Solution Evaluation Benchmark

Executive Summary

The Aerospace & Defense PLM Action Group (AD PAG) engaged with a select set of digital twin-digital thread (Dtw-Dth) solution providers in an initiative to assess the capabilities of commercially available Dtw-Dth solution offerings, including software and services. This Digital Twin-Digital Thread Solution Evaluation Benchmark (Dtw-Dth Benchmark) is the culmination of a multiyear project workstream to define and characterize the value potential of Dtw-Dth investment within the A&D industry. Recognizing the topic's breadth and state of maturity, the Dtw-Dth Benchmark inquiry was not focused solely on "measuring how well it is done" but more broadly on "understanding *how* it is done, *what* is real today, and *where* it is going."

Objectives

The Dtw-Dth Benchmark was planned to achieve the following objectives:

1. A broad assessment of the capabilities of commercially available Dtw-Dth solution offerings, including software and services
2. Mutual education and alignment of thought leaders from industry and leading solution providers on Dtw-Dth use cases and solution strategies
3. Advancement of industry's awareness and understanding of the current practical value potential of Dtw-Dth investment

In addition, the learnings will be useful for future engagement with industry organizations for enrichment of standards to address Dtw-Dth requirements.

Scope

Participants

Primary participants included use case contributors and benchmark evaluators, solution providers, and the benchmark administrator.

Contributors and Evaluators

Recognizing that many industry organizations are deeply engaged in examining the nature and potential value of digital twins and digital threads, the AD PAG project team determined that collaboration with the following organizations would provide a substantial mutual benefit.

Aerospace & Defense PLM Action Group

The following AD PAG member companies contributed domain experts (also known as *subject matter experts*) for participation in this activity as use case authors, benchmark demonstration evaluators, and analysts.

- Airbus SE
- The Boeing Company
- GKN Aerospace Engine Systems
- Moog Inc.
- RTX
- Safran S.A.
- Spirit AeroSystems

Partnering Organizations

A total of seven industry organizations were invited to participate in the benchmark. Of those, four accepted the terms of the invitation and agreed to participate, and all contributed use cases.

- AIAA Digital Engineering Integration Committee (AIAA-DEIC)
- OMG, Digital Twin Consortium (DTC), A&D sub-team
- prostep ivip, Collaborative Digital Twin (CDT) working group
- SAE International, G-31 Digital Communications Committee

Participating Solution Providers

Twenty-one solution providers, including software providers, infrastructure providers, and systems integrators, were invited to participate in the benchmark. Of those, seven accepted the terms of the invitation and agreed to participate.

- Ansys (part of SYNOPSYS)
- Capgemini
- Cortona3D
- eQ Technologic
- Hexagon
- Infosys
- PROSTEP AG

Benchmark Administrator

CIMdata facilitated the planning and managed the execution of the solution evaluation benchmarks process.

Engagement and Demonstration Sessions

A primary Dtw-Dth Benchmark objective was mutual education and alignment of thought leaders from industry and leading solution providers on Dtw-Dth use cases and solution strategies. The

scope of those learnings, as noted above, was to understand *how* it is done, *what* is real today, and *where* it is going. To that end, engagement sessions were structured in three parts.

Part 1: Solution Strategy and Implementation Approach

Part 2: Use Case Demonstrations

Part 3: View of the Future

Demonstration Use Cases

Based on relevance and business value to AD PAG member companies, an initial set of use cases was proposed by domain expert members of the AD PAG Dtw-Dth project team. The final set of use cases selected for demonstration was negotiated with partnering business organizations and participating solution providers to capitalize on their existing inventories of use cases. The resulting 28 use cases span all lifecycle stages and all technical domains relevant to development, production, utilization, and support of aircraft and aerospace systems.

Methodology

For this project, the process was augmented with the use of an artificial intelligence (AI) tool as an analysis aid.

Process

The Dtw-Dth Benchmark process was adapted from CIMdata's best practice *Solution Evaluation and Selection* methodology.[*] The process proceeded in five stages.

Engagement and Plan Finalization

Engagement with the industry organizations and solution providers to secure their commitment to participate and then balancing the objectives and interests of all participants to reach consensus on a final project plan was a managed dialogue.

Benchmark Preparation

CIMdata issued invitations to those solution providers selected to participate, and each party participating in the Dtw-Dth Benchmark identified and secured availability of internal domain experts to support their role.

Benchmark Execution

After the preparation period, Dtw-Dth solution evaluation benchmark activity began. Activities were to progress through three phases.

- Use case selection and refinement
- Engagement sessions preparation and demonstrations configuration
- Engagement sessions and demonstrations execution

[*] https://www.cimdata.com/en/education/educational-webinars/webinar-plm-solution-evaluation-selection-2021

These phases were not managed with “hard stops” but rather with a gradual transition in the type of activities over time. The working relationship throughout the evaluation benchmark execution was intended to be highly collaborative between AD PAG domain experts and solution providers.

Analysis

Following completion of Dtw-Dth engagement sessions and solution demonstrations, observations and scores from the individual AD PAG domain expert evaluators were consolidated and analyzed. Group discussions were conducted to reconcile outliers and develop consensus on learnings and assessments from the engagement sessions and the scores and assessments of each use case.

Report Out

Multiple reports were generated in accordance with the interests of various communities within the PLM ecosystem. This set of reports was subjected to review and revision prior to release and distribution to the targeted communities.

Use of Artificial Intelligence

ChatGPT was applied as a productivity aid to assist in summarizing and analyzing the outcome of over 60 hours of intensive engagement with the solution providers.

Summarizing Large Volumes of Data

ChatGPT was useful in generating summaries of the volume of information presented to the AD PAG domain experts during engagement sessions with the participating solution providers. All summaries were reviewed by multiple domain expert evaluators. The main impact of the reviews was to clarify and augment the ChatGPT-generated summary. Corrections were significant but not extensive. The productivity outcome was roughly a 50% reduction in overall effort.

Analyzing Data

ChatGPT was less reliable but still valuable as a productivity aid for analyzing data. ChatGPT was applied to compare the summaries of solution provider-presented material and was also applied to the summaries of evaluators’ observations and assessments. These comparisons identified significant similarities and differences but were incomplete and contained errors. Therefore, all AI-generated analyses required rigorous validation by domain experts prior to inclusion in any formal deliverable.

Community Engagement

Securing collaborative involvement of a broad range of industrial organizations and solution providers was essential to achieving the project objectives. In addition to benefiting from their contributions to the project work products, interaction with these communities provided unexpected learnings and insights into their operational structure and approach to collaborative engagement.

Conclusions

The original purpose of the Digital Twin-Digital Thread (Dtw-Dth) Benchmark was to broadly assess the capabilities of commercially available Dtw-Dth solution offerings, including software and services. This purpose was augmented to include assessment of solution strategies, implementation approaches, and future directions of commercial solution providers. A summary of that assessment follows.

The Dtw-Dth Benchmark assessment reveals a dynamic and rapidly maturing market for Dtw-Dth solutions. Researchers discovered an evolving landscape of highly capable commercial solutions offering varied approaches and a clear set of technological and organizational challenges that must be addressed to unlock the full potential of this paradigm. In summary, the current practical value potential of Dtw-Dth investment is real and substantial, as verified by demonstration of very powerful Dtw-Dth solutions provided to industry today.

Key Findings

Digital Twin and Digital Thread

A critical and unifying takeaway is that the digital thread is the foundational construct. The digital twin, as a dynamic virtual representation of a physical asset, may be the ultimate objective, but its fidelity and value are entirely dependent on the robustness of the underlying digital thread (i.e., the communication framework that provides a seamless, traceable flow of authoritative data across the entire lifecycle).

Divergent Solution Strategies

The market is not monolithic. Two dominant strategic solutions approaches have emerged: focused and general. With focused solutions, providers offer deep mature capabilities in a specific domain (e.g., simulation-led design, technical publications, or metrology). Their strategy is to leverage their core strength and integrate outwards. Providers of general solutions focus on the broader challenge of connecting disparate enterprise systems—PLM, ALM (Application Lifecycle Management), ERP (Enterprise Resource Planning), MES (Manufacturing Engineering System)—to create a robust and adaptable data backbone. Their strength lies in architecture and interoperability rather than in domain-specific depth.

Architectural Evolution: From Connectors to a Virtual-Data-Landscape

A significant technical trend is the move from simple point-to-point integrations toward more sophisticated architectural patterns. The concept of a federated digital fabric or digital backbone was a notable innovation.

Role of the Major PLM Platform Solutions

The role of major PLM platforms is foundational but evolving within the broader Dtw-Dth ecosystem. The PLM system continues to serve as the authoritative source for ‘as-designed’ product data and the backbone for configuration and change management, yet its position as the central program hub is increasingly being challenged and redefined by more open, federated, and data-centric architectures.

Pragmatic Integration of AI

AI (artificial intelligence) and ML (machine learning) have transitioned from conceptual ideas to practical enablers for advanced Dtw-Dth functionalities. The applications are concrete and focused on delivering the following specific business values:

- Predictive analytics and model recalibration
- Operational efficiency
- Data quality management

However, pragmatic caution exists, particularly around applying generative AI in highly regulated environments where absolute accuracy and traceability are paramount.

Critical Prerequisites for Success

The Dtw-Dth Benchmark highlighted that successful Dtw-Dth implementation is not just a matter of software. It depends on several critical prerequisites.

- Integrated multi-domain models
- PLM, ERP, MES integrations
- Open standards and interoperability
- Robust data governance and archival
- Robust security and data sovereignty in federated architectures
- Workforce skills development

Persistent Challenges and Industry Gaps

Despite the progress, the industry faces significant hurdles.

Legacy System Integration

The rip-and-replace approach is not feasible. Integrating with deeply entrenched legacy systems remains a primary technical and financial barrier.

Long-Term Maintainability

Total cost of ownership is a major concern. The long-term effort required to maintain a complex web of connectors, adapters, and data models as underlying systems evolve is substantial and must be planned for.

Organizational Readiness

Technology is often more mature than the organization's ability to adopt it. A lack of clear vision, robust data governance, and effective Organizational Change Management (OCM) are significant impediments to realizing return on investment (ROI). While growing, the A&D industrial community's readiness is still in its early stages.

Future Outlook

The future of Dtw-Dth solution offerings is moving toward integration platforms, rather than toolkits. The focus will continue to shift from simply connecting data to enabling data intelligence.

The next generation of solutions will be defined by deepening integration of AI, commitment to open standards, and intense focus on user experience to manage complexity. The journey is far from over. This benchmark confirms that the foundational technologies and methodologies are falling into place, paving the way for a more connected, efficient, and intelligent industrial future.

To ensure AD PAG publications continue to address the most critical industry challenges, we invite your perspective on this publication. [Time to complete: < 60 seconds]

Provide Strategic Feedback

Introduction

This section describes the multi-phase Aerospace & Defense PLM Action Group (AD PAG) Digital Twin and Digital Thread (Dtw-Dth) project and introduces the Digital Twin-Digital Thread Solution Evaluation Benchmark (Dtw-Dth Benchmark), which is the subject of this report.

Background

In March 2021, leadership from the AD PAG members chartered a project team of domain experts (also known as *subject matter experts)* from their companies to define objectives, requirements, and roadmaps for Dtw-Dth solutions used to create and manage the digital representation of a product through the product lifecycle within the A&D ecosystem. The team's charter included identifying, defining, and demonstrating use-case-level value propositions, and validating benefits to the PLM ecosystem, including the following:

- Improved data portability and transparency of PLM events
- Reduced operational friction, resulting in lower operations costs
- Improved product operational transparency, resulting in improved safety, operational efficiencies, and product design

The project has been executed in phases, employing Agile methods to publish the team's work incrementally at the speed of consensus.

Phase 1: Digital Twin/Thread Research and Scoping (not released)

Phase 2: Digital Twin/Thread Position Paper

Phase 3: Digital Twin/Thread Business Architecture / Methodologies paper

Phase 4: Digital Twin/Thread Comparative Analysis of Industry Standards paper

Phase 5: Value Proposition of the Digital Twin/Thread to the A&D industry

Phase 6: Forward-looking Digital Twin/Thread Strategy and Roadmap

Phase 7: Project Consolidation

The project team's work in phases 1 through 4 has been documented in a series of position papers available for download from the AD PAG's website.[†]

The purpose of Phase 5 was to characterize and validate the value proposition of Dtw-Dth to the A&D industry. This solution evaluation benchmark (Dtw-Dth Benchmark) is how that purpose was addressed.

Dtw-Dth Benchmark Overview

The AD PAG engaged with a select set of Dtw-Dth solution providers, inviting them to participate in an initiative to assess the capabilities of commercially available Dtw-Dth solution offerings, including software and services, through a series of use case demonstrations. Recognizing the topic's breadth and state of maturity, the benchmark inquiry was not focused solely on "measuring how well it is done" but more broadly on "understanding *how* it is done, *what* is real today, and *where* it is going." Solution provider engagement was structured into three parts, each addressing one of these three lines of inquiry.

To evaluate *what* is real today, the AD PAG Digital Twin-Digital Thread project team drafted a set of use cases and an initial plan for conducting use case demonstrations before reaching out to the solution providers. Each participating solution provider was asked to demonstrate use cases from their current catalog that align with use cases in the AD PAG catalog. Focusing on the participating solution providers' current use case catalogs minimized preparation effort and lead time, which were major considerations in planning the project. But more importantly, this approach intentionally focused the evaluation on the strengths of each participating provider's solution. The published results in this report provide a composite profile of capabilities across the current Dtw-Dth commercial solutions landscape.

To increase both the expert insight applied to this initiative and a consensus on the results within the A&D PLM ecosystem, the AD PAG Digital Twin-Digital Thread project team also secured agreements for collaboration and contribution of use cases from industry organizations known to be active in this space.

The solution evaluation benchmark plan was developed with the following guidelines in mind:

- Maximize efficiency and minimize costs to participating solution providers and AD PAG members
- Provide benefits to all participants (i.e., AD PAG members, partnering industry organizations, and participating solution providers)
- Extract and report objective, fact-based information and insights from the benchmark that provide a generalized assessment of the state-of-the-industry and not a competitive comparison between benchmarked solutions

Collaborative engagement of partnering industry organizations and participating solution providers was achieved though iterative rounds of negotiating and refining the project plan.

[†] https://www.cimdata.com/en/aerospace-and-defense/publications/digtaltwin-digitalthread

Objectives and Constraints

This section describes the Dtw-Dth Benchmark objectives, outlines the criteria for measuring success, and clarifies the applicable constraints.

Objectives

The benchmark was planned to achieve the following objectives:

1. A broad assessment of the capabilities of commercially available Dtw-Dth solution offerings, including software and services
2. Mutual education and alignment of thought leaders from industry and leading solution providers on Dtw-Dth use cases and solution strategies
3. Advancement of industry's awareness and understanding of the current practical value potential of Dtw-Dth investment

In addition, the learnings will be useful for future engagement with industry organizations for enrichment of standards to address Dtw-Dth requirements.

Success Criteria and Constraints

Success criteria and constraints for the benchmark follow.

Success Criteria

- Agreement is reached with the selected PLM solution providers to participate in the evaluation activity as planned
- Evaluation results provide a useful, capability-level indication of each evaluated solution to satisfy defined Dtw-Dth use cases and requirements
- All evaluation benchmark participants, including AD PAG members and PLM solution providers, judge the execution to be thorough and balanced and the results to be fair and meaningful

Constraints

- Planning, execution, and results reporting from this Dtw-Dth solution evaluation are conducted in strict conformance with AD PAG anti-trust guidelines[‡]
- Participating PLM solution providers bear their own cost for participation
- Participating PLM solution providers' costs are minimized by staging and executing the benchmark demonstrations at each provider's location

[‡] https://www.cimdata.com/en/aerospace-and-defense/anti-trust-statement

- AD PAG members' costs are minimized by providing the capability for member domain experts to observe the benchmark demonstrations remotely via web access from their home locations

Scope

This section lists and describes the communities of project participants, the engagement and demonstration sessions, the demonstration use cases, and the demonstration environments.

Participants

Communities of project participants included use case contributors and benchmark evaluators, solution providers, and the Benchmark Administrator.

Use Case Contributors and Benchmark Evaluators

Recognizing the fact that many industry organizations are deeply engaged in examining the nature and potential value of digital twins and digital threads, the AD PAG project team determined that collaboration with these organizations would provide a substantial mutual benefit.

Aerospace & Defense PLM Action Group

The following AD PAG member companies contributed domain experts for participation in this activity as use case authors, benchmark demonstration evaluators, and analysts. The individuals assigned had decades of aerospace PLM and configuration management experience.

- Airbus SE
- The Boeing Company
- GKN Aerospace Engine Systems
- Moog Inc.
- RTX
- Safran S.A.
- Spirit AeroSystems

Partnering Organizations

Seven industry organizations were invited to participate in the benchmark. Of those, four accepted the terms of the invitation and agreed to participate, and all have contributed use cases.

- AIAA, Digital Engineering Integration Committee (AIAA-DEIC)
- OMG, Digital Twin Consortium, (DTC) A&D sub-team
- prostep ivip, Collaborative Digital Twin (CDT) working group
- SAE International, G-31 Digital Communications Committee

Appendix A: Partnering Industry Organizations provides a description of the four industry partners.

Participating Solution Providers

Twenty-one solution providers, including software providers, infrastructure providers, and systems integrators, were invited to participate in the benchmark. Of those, seven solution providers accepted the terms of the invitation and agreed to participate.

- Ansys (part of SYNOPSYS)
- Capgemini
- Cortona3D
- eQ Technologic
- Hexagon
- Infosys
- PROSTEP AG

Benchmark Administrator

CIMdata was engaged to facilitate the planning and to manage the execution of the solution evaluation benchmarks process.

Engagement and Demonstration Sessions

As stated above, a primary objective of the Dtw-Dth Benchmark was mutual education and alignment of thought leaders from industry and leading solution providers on Dtw-Dth use cases and solution strategies. The scope of those learnings was to understand *how* it is done, *what* is real today, and *where* it is going. To that end, engagement sessions were structured in three parts.

- Part 1: Solution Strategy and Implementation Approach
- Part 2: Use Case Demonstrations
- Part 3: View of the Future

The scope of information exchanged within the engagement and demonstration sessions is detailed below.

Part 1: Solution Strategy and Implementation Approach

The solution provider was asked to:

- Present their ***solution strategy*** in clear terms
- Document their ***definitions*** of Dtw-Dth
- Explain their ***approach*** to building these systems
- Describe their target ***architecture*** (logical and physical)
- Highlight ***A&D-specific characteristics*** of their solutions

The solution provider was asked to describe their approach for:

- ***Engaging with customers*** to specify the solution, including scoping the digital twin or digital thread and defining its purpose and business benefits
- ***Adapting their foundational architecture*** to a customer's specific needs
- Identifying the ***organizational roles*** and responsibilities for creating, maintaining, and consuming the Dtw-Dth
- ***Developing*** the technical solution
- ***Deploying*** the solution to the user community

Part 2: Use Case Demonstrations

For each use case, the solution provider was asked to:

- Provide information about the demonstration environment
  - Define the ***business objective*** and anticipated ***value*** of each use case
  - Provide specific ***data scope*** (categories and scope of data used)
  - Document the ***applications,*** and computing and communication ***infrastructure*** involved
- Perform the use case script with their solution

For each use case, the evaluators were asked to:

- Assess how well the demonstrated solution fulfilled the use case goal
- Assess the solution for ***robustness***, ***ease of use***, and ***adaptability*** to a heterogeneous and distributed environment
- Analyze how well the solution architecture addresses real-world needs like ***scalability*** and ***integration*** across a distributed value chain

Part 3: View of the Future

Each solution provider was asked to present their view of:

- How the value footprint of Dtw-Dth will expand over time
- How they plan to enrich their Dtw-Dth solutions to deliver greater value to the industry
- How emergent technical developments will be incorporated into their solutions

Demonstration Use Cases

An initial set of use cases was proposed by domain expert members of the AD PAG Digital Twin-Digital Thread project team. Use cases were selected for proposal based on relevance and business value to AD PAG member companies. The final use cases set selected for demonstration was negotiated with partnering industry organizations and participating solution providers to capitalize on their existing inventories of use cases.

Appendix B: Listing of Digital Twin and Digital Thread Demonstrated Use Cases is organized into two tables by use case category type: digital twin and digital thread. Information for each use case includes the contributing organization, title, description, and applicable lifecycle stage(s).

Methodology

In addition to describing the process followed and presenting the overall activity timeline, this section addresses an artificial intelligence (AI) tool's use as an aid in analysis, including its benefits and limitations and the safeguards applied.

Process

The Dtw-Dth Benchmark process was adapted from CIMdata's best practice *Solution Evaluation and Selection* methodology.[§] The process proceeded in five stages.

1. Engagement and plan finalization
2. Benchmark preparation
3. Benchmark execution
4. Analysis
5. Report out

For simplicity, the stages are described in past tense, but individual activities within each stage are presented as declarative statements. Activities not otherwise attributed are performed by CIMdata.

Stage 1: Engagement and Plan Finalization

Engaging with industry organizations and solution providers to secure commitment to participate and then balancing the objectives and interests of all participants to reach consensus on a final project plan was the least precise stage of the overall activity.

1. Draft *Digital Twin-Digital Thread Benchmark–Guidelines for Solution Providers* document and *Digital Twin-Digital Thread Benchmark–Invitation to Participate* presentation

   Note: Guidelines submitted for review by AD PAG domain experts and AD PAG leadership, and revised in response to comments received
2. Prepare a Solution Evaluation briefing package for engaging candidate PLM software providers, including *Digital Twin-Digital Thread Benchmark–Invitation to Participate* presentation, *Digital Twin-Digital Thread Solution Evaluation–Benchmark Guidelines* document and backup materials, such as example use cases
3. Invite candidate PLM software providers to participate in the evaluation benchmark and request feedback on the *Digital Twin-Digital Thread Solution Evaluation–Benchmark Guidelines* document

   Note: Guidelines revised in response to comments received

[§] https://www.cimdata.com/en/education/educational-webinars/webinar-plm-solution-evaluation-selection-2021

4. Finalize the *Digital Twin-Digital Thread Solution Evaluation–Benchmark Guidelines* document and project plan

   Note: In Dec 2024, based on realization that industry's understanding of how digital twins and digital threads are created, managed, and consumed is uneven and generally immature, the project focus and approach shifted from "measuring how well it is done" to "understanding *how* it is done, *what* is real today, and *where* is it going"
5. Confirm the final list of participating PLM software providers

   Note: First solution provider confirmed in early September; last confirmed in late October of 2024

Stage 2: Benchmark Preparation

CIMdata issued invitations to those solution providers selected to participate, and each party participating in the Dtw-Dth Benchmark identified and secured availability of internal domain experts to support their role.

6. Formal invitation to participate in the Dtw-Dth Benchmark is issued

   Note: The finalized *Digital Twin-Digital Thread Solution Evaluation–Benchmark Guidelines* which includes the AD PAG use case catalog as an appendix is delivered along with the invitation to each participant; solution providers are asked to review and select use cases of interest for consideration as demonstration candidates
7. Each participating PLM software provider identifies and assigns their team of technical solution demonstration experts and prepares their internal workspace
8. Each participating AD PAG member company and partnering industry organization identifies and assigns their domain experts for participation in use case selection and refinement discussions and solution provider evaluation sessions

Stage 3: Benchmark Execution

Three types of activities occurred during the benchmark execution phase.

- Use case selection and refinement
- Engagement sessions preparation and demonstrations configuration
- Engagement sessions and demonstrations execution

These activities were not managed with "hard stops," but rather with a gradual transition in the type of activities over time. The working relationship throughout evaluation benchmark execution was intended to be highly collaborative between AD PAG domain experts and solution providers. Give-and-take and flexibility in the definition of work products delivered during the engagement sessions and benchmark demonstrations was expected. That said, much was to be done, so schedules were published and managed to keep the overall flow of work progressing.

Use Case Selection and Refinement

At the start of the benchmark execution stage, emphasis was on review and comparison of use cases in the solution provider's catalog with use cases in the catalog drafted by AD PAG domain experts and their colleagues from partnering industry organizations. The desired outcome was to

agree on a set of use cases from the solution provider's catalog that could be readily demonstrated and that corresponded to use cases in the AD PAG catalog.

9. AD PAG domain experts conference with each solution provider team to review and discuss use cases from their respective catalogs and select a set that would reasonably represent the solution provider's capability, that they could readily demonstrate, and that align with use cases from the AD PAG catalog
10. AD PAG works directly with each solution provider team to transcribe their selected use cases into the standard project use case template and refine, to the degree possible, alignment with AD PAG catalog use cases
11. AD PAG domain experts conference with each solution provider team to review refined use case documentation to confirm mutual understanding

Engagement Sessions Preparation and Demonstrations Configuration

As use case selection and refinement activities closed, emphasis shifted to solution definition and configuration by the solution providers' technical demonstration experts.

12. AD PAG domain experts interact with each solution provider's technical demonstration experts when requested

    Note: In general, the interactions are expected to be ad-hoc and informal; however, a sign-up sheet will be available for scheduling meeting times as an option

13. Solution providers prepare presentation materials to convey perspectives on their solution strategy and implementation approach and their view of the future

Engagement Sessions and Demonstrations Execution

At the culmination of the benchmark execution stage, emphasis shifted to mutual learning through a) solution provider interactive presentations on strategic topics, b) use case demonstration by the solution providers' technical experts, and c) evaluation by AD PAG domain experts (i.e., evaluators).

14. AD PAG negotiates schedules with solution providers and publishes a complete schedule of engagement sessions and use case materials for the solution providers and evaluators
15. Solution providers present and discuss perspectives on agreed strategic topics; their technical experts perform use cases demonstrations; the evaluators record observations and grade the solution demonstrations

Stage 4: Analysis

With engagement sessions and solution demonstrations complete, individual evaluators' observations and scores were consolidated and analyzed. Group discussions were conducted to reconcile outliers and develop consensus on learnings and assessments. Then, a set of summary observations and assessments was consolidated and summarized for each strategic topic, for each demonstrated use case, and for sets of use cases that constitute a predefined class of solutions.

16. Consolidate engagement sessions' evaluations (i.e., use case demonstration scores and comments) and perform a preliminary analysis

17. Evaluate completeness, specificity level, and volume of information received from evaluators, and devise appropriate methods for reducing and consolidating evaluator observations and ratings

    Note: The goal is to effectively report learnings, as well as general and comparative assessments of the solution providers' perspectives and solution capabilities without attribution to specific providers
18. Analyze the evaluation assessments and observations, and facilitate AD PAG domain expert discussions to reach consensus on learnings, assessments, and use case demonstration scores

Stage 5: Report Out

Multiple reports were generated in accordance with interests of various communities within the PLM ecosystem. This set of reports was subjected to review and revision prior to release and distribution to the targeted communities.

19. Draft a set of reports on benchmark results
20. Deliver draft reports to AD PAG domain experts and then to AD PAG leadership for review and comment; selectively share report content with participating solution providers to receive and respond to their corrections or concerns
21. Incorporate revisions in response to comments received, and publish the final reports

Activity Timeline

Project activity began with completion of Pre-work and Engagement Preparation in mid-June 2024. The flow of project activities and the original and actual project timelines are shown in Figure 1.

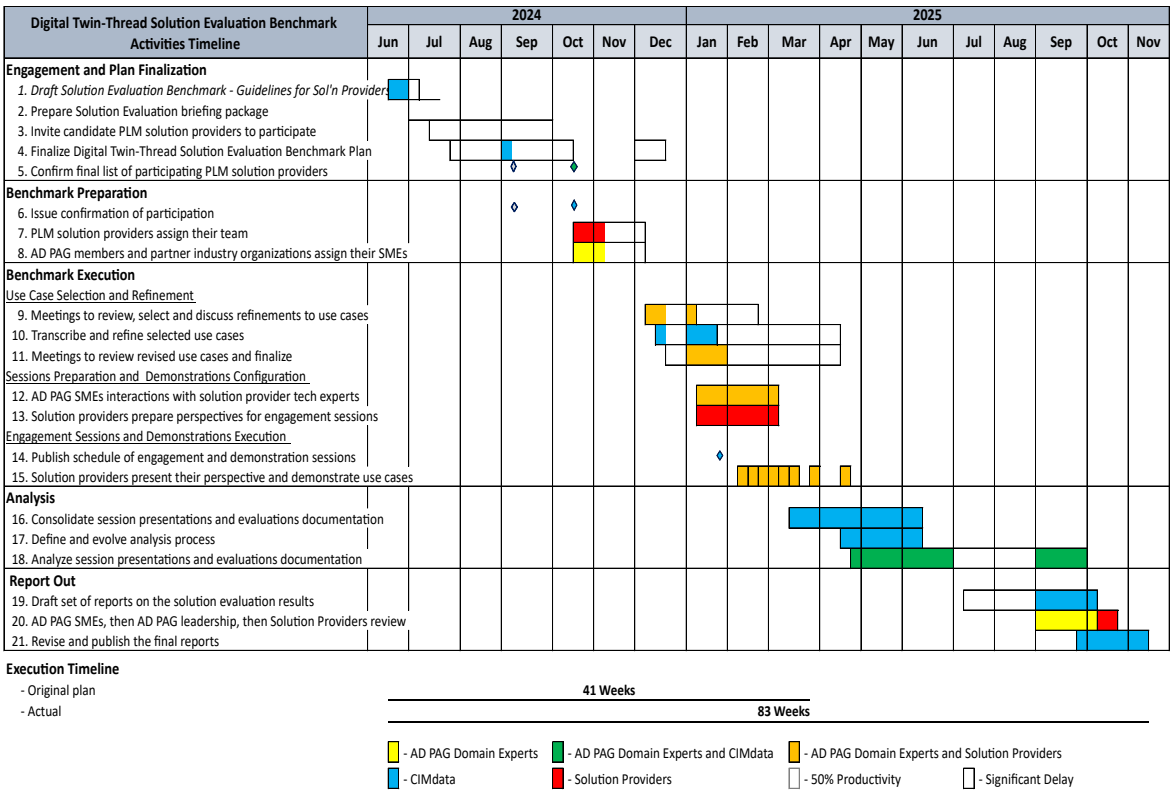


Figure 1 - Digital Twin-Digital Thread Solution Evaluation Benchmark Activity Timeline

Project activity proceeded according to plan with four exceptions. The protracted discussions required to reach final agreement on the plan with the participating solution providers added six weeks to the schedule. For some solution providers, the time required to identify and assign resources was dependent on the selection of use cases to be demonstrated, which added four weeks to the schedule. The logistics for scheduling and managing sessions to review and compare the use case catalogs of seven solution providers with the AD PAG catalog and agree on the appropriate set to be demonstrated by each added several weeks to the schedule.

In parallel, the turnaround time on transcription and revision of the use cases in response to review discussions with the solution providers was slower than anticipated. The complexity of these two activities executed together added 12 weeks to the schedule. Negotiating logistics for the benchmark demonstrations was complicated by the delay in finalizing the use cases and other factors, adding eight weeks to the schedule. Finally, the period for analysis was extended by several weeks due to delays over the summer holiday period. With these 5 deviations, the original execution timeline of 41 weeks was extended to 83 weeks.

Use of Artificial Intelligence

ChatGPT, a generative artificial intelligence chatbot developed by OpenAI, was applied as a productivity aid to assist in reporting the outcome of over 60 hours of intensive engagement with the solution providers presenting and demonstrating to multiple evaluators.

Summarizing Large Volumes of Data

ChatGPT was found to be a useful aid in generating summaries of the large volumes of information presented to evaluators during engagement sessions. It was also used to generate summaries of observations and assessments noted by the evaluators. The following procedure was followed to produce session summaries.

1. Information to be presented in a session was prescribed in an outline, and online evaluation forms were provided to each evaluator in advance
2. Each evaluator was required to receive 1-hour training in advance, including expectations and responsibilities of an evaluator and proper use of the evaluation form
3. Each session was attended by six or more evaluators, and the evaluators returned their completed evaluation forms to the Benchmark Administrator (BA) for processing
4. Video recordings and transcripts were produced for each session and made available to the evaluators for completing their evaluation forms and for future reference
5. The BA collected the solution provider presentation session transcript (approximately 50 pages of text)
6. The BA used ChatGPT to generate a summary
7. Several AD PAG domain experts (analysts) reviewed and marked the ChatGPT-generated summary; for this review, the analysts referenced their evaluation forms, their own memories, the session transcript, and/or the session video recording
8. The BA consolidated the analysts' reviews in preparation for reconciliation workshop(s)
9. The analysts met in one or more workshops to discuss and reconcile inconsistencies in their reviews

Corrections were significant but not extensive. The main impact of the reviews was to clarify and augment the ChatGPT-generated summary. A rough estimate of the productivity impact was a 50% reduction in overall effort by using ChatGPT.

Analyzing the Data

ChatGPT was found to be less reliable, but still of value, as a productivity aid for analyzing data. ChatGPT was applied to compare summaries of solution provider-presented material and was also applied to summaries of evaluators' observations and assessments.

Although ChatGPT effectively accelerated identification of recurring themes and contrasting viewpoints, its outputs were occasionally incomplete or contained factual and contextual inaccuracies. Some of these resulted from over-generalization or inference when data was ambiguous or unevenly represented across sources. Therefore, all AI-generated analyses required AD PAG domain expert review and validation before inclusion in any formal deliverable.

The analytical procedure followed a process similar to Steps 6 through 9 described above, involving data consolidation, structured comparison, and human verification. Additional safeguards, such as cross-checking AI-generated findings against evaluator source documents,

presentation transcripts, and assessment tables, were implemented to ensure reliability and traceability.

An important aspect of this process involved instructing ChatGPT to summarize input materials at different levels of consolidation. This approach produced outputs that ranged from highly condensed executive summaries to detailed thematic analyses, allowing AD PAG domain experts to adjust the level of abstraction to suit specific reporting needs. Each level of consolidation offered a distinct balance between brevity and detail, enabling more efficient exploration of large datasets without losing critical insights.

Equally important, ChatGPT was consistently directed to use only the content explicitly provided as input for each consolidation activity. This ensured resulting summaries, comparisons, and synthesized insights reflected only information contained in the Dtw-Dth Benchmark project's materials and evaluator submissions. This was critical to maintaining data integrity and traceability throughout the process.

Results and Analysis

This section documents the results and analysis of engagement sessions when the solution providers presented their perspectives on a range of topics (e.g., strategy, approach, future view) and performed use case demonstrations utilizing their solution capabilities.

AD PAG and partnering organization domain experts observed, discussed, and evaluated the information received in these sessions. As noted in the *Scope* section above, the information exchange was organized into three parts, and the results and analysis of those sessions are presented in three parts as well.

Part 1: Solution Strategy and Implementation Approach

Part 2: Use Case Demonstrations

Part 3: View of the Future

To maintain focus and continuity of the evaluator–solution provider experience, the engagement sessions with each solution provider were scheduled to occur within a single week dedicated to that solution provider.

The number of engagement sessions and total time of evaluator engagement was left to the discretion of the participating solution provider. Evaluator–solution provider engagement varied from 5 hours over 2 sessions to 12 hours over 5 sessions, with involvement of 4 to 7 solution provider individuals in each session.

Twelve evaluators from AD PAG member companies and partnering organizations participated remotely via webcast. A minimum of six evaluators attended and recorded their observations at each session.

After the engagement sessions were completed, the evaluators collaborated to prepare summaries of the information presented and their evaluations. The summaries highlight the learnings conveyed during the sessions.

Community Engagement

Securing the collaborative involvement of a broad range of industrial organizations and solution providers was essential to achieving the project objectives. In addition to the benefit of their contributions to the project work products, the interaction with these communities provided unexpected learnings and insights into their operational structure and approach to collaborative engagement. *Appendix C: Community Engagement* addresses the importance and recounts the experience and lessons learned from the industry organization and the solution provider collaborations established during this Dtw-Dth Benchmark project.

Part 1: Solution Strategy and Implementation Approach

Each participating solution provider was invited to present their Dtw-Dth solution strategy and implementation approach.

Evaluator Observations

This section consolidates the recorded observations of the evaluators who attended and assessed the Part 1 presentations of the seven solution providers. It is a record of the evaluators' view of key points, similar themes and distinctions between the solution strategies, and implementation approaches of the participating solution providers.

Solution Strategy

Solution Strategy Overview

Several solution providers received praise from the evaluators for their clear strategy overview. One provider was commended for their understanding and ability to effectively communicate the complexity and disparity of systems, data structures, and data stores. However, while most evaluations were positive, not all providers met the evaluators' expectations.

Evaluators highlighted key solution strategy elements they considered to be strengths or differentiators, such as evidence of deep experience, strong focus on customer outcomes, end-to-end digital thread capabilities, or a software-agnostic approach. Many other elements described by the solution providers were noted by evaluators as foundational, such as focus on open standards, system thinking, and interoperability, offering frameworks and accelerators, and providing a portfolio of connectors to a range of PLM, ERP (Enterprise Resource Planning), and MES (Manufacturing Engineering System) applications.

Definition of Digital Twin and Digital Thread (Dtw-Dth)

Digital Twin

Evaluators noted that most providers' definitions of digital twin were straightforward, such as "the digital representation of real-world products or processes." Some providers added a qualifier, such as "synchronized at a specific specified frequency and fidelity." It was noted that providers offering focused solutions tailored their definitions to include scope or purpose that aligns with the solutions they offer, with phrases such as "supports quality control, assurance, and management across the product lifecycle" or "enables 'what-if' modeling without requiring a physical prototype."

Digital Thread

Evaluators noted with interest that while some providers emphasized digital twin, most emphasized digital thread. While some definitions were conventional, evaluators noted that some providers' definitions of digital thread were expansive and detailed. It was noted that one provider defined digital thread as a view of the persistent and federated digital fabric and then expounded on the nature and characteristics of the digital fabric. Another provider offered a definition they found in Wikipedia – judged by the recording evaluator to be a perfectly acceptable definition.

Overview of Approach to Implementing Dtw-Dth Solutions

Evaluators noted several key implementation approach elements they consider a unique strength or differentiator. One solution provider who offers data as a service focuses implementation on data delivery guarantees. This provider organizes sourced data in a graph database, provides user access with a data as a service (DaaS) approach, and rejects the need for data lakes or centralized repositories. It was noted that another provider's digital thread solution is supported by AI-driven development. A third provider was noted for applying a connector-based integrated data environment (IDE) framework.

Evaluators noted other key elements common to several providers, such as leveraging business process assessments, an Agile methodology, or an enterprise value chain approach, a clear focus on standards (e.g., SysML V2.0, open APIs), and an agnostic view toward source systems.

Evaluators noted some providers tune their implementation approach to their solution focus, whether that be collaboration engineering, additive manufacturing, virtual assembly, automated quality assurance, or document publishing.

Dtw-Dth Solution Architectures

Evaluators were particularly impressed with one provider who demonstrated Agility and strong partner integration within their solution architecture.

Evaluators noted several particular strengths and differentiators in the solution architectures presented, such as intellectual property (IP) protection supported via tessellated data, connectors visualizing and managing data via a graph database, administrative process dashboards and translation capabilities, and powerful platforms offered by some of the providers to connect internal and external systems.

Other key elements noted by evaluators that are common across most of the providers' solution architectures include integrations with multiple PLM, ERP, and MES systems; a broad portfolio of connectors; and support of cloud, on-premises, and hybrid environments.

A&D-Specific Characteristics

The extensive list of provider-enumerated solution characteristics impressed evaluators. Some of the more common elements cited by evaluators include long lead times to market addressed through digital thread alignment and enterprise-wide integration, export control compliance, high-security network integration, standardized formats and connectors for common A&D platforms, and features that align with digital engineering and an integrated data environment (IDE) approach. Some of the more unique elements cited include reduced-order models for simulation efficiency

and complexity management, serial-number-specific document handling, targeting legacy systems and factories (i.e., transactional models support data continuity without modifying the underlying systems). It was noted that one provider's platform currently supports U.S. Government and major A&D clients globally.

Implementation Approach

Customer Engagement Process

Evaluators noted that most providers initiate engagements with some form of business process assessment (BPA) that documents objectives, outcomes, and value, and most follow a proven formal methodology for development and deployment. Two providers were acknowledged for conducting BPAs and designing digital threads within a formal Enterprise Architecture framework.

It was noted that two providers emphasize out-of-the-box and minimum customization. In contrast, some providers focus on modeling and cleansing the customer's data resource and their engagements are highly tailored to customer data ecosystems.

Evaluators praised some providers for demonstrating strong legacy system support and data model transformation capabilities or demonstrating a deep understanding of customer needs in targeted business areas, including ROI mapping and data exchange validation.

Evaluators appreciated that several of the providers illustrated their customer engagement process during their use case demonstrations.

Adapting Architecture to Customer Needs

Evaluators documented several key practices that are common to most of the providers for adapting their solution architecture to customer-specific needs. These include mapping data and data flows, applying flexible models based on APIs to integrate PLM, ERP, MES and or other data source applications, and deploying in on-premises, cloud or hybrid environment.

A significant potential strength cited by the evaluators for the majority of providers is their unique software products, which are core to the solutions they deliver. Another unique strength cited by evaluators for one provider include supporting federated, secure access across multiple source systems using graphical mapping and ontology-based comparison. This is the provider who also offers data as a service.

Evaluators noted their appreciation that one provider demonstrated integrations across multiple lifecycle phases including design, shop floor, and service.

Roles and Responsibilities

Evaluators noted that several of the providers embed roles and responsibilities within the solution common data model (CDM) via low-code software development kits (SDKs) and APIs. Certain digital twin or digital thread creation and maintenance roles are preconfigured, including governance, system architecture, and master data management. Other roles from within the business areas are identified and configured within the solution. One provider was cited as documenting roles through a functional support model that includes troubleshooting and maintenance procedures for the data model.

Technical Development and Deployment Process

Evaluators noted that several providers follow Agile implementation methods which support a stepwise implementation model. It was noted that for one provider deployment includes proof of concept followed by full implementation with a timeline that ranges from 16 to 30 weeks depending on complexity.

A noted differentiator for one provider is that their development teams operate across multiple regions, enabling compliance with A&D-specific access requirements.

General Observations

Evaluators praised several providers for their presentations. These presentations were seen as comprehensive, covering both solution strategy and implementation approach thoroughly, and inclusive of detailed architectural and technical insights.

Evaluators highlighted strengths and differentiators of several solution providers:

- One provider was praised for their ability to meet the use case needs and for the level of integration achieved with third-party APIs and systems.
- Another provider was praised for the power of their solution platform, in particular its ability to unify disparate systems via a secure, federated backbone.
- For one, it is the maturity of their solution portfolio in their focus area.
- For another, it is their reuse-driven approach, their solution's alignment with PLM workflows, and the simplification of how they are enabled in their customers' way of working.
- For still another, it is global experience, relevance of their solution's focus to aerospace, and their software's ability to support integration across multiple environments and users.
- And for one more, it is their long-standing industry experience, successful practice of tracking technology evolution to define an "industry of the future" vision aligned with technology futures and partnering with the Tier 1 PLM solution providers to deliver timely solutions.

All participating solution providers engaged with openness and generosity to communicate their solution strategies and implementation approaches. The evaluators who participated in these sessions gained valuable knowledge from each of them.

Part 2: Use Case Demonstrations

The purpose of use case demonstrations was to assess, through observing the performance of actual Dtw-Dth solutions, the capability of such solutions to deliver business value.

Demonstrated Use Cases

The following use cases were demonstrated by the participating solution providers. Since each use case was demonstrated by only one provider, it is not possible to preserve neutrality of results without masking the association of the demonstrated use case to the solution provider. Additional detail is provided for each use case in *Appendix B: Listing of Digital Twin and Digital Thread*

Demonstrated Use Cases, which is organized in two tables by use case category type: digital twin and digital thread.

Information for each use case includes the contributing organization, title, description, and applicable lifecycle stage(s). As shown in Figure 2, each lifecycle stage is represented by a letter: A - Concept Stage, B - Development Stage, C - Production Stage, D - Utilization Stage, E - Support Stage, and F - Retirement Stage.

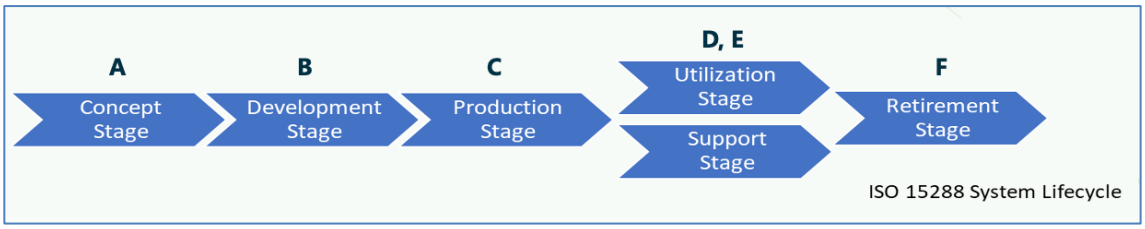


Figure 2 – Lifecycle Stages

The sets of use cases demonstrated are listed in Figure 3 and Figure 4. To convey the scope of each use case the graphic depicts the span of lifecycle stages over which the digital twin or thread are created and consumed.

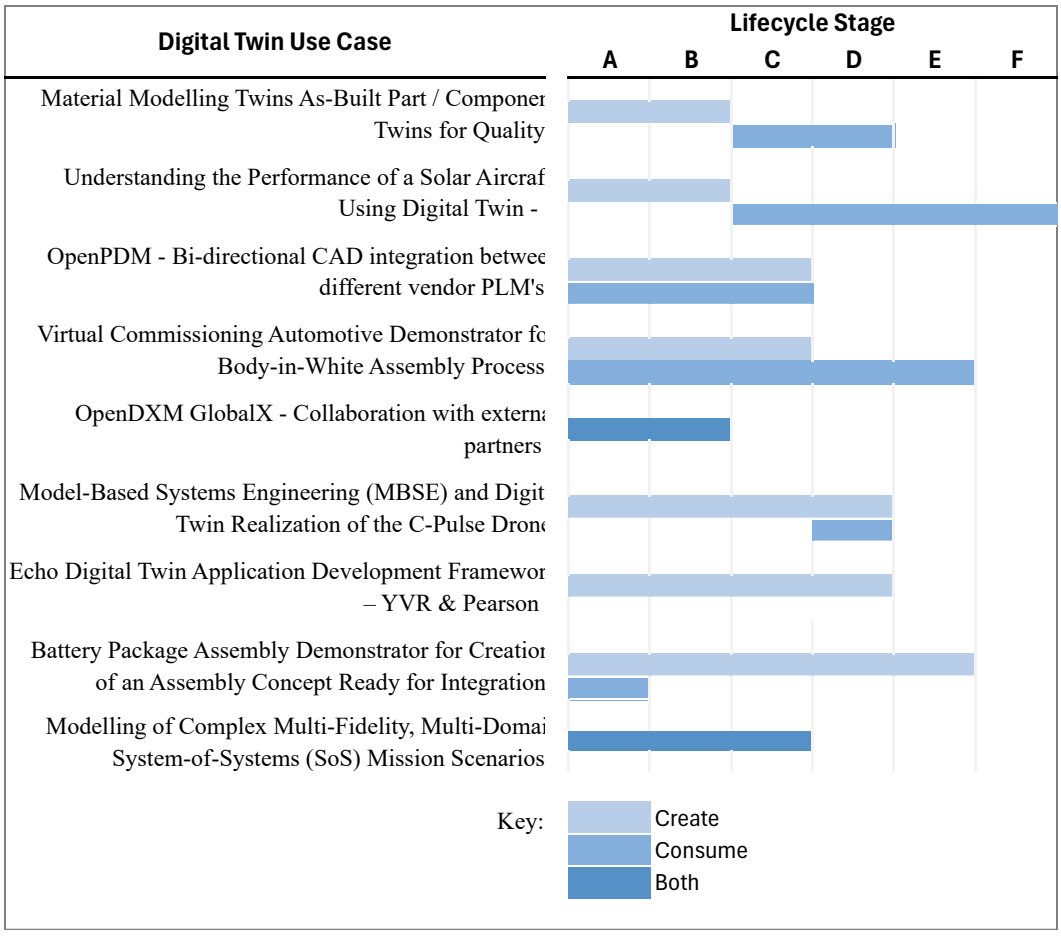


Figure 3 – Digital Twin Use Cases and Their Associated Lifecycle Stage(s)

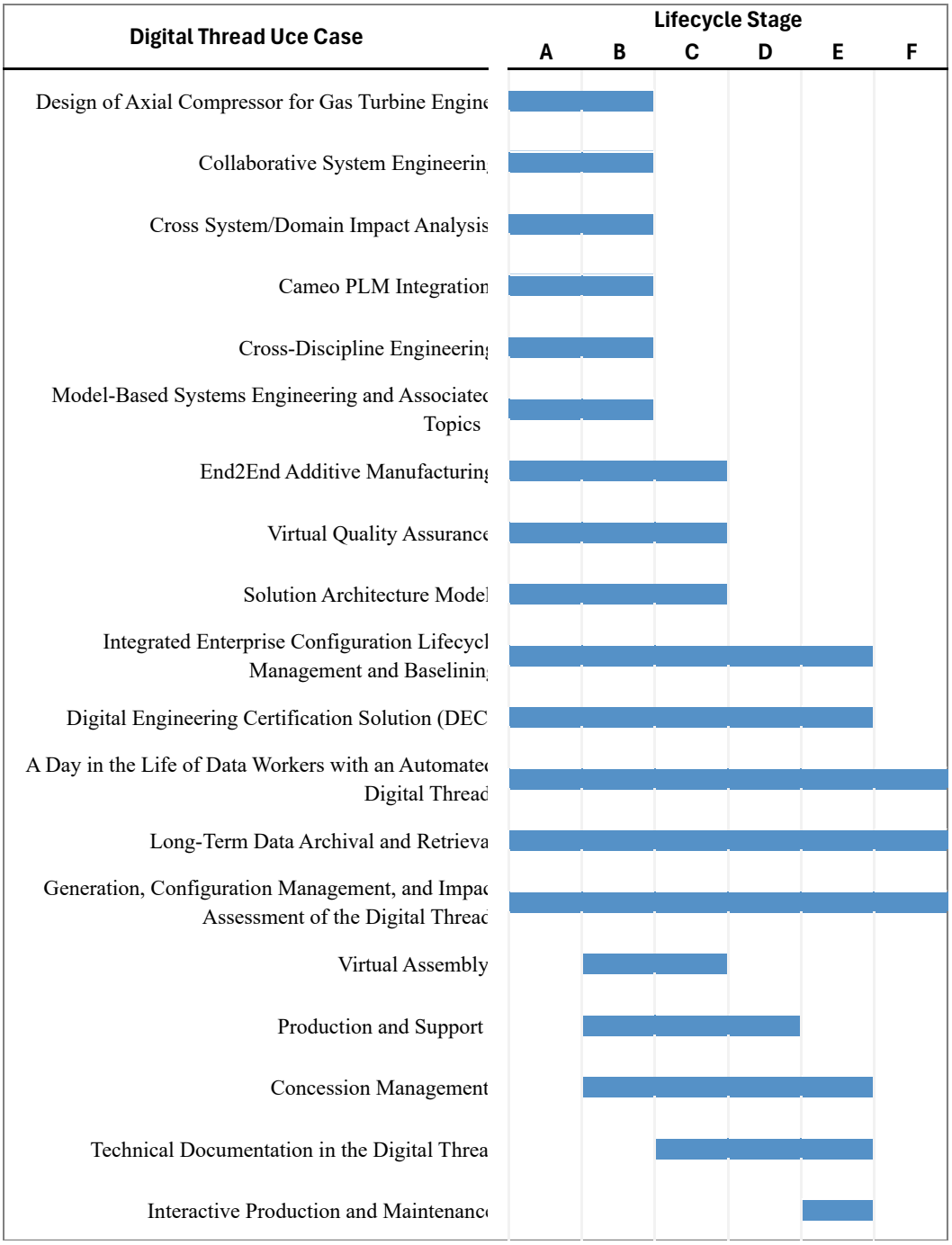


Figure 4 – Digital Thread Use Cases and Their Associated Lifecycle Stage(s)

Use Case Examples

To convey a deeper understanding of the nature and scope of the demonstrated use cases, a representative set is illustrated below.

Ansys – Understanding the Performance of a Solar Aircraft Using Digital Twin

Objective

Demonstrate how digital twins at the component and subsystem levels can be seamlessly integrated into a full system-of-systems (SoS) model to analyze and predict solar aircraft performance across mission conditions

Business Context

Supports aerospace and defense stakeholders seeking to enhance efficiency, optimize performance, and extend asset lifecycle by applying digital twin technology across multiple stages of asset management—from design and testing through operations and sustainment

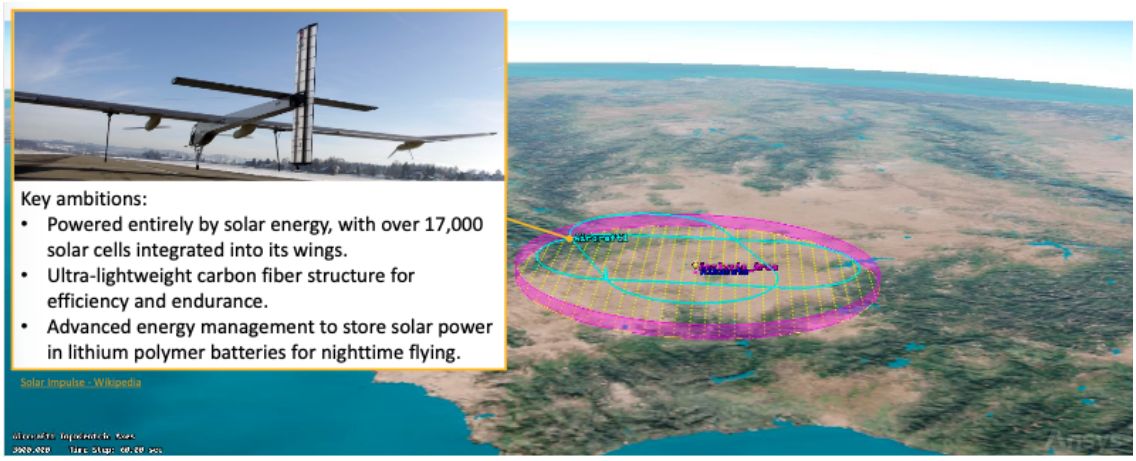


Figure 5 - Ansys Developing a Solar Powered Aircraft

Highlights

Seamless integration of component- and subsystem-level digital twins into a full SoS model - Robust performance analysis across varying mission and environmental conditions - Strong focus on efficiency, optimization, and lifecycle extension - Clear demonstration of practical A&D applications, enabling improved decision-making from design through sustainment (Figure 5)

Capgemini – Echo Digital Twin Application Development Framework – Vancouver International and Pearson Airports

Objective

Demonstration of digital twin capabilities using an SoS approach for airport operations and sustainability

Business Context

Vancouver and Pearson airports use the Echo framework to model terrain, simulate daily operations, and evaluate collision avoidance and net-zero carbon strategies (Figure 6)

Figure 6 - Echo Digital Twin Application Development Framework – Vancouver International and Pearson Airports

Highlights

Comprehensive modeling of airport systems and subsystems - Detailed variable handling down to elevator-level granularity - Strong adaptability, supporting multiple operational scenarios - Aligned with sustainability and safety (collision avoidance) goals

Cortona3D – Technical Documentation in the Digital Thread

Objective

Demonstration of automation in creating and maintaining technical documentation directly from PLM data, enabling streamlined publication processes and downstream digital thread alignment

Business Context

Focused on semi-automated generation of technical documentation based on CAD, BOM, and Bill of Process (BOP) data to enhance efficiency and accuracy in authoring and enabling automated updates; integrated with Siemens Teamcenter as source of engineering data and target of technical publications (Figure 7)

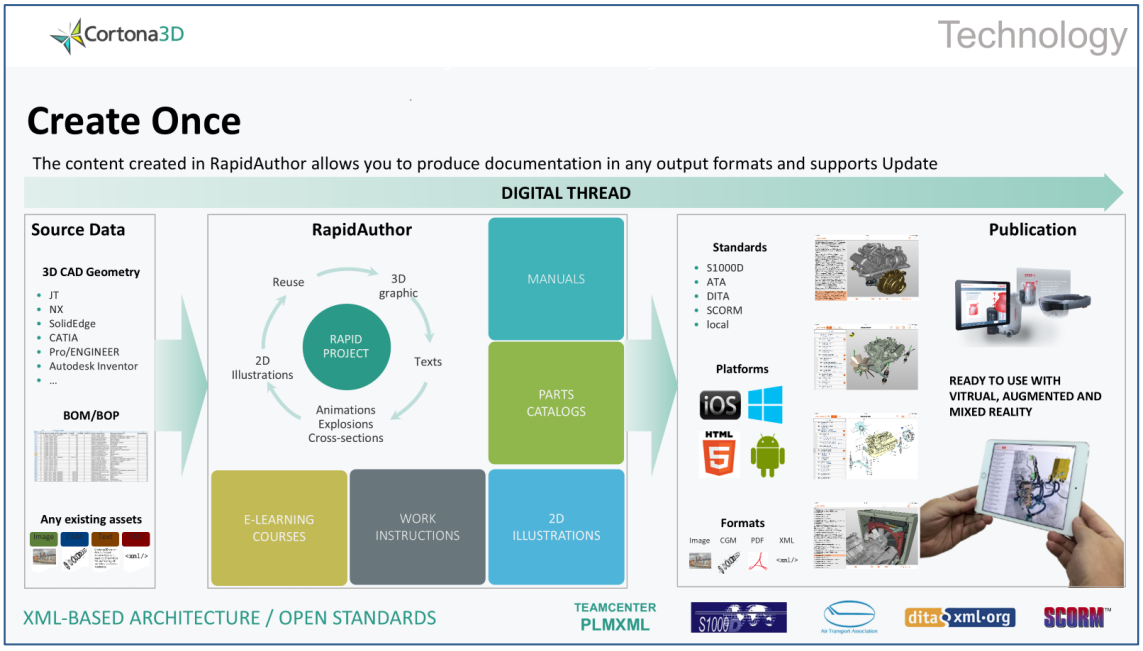


Figure 7 – Cortona3D Technical Documentation in the Dth

Highlights

Automated generation and update of documents from PLM - Tight integration with Siemens Teamcenter, including BOM and BOP - Comprehensive demonstration covering authoring, release, and revision workflows - High usability

eQ Technologic – Generation, Configuration Management, and Impact Assessment of the Digital Thread

Objective

Demonstration of generation, configuration, and impact assessment of a Dth, introducing related concepts such as integrated business process based data-flows establishing digital thread leading to digital fabric and digital stitch, while enabling secure multi-platform data connectivity

Business Context

Showcased ability to connect and integrate heterogeneous systems through governed data relationships, role-based visibility, and visual impact analysis, highlighting governance and flexibility in cross-platform digital threads (Figure 8)

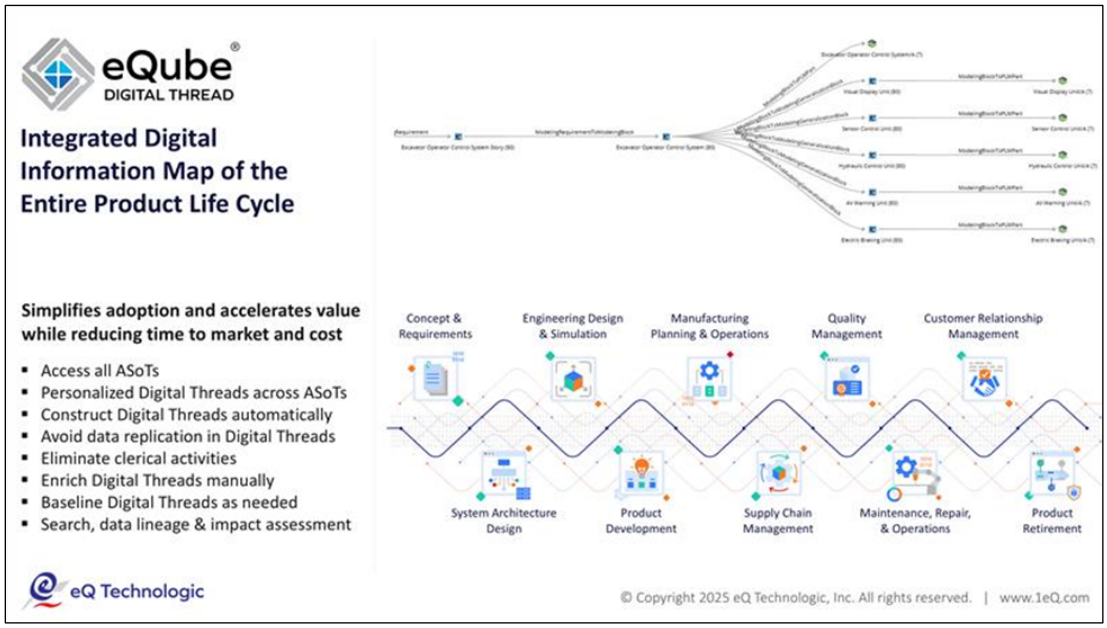


Figure 8 – eQube Dth: An Integrated Digital Information Map of the Entire Product Lifecycle

Highlights

Integrated view of digital thread, digital fabric, and digital stitch concepts - Secure data connectivity between multiple systems driven by CDM and data virtualization, no-code platform capabilities, 100+ COTS connectors, while maintaining access controls - Dynamic visualization of relationships and impact assessment - Role-based access and collaboration

Hexagon – Digital Thread End-to-End Automated Inspection

Objective

Automation of the quality assurance process for aerospace components—including fuselage and engine structures—to ensure structural integrity, dimensional accuracy, and compliance with safety standards

Business Context

Modern aerospace manufacturing faces increasing complexity and demand for precision, with quality control processes often being bottlenecks; this use case demonstrates how Dth integration of PLM, MES, and automated inspection systems eliminates data silos, improves traceability, and supports data-driven decision making (Figure 9)

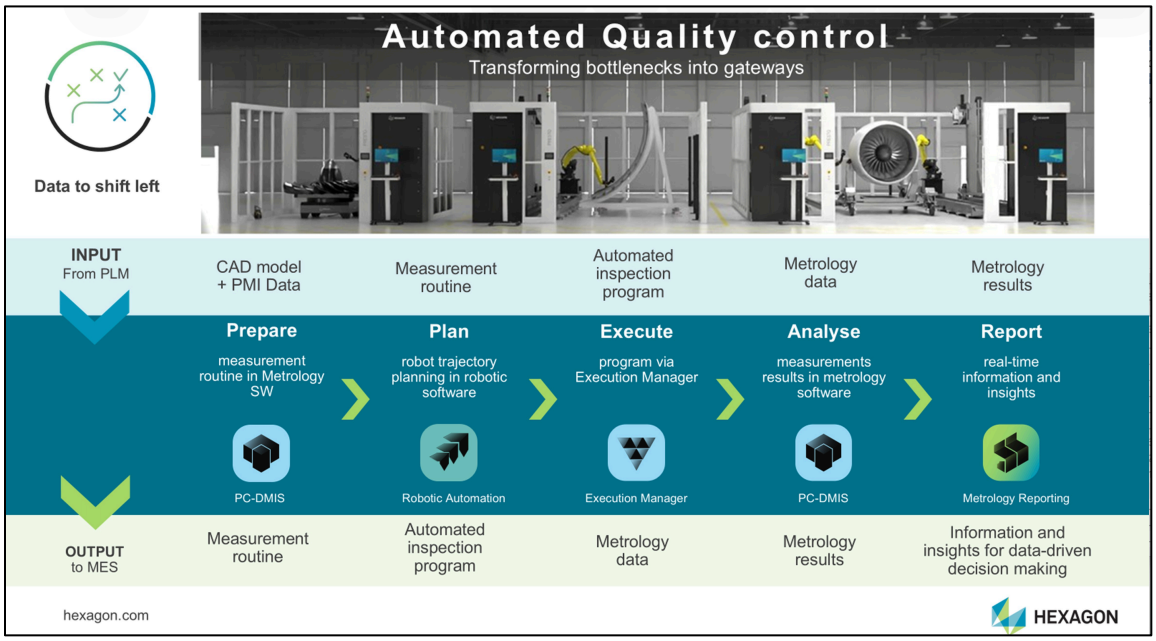


Figure 9 – Hexagon Automated Quality Control

Highlights

End-to-end, digitally connected workflow links PLM, MES, and metrology systems through the PRESTO platform - Enables real-time inspection automation, traceability, and continuous improvement - Implementation in 16 to 30 weeks - "Shift-left" quality control brings inspection insights early in the lifecycle to boost efficiency, reduce rework, ensure compliance

Infosys – Production and Support: AI-Enhanced PLM-MES Integration for Manufacturing Conformance Management

Objective

Demonstration of integration between PLM and MES systems within Dassault's 3DX platform, leveraging AI to predict and prevent nonconformities during A&D manufacturing processes

Business Context

The solution illustrates how AI-enabled digital threads can connect design and production, capturing and analyzing manufacturing data for compliance to improve quality, efficiency, and traceability (Figure 10)

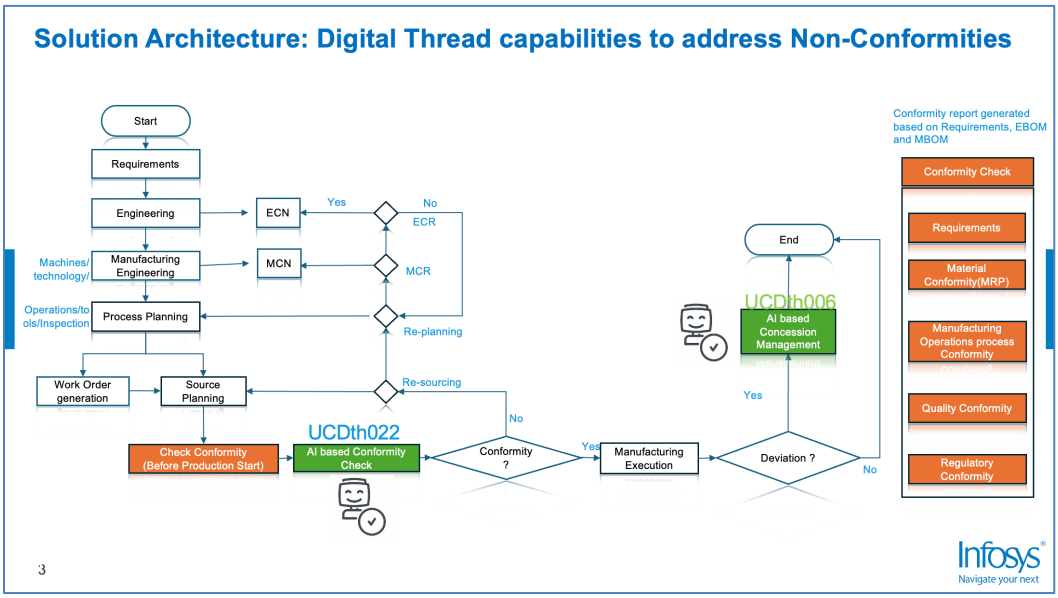


Figure 10 - Solution Architecture: Dth Capabilities to Address Non-Conformities

Highlights

Strong PLM-MES integration demonstrated on the 3DX platform - AI-assisted quality monitoring and nonconformance prediction - Data capture and visual analysis within Enovia, Delmia, and Aprisio environments - Alternate manufacturing conformance management path demonstration for adaptability - High relevance to A&D production workflows

PROSTEP AG – OpenPDM - Bidirectional CAD Integration Between Different Vendor PLMs

Objective

Demonstration of a complete end-to-end process using OpenPDM tools for integration and migration of data across a variety of Commercial-Off-the-Shelf (COTS) connectors; bidirectional integration of CAD data between different vendor PLM systems, such as Windchill, 3DEXPERIENCE (3DX), and Teamcenter

Business Context

Solution highlighted PROSTEP's robust, configurable, automated, and dependable integrations between Windchill, 3DX, Teamcenter, and other PLM systems addressing interoperability and Dth continuity across engineering and manufacturing enterprise systems; ability to synchronize native CAD and BOM data enables seamless Dtw, utilizing the ASOT systems and data interoperability enabled with PROSTEP Digital Thread Platform (Figure 11)

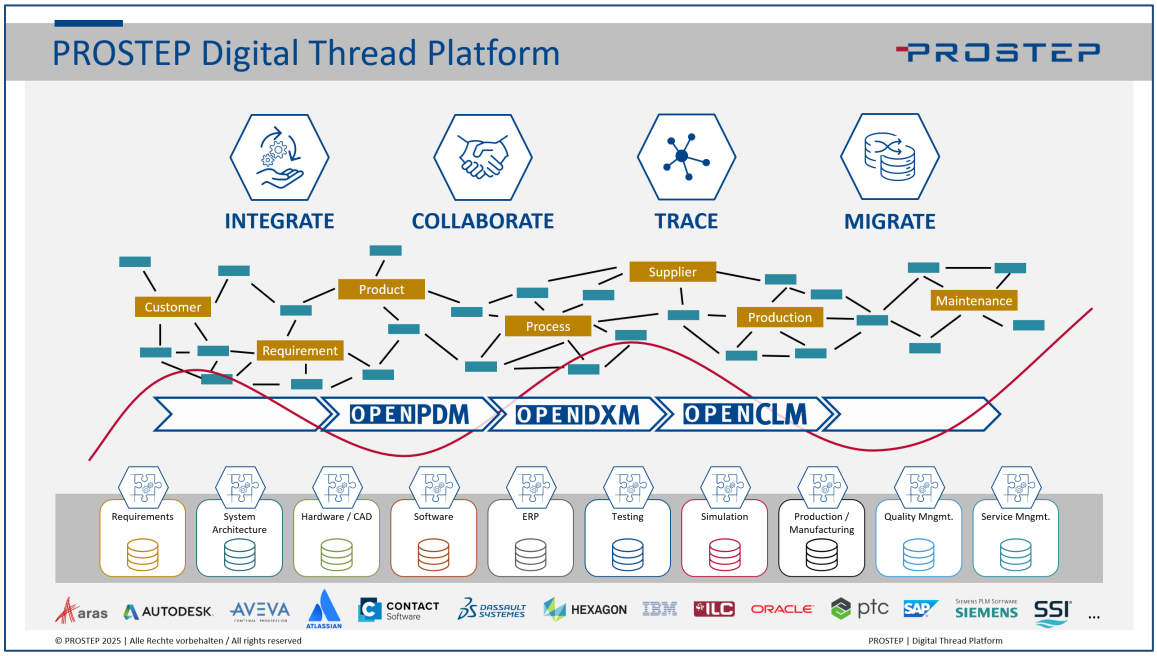


Figure 11 – PROSTEP Digital Thread Platform for Heterogenous System Integration, Traceability, and Consistent Product Lifecycle Collaboration

Highlights

End-to-end demonstration of data integration between engineering enterprise systems focused on PLM and CAD data interoperability - PROSTEP Digital Thread Platform's broad PLM/ALM/ERP/CAD/SPLM/REQ compatibility with a mature, proven platform with 30+ years of use - PROSTEP's focus to provide Dtw-Dth tools that enable traceability, enhanced governance, automation, and reliability using API-based integrations supporting enterprise collaboration

The above use cases are only 7 of the 28 that were demonstrated and evaluated. Overall, the AD PAG Digital Twin-Digital Thread project team considers the full set to be a fair representation of the needs of the A&D industry for the purposes of this project.

Evaluation Dimensions and Ratings Scale

The following agenda was proposed for the use case demonstration sessions.

- Demonstration overview
  - Business objectives and anticipated value
  - Data scope
  - Applications
  - Computing and communications infrastructure
- Demonstration execution, highlighting the following:
  - Goal and value achievement
  - Use Case Actions

  - Ease of Use
  - Robustness
  - Adaptability
- Q&A

Evaluation Dimensions

The following performance dimensions were evaluated and rated for each of the demonstrated use cases. The ratings and evaluator observations were recorded on grading sheets and submitted to the Benchmark Administrator for consolidation and analysis.

Use Case Goal

The intended outcomes and business value to be achieved by execution of the use case

Use Case Actions (digital thread only)

The standard sequence of actions and their corresponding outcomes, illustrating the expected progression of a specific scenario within a project or system

Robustness

The ability of a system or solution to consistently perform well under various conditions, including handling errors, high loads, and unexpected situations without failure

Ease of Use

The simplicity and intuitiveness of the system or solution, ensuring that users can efficiently interact with it without extensive training or difficulty

Adaptability

The ability of a system or solution to adjust and evolve in response to changing requirements, environments, or user needs

Ratings Scale

During each use case demonstration, the following rating scale was applied by the evaluators against each of the evaluation dimensions:

0-Not shown

1-Minimally meets requirement

2-Mostly meets requirement

3-Meets requirement

4-Exceeds requirement

5-Far exceeds requirement

Demonstration Results

Demonstration results are reported without attribution to specific providers. This is consistent with the stated intent to provide a composite profile of capabilities across the current Dtw-Dth commercial solutions landscape rather than a competitive comparison of solution provider capabilities. Each chart presented in this section displays the minimum, maximum, and average ratings[**] assigned to the evaluation dimensions for a grouping of use cases.

Use Case Categories

In addition to presenting results for all demonstrated use cases, the following categories were defined as a means for grouping use cases to highlight any differences in the results that potentially relate to different characteristics of use cases in different groups.

Solution Provider (A thru G)	Solution Type		Solution Elements		Solution Scope	
	Thread	Twin	Software & Services	Services Only	General	Focused

All Use Cases

The composite ratings for all 28 Dtw-Dth use case demonstrations are presented in Figure 12. Ratings are displayed by evaluation dimension (e.g., Final Grade, Goal, Actions, Robustness, etc.).

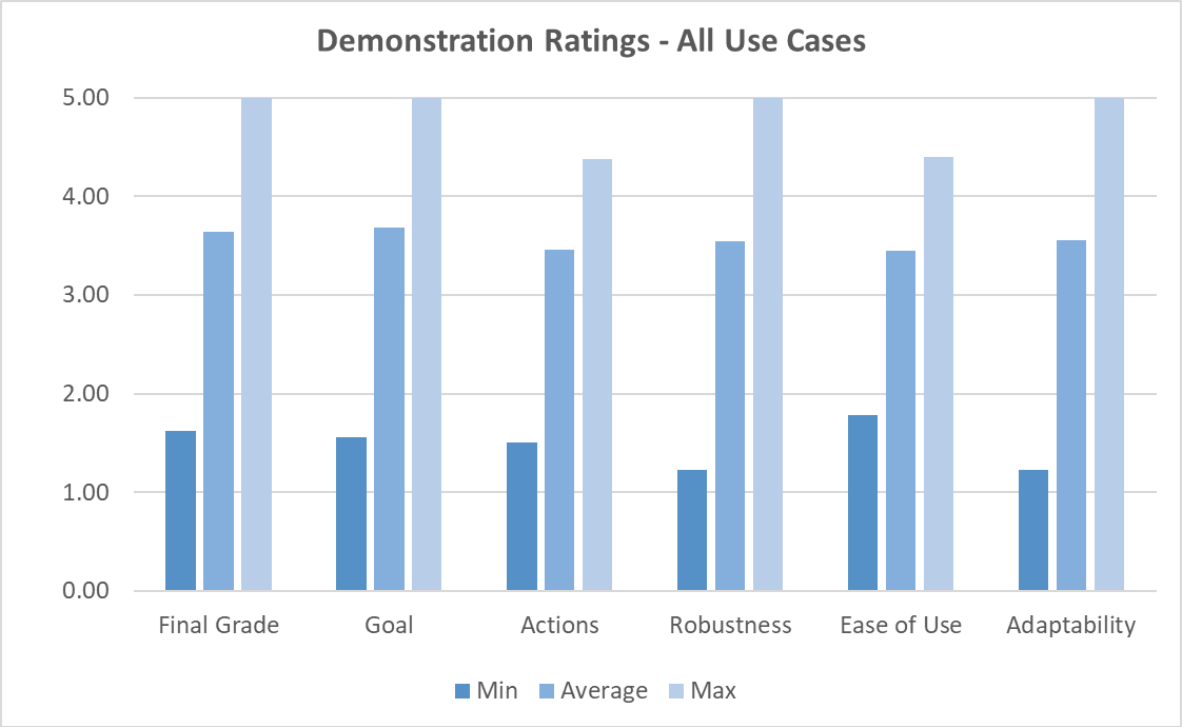


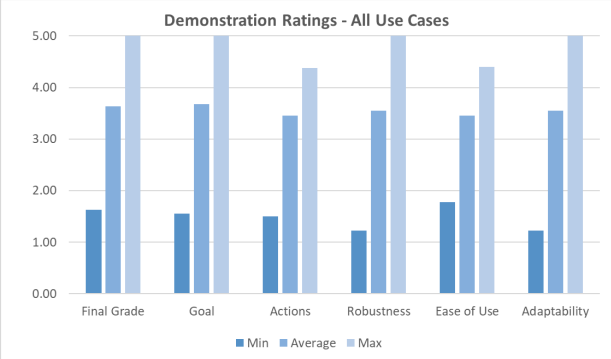
Figure 12 – Composite Demonstration Ratings of All Dtw-Dth Use Cases

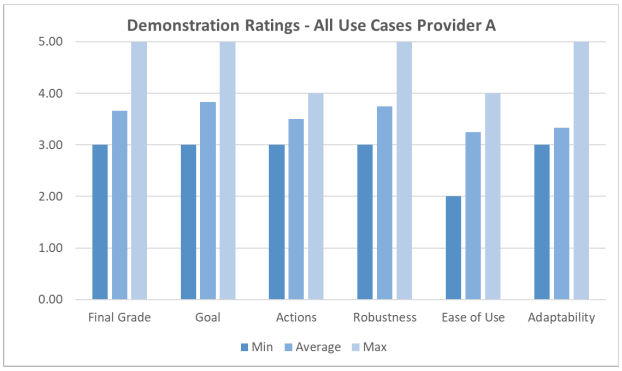
[**] The assigned rating is the average of scores assigned by the demonstration evaluators for that dimension in that use case.

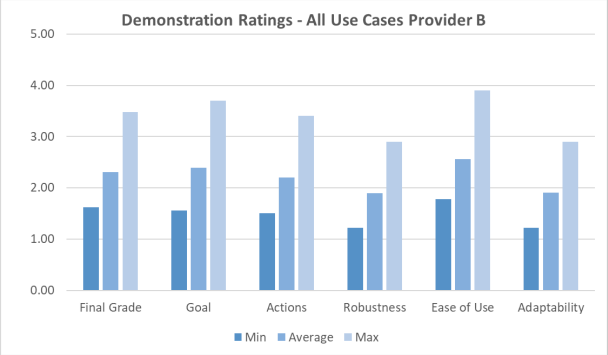
The ratings reveal generally positive impressions, with average scores above 3.0, indicating that most use case demonstrations met or exceeded expectations across all evaluation categories. However, minimum scores of 1.0-2.0 across all categories indicate performance of one or a few use case demonstrations failed to meet expectations. Most demonstrations were seen as mature and strategically aligned, while others raised questions of practical readiness and execution quality.

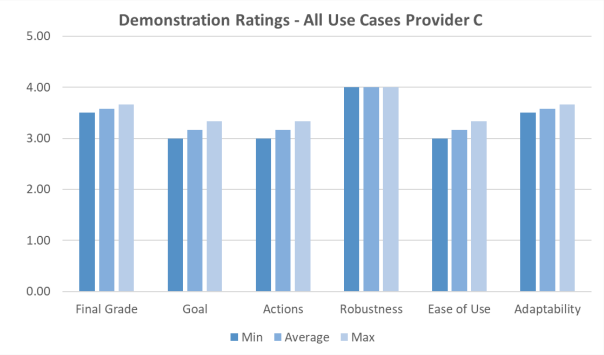
By Solution Provider

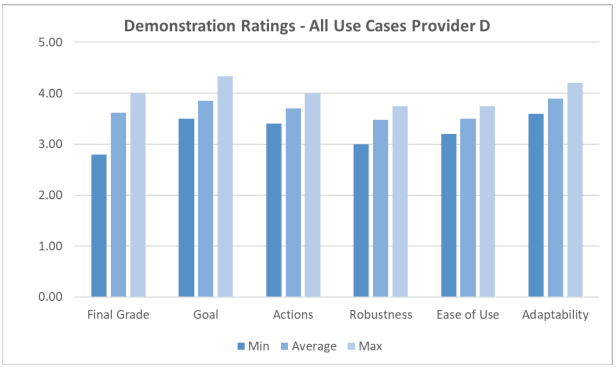
The following graphs shown in Figure 13 represent the minimum, average, and maximum demonstration ratings of all use cases and of all use cases by individual provider.











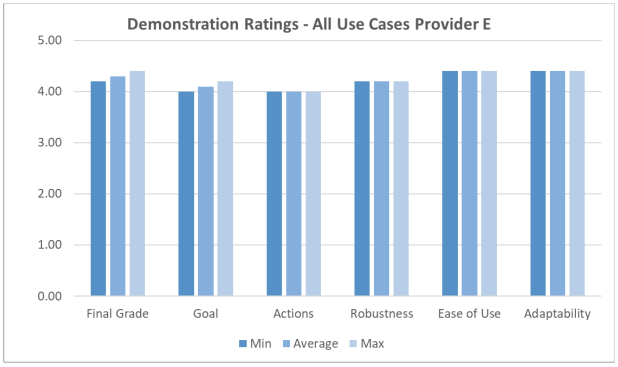


Figure 13 - Use Cases Demonstration Ratings: All and by Provider

Evaluator ratings revealed limited differentiation among providers' use case demonstration performances. There are clearly differences, but the sample size is insufficient to consider this comparison definitive.

By Solution Type

The comparison of Dth-Dtw use case demonstration performance is shown in Figure 14.

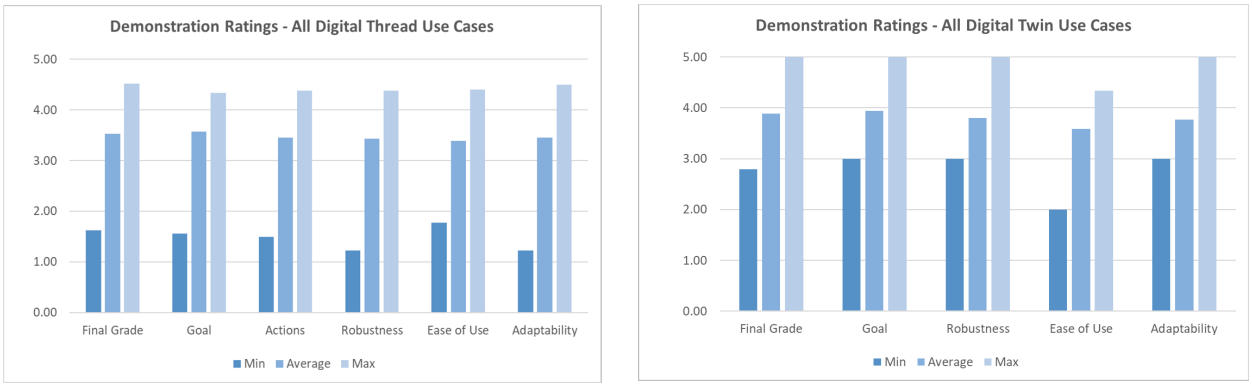


Figure 14 - Demonstration Ratings for Digital Thread Use Cases Compared with Demonstration Ratings for Digital Twin Use Cases

A clear distinction by solution type exists, with digital twin use case demonstrations performed at a higher level than digital thread use cases. While interesting to observe, the sample size is insufficient to consider this comparison definitive.

By Solution Elements

The performance difference between providers offering solutions composed of their products and services and providers offering services only is shown in Figure 15.

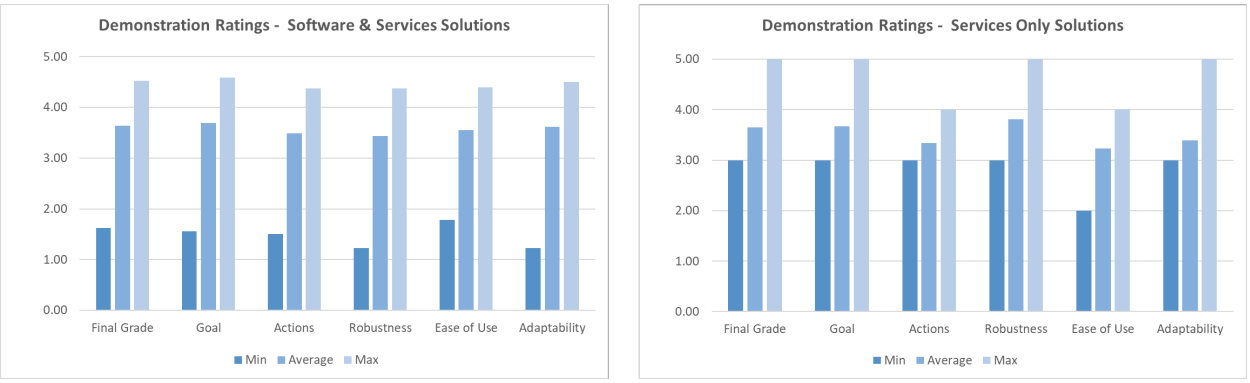


Figure 15 - Demonstration Ratings for Providers Offering Software and Services Solutions Compared with Demonstration Ratings for Providers Offering Services Only Solutions

A clear distinction by solution type appears, with providers offering services only performing at a higher level than those offering solutions that incorporate their software. As noted above, these results are interesting, but the sample size is insufficient to consider the comparison definitive.

By Solution Scope

The performance difference between providers offering general solutions without limitation and providers offering solutions focused on specific domains or categories of use cases is shown in Figure 16.

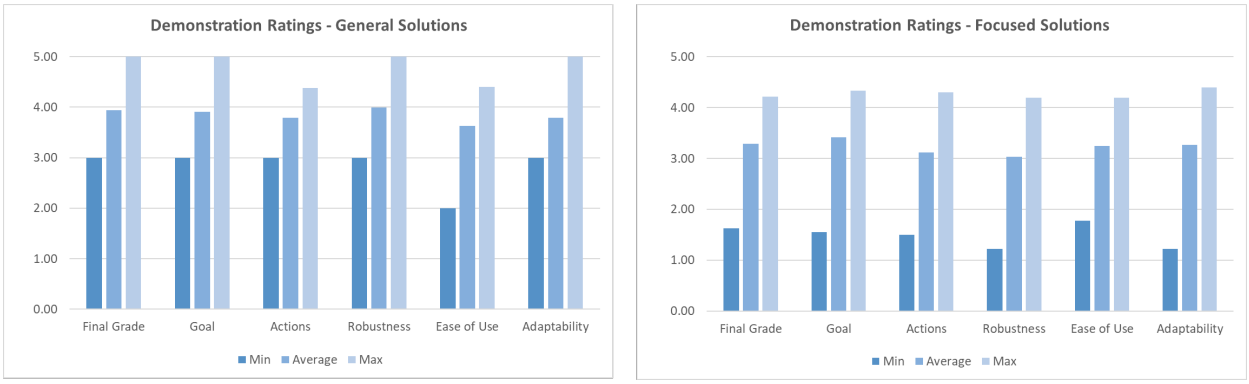


Figure 16 - Demonstration Ratings of General Solutions and Focused Solutions

As was the case in the dichotomies presented above, distinction in performance levels of the two exists. These distinctions should not be accepted as firm, but neither should they be dismissed. They should be accepted as preliminary findings worthy of further investigation.

Trends and Insights

Evaluators agreed on a few key points that drive success in this market:

1. Consistency matters a great deal. Providers who executed their use cases uniformly and transparently scored higher. Even if individual features were strong, uneven demonstrations eroded confidence.

2. Usability and adaptability are the major differentiators. Technical strength is assumed, but solutions offering intuitive interfaces and configurable frameworks were perceived as far more market ready.
3. Integration depth is uneven. Some providers convincingly connected the entire digital thread, from requirements through simulation, but others remained conceptual, focusing only on the presentation level.

Summary

In summary, Dtw-Dth solutions are maturing, but execution remains uneven. Moving forward, providers need to focus intently on improving consistency, expanding adaptability, and demonstrating truly robust integration if they want to solidify their market standing. Evaluators want pragmatic use cases and clarity on how the 'thread' connects the model, the data, and the process.

Evaluator Observations

Considering the project's emphasis on learning and qualitative over quantitative assessment, the evaluators' observations are of greater value than the scores they assign.

During the demonstration session each evaluator documented their assessment of the solution provider's performance on a grading sheet. The grading sheet provided space to record a rating and observations for each of five evaluation dimensions, as well as a final grade and general observations.

After the demonstration sessions, the evaluators' observations were extracted from their grading sheets and consolidated and summarized for each evaluation dimension of each use case. Those summaries were then consolidated and summarized for each evaluation dimension across the set of use cases demonstrated by each solution provider. The summaries for each of the solution providers were analyzed to determine similarities and differences across solution providers. That comparison is presented here.

Final Grade/General Observations

Across the seven solution providers, common themes emerged alongside clear points of differentiation in scope, maturity, execution style, and strategic emphasis.

Similarities Across Solution Providers

All demonstrations emphasized the importance of interoperability and integration across multiple domains, including design, manufacturing, quality, and lifecycle management. Each provider highlighted their ability to connect disparate systems—often spanning CAD, PLM, MES, simulation, and analytics—into a cohesive digital thread. Another shared strength was visualization, and structured workflows use to improve traceability, decision-making, and collaboration. Several providers underscored scalability and openness, positioning their solutions as adaptable foundations, rather than closed ecosystems.

Key Differences and Differentiators

Execution quality and engagement varied significantly. Most solution providers delivered engaging and complete demonstrations, marked by live content, clear workflows, and tangible end-to-end scenarios. In contrast, some relied more heavily on conceptual explanations or partial demonstrations, which reduced perceived completeness and left gaps between vision and execution.

Solution providers also differed in strategic emphasis. One stood out for its strength in simulation, multi-domain modeling, and what-if analysis, positioning digital twins as analytical engines across the lifecycle. Another emphasized inspection, metrology, and data capture as foundational elements of the digital thread, demonstrating strong interoperability across tool chains. Still another differentiated itself through deep configuration, change management, and standards-based interoperability, earning strong praise for transparency and trustworthiness.

One provider focused on usability and clarity. Their digital thread creation was presented as accessible and intuitive, though reviewers cautioned that governance discipline would be critical to manage its breadth at scale. Another distinguished their offering through applied AI and analytics, particularly in concession management and compliance monitoring, showcasing practical operational value rather than platform breadth alone.

Overall Assessment

Collectively, the demonstrations confirmed strong industry momentum toward integrated Dtw-Dth capabilities. The strongest solutions balanced breadth with execution clarity, showing not only what is possible, but how organizations can realistically adopt and govern the capabilities. Differentiation increasingly lies, not in the presence of features, but in usability, governance readiness, ecosystem openness, and ability to clearly demonstrate value across real-world A&D scenarios.

Goal

Across the seven solution providers, stated goals consistently focused on demonstrating Dtw-Dth value through end-to-end traceability, verification and validation (V&V), and cross-domain integration. While all providers aligned conceptually around these objectives, the degree to which goals were clearly articulated, convincingly demonstrated, and consistently executed varied.

Common Themes

A shared objective across nearly all demonstrations was to establish traceability across the product lifecycle, from requirements and system models through design, manufacturing, quality, and validation. Solution providers emphasized linking digital artifacts to authoritative sources such as CAD, BOMs, and system models, reinforcing digital thread continuity. Another common theme was V&V in complex system-of-systems environments, with several providers highlighting simulation, analytics, inspection, or AI-driven approaches to validate performance, compliance, and change impact.

Many demonstrations aimed to show business relevance by connecting technical capabilities to outcomes, such as reduced rework, faster design cycles, improved sustainability, and proactive

quality management. Reviewers recognized strong alignment between stated goals and industry needs, particularly for A&D contexts.

Differences in Clarity and Execution

Most solution providers exhibited strong goal alignment and execution. One provider demonstrated ambitious lifecycle traceability and SoS modeling, effectively linking simulation, analytics, and optimization to digital twin objectives.

Two others stood out for clearly defined goals that were convincingly met. One of those demonstrations emphasized visualization of process flows, roles, and requirements using templates and personas, reinforcing their strength in practical digital thread implementation. The other exceeded expectations by demonstrating robust end-to-end traceability, V&V, and interoperability across MBSE, CAD, and PLM systems, with strength in change impact analysis and extended enterprise architectures.

A third provider differentiated itself through applied AI and analytics, clearly framing its goal around validating digital thread implementation within Dassault Systèmes environments. Reviewers agreed the goal was achieved, particularly in predictive quality and compliance monitoring, though the limited scope constrained exploration of broader scenarios.

Another provider's goals were largely achieved, with strong demonstrations in collaborative design review, inspection, and data capture.

Two solution providers presented well-defined goals conceptually, but execution limited their overall impact.

Overall Assessment

Collectively, the goal assessments confirmed strong alignment across providers on the importance of lifecycle traceability, V&V, and cross-domain integration. Differentiation emerged not from goal statements themselves, but from the clarity, completeness, and realism of execution. Providers that demonstrated concrete end-to-end scenarios with clear governance and validation considerations were perceived as more mature and ready for enterprise adoption, while others showed promise but will require deeper execution to fully realize their stated goals.

Actions

Actions focused on how effectively each solution provider executed their stated goals through concrete workflows, integrations, and demonstrations. Evaluators consistently assessed the clarity, completeness, and realism of step-by-step actions, particularly those in support of digital thread continuity, verification activities, and cross-domain execution.

Common Patterns

Most providers emphasized structured, sequential workflows that traced data and decisions across engineering, manufacturing, and validation contexts. Actions typically included requirements traceability, simulation or analysis, data synchronization across systems, and progress and relationships visualization. Automation, where present, was viewed as a key enabler for reducing manual effort, reinforcing compliance, and supporting scalability. Evaluators valued

demonstrations that clearly mapped actions to business or certification objectives, reinforcing practical applicability, rather than conceptual intent.

Another recurring theme was the balance between breadth and depth. Several demonstrations showcased wide-ranging capabilities. However, time constraints or presentation pacing sometimes limited evaluators' ability to fully assess each action. In such cases, evaluators noted that while the actions were credible, deeper execution detail was required to confirm enterprise readiness.

Differences in Execution and Maturity

Most solution providers delivered complete and convincing action-oriented demonstrations. One provider presented a thorough, step-by-step walkthrough of traceability, simulation, and trade-off analysis, clearly linking actions to business goals and lifecycle objectives. While occasionally dense, the session reinforced strong data flow integration and completeness.

Another solution provider stood out for their detailed illustration of digital thread progression, highlighting automation, Jira integration, and mapping between engineering and manufacturing objects. Evaluators valued the solution's ability to close gaps between domains. Yet, questions remained around governance clarity and automation of certain functions.

A third solution provider was differentiated through deep demonstrations of assembly, inspection, and metrology workflows. Evaluators praised the virtual assembly realism, inspection automation, and analytics-driven efficiency gains.

A fourth solution provider's actions were consistently praised for clarity, transparency, and alignment with industry practices. The end-to-end walkthrough demonstrated strong change management, synchronization, and validation using their commercial integration tools. Evaluators viewed the actions as practical, repeatable, and well-suited to extended enterprise environments.

A few solution providers demonstrated credible action frameworks but with more variable execution depth. One showcased structured, standards-driven validation strategies, and strong alignment with certification processes. However, the live execution did not always fully support the breadth of the vision presented. Another provider's actions ranged from effective, low-effort workflows to more limited demonstrations of advanced integration. In several cases, pacing and partial coverage reduced clarity.

One solution provider demonstrated flexibility through two complementary action paths, reinforcing adaptability across contexts such as core digital thread execution and manufacturing-focused deployment. While those demonstrations were limited in scope, they confirmed essential actions around connectivity, integration, and traceability. Still, evaluators expressed a desire for greater depth to assess scalability.

Overall Assessment

Across providers, the Actions dimension highlighted that execution quality—not just capability breadth—drives confidence in digital thread solutions. Providers that demonstrated clear, end-to-end, and well-paced actions with strong traceability and automation were perceived as more mature and deployment ready. Others showed promising capabilities but will benefit from deeper, more consistent execution to fully substantiate their action frameworks.

Robustness

Robustness was evaluated in terms of architectural resilience, scalability, reliability under varying conditions, and ability to sustain digital thread continuity across complex, multi-system environments. Though all solution providers addressed robustness conceptually, demonstration depth and consistency varied considerably, thereby influencing evaluator confidence.

Common Themes

Most solution providers emphasized adaptable architectures capable of handling complex variables, large data volumes, and cross-domain integrations. Scalability—from smaller assemblies to enterprise-scale or SoS applications—was frequently cited as a design goal. Evaluators also sought evidence of stability under load, error handling, traceability preservation, and standards-based interoperability as indicators of long-term sustainability. Confidence increased significantly when robustness was clearly demonstrated through live execution, error recovery, or configuration management.

Another recurring theme was the importance of governance and planning. Several solutions were described as powerful and potentially disruptive. Evaluators noted strong governance frameworks would be essential to fully realize robustness in production environments. Confidence in operational robustness was reduced where demonstrations relied on static outputs or pre-recorded material.

Differences

Most solution providers demonstrated strong robustness characteristics. One solution provider showed effective handling of variables, subsystems, and system-of-systems modeling, supported by standards-based architecture. While some performance slowdowns were noted and calibration was not fully demonstrated, evaluators largely agreed that the platform's robustness and long-term sustainability were evident.

Another solution provider highlighted robustness as a core architectural strength, emphasizing adaptability across processes, data types, and sources. Although not all robustness scenarios were explicitly demonstrated, evaluators expressed confidence in the underlying design. Concerns centered less on technical resilience and more on organizational readiness and governance needed to manage the solution's disruptive potential.

A third provider's solution was viewed as robust and scalable, particularly in supporting large aerospace assemblies and inspection-driven workflows. The proactive focus on early error detection and prevention reinforced confidence.

A fourth solution provider was consistently rated as highly robust, with no issues observed during demonstrations. Reviewers praised their stability, configuration management, bi-directional synchronization, and multi-format interoperability. Features such as error tracking, monitoring dashboards, and visualization of incidents reinforced confidence in enterprise readiness and reliability.

Other solution providers demonstrated more variable or partial robustness. One solution provider's demonstration revealed strong depth and precision in handling complex variables, but a significant delay undermined confidence in reliability. Another provider's robustness was inconsistently

demonstrated; reliance on PDF outputs and limited live execution raised concerns about digital thread continuity, LOTAR compliance, and scalability.

One solution provider showed architectural promise and encouraging use of AI for predictive and proactive management, but robustness was validated only within limited scenarios. Evaluators noted the need for broader demonstrations to assess resilience, scalability, and performance across diverse enterprise contexts.

Overall Assessment

Overall, robustness emerged as a key differentiator among providers. Solutions that demonstrated live stability, configuration control, standards-based interoperability, and proactive error handling were viewed as more mature and enterprise-ready. Others showed promising architectures but need deeper, more transparent demonstrations to fully validate robustness under real-world operating conditions.

Ease of Use

Ease of Use was assessed based on interface intuitiveness, learning curve, workflow clarity, and extent to which demonstrations validated accessibility for both expert and less specialized users. While all solutions showed functional usability, perceptions varied significantly depending on execution style, audience focus, and depth of live interaction shown.

Common Themes

A recurring theme across solution providers was the distinction between usability for expert users versus accessibility for broader adoption. Many platforms appeared to be logical and efficient when operated by skilled practitioners, but evaluators frequently noted that ease of use for new or non-specialist users was not always convincingly demonstrated. Automation (particularly in documentation), traceability, and analytics, were consistently viewed as positive contributors to usability due to reducing manual effort and cognitive load.

Another common observation was the impact of demonstration format. Where live, step-by-step interaction was limited or replaced by pre-recorded content, evaluators found it harder to validate true usability. Consequently, confidence in ease of use was often based on perception, rather than hands-on evidence.

Differences in Usability and Validation

Two solution providers emerged as the strongest performers in ease of use. One was consistently praised for their intuitive interface, manual task automation, and seamless integration with existing customer toolsets. Evaluators noted minimal training appeared sufficient for basic applications, reinforcing accessibility and practicality; however, governance would be required to manage scale and complexity. The other solution provider likewise received strong usability feedback, with evaluators highlighting intuitive navigation, logical workflows, and clear role-based organization. The demonstration conveyed that operators could follow processes without extensive training, supporting confidence in day-to-day usability, even as advanced optimization scenarios would still require domain expertise.

One solution provider was widely recognized for intuitive use. The interface was described as operator-friendly and easy to learn. However, limited demonstration depth reduced evaluators' ability to fully validate long-term usability and scalability beyond initial impressions.

Two solution providers demonstrated promising usability but with less direct validation. One provider's interface was viewed as strong and straightforward, with intuitive workflows and reporting. Yet, evaluators emphasized effective use is best suited to skilled specialists and requested more hands-on execution to confirm ease of use. The other solution provider did not center usability in their demonstration. However, the automation-driven workflows, particularly through AI-enabled concession handling, suggested reduced complexity and logical flow. Additional user interaction demonstrations were requested to strengthen confidence in accessibility.

Two other solution providers received mixed feedback. One was recognized for logical, modular workflows and powerful tools such as reduced-order modeling, but evaluators indicated the platform could seem overwhelming for new users and may require significant training. The other's solution appeared usable in the hands of experts, but the demonstration did not clearly convey simplicity or intuitive design for broader audiences, leaving initial impressions of complexity.

Overall Assessment

Overall, ease of use differentiated providers less by feature availability and more by how clearly usability was demonstrated. Solutions that combined intuitive interfaces with visible automation and clear role-based workflows were perceived to be more accessible and deployment-ready. Others showed strong functional usability but will benefit from deeper, more interactive demonstrations to validate ease of use across diverse user profiles.

Adaptability

Adaptability was assessed in terms of flexibility across industries and use cases, interoperability with heterogeneous toolsets, scalability across enterprise contexts, and the ability to evolve with changing requirements. Overall, adaptability emerged as a strong differentiator, with most providers demonstrating conceptual alignment but varying in execution depth and validation.

Common Themes

A consistent theme across solution providers was the emphasis on interoperability and flexibility in multi-vendor environments. Many solutions highlighted support for diverse CAD, PLM, ALM, MES, and analytics tools, positioning adaptability as essential for SoS digital twin and digital thread deployments. Scalability across industries, particularly aerospace, defense, and manufacturing, was frequently cited, along with the ability to extend solutions through APIs, scripting, and templates.

Evaluators also associated adaptability with long-term sustainability. Solutions that avoided vendor lock-in, supported bidirectional synchronization, and demonstrated reuse across processes and domains were viewed as better positioned to adapt to evolving enterprise needs. Confidence was correspondingly lower where adaptability relied more on stated capability than demonstrated execution.

Differences in Demonstrated Adaptability

Most solution providers demonstrated strong adaptability characteristics. One solution provider was praised repeatedly for flexibility across inputs, simulations, and deployment contexts, supported by scripting, Python exports, and strong multi-vendor interoperability. Demonstrations spanning defense, aerospace, and commercial domains reinforced confidence in long-term adaptability.

Another solution provider stood out for their vendor-neutral, scalable architecture, and extensive use of APIs and templates to support diverse integration requirements. Evaluators highlighted the solution's ability to avoid vendor lock-in and adapt across heterogeneous environments, noting strong potential for enterprise-wide deployment even though some ad hoc connectors may still be required.

A third solution provider was consistently rated as highly adaptable, demonstrating broad interoperability across PLM, CAD, and ALM systems, including Jira, Doors, Cameo, Windchill, and Codebeamer. Certified APIs, bidirectional synchronization, and cross-industry applicability reinforced flexibility, scalability, and partner-friendly positioning.

A fourth solution provider demonstrated strong adaptability through support for multiple CAD inputs, APIs for customization, and integration with ML. Evaluators valued the collaborative 3D Whiteboard environment and flexibility in handling diverse data types. However, incomplete demonstrations of standards compliance and interoperability with third-party and enterprise systems tempered confidence in full maturity.

Another solution provider showed high adaptability conceptually, particularly in handling diverse variables and SoS simulations. Interoperability across two major PLM platform environments earned positive recognition, though reviewers noted that live execution depth did not always fully substantiate the breadth of adaptability described.

Two other solution providers demonstrated adaptability more implicitly than explicitly. One of those showed promise through scalable APIs and strong integration with a major PLM platform, but heavy reliance on one of those environments restricted confidence in broader applicability. The other solution provider implied adaptability through dual-path scenarios and PLM–MES integration, but evaluators emphasized the need for broader, real-world demonstrations to validate adaptability across heterogeneous enterprise contexts.

Overall Assessment

Overall, adaptability emerged as a notable strength across the benchmark, with clear differentiation driven by execution clarity and interoperability breadth. Solution providers demonstrating live, multi-vendor integration and scalable architectures were viewed as more adaptable and enterprise-ready, while others showed credible potential that will require further validation to confirm adaptability beyond primary ecosystems.

Part 3: View of the Future

Each participating solution provider was invited to present their view of the future and to participate in a collaborative discussion of the A&D industry's view of the future. The following agenda was proposed:

- Solution Provider's View of the Future
  - How the scope of Dtw-Dth implementations will expand to address the interests and needs of the A&D industry
  - Future plans to enhance their solutions for greater industry value
  - How emergent technical developments will be incorporated into their solutions
- Collaborative Discussion of "A&D Industry's View of the Future"
  - Dtw-Dth-related interests and needs of the A&D industry
  - Emergent Dtw-Dth-related technical developments of interest to the A&D industry

Solution Providers' View

Some solution providers followed the proposed agenda closely, others loosely. The summaries below are organized to reflect the flow of the providers' presentations.

Toward the end of each solution provider session, an AD PAG representative presented an "A&D Industry's View of the Future" prepared by the AD PAG member companies. That material is included following the solution providers' presentation summaries.

Digital Twin-Digital Thread Value Expansion

All providers presented their view of Dtw-Dth value expansion from the perspective of their current solutions and the evolving needs and opportunities within their targeted customer set.

Drivers

Two providers stated explicitly that their priorities and objectives are driven by requests and needs of their current and target customers. Others cited industry trends, foreseeing Dtw-Dth capabilities becoming foundational for program and product management across A&D, and real-time operational data fueling increasingly predictive digital twins.

Goals

Providers went on to state their goals for expanding the value of their Dtw-Dth solutions. Several are focused on enabling a step function value increase in their customers' way of working, expressed in phrases such as "collective Agility paradigm," "digital engineering ecosystem," and "end-to-end digital reality." Others are focused on integrating their software solutions into full function Dtw-Dth platforms. Another provider's goal is to revolutionize organizational efficiency by unleashing the power of digital thread and AI.

Digital Thread

Integration

All providers envision a web of digital threads that is ever more expansive and richer in content. Several spoke of a deeper coupling of physics-based simulation with real-time analytics and control system feedback from IoT and manufacturing systems. Another spoke of enabling interoperable, cross-domain collaboration; traceability; and compliance.

Data

Several providers envision greater support for new data standards and emerging modeling frameworks that provide open access to data and seamless integration. One provider highlighted the strategic imperative to ensure data quality and how data is consumed through the digital lifecycle.

Artificial Intelligence and Machine Learning

Some of the providers spoke of enhancing AI/ML-based predictive analytics via the data orchestrated through digital threads.

Digital Twin

For many solution providers, the intent of expansion and enrichment of the digital thread is to enable digital twins of enhanced fidelity and lifecycle scalability. One provider spoke of providing digital twins that are not just engineering tools for design optimization and validation, but operational assets integrated with IoT systems.

Customer Way of Working

A significant aspect of the DT-Dth vision for most providers is the expansion of support and enrichment of the customer's way of working.

Industry Context

One provider spoke of alignment with defense digital engineering standards and secure digital platform architectures.

Use Cases

Several providers spoke of the expanding scope across engineering, production, and sustainment lifecycles. Others highlighted a broad collection of future use cases, including autonomous systems and multi-domain operational integration. One provider envisions supporting their customers' transition from a "Build to Last" paradigm to a "Built to Adapt" and "Collective Agility" paradigm.

User Experience

A few solution providers described a future view of the user experience with expanded automation and embedded intelligence within digital twins and AI-assisted navigation of digital threads. One spoke of enhanced visual analytics tools. Another provider envisions providing access across augmented reality and virtual reality (AR/VR), mobile, and desktop platforms.

Solution Delivery

Software Architecture

More than half of the providers envision significant rearchitecting of their solutions' software elements. These solution providers will consolidate and integrate their suites of software products into platforms to enable greater flexibility and integration of workflows across these elements. Two mentioned making the move to deliver "digital thread as a service."

Efficiency

Beyond the software aspect, some of the providers envision changes that will improve the efficiency of solution development and deployment. Envisioned improvements include more preconfigured templates and flexible deployment models. One provider envisions a more wholistic approach to assure deliverables from multiple projects are interoperable.

Ecosystem

One of the providers maintains an ecosystem of MBSE and PLM vendor partners to ensure open integration. They envision growing their ecosystem through support for new data standards and emerging modeling frameworks. Another provider envisions partnering with Microsoft in their CONTOSO Hypermarket††.

Priority Solution Enhancements

The providers went on to articulate plans for enhancing their solutions to deliver the expanded Dtw-Dth value footprint they envision.

The interrelationship of Dtw-Dth is very apparent in the details of the enhancements described here. While there are independent use cases for digital thread, all digital twin use cases implicitly require an enabling digital thread. Consequently, an enhancement to digital twin capabilities often requires enhancement to the enabling digital thread. The most common example is the scope of data comprehended in the digital thread design that is necessary to support the desired capability of the digital twin it enables. For the sake of clarity, a new or expanded capability is called out below as digital thread or digital twin without rigorous cross-referencing between the two.

Digital Thread

Integration

All solution providers plan significant expansion of the data landscape encompassed by the digital threads they deliver. To accomplish this, most are planning deeper integrations with a broader set of PLM systems. Most plan to expand their portfolio of connectors and adapters to connect via APIs to legacy systems. Some providers expressed support for industry standard approaches, such as model-based integration standards, Enhanced RESTful APIs, and the Open Services for Lifecycle Collaboration (OSLC) standard for linking.

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†† On Nov 19, 2024, Microsoft announced their Jumpstart Agora scenario - Contoso Hypermarket as the third scenario in Jumpstart Agora. Each scenario highlights unique industry-specific use-cases powered by Azure Arc and Azure AI services. The Contoso Hypermarket scenario brings together a range of technologies to address both retail and industrial manufacturing needs. Contoso Motors is an AI-enhanced cloud-to-edge accelerator for manufacturers.

Data

One provider highlighted their continued focus on interoperability with standards such as S1000D, Sharable Content Object Reference Model (SCORM), 2000M, GEAI0007, and other standards. Another provider declared their support for open data spaces.

Digital Twin

Modeling and Simulation

Several providers plan to expand the modeling and real-time simulation capabilities of their digital twins. An example is to determine in-service product performance. One provider seeks to define digital products and predict how the physical counterpart will perform in the operational environment based on measurable uniqueness. A second example is to enable dynamic runtime modeling.

Monitoring and Analysis

Several providers plan to expand utilization of IoT for performance feedback and exploit AI for event interpretation and to assist in analysis of digital twin performance. One provider will use these capabilities to expand into sustainability monitoring and operational carbon accounting. Another will use them to enable real-time synchronization between shop floor measurements and upstream design models and to extract data from fleets of in-service products in support of digital twin simulation and product development.

Customer Way of Working

Industry Context

Providers enumerated planned solution enhancements to improve governance features for regulated industries (e.g., export control, cybersecurity) and broaden deployment support for defense and commercial customers with multi-format export and localization tools. One provider plans on enhancements to enable their customers' ability to incorporate DOD 5000.97-Digital Engineering strategy into the product design stage.

User Experience

Several providers plan to enhance their users' experience through automation. Examples include simulation workflows automation through AI-driven model updates and AI-assisted authoring to auto-generate procedure steps. Another area of enhancement by several providers is decision support by exploiting AI, improving business analytics, and enriching dashboards. One provider plans to have analytics track digital twin usage and business impact. Multiple providers will leverage AR/VR. One use case is for real-time remote issue diagnostics. One provider explicitly mentioned enabling IETM/IETP‡‡ viewer connection.

‡‡ IETM and IETP are acronyms related to technical documentation in engineering and technology. They are common in the world of complex systems like aircraft, machinery, and large equipment. IETM stands for Interactive Electronic Technical Manual, and IETP stands for Interactive Electronic Technical Publication. The terms are closely related, almost interchangeable. Users from an S1000D background will be most familiar with IETP. Users in the US military will more likely use IETM. This is also true in other parts of the world where S1000D and IETP are fairly new, but IETM is well established.

Solution Delivery

Software Architecture

Multiple providers offer Dtw-Dth enabling software as part of their solution. All providers have plans for significant software architecture changes. As mentioned above, several of these providers will consolidate and integrate their software products into platforms, and two contemplate offering "digital thread as a service." One provider indicated moving to a microservices architecture with containerized, scalable components, and providing support for SaaS, iPaaS§§, and on-premises deployments. Another plans containerization of systems to support customers with competitive partnerships.

Efficiency

One provider described planned enhancements to their Dtw-Dth delivery services that will simplify and streamline solution implementation for their customers, including increased data flow definition automation using generative AI, as well as embedded AI agents to assist in common data models and transformations development.

Incorporation of Emergent Technologies

Several applications of emergent technology, such as AI, have been addressed in the discussion of Dtw-Dth value expansion and solution enhancements. To provide a complete picture, those examples are cataloged in this section along with several other examples presented by the solution providers.

Artificial Intelligence

It is no surprise that AI is the most prominent emergent technology, but it is not the only one. The solution provider-presented examples of how AI is, and will be, applied are organized in several categories below. These are followed by examples of other emergent technologies being applied in Dtw-Dth solutions.

AI Positioning

One provider positions AI as an inevitable component in the digital thread transformation. They go further to state that AI, and specifically Gen AI, will change product lifecycles and the implementation of automated processes. None of the other providers made such statements, but considering the steps they are taking it appears that they hold similar views.

AI for Workflow Automation

Most providers are enhancing solutions with AI for workflow automation. As noted previously, some providers are enhancing their software offerings with AI-driven model updates and AI-assisted authoring to auto-generate procedure steps. Other providers are implementing AI for requirements and issue alignment, and for intelligent search, recommendation, and impact analysis capabilities.

AI for Performance Analysis

Most providers are enhancing their solutions with AI for performance analysis. Several examples have been noted previously, including digital twin performance analysis, dynamic

§§ Integration platform as a service (iPaaS) is a cloud-based software model for integrating data from multiple applications into a single solution.

runtime modeling and AI-driven event interpretation, and AI-based quality prediction. Other provider-cited examples include applying AI for the following: analysis of data used in reliability-centered maintenance, diagnostics and health prediction, autonomous twin feedback loops (monitor-adapt-optimize), assistance with system modeling and validation documentation, and use as smart agents for lifecycle compliance verification.

AI for Data Curation

Two providers discussed plans to apply AI for data curation. Examples discussed previously include increasing automation of data flow definition using generative AI and embedding AI agents to assist in development of common data models and transformations. Another example will be to address an expected increase in data complexity (e.g., use of AI to enable integration of new data sources). One of the providers is embedding AI capabilities into their integration and data curation tools for automated data clean-up and transformation. This provider noted their support for the prostep ivip FAICE (Framework for AI-Enabled Collaborative Engineering) initiative***.

AI for Knowledge Management

One provider shared plans to apply AI for knowledge management. Examples cited included providing an AI assistant to capture tribal knowledge, utilizing AI for analysis of collaborative discussions–to be managed in a knowledge base, and enriching their strategy for AI-assisted engineering.

Other Emergent Technologies

Several providers presented plans to exploit other emergent technologies in addition to AI. Examples discussed previously include expanding utilization of IoT to enable interoperability with digital twins, leveraging AR/VR platforms for real-time remote issue diagnostics and resolution, and incorporating conversational analysis capability using a natural language interface to improve report generation. Other examples include providing native support for Open Model-Based Engineering Environment (OpenMBEE) and SysMLv2 for next-generation MBSE, implementing event-driven architectures and semantic integration, supporting surrogate models (or reduced order models) to evaluate sensor information for predictive maintenance, supporting the International Data Spaces Association (IDSA)††† for data exchange in the supply chain, and representing the results of tribal knowledge capture in knowledge graphs.

*** FAICE was founded to address the emerging gap in leveraging AI with engineering data in cross-company projects. Its vision is to improve product innovation in engineering through collaborative, user-friendly, secure, and trustful AI. To achieve this, FAICE focuses on developing a secure and industry-compliant framework for AI collaboration in engineering, demonstrating its value through concrete use cases, and optimizing it for broad adoption and market implementation. prostep ivip: Framework for AI-Enabled Collaborative Engineering" (FAICE)

††† The International Data Spaces Association (IDSA) is a non-profit organization focusing on establishing and promoting standards for data spaces – trusted environments where organizations can share data while retaining full control over its use. Home - International Data Spaces

Vision for A&D Adoption

Solution Positioning

Most providers expressed a strong commitment to serving specific needs of the A&D industry. Some seek to achieve recognition as critical solution contributors, using phrases such as "go-to environment for lifecycle support documentation" and "a key enabler for precision manufacturing in aerospace and defense." Others emphasize the importance of their solution focus, such as "operationalizing mission digital twins" or "realizing the IDE (Integrated Digital Environment) vision."

Key Solution Elements

Standards

Most of the providers do align or plan to align to the MOSA framework and other government standards, such as S1000D. One provider offers certification-ready integrations aligned to MOSA.

Traceability

Several providers emphasize lifecycle traceability, including traceable collaboration across OEMs, suppliers, and partners. One provider's solution delivers validated digital thread maps for system certification and sustainment. Another provider offers robust compliance and traceability tools built on industry standards.

Security

Multiple providers feature capabilities to meet stringent security requirements, such as integration with secure enclaves, command center systems, and support for defense cloud environments.

Digital Continuity

One provider highlighted that their solution provides digital continuity across long lifecycle programs.

A&D Industry's View

The intent of the AD PAG's presentation, "A&D Industry's View of the Future," was to stimulate a collaborative discussion of the points introduced. The points below were received with interest by the solution providers.

Digital Twins

- PLM products need to support digital twin in its AIAA-DEIC/National Academies of Sciences/OMG definitions.
- In support of digital twin definition and utilization, PLM tools must be able to transform
  - Structure Forms/Factors (e.g., CAD),
  - Properties (e.g., Features), and
  - Behaviors (e.g., a physics-based model)

  of a digital system model into modular components that have well-defined, standards-based interfaces to invoke both simulated and real-world datasets and events.

- These modularized components must utilize standards-based interfaces to support compositions of these modules (e.g., a digital thread framework).

Currently, none of the PLM products on the market could do such basic functionality, let alone advanced capabilities like predictive simulation.

Digital Threads

- The A&D industry needs a digital thread strategy that extends broadly across the product lifecycle.
- Among other characteristics, it involves
  - Connector access to instance data contained in various repositories,
  - An understanding of cross-domain information structure and relationships and how those are implemented in the repositories, and
  - Provisions for user interactions to support use-case-specific connectivity, analysis, and query logic.
- This will require converting information exchange standards from whatever form they originate in (XMI/XML?) to a graph standard (RDF/OWL) and the actual knowledge of the information structure applicable across each of the very large number of information repositories (systems of record, data warehouses, other information stores, etc.).

Trust Framework

- A type of trust framework where the data (threads), ontologies, and ultimately digital twins can be shared is desirable.
- To create a digital twin of something complex with the intent for it to persist across the lifecycle, data is needed from all of them (threads, ontologies, twins) to create anything meaningful, especially in the product support phase. When applied to all components on an aircraft, it's clear a digital twin of the aircraft may become very large.
- When a digital twin is created, the twin may need to be considered a shared commodity.

Conclusions

The original purpose of the Digital Twin-Digital Thread Benchmark was to broadly assess capabilities of commercially available Dtw-Dth solution offerings, including software and services. This purpose was augmented to include assessing solution strategies, implementation approaches, and future directions of commercial solution providers. A summary of that assessment follows.

The benchmark assessment reveals a dynamic and growing market for Dtw-Dth solutions with a need for industry standards. While significant progress has been made, the landscape is characterized by highly capable commercial solutions offering varied approaches, and a clear set of technological and organizational challenges that must be addressed to unlock this paradigm's full potential. In summary, the current practical value potential of Dtw-Dth investment is real and substantial, as verified by demonstration of very powerful Dtw-Dth solutions provided to industry today.

Key Findings

Dtw-Dth

A critical and unifying takeaway is that the digital thread is the foundational construct. The digital twin, as a dynamic virtual representation of a physical asset, is the ultimate objective, but its fidelity and value are entirely dependent on the robustness of the underlying digital thread—the communication framework that provides a seamless, traceable flow of authoritative data across the entire lifecycle.

Divergent Strategies

The market is not monolithic. Two dominant, strategic solution approaches have emerged: focused and general.

Focused Solutions

These solution providers offer deep, mature capabilities in a specific domain (e.g., simulation-led design, technical publications, or metrology). Their strategy is to leverage their core strength and integrate outwards.

General Solutions

These solution providers focus on the broader challenge of connecting disparate enterprise systems (PLM, ALM, MES, ERP) to create a robust and adaptable data backbone. Their strength lies in architecture and interoperability, rather than domain-specific depth.

This divergence of approaches results in a market where overall maturity is inconsistent. While individual solutions are technologically strong, no single provider demonstrated mastery across all benchmarked use cases. The industry's ability to create a truly seamless, end-to-end digital thread is still evolving.

Architectural Evolution: From Connectors to a Virtual-Data Landscape

A significant technical trend is the move from simple point-to-point integrations toward more sophisticated architectural patterns. The concept of a federated digital fabric or digital backbone was a notable innovation.

Technical Example

This architecture connects disparate systems by maintaining persistent references to the ASOT, rather than replicating data. This federated approach directly tackles critical issues of data duplication, integrity, and latency. It often utilizes a CDM and increasingly accessible no-code or low-code integration models, which reduce the reliance on custom development for connecting complex systems.

Role of the Major PLM Platform Solutions

The role of major PLM platforms is foundational but evolving within the broader Dth-Dtw ecosystem. The PLM system continues to serve as the authoritative source for ‘as-designed’ product data and the backbone for configuration and change management. Yet, its position as the

central program hub is being increasingly challenged and redefined by more open, federated, and data-centric architectures. Future innovation in Dtw-Dth solutions will come more from system2system integrators, who integrate major PLM platforms with each other and with other enterprise systems. This is a practice already followed in advanced industries like automotive.

Pragmatic Integration of AI

AI and machine learning (ML) have transitioned from conceptual ideas to practical enablers for advanced Dtw-Dth functionalities. The applications are concrete and focused on delivering the following specific business value:

Predictive Analytics and Model Recalibration

Using ML in conjunction with simulation models to predict operational failures or for the recalibration of simulation models with real-world operational data to improve the twin's fidelity over time.

Operational Efficiency

Deploying LLMs to create tools like a "Concession Guru" that analyzes non-conformity data to accelerate dispositioning and reduce customer wait times.

Data Quality Management

Leveraging AI to manage and ensure the quality of the vast datasets flowing through the digital thread. However, there is pragmatic caution, particularly regarding application of generative AI in highly regulated environments where absolute accuracy and traceability are paramount.

Critical Prerequisites for Success

The benchmark highlighted that successful Dtw-Dth implementation is not just a matter of software. It depends on several critical prerequisites, which follow:

Integrated Multi-Domain Models

The ability to connect models from various domains (e.g., design, cost, supply chain, physics-based simulation) is essential for holistic analysis.

PLM-MES Integration

Seamless, bidirectional link between the PLM system (‘as-designed/as-architected’) and the MES (‘as-manufactured/as-built’) is fundamental.

Open Standards and Interoperability

Reliance on open, neutral standards, such as STEP, JT, OpenUSD, as well as other Dtw-Dth-specific standards yet to be defined, is crucial for avoiding vendor lock-in and ensuring long-term data exchangeability and collaboration across the ecosystem.

Robust Data Governance and Archival

For industries like A&D, a strategy for archiving and accessing data for decades is a non-negotiable requirement. Equally essential is a comprehensive data governance framework that ensures data integrity, traceability, and controlled access across its entire lifecycle, enabling trusted use of information long after its initial creation.

Robust Security and Data Sovereignty in Federated Architectures

Shift to a federated digital fabric and connecting legacy systems drastically expands the attack surface. This point is a critical non-negotiable for highly regulated sectors. This increases the need for robust security frameworks, immutable tracking and logging, and strict access controls to ensure data sovereignty and compliance across distributed systems.

Workforce Skills Development

Specific skills are required to build, manage, and exploit complex Dtw-Dth ecosystems. Today, technology is often more mature than the people who implement and use it. There is urgent need for a targeted strategy to develop the integrated IT/operations technology (OT)/domain-specific skills required to build, manage, and exploit complex Dtw-Dth ecosystems.

Persistent Challenges and Industry Gaps

Despite progress, the industry faces significant hurdles, such as the following:

Legacy System Integration

The rip-and-replace approach is not feasible. Integrating with deeply entrenched legacy systems remains a primary technical and financial barrier.

Long-Term Maintainability

Total cost of ownership is a major concern. The long-term effort required to maintain a complex web of connectors, adapters, and data models as underlying systems evolve is substantial and must be planned for.

Organizational Readiness

As noted above, technology is often more mature than the organization's (and workforce's) ability to adopt it. Lack of clear vision, robust data governance, and effective Organizational Change Management (OCM) are significant impediments to realizing ROI. The A&D industrial community's readiness, while growing, is still in its early stages.

Closing the Loop: Focus on System Utilization and Service Lifecycle

While the demonstrated use cases focused heavily on PLM ('as-designed') and MES ('as-manufactured'), the greatest value of the digital twin is often realized in the 'as-operated' and 'as-maintained' stages. This highlights the critical challenge of securely capturing, aggregating, and feeding back operational data from sensors, field reports, and maintenance logs to continuously recalibrate the digital twin and drive performance optimization and service-centric business models.

Future Outlook

The future of the Dtw-Dth solution offerings is moving toward integration platforms, rather than siloed tools. The focus will continue to shift from simply connecting data to enabling data intelligence. The deepening integration of AI, a commitment to open standards, and an intense focus on user experience to manage complexity will define the next generation of solutions. As application of AI expands, procedures should be established to close the loop for training the AI models with real data.

The journey is far from over. But this benchmark confirms the foundational technologies and methodologies are falling into place, paving the way for a more connected, efficient, and intelligent industrial future.

Help Align AD PAG Publications: *Your feedback is instrumental in prioritizing future work projects for the Aerospace & Defense PLM Action Group. Please take a moment to evaluate the utility of this report and suggest areas for further exploration. Your responses will be used solely to improve the quality and relevance of our publications.*

Provide Strategic Feedback

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About A&D PLM Action Group

The Aerospace & Defense PLM Action Group (www.ad-pag.com) is an association of aerospace and defense companies within CIMdata's globally recognized PLM Community Program, which functions as a ***PLM advocacy group*** to:

- Set the direction for the aerospace & defense industry on PLM-related topics that matter to members (*including promoting, not duplicating, the work of standards bodies*)
- Promote common industry PLM processes and practices
- Define requirements for common interest PLM-related capabilities
- Communicate with a unified voice to PLM solution providers
- Sponsor collaborative PLM research on prioritized industry and technology topics

CIMdata administers Group operations, coordinates research, and manages the progression of policy formulation.

About CIMdata

CIMdata, a global strategic management consulting firm, provides services designed to maximize an enterprise's ability to design, deliver, and support innovative products and services. For more than forty years, CIMdata has provided industrial organizations, providers of digital technologies and services, and investment firms with world-class insight, expertise, and best-practice methods on a broad set of product lifecycle management (PLM) topics and the digital transformation they enable. CIMdata also offers research, subscription services, publications, and education through certificate programs and international conferences. To learn more, visit www.CIMdata.com or email info@CIMdata.com.

Appendix A: Partnering Industry Organizations

The partnering organizations that contributed to the use cases include American Institute of Aeronautics and Astronautics, Object Management Group Digital Twin Consortium, prostep ivip, and the SAE International Digital Communications Committee.

American Institute of Aeronautics and Astronautics (AIAA)

The AIAA (https://www.aiaa.org/) is the world's largest aerospace technical society, representing nearly 30,000 individual members and 95 corporate members from 91 countries. It advances engineering and science in aviation, space, and defense through forums, publications, standards development, and advocacy. AIAA provides tools, insights, and collaboration opportunities that empower aerospace professionals to shape the future of the global aerospace industry.

AIAA Digital Engineering Integration Committee (AIAA-DEIC)

The AIAA Digital Engineering Integration Committee (DEIC) is a specialized group within the American Institute of Aeronautics and Astronautics (AIAA) designed to accelerate the adoption of digital technologies across the aerospace industry. It works to integrate disparate digital activities—such as digital twins, digital threads, and model-based systems engineering (MBSE)—to improve national competitiveness, security, and operational readiness.

OMG Digital Twin Consortium (OMG DTC)

The OMG DTC (https://www.digitaltwinconsortium.org/) is a global organization dedicated to advancing the adoption and effective use of digital twin technology—virtual representations of physical objects or systems. It collaborates with members worldwide to accelerate market growth and innovation in digital engineering. Through development, awareness, adoption, and interoperability initiatives, DTC drives the realization of digital twins' full potential across industries.

prostep ivip

prostep ivip (https://www.prostep.org/en/) is an international association dedicated to advancing standards and best practices in product data management (PDM) and product lifecycle management (PLM). It fosters collaboration and interoperability across industries to enable efficient, integrated digital engineering processes. Through joint projects, standards development, and knowledge exchange, prostep ivip drives innovation and digital transformation in manufacturing and engineering.

SAE International

SAE International (https://www.sae.org/) is a global association dedicated to advancing knowledge and standards in the aerospace, automotive, and commercial vehicle industries. It serves as a leading resource for engineering professionals through technical standards, professional development, and networking opportunities. SAE fosters innovation and collaboration to enhance safety, efficiency, and sustainability across mobility engineering fields.

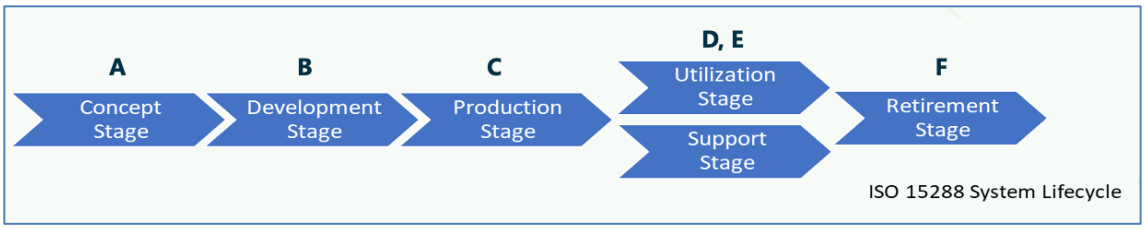
SAE G-31 Digital Transactions for Aerospace Committee

The SAE G-31 Committee (https://standardsworks.sae.org/standards-committees/g-31-electronic-transactions-aerospace-committee) provides industry stakeholders, including airlines, component manufacturers, maintenance repair organizations (MRO), and regulatory authorities, consensus defined standards for sharing electronic data within the aerospace community.

Appendix B: Digital Twin and Digital Thread Demonstrated Use Cases

The participating PLM solution providers selected the following use cases to demonstrate their respective digital twin and thread capabilities. The demonstrated use cases are listed in two tables by use case category type: digital twin and digital thread, respectively. Information for each use case includes the contributing organization, title, description, and applicable lifecycle stage(s).

Each stage is represented by a letter: A - Concept Stage, B - Development Stage, C - Production Stage, D - Utilization Stage, E - Support Stage, F - Retirement Stage. As shown in the following tables, use cases typically span more than one lifecycle stage.



Digital Twin Use Cases

Contributor	Digital Twin Title	Description	Lifecycle Stage	
			Dtw Development	Dtw Utilization
Solution Provider	Material Modelling Twins 'As-Built' Part / Component Twins for Quality	Demonstrates material modeling using simulations of grain structure and distributions. Includes calibration with experimental or virtual material data and models that capture part-level nonconformances and deviations from engineering releases.	A, B	C, D
Solution Provider	Understanding the Performance of a Solar Aircraft Using Digital Twin	This demonstration illustrates how digital twins at the component and subsystem levels can be seamlessly integrated into a comprehensive system-of-systems (SoS) model	A, B	C, D, E, F

Contributor	Digital Twin Title	Description	Lifecycle Stage	
			Dtw Development	Dtw Utilization
Solution Provider	OpenPDM - Bidirectional CAD Integration between Different Vendor PLMs	OpenPDM includes tools for integration and migration of data across a variety of PLM and other engineering data systems with Commercial Off the Shelf (COTS) connectors; including bidirectional integration of CAD data between different vendor PLM systems (Windchill, 3DX, Teamcenter) Multiple different vendor systems product lifecycle management (PLM) is utilized within the enterprise for managing mechanical design; this variety of systems may be the result of mergers, program-specific tools, or chosen for compatibility of the mechanical design tool with the PLM vendor tool.	A, B, C	A, B, C
Solution Provider	Virtual Commissioning Automotive Demonstrator for Body-in-White Assembly Process	Showcase with an automotive use case how virtual commissioning solutions can develop and be integrated as part of a digital twin	A, B, C	A, B, C, D, E
Solution Provider	OpenDXM GlobalX - Collaboration with External Partners	OpenDXM is a tool for automating exchange of Digital Data Packages (DDP) between partners. This supports context-based exports for native CAD and product data for engineering and manufacturing, including release data and change management for CAD modifications.	A, B, C	Unlisted

Contributor	Digital Twin Title	Description	Lifecycle Stage	
			Dtw Development	Dtw Utilization
Solution Provider	Model-Based Systems Engineering (MBSE) and Digital Twin Realization of the C-Pulse Drone	"C.PULSE Drone" is a Capgemini project that was developed to demonstrate our capabilities in the field of Twin and Digital Continuity (Thread) with a pivotal role played by Model-Based Systems Engineering (MBSE). In addition, C.PULSE showcases our capabilities in related topics such as Physics Simulations, Virtual and Augmented Reality (VR/AR) as well as enabling real-time data exchange leading to a digital twin realization and early Verification and Validation.	A, B, C, D	D
Solution Provider	Echo Digital Twin Application Development Framework – Vancouver International and Pearson Airports	Demonstrates the Echo Digital Twin Framework from the YVR and Pearson Projects, showcasing digital twin applications in aerospace operations, retail, security, emergency response, and asset management.	A, B, C, D	Unlisted
Solution Provider	Battery Package Assembly Demonstrator for Creation of an Assembly Concept Ready for Integration	Shop floor assembly line layout simulation and planning.	A, B, C, D, E	A

Contributor	Digital Twin Title	Description	Lifecycle Stage	
			Dtw Development	Dtw Utilization
Solution Provider	Modelling of Complex Multi-Fidelity, Multi-Domain, System-of-Systems (SoS) Mission Scenarios	Demonstrates SoS mission modeling to integrate and analyze multi-domain digital twins in complex scenarios. Supports lifecycle stages from concept to operations, enabling progressive model fidelity, validation and verification (V&V), and integration of software-in-the-loop/hardware-in-the-loop (SIL/HIL) systems for faster development, early issue detection, and reduced costs.	Unlisted	Unlisted

Digital Thread Use Cases

Contributor	Digital Thread Title	Description	Lifecycle Stage
Solution Provider	Design of Axial Compressor for Gas Turbine Engine	This workflow focuses on the design of an axial compressor (continuously pressurizes gases) for a gas turbine engine through its various phases and stages of development from concept to the detailed design of a blade to the overall production of the compressor	A
Solution Provider	Collaborative System Engineering	Connecting design and simulation engineers onto the same 3D system model allowing faster design optimization iterations in real time	A, B
Solution Provider	OpenCLM - Cross System / Domain Impact Analysis	Separate software solutions exist that are data repositories and Authoritative Sources of Truth (ASOT) for domain data; utilizing OpenCLM with connectors to PLM, MBSE, ALM, ERP, or other systems systems demonstrates OpenCLM operation, process templates, linking data from external sources, evaluating impact analysis, and visualizing impacts though data graph visualization	A, B, C, D, E
Solution Provider	OpenPDM Cameo PLM Integration	PLM integration with DS Cameo via client plugin, OSLC Datahub interface, and Teamwork Cloud Connector, enabling seamless data exchange across systems	A, B

Contributor	Digital Thread Title	Description	Lifecycle Stage
Solution Provider	Cross-Discipline Engineering	Accessibility and traceability of mechanical, electrical, electronics, and embedded software product content to cross-disciplinary engineering teams	A, B
Solution Provider	Model-Based Systems Engineering and Associated Topics	Model-Based Systems Engineering and Associated Topics	A, B
Solution Provider	End2End Additive Manufacturing	Connecting component CAD data with 3D printing machine data and metrology (quality control) machines to enable a virtuous data loop allowing to automatically refine machine parameters and component design based on an advanced quality-controlled process	A, B, C
Solution Provider	Digital Thread End-to-End Automated Inspection	Automate the quality assurance process for aerospace components—including fuselage and engine structures—to ensure structural integrity, dimensional accuracy, and compliance with safety standards.	A, B, C
Solution Provider	Solution Architecture Model	Showcase how a solution architecture framework in a modeling tool such as DS CATIA Magic (formerly No Magic Cameo) can enhance collaborative model-based practices across an organization by connecting digital thread use cases to the technical solution	A, B, C
Solution Provider	OpenCLM - Integrated Enterprise Configuration Lifecycle Management and Baselining	OpenCLM (Open Configuration Lifecycle Management) is a tool for creating the digital thread though integrated data; this allows for linking data from connected systems, provide semantic relationships between them, and creating immutable baselines of the data in OpenCLM for permanent configuration records	A, B, C, D, E
Solution Provider	Digital Engineering Certification Solution (DECS)	Accelerating the digital aircraft certification process within a comprehensive tool landscape, including a digital ledger	A, B, C, D, E

Contributor	Digital Thread Title	Description	Lifecycle Stage
Solution Provider	A Day in the Life of Data Workers with an Automated Digital Thread	Demonstrates automated digital thread creation using eQube®-DaaS and eQube-DTA. Integrates data across COTS, GOTS, and internal systems while preserving security. Showcases seamless connectivity between tools like Jira, DOORS, SAP, and Windchill to enhance productivity, data access, and lifecycle traceability in a system-agnostic, future-proof environment.	A, B, C, D, E, F
Solution Provider	Long-Term Data Archival and Retrieval	Long-term maintenance of data, including archival and retrieval of digital product and technical data. Archiving is required until the product's End of Life (EOL)	A, B, C, D, E, F
Solution Provider	Generation, Configuration Management, and Impact Assessment of the Digital Thread	Showcases eQube®-DaaS and eQube-DTA for creating and managing configuration-controlled digital threads. Enables secure, role-based filtering, impact assessment, and collaboration across systems. The future-proof, system-agnostic platform supports integration and evolution of applications throughout the product lifecycle, enhancing data access, quality, and productivity.	A, B, C, D, E, F
Solution Provider	Virtual Assembly	Using 3D geometry data of the real parts being manufactured to virtually predict the compliance of next assembly system; and subsequent corrective actions needed if not compliant	B, C
Safran	Production and Support	Native digital data traceability from Product Lifecycle System (PLS) 'as-designed' to recording in the MES during production operations to confirm conformity before delivery	B, C, E
Safran	Concession Management	Manages 'as-built' vs. 'as-designed' nonconformities requiring Design Office approval. Tracks concessions through PLM. Often, reported production defects are later identified as false positives by Customer Service.	B, C, D, E
Solution Provider	Technical Documentation in the Digital Thread	Develop technical documentation based directly on product data for manufacturing and service	C, D, E
Solution Provider	Interactive Production and Maintenance	Interact with products based on augmented reality using models and technical documentation	E

Appendix C: Community Engagement

Outreach to communities within the PLM ecosystem was a major element of the Dtw-Dth Benchmark project. Securing collaborative involvement of a broad range of industrial organizations and solution providers was essential to achieving the project objectives. In addition to the significant benefit of their contributions to the project work products, the interaction with these communities provided unexpected learnings and insights into their operational structure and approach to collaborative engagement.

Invitation and Agreement to Partner

The framework for collaboration was established during early outreach and invitation to partner. This was a multifaceted exercise facilitated by CIMdata to formalize participation agreements, clarify expectations, and align objectives among CIMdata, AD PAG member companies, participating solution providers, and partner organizations. Overall, this stage of engagement went well; it was efficiently executed, and resulting working agreements were positive, clear, and well accepted.

Industry Organization Partnerships

At the outset of the Dtw-Dth Solution Evaluation Benchmark project, CIMdata, on behalf of the AD PAG Digital Twin-Digital Thread project team, reached out to seven industry organizations, standards bodies, and consortia with an invitation to participate in the Dtw-Dth Benchmark. Four organizations accepted the invitation.

It was recognized that partnering with other industry organizations would offer substantial benefits to all parties involved.

For the invited industry organizations:

- Have their Dtw-Dth definitions and use cases tested in benchmark demonstrations by PLM software providers
- Share perspectives and learnings with a broad community of thought leaders

For the AD PAG:

- Increase consensus and acceptance of results within the A&D PLM ecosystem
- Increase expert insight being invested in the project
- Increase leverage with PLM software providers invited to participate in the project

Engagement with partnering industry organizations progressed through the following three stages:

- Contribution of use cases
- Participation in use case demonstrations
- Participation in analysis and reporting

Contribution of Use Cases

All four partnering organizations contributed use cases from their internal Dtw-Dth project libraries/catalogs. These use cases were diverse and generally of high quality, modeling high value opportunities in A&D. In the catalog of 92 Dtw-Dth use cases assembled for the project, the partnering industry organizations contributed 39 of the total.

Participation in Use Case Demonstrations

CIMdata coordinated a structured series of Use Case Review sessions to align provider demonstrations with contributed use cases. The partnering industry organizations were invited to designate domain experts (subject-matter experts) to participate in these discussions to clarify requirements and refine scope.

As engagement and demonstration sessions were scheduled with the participating solution providers the partner organizations were encouraged to nominate representatives to observe and evaluate providers' performance.

CIMdata, as Benchmark Administrator, organized Evaluator Training sessions, covering project overview, confidentiality standards, scoring protocols, and grading criteria. Partnering organizations were required to provide the name, title, and employer of each representative who would be an evaluator. Those individuals were required to participate in a live training session and confirm in writing their agreement to comply with confidentiality standards. Seven individuals drawn from all four of the partnering organizations went through the process.

In the end, participation of these representatives in the solution provider sessions and use case demonstrations was relatively modest. This indicated the individuals, regardless of personal motivation and intent, simply could not spare the time in light of their other obligations.

Participation in Analysis and Reporting

After the use case demonstrations and other solution provider engagement sessions were concluded, participating partnering industry organization representatives submitted completed scoring sheets for the sessions and demonstrations they attended. Here again, representatives were invited, but participation in analysis and reporting was minimal.

Despite the modest level of participation in project execution, partnering industry organizations' contribution to the AD PAG Dtw-Dth project was substantial and highly valued by the project team. The use cases they contributed and the conversations early in the project added measurably to the project outcome.

Solution Provider Participation

CIMdata, on behalf of the AD PAG Dtw-Dth project team, reached out to 21 software, infrastructure, and systems integration solution providers to review the benchmark project plan and invite their participation.

Several benefits of participation were enumerated during the initial solution provider discussions.

- Gain in-depth exposure to critical Dtw-Dth requirements of nine major A&D OEMs and Tier 1 suppliers (i.e., AD PAG member companies)
- Contribute to the refinement of AD PAG Dtw-Dth use cases
- Assess performance and identify gaps in their current Dtw-Dth solution in a non-competitive setting
- Influence future Dtw-Dth compliance protocols that will be adopted and exercised by CAx-IF organization(s) sponsored by the AD PAG
- Receive acknowledgement of their contribution to advancing the state-of-the-art of Dtw-Dth management in future AD PAG publications and events

The engagement with participating solution providers progressed through the following three stages:

- Use case selection and refinement
- Demonstration configuration
- Demonstration execution

A summary of the actual process as it occurred in each of the three engagement stages is reported below.

Use Case Selection and Refinement

The use case selection and refinement process with each of the solution providers followed a structured, collaborative approach to ensure he most relevant and well-defined scenarios were chosen for demonstration. The process began with exchange of initial use case titles and descriptions, where participants reviewed a proposed list and aligned on terminology and scope. From this list, the participants prioritized use cases based on their importance to the benchmark objectives and the level of definition available.

Once priorities were set, agreement was reached on a standardized documentation template. This standard use case template would ensure consistency across all use cases by capturing key details in a structured way and providing a common framework for discussion, and later for evaluation and reporting. After solution providers had template alignment, final selections were made for which Dtw-Dth use cases would move forward into demonstrations.

Demonstrations Preparation

The chosen use cases were documented using the agreed template, followed by an iterative review and refinement process. This collaborative review cycle ensured accuracy, completeness, and consensus, resulting in a clear and well-structured set of finalized use case documents.

The starting point with most solution providers was a set of PowerPoint slides and or a video that provided an overview of the solution provider's use case. The use cases templates contained several defined terms and were reviewed with each solution provider to ensure they understood the intent of each attribute of the use case template. Multiple review meetings were conducted with the providers to clarify expectations, refine documentation, and enable interactive Q&A. CIMdata also went to great lengths to extract content from solution provider use case presentations to place into the use case templates and then review and refine with the solution providers.

Benchmark demonstration planning focused first on estimating the effort required to conduct the demonstrations. This included determining the number of use cases to be shown and estimating the time needed for each demonstration. Logistics, such as lead time necessary for preparation, options available for onsite locations, and demonstration agenda structure, were considered.

Demonstrations Execution

The demonstrations and evaluations were conducted through scheduled sessions organized to highlight key evaluation dimensions defined in the use case templates. Each demonstration was delivered as an interactive, recorded, and narrated walkthrough of the selected use cases, allowing evaluators to gain a detailed understanding of solution capabilities.

Prior to each session, the evaluators were provided with supporting documentation to prepare. They completed structured evaluation forms to capture their observations and feedback systematically. While the process was rigorous and demanding, it proved highly valuable by generating critical insights into how solution providers approach Dtw-Dth implementations, where notable gaps remain, and how industry practices may evolve to address these challenges.