NASA/TM-20260001929

Integrated Computational Materials Engineering (ICME) Capability Maturity Levels for Ecosystems Enabling Digital Transformation

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March 2026

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Acknowledgments

The authors would like to thank John F. Matlik, Materials and Process Modeling, Northrup Gruman and Richard B. Arthur, Sr. Principle Engineer, Adv. Computational Methods Research, GE Research, and Brandon L. Hearley, NASA Glenn for their helpful comments and discussion during the preparation of this paper. The authors also wish to acknowledge the support of the NASA Transformational Tools and Technologies Project for funding this work.

This work was sponsored by the
Transformative Aeronautics Concepts Program.

Level of Review: This material has been technically reviewed by technical management.

NASA STI Program/Mail Stop 050
NASA Langley Research Center
Hampton, VA 23681-2199

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Abstract

Digital engineering (DE) and integrated computational materials engineering (ICME) are widely recognized as critical enablers of faster, more affordable, and more reliable aerospace systems. However, many organizations have struggled to realize the promised return on investment (ROI) from digital initiatives. A primary reason is the absence of a shared, decision-focused framework that distinguishes simple digitization of existing workflows from true digital transformation that fundamentally changes how engineering decisions are made.

This paper introduces an *ICME capability maturity framework* that fills this gap. The framework defines six cumulative ICME capability maturity levels (CMLs), explicitly tied to decision authority, engineering integration, optimization, and uncertainty management across material, process, structure, and performance scales. It is designed to complement established readiness metrics such as technology readiness levels (TRLs), manufacturing readiness levels (MRLs), and integration readiness levels (IRLs), by addressing a missing dimension: the conditions required for model-informed decision authority across scales.

A unifying figure and capability table illustrate the six-level ICME Capability Maturity Framework, showing how organizations progress from digitization—with limited or negative ROI—to true digital transformation, where ICME-enabled workflows deliver measurable improvements in decision quality, cycle time, risk reduction, and reuse. The framework is intended for both technical practitioners and executive leadership, providing a common language to assess current state, guide roadmaps, align software ecosystem investments, and set realistic expectations for digital transformation outcomes. A regulatory-relevant statement clarifying the relationship between ICME capability and existing certification frameworks is provided.

1.0 Introduction

Over the past decade, digital engineering (DE) and integrated computational materials engineering (ICME) have emerged as cornerstone concepts in aerospace and defense modernization efforts. Major organizations and communities—including AIAA, NASA, NAFEMS, the National Center for Optimization and Simulation in Engineering (NCOSI), and multiple government and industry consortia have produced position papers, implementation guides, and roadmaps that articulate the promise of digital engineering, digital twin, digital thread, model-based systems engineering (MBSE), systems engineering, and computationally enabled materials and structures design (Refs. 1 to 8).

In parallel, long-established readiness frameworks such as NASA's technology readiness levels (TRLs) (Ref. 9), manufacturing readiness levels (MRLs) (Ref. 10), and related integration (IRL) and

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system (SRL) readiness metrics (Refs. 11 and 12) have provided a common language for assessing technological and production maturity. These frameworks have proven invaluable for managing risk, aligning expectations, and guiding investment decisions across the aerospace lifecycle.

Despite this substantial body of prior work, a critical gap remains. While existing frameworks (readiness levels) address *what technologies exist*, *whether they can be built*, and *whether they interface*, they do not explicitly address the maturity of decision-making capability across material, process, structure, and performance scales. As a result, organizations frequently conflate digitization with transformation, overestimate their ICME maturity capability, and invest heavily in digital infrastructure without achieving commensurate return on investment (ROI).

This paper proposes a formal *ICME Capability Maturity Framework* to address this gap. The intent is not to replace existing readiness metrics, but to complement them by introducing a missing dimension: decision readiness enabled by integrated, multiscale materials and structural engineering. The framework provides a common language to distinguish between possessing ICME ingredients and exercising true ICME capability (Refs. 1, 13, and 14), between digitizing existing workflows and transforming how engineering decisions are made.

1.1 Prior Work and Its Limitations

AIAA, NASA, NAFEMS, NCOSI, and related organizations have articulated compelling visions for digital engineering, digital threads, and digital twins through position papers, implementation guides, and community roadmaps (Refs. 2 to 7). These efforts emphasize traceability, model connectivity, lifecycle continuity, and improved collaboration across disciplines. Similarly, ICME-focused roadmaps originating from government, academia, and industry have highlighted the integration of processing-structure-property-performance relationships and the potential to reduce development time and cost.

Long-established readiness frameworks—most notably NASA's TRLs, MRLs, IRLs, and SRLs have provided a durable and widely understood language for assessing maturity and risk. These frameworks have been instrumental in program planning, milestone reviews, and investment prioritization. Further, these frameworks address whether a technology functions (TRL), whether it can be produced reliably (MRL), and/or whether components interface effectively (IRL and SRL). However, these readiness levels do not *explicitly assess the maturity of decision-making capability* across material, process, structure, and performance scales.

As a result, organizations frequently conflate digitization with transformation, overestimate their ICME maturity, and invest heavily in digital infrastructure without achieving commensurate ROI. The absence of a clear, staged definition of ICME capability has led to 1) ICME-washing, where the presence of models or databases is mistaken for integrated capability; 2) misaligned expectations between leadership, engineers, and software providers; and 3) systematic underestimation of the effort required for scale handshaking, validation, and uncertainty management.

For completeness and ease of reference, summary charts of TRL, MRL, IRL and SRL definitions are provided in Appendix A, highlighting both their strengths and the dimension they do not address.

Collectively, prior maturity constructs have advanced the state of predictive credibility, verification and validation discipline, digital artifact governance, and enterprise transformation strategy. However, these constructs typically assess maturity along isolated dimensions—tool rigor, simulation process credibility, infrastructure integration, or technology deployment. They do not explicitly evaluate whether an integrated ICME ecosystem has matured sufficiently to alter engineering decision authority across coupled materials–structural workflows.

The gap addressed in this paper is therefore not tool maturity, nor digital infrastructure maturity, but ecosystem-level decision authority maturity. Specifically, under what conditions does integrated, multiscale ICME capability legitimately shift engineering decisions upstream in a defensible, uncertainty-aware manner? The framework proposed herein synthesizes predictive credibility, verification/validation, digital maturity, and enterprise transformation literature to address this question.

1.2 Working Definitions

For clarity, the following working definitions are used throughout this paper.

- *Digital engineering (DE)* refers to the use of integrated digital models, data, and digital threads to support engineering activities across the system lifecycle by enabling traceability, consistency, and information reuse. DE primarily provides the digital infrastructure and information backbone required to support modern engineering practices (Refs. 3 to 5, 8, and 15).
- *Integrated computational materials engineering (ICME)* is a decision-centric engineering discipline that integrates physics-based and/or data-driven materials models, methodologies, data, and experiments across multiple length and time scales to inform materials and system-level design, manufacturing, and lifecycle decisions. ICME explicitly seeks to connect processing, structure, properties, and performance in a predictive, uncertainty-aware, validated, and governed manner (Refs. 13, 16 to 19). In this framework, ICME is interpreted as an integrated, multiscale computational engineering paradigm spanning materials, processing, structure, properties, performance, and system-level behavior, including bidirectional optimization and decision integration across these domains.

The distinction between DE as enabling infrastructure and ICME as a decision discipline is explored in greater detail in Section 5.0.

- *Multiscale modeling* refers to the coordinated use of models and data across multiple length and time scales to represent material behavior and system response in a manner that is consistent, traceable, and physically meaningful. In the context of ICME, multiscale modeling is not simply the use of models at different scales, but the deliberate handshaking and integration of information linking processing conditions to microstructure evolution, microstructure to material properties, and properties to component- and system-level performance. This integration may involve physics-based models, data-driven models, or combinations thereof, and may be implemented through hierarchical, concurrent, or reduced-order approaches. Multiscale modeling is therefore foundational to ICME, as it enables material behavior at lower scales to inform higher-level design and performance decisions in a predictive and validated manner (Refs. 1, 13, 14, and 16).
- *Scale Handshake* refers to a validated and traceable transfer of information between models, experiments, or analyses operating at different material, process, structural, or system scales, in which assumptions, uncertainty bounds, and governing quantities are explicitly reconciled to ensure physically consistent integration.
- *Bounded* (in the context of ICME) refers to the practice of explicitly constraining model applicability, uncertainty treatment, decision authority, and organizational acceptance, such that ICME-informed results are interpreted and applied only within defined regimes, assumptions, data coverage, and intended uses.
- *Digital thread* is "a linked set of authoritative digital artifacts whose consistency is actively managed over the life cycle of a product, process, or system," see References 3 and 5
- *Digital twin* is "A set of virtual information constructs that mimics the structure, context and behavior of an individual / unique physical asset, or a group of physical assets, is dynamically updated with data from its physical twin throughout its life cycle and informs decisions that realize value." see References 4 and 5. Note a digital representation is typically a digital twin that is out of sync with its physical asset or group of assets.

- *Design with material* refers to an engineering approach in which material properties are treated as predefined inputs to the design process, and component geometry or structural configuration is developed subject to the constraints imposed by available materials, see Reference 17.
- *Design the material* refers to an engineering approach in which material composition, processing, and microstructure are intentionally tailored to achieve targeted system-level performance objectives.

Note ICME enables progression from designing with available materials toward designing fit-for-purpose materials intentionally to meet system performance objectives.

- *Ecosystem* refers to the integrated set of models, workflows, toolchains, data infrastructure, governance structures, uncertainty management practices, and workforce competencies that collectively enable model-informed engineering decisions within a defined context. An ICME ecosystem represents the persistent integrated environment of models, workflows, tools, data infrastructure, governance, and workforce competencies within which different decision workflows are activated depending on the decision context (Refs. 3 to 5, 8, and 15).
- *Fit-for-Purpose Material* refers to a material whose composition, processing, and resulting microstructure have been optimized and sufficiently validated for a specific mission, application, or operating context such that its performance can be used with defined confidence in engineering decision-making.
- *Workflow Automation* refers to the orchestrated execution of interconnected modeling, simulation, data management, and analysis processes with minimal manual intervention, enabling repeatable, scalable, and traceable ICME workflows.
- *Decision Authority* refers to the degree to which model-informed predictions are trusted, governed, and accepted within established engineering and organizational processes to inform, justify, or substantiate decisions commensurate with their intended use and consequence (including certification when applicable).
- *Return on Investment (ROI)* is the measurable improvement in engineering or business outcomes achieved relative to the resources invested in developing and applying ICME capability, including improvements in decision quality, risk reduction, development efficiency, and lifecycle cost.

2.0 Digitization Versus Digital Transformation

A central premise of this paper is that digitization and digital transformation are not the same.

Digitization focuses on converting existing artifacts and workflows into digital form, i.e., PDF reports, scanned test data, machine readable data formats, shared drives, and disconnected or unstructured databases. While digitization can reduce friction and improve access to information, it does not fundamentally change how engineering decisions are made. In many cases, digitization can increase cost without delivering significant ROI because it preserves legacy decision processes while adding digital overhead.

Digital transformation, by contrast, changes the *way an organization conducts engineering*. Decisions become workflow-driven, traceable, repeatable, optimization-informed, and uncertainty-aware. It is only under digital transformation that organizations see sustained ROI through reduced rework, shortened decision cycles, targeted testing, and improved reuse across programs.

This distinction is well established in the broader digital transformation literature, which consistently emphasizes that sustained impact depends more on changes in decision authority, governance, and culture than on technology adoption alone (Refs. 20 to 22).

The proposed ICME maturity levels make this distinction explicit by tying maturity not to tools or artifacts, but to *decision authority and engineering integration, see* Figure 1 .

Digitization Versus Digital Transformation: A Practical Litmus Test

Digitization converts existing artifacts into digital form—PDFs of reports, scanned material cards, shared drives of spreadsheets. While useful, digitization alone does not change how decisions are made and often increases cost without delivering ROI.

Digital transformation changes decision-making itself. The right information is available at the right time, in the right form, at the right scale, with known pedigree and uncertainty. Engineering becomes a managed, repeatable workflow rather than a collection of heroic efforts.

A simple test:

If engineers still spend significant time searching for data, reformatting results, rerunning known analyses, or debating assumptions, the organization is digitizing—not transforming.

Only organizations that reach higher ICME capability levels achieve sustained ROI from Digital Engineering investments.

Figure 1.—An example of litmus test of digitization versus digital transformation.

It is important to acknowledge that *ICME investments can fail to deliver ROI* when applied to the wrong decisions, at the wrong maturity level, or without appropriate governance. ICME is not uniformly beneficial across all problems; its value emerges only when the decision context justifies the cost of increased data management, multiscale modeling, validation, and uncertainty management.

3.0 ICME Capability Maturity Levels: A Missing Readiness Dimension

Organizations routinely claim ICME capability based on the presence of models, tools, or data infrastructure. However, without a clear maturity framework tied to decision authority, such claims obscure real capability gaps and lead to misaligned expectations, delayed ROI, and program risk. Consequently, this section presents the proposed *ICME capability maturity levels (CMLs)* in detail. The framework defines six cumulative levels of capability, explicitly tying ICME maturity to decision authority, engineering integration, multiscale handshaking rigor, uncertainty-awareness and digital transformation, rather than to the mere availability of tools or multiscale modeling methods alone.

3.1 Overview of ICME Capability Maturity Levels

ICME CMLs are applied to a defined decision context and the integrated ICME-enabled ecosystem supporting that decision. They are not intended as blanket organizational labels nor as tool-specific maturity ratings. An organization may demonstrate Level 4 capability for a composite optimization workflow within the ecosystem while exhibiting Level 2 capability for a metallic durability prediction ecosystem. Accordingly, CML assessment is case-by-case and decision-specific within a defined ecosystem. When multiple decision ecosystems are evaluated, an organization may identify a baseline maturity ceiling reflecting sustained technical integration, institutional infrastructure, and cultural readiness. However, exercised decision authority for any given decision remains bounded by the maturity of the specific ecosystem supporting that context.

Table 1 summarizes the proposed ICME CMLs, highlighting the progression in core characteristics, decision authority, and engineering integration. As illustrated conceptually in Figure 2, advancement through these levels corresponds to a transition from simple digitization toward true digital transformation, with associated increases in decision authority and realized ROI.

Figure 2 provides a unifying visual interpretation of the framework, showing ICME CMLs overlaid on a continuum from digitization to transformation, aligned qualitatively with TRL, MRL, and IRL/SRL progression. The figure emphasizes that meaningful ROI is achieved only when ICME capability reaches levels where optimization, validated multiscale handshaking, and uncertainty-aware decision-making are embedded in normal engineering practice.

TABLE 1.—ICME CAPABILITY MATURITY LEVELS AND DECISION AUTHORITY

Level	Descriptor	Core characteristic	Decision authority	Engineering integration
0	No ICME	Disconnected activities	Limited (corporate knowledge/historical precedent)	None
1	ICME ingredients	Capabilities exist, no integration	Traditional engineering (material selection separate but connected to structural design)	Design with material
2	Manual ICME	Conceptual integration, manual scale handshakes	Engineering insight	Design the material
3	Minimal ICME	Digitally enabled handshakes across models; limited workflow automation	Predictive within known regimes	Integrated material-structure design
4	Advanced ICME	Automated workflow orchestration with uncertainty-aware optimization	Optimization support with bounded risk	Optimization of fit-for-purpose materials
5	Full ICME	End-to-end closed-loop, automated integration with governed handshakes	Governed requirement-relevant decision authority	Optimized material and structural applications

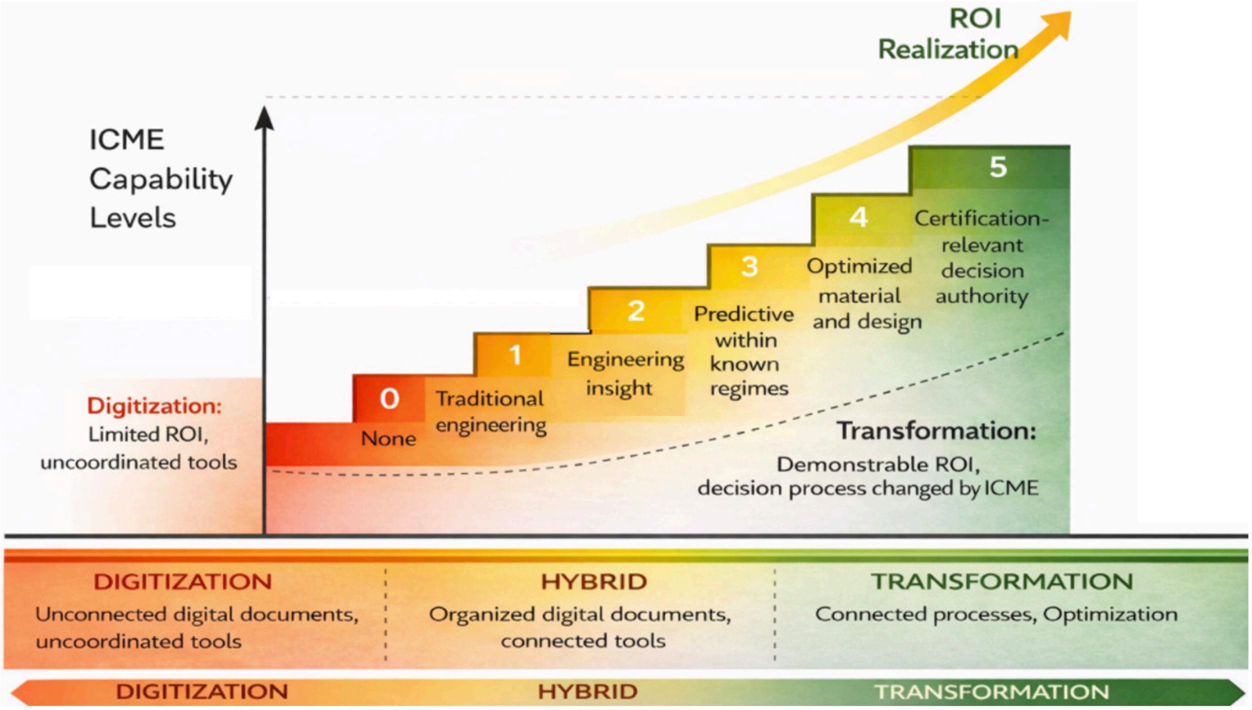

Figure 2.—ICME Capability Maturity Levels Mapped against the progression from digitization to digital transformation, wherein increasing decision authority and ROI increase as ICME capability matures. Traditional readiness levels (TRLs, MRLs, IRLs, SRLs) may occur at any ICME CML and are not inherently coupled to ICME maturity.

These levels are cumulative: higher levels assume that all lower-level capabilities are established, sustained, and governed. Movement from one level to the next represents not incremental tooling improvement, but a substantive change in how material and structural engineering decisions are formulated, justified, and executed. Progression through the higher maturity levels is therefore not strictly linear. The transition from Level 3 to 4 represents a shift from research-oriented demonstration toward sustained engineering application, where integrated workflows, automated execution, and managed uncertainty enable repeatable design decisions. This transition often requires significant changes in engineering practice, workflow integration, and organizational adoption beyond technical model development alone.

The subsequent transition from Level 4 to 5 represents a further shift from engineering application to decision authority. Even organizations with strong Level 4 capabilities may encounter substantial barriers related to workforce readiness, governance structures, legal risk, institutional precedent, and regulatory acceptance. Successfully achieving Level 5 typically requires deliberate investment in workforce development, evolution of decision governance, and early engagement with certification authorities, in addition to technical capability alone. In this sense, ICME maturity progresses through distinct institutional thresholds: first becoming an engineering capability and ultimately becoming a certifiable decision authority.

Additional discussion of the impact of organizational culture is provided in Section 7.1. Consistent with the working definition in Section 1.2, *decision authority* refers here to the degree to which ICME-informed results are trusted, governed, and accepted to directly support engineering, programmatic, or requirement-relevant decisions, including their use in formal trade studies, requirements compliance, or certification artifacts. Furthermore, in this framework, decision authority is understood as an emergent outcome of integrated ecosystem capability rather than a self-declared maturity label. It arises when physics-based and data-informed models are validated within defined regimes, scale handshakes are governed and traceable, information management establishes authoritative sources of truth across the digital thread, uncertainty is explicitly managed, and organizational governance and workforce culture support consistent use of model-informed evidence in engineering and requirement-relevant decisions, including certification when applicable. In this sense, decision authority reflects the convergence of technical integration, information integrity, and institutional readiness. When such ecosystem readiness is achieved, integrated capability establishes consistency across scales and disciplines; consistency enables trust in predictive outcomes; trusted outcomes support governed use; and governed use ultimately enables decision authority appropriate to the requirements and consequence of the decision being supported.

The following subsections describe each ICME CML in more detail.

3.1.1 Level 0—No ICME Capability

At Level 0, ecosystems operate with no explicit ICME capability. Instead, they use isolated, point-in-time physics-based analyses applied in a traditional, discipline-siloed manner, without cross-discipline integration across length scales, processing–structure–property linkages, or lifecycle traceability. Engineering decisions are dominated by historical precedent, conservative margins, and implicit corporate knowledge. While digital tools may exist, they are not systematically integrated into decision-making workflows or authoritative sources of truth; thus, learning across programs can be minimal.

Description: Engineering activities are largely siloed, document-centric, and reactive. Decisions rely on historical precedent, corporate memory, and conservative margins rather than integrated analysis.

Entry criteria (demonstrably true): Materials data and siloed modeling capabilities exist primarily in reports, PDFs, and slide decks and structural design proceeds largely independent of material modeling. No formal digital thread, integration, or governance structure exists.

Typical Failure Points in ICME Practice: Repeated reinvention of allowables, test programs, and analysis or engineering models; limited learning across programs; reliance on key individuals to preserve corporate memory.

What cannot be claimed: Integrated multiscale physics-based decision authority; governed and traceable use of predictive material models across programs; enterprise-governed digital twin capability.

3.1.2 Level 1—ICME Ingredients Established

Level 1 represents the state most organizations identify with when they first claim ICME relevance. The foundational ingredients—experimental data, models at different length scales, and digital repositories—exist, but they are not integrated into a coherent, decision-centric workflow. Materials and structures remain sequentially coupled rather than codesigned.

Description: The foundational ingredients for ICME exist, but they are not integrated into a coherent workflow.

Entry criteria: Experimental, modeling, and optimization capabilities exist at multiple scales; material selection informs structural design sequentially; digital information management, modeling tools, and engineering workflows exist but remain siloed and weakly integrated.

Typical Failure Points in ICME Practice: Tool accumulation without integration ("tool sprawl"); nontransferable methods, models, or results across programs, tools, or loading/application contexts; treating digitized data repositories or isolated modeling tools as substitutes for integrated ICME workflows.

What cannot be claimed: Existence of integrated ICME workflows; optimization-driven decisions; connected[1] material-level and structural-level digital twins appropriate to the decision being informed.

3.1.3 Level 2—Manual ICME Capability

At Level 2, ecosystems begin to exhibit the technical benefits of ICME, but only through significant human effort. Expert judgment is used to manually integrate information across scales, enabling deeper engineering insight and more informed material selection or design decisions for specific applications.

Description: Conceptual ICME workflows are understood and executed through expert-driven, manual processes enabled by human-mediated scale handshakes.

Entry criteria: Material selection or material design explicitly driven by application requirements; manual transfer of data, assumptions, requirements, and parameters across scales and among people; iteration possible, but slow, error-prone, and non-repeatable.

Typical Failure Points in ICME Practice: Single-point workflow vulnerability due to reliance on manual scale handoffs and individual expertise ("heroic individuals" dependence); loss of capability continuity when key personnel leave or are reassigned; increased risk of data or model misinterpretation arising from non-standardized workflows.

What cannot be claimed: Enterprise repeatability; quantified uncertainty at scale; sustained ROI.

3.1.4 Level 3—Minimal ICME Capability

Level 3 marks the transition point from digitization toward transformation. Digital connections across processing-structure-property-performance (PSPP) workflows enable repeatable analyses and limited automation within individual model chains. Information exchange between scales increasingly occurs through digitally enabled scale handshakes rather than manual translation, although these handshakes remain only partially governed and inconsistently coordinated across the workflow. However, while optimization, uncertainty analysis, and validation activities may be performed at individual scales or for specific models, they are not yet *integrated across scales or embedded within a coherent, end-to-end ICME workflow*. Coupling between models remains largely manual, orchestration across PSPP segments

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[1] Here, "connected" denotes that material-level or structural-level digital twins are explicitly linked through shared data, metadata, and traceability mechanisms, enabling reuse beyond their original development context.

is limited, and uncertainty propagation and validation are not systematically coordinated across processing, structure, properties, and performance. As a result, decision authority remains bounded[2] to known regimes and specific use cases, limiting applicability at the system level. Highly integrated research and advanced development programs may exhibit many characteristics of Level 3 ICME capability without satisfying the uncertainty propagation, optimization, and governance requirements necessary to confer Level 4 or Level 5 decision authority.

Description: Digital connectivity enables repeatable workflows across major PSPP segments through digitally enabled scale handshakes; however, these handshakes remain analyst-orchestrated and lack integrated cross-scale optimization or coordinated uncertainty propagation.

Entry criteria: Digital connections across PSPP; defined data and metadata schemas, and configuration control; limited, regime-specific validation.

Typical Failure Points in ICME Practice: Overconfidence in digitally connected models without sufficient verification of cross-scale handshakes, coordinated uncertainty propagation, or clearly bounded applicability limits; continued reliance on human-orchestrated workflows that do not scale or generalize.

What cannot be claimed: Integrated, cross-scale optimization; workflow-level uncertainty awareness; requirement-relevant decision authority.

3.1.5 Level 4—Advanced ICME Capability

At Level 4, ICME begins to fundamentally change how engineering decisions are made. Optimization loops are embedded within both material design and structural performance domains, supported by validated and managed multiscale, multiphysics scale handshakes and explicit uncertainty representation. Because few organizations currently operate at sustained Level 4 ICME capability, the failure points identified here and in Level 5 should be interpreted as potential and anticipated challenges inferred from pilot implementations and known scaling constraints.

Description: Optimization and automation are embedded within major segments of the ICME workflow, with managed orchestration, configuration control, and human-in-the-loop oversight to ensure consistency of cross-scale handshakes as models, data, uncertainty and assumptions evolve.

Entry criteria: Separate optimization loops for material design and structural performance; tight integration with managed automation and workflow orchestration; validated and repeatable cross-scale handshakes enabling coordinated propagation of model and data updates with role-appropriate notification and human sign-off; surrogate models (e.g., reduced order or AI/ML) used for multiscale acceleration; explicit uncertainty representation.

Typical Failure Points in ICME Practice: Underinvestment in governance and sustainment; gradual erosion of validated cross-scale handshakes as models, assumptions, or workflows evolve; automation without clear ownership or escalation paths when workflows fail or assumptions change.

What cannot be claimed: Fully autonomous decision-making; elimination/major minimization of physical testing particularly at lower length scales. Note, even at high ICME capability levels, coupon-level and structural testing remain essential; however, ICME maturity shifts testing from broad exploration toward targeted, hypothesis-driven, information-optimal experiments designed to reduce dominant sources of uncertainty.

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[2] Here, "bounded" may include one or more of the following: physics bounds (e.g., loading modes, environments, rates), material or process bounds (e.g., alloy, microstructure, process window), decision bounds (e.g., trade studies vs certification), programmatic bounds (e.g., program-specific vs enterprise-wide), and uncertainty bounds (e.g., quantified but not fully propagated).

3.1.6 Level 5—Full ICME Capability

At Level 5, ICME attains sustained requirement-relevant decision authority and represents full digital transformation as realized through ICME-enabled decision workflows. End-to-end ICME workflows are continuously integrated, uncertainty-aware, and governed across the product lifecycle. Optimization loops span material design, structural performance, and system-level objectives, supported by institutionally governed multiscale, multiphysics handshakes and comprehensive uncertainty propagation. Automation at this level is event-driven and adaptive, enabling workflows to be re-executed automatically in response to changes in data, models, requirements, or assumptions. Decisions at this level carry requirement-relevant authority; in regulated domains this includes certification-relevant authority, meaning that ICME-informed results may credibly support certification artifacts when properly bounded, validated, and accepted by the relevant authority. At this level, ICME also supports sustained, enterprise-scale ROI across programs by enabling institutionally governed reuse, lifecycle traceability, and enduring decision authority.

Description: ICME workflows operate as managed, closed-loop systems with continuous monitoring of model applicability, uncertainty bounds, validation status, and cross-scale handshake integrity. Changes in inputs or assumptions trigger automated re-analysis, with role-appropriate notification and required human review or sign-off to maintain decision traceability and regulatory confidence.

Entry criteria: End-to-end ICME workflows spanning materials, structures, and systems (i.e., process to performance); closed-loop optimization with uncertainty propagation across scales through governed and continuously monitored cross-scale handshakes; automated detection of operation outside validated regimes; governed escalation, notification, and human approval mechanisms; full integration with digital thread, along with actively maintained digital twins at various scales and certification artifacts.

Typical Failure Points in ICME Practice: Automation-induced overconfidence; erosion of active model interrogation; erosion of governance discipline leading to degradation of previously validated scale handshakes; insufficient monitoring of applicability limits leading to silent drift beyond validated domains; governance breakdowns that allow automated outputs to be accepted without appropriate review; and failure to adapt as physics understanding, data availability, or operational experience evolves.

What cannot be claimed: Fully autonomous certification decisions; elimination of engineering judgment; elimination of physical testing at relevant scales. Even at Level 5, ICME augments—but does not replace—human decision authority and regulatory oversight.

ICME maturity is not defined by tools or models, but by the level of engineering decision authority that can be credibly exercised across material, process, structure, and performance scales.

3.2 Summary: ICME Capability Maturity Levels

Taken together, the ICME CMLs describe a progression not only in modeling sophistication, but in how engineering decisions are formed, justified, and trusted across PSPP scales. Lower maturity levels (0–1) are characterized by isolated, discipline-siloed analyses, manual integration, and implicit treatment of uncertainty, yielding engineering insight but limited decision authority. Mid-levels (2–3) introduce digital connectivity with increasingly authoritative sources of information and bounded predictive capability across defined regimes and scales, enabling repeatability while still constraining optimization, uncertainty awareness, and certification relevance. Higher levels (4–5) require governed multiscale handshaking, orchestrated automation, explicit uncertainty propagation, and lifecycle consistency management, culminating in decision authority. Importantly, advancement through these levels reflects increasing rigor in integration, validation, governance—particularly with respect to consistency management—and organizational readiness, rather than merely the accumulation of tools or models. Figure 3 provides an illustrative example of the importance of understanding the difference between the maturity required and that exercised.

Fit-for-Purpose ICME Capability: Assessed Versus Required Maturity

ICME CML should not be interpreted as a mandate to maximize the scale or level. Consistent with established modeling and digital maturity guidance, the appropriate level of ICME implementation depends on intended use, decision consequence, and value proposition (Refs. 23 to 25).

Two distinct concepts are therefore recognized:

- Assessed ICME CML.—The level objectively demonstrated by evidence, bounded predictive authority, and appropriate review.
- Required ICME CML.—The level necessary to credibly support a specific engineering decision or mission outcome.

Not all programs require Level 5 capability. Early concept trades, material down-selection, and process screening can derive substantial value from Levels 2 and 3, where models provide comparative guidance and bounded predictive insight sufficient to reduce experimental iteration and focus development. Level 4 becomes justified when optimization is performed under bounded risk, and uncertainty must be explicitly characterized and managed. Level 5 is warranted when materials-structural predictions materially influence requirement-relevant or safety-critical decisions and therefore require the highest rigor in validation, governance, and traceability. Because higher capability levels increase validation cost, governance burden, and infrastructure demands, ICME capability should be developed to the level justified by decision consequence and ROI rather than pursued as an abstract end-state.

Figure 3.—Example of fit-for-purpose ICME capability, assessed versus required maturity.

4.0 Relationship to Existing Readiness Metrics

The ICME CMLs are intended to *complement*, not replace, existing readiness frameworks (see Appendix A):

- TRLs assess whether a technology works.
- MRLs assess whether it can be manufactured reliably.
- IRLs and SRLs metrics assess whether components and technologies interface.

The ICME CMLs address a different question: *Are we able to make credible, optimized, and defensible engineering decisions across material and structural scales?*

By aligning ICME CML conceptually with TRL, MRL, IRL and SRL progression, the framework helps explain why programs with high readiness levels can still experience late-stage redesigns, material surprises, or certification challenges. These issues often stem not from immature technology, but from immature decision integration across scales.

4.1 Relationship to Tool- and Model-Centric Maturity Frameworks

Several prior works have defined maturity constructs for modeling and ICME tools, most notably the tool maturity level (TML) framework of Cowles et al. (Ref. 23) and the Sandia Predictive Capability Maturity Model (PCMM) (Ref. 24). These approaches focus primarily on the credibility of models and simulation processes, emphasizing verification, validation, uncertainty quantification, defined applicability ranges, and the principle that required rigor depends on intended use and decision consequence. PCMM further distinguishes between objectively assessed maturity and the maturity required for a given application, noting that higher maturity entails increased cost and organizational burden.

The framework advanced here is complementary but distinct. Rather than assessing the maturity of individual models or simulation processes, this work defines ICME capability maturity in terms of bounded engineering decision authority across material, process, structure, property and performance scales. Tool maturity becomes necessary evidence within the broader construct, but it is not sufficient to establish organizational ICME capability. Capability maturity requires cross-scale handshake integrity, governance of predictive authority, traceable digital workflows, and explicit alignment between model credibility and decision consequence. In this sense, the proposed framework extends tool-centric maturity constructs into an ecosystem-level decision-authority paradigm.

While predictive credibility and maturity constructs evaluate the rigor and evidentiary support of simulation tools and modeling processes relative to intended use, the present framework evaluates the maturity of organizational decision authority across coupled materials–structural workflows. It therefore extends beyond simulation credibility to assess the conditions under which integrated multiscale capability legitimately alters engineering decisions.

4.2 Mapping ICME CML to TRL, MRL, and IRL

While TRLs, MRLs, and IRLs assess technology, manufacturing, and interface maturity respectively, *ICME CMLs assess decision and connectivity maturity across scales*. Table 2 provides an explicit qualitative mapping. It is essential to emphasize that high TRL, MRL, and IRL do not imply high ICME capability. Aerospace systems have been successfully developed and fielded at high readiness levels for decades using traditional engineering approaches. ICME CMLs measure a distinct dimension: the maturity of decision-making and connectivity across material, process, structure, and performance scales.

Allowing readiness ranges to extend to Level 9 reflects the reality that systems may reach full operational maturity using either traditional or ICME-enabled approaches; the distinguishing factor is not the achieved readiness level, but when and how decision authority is exercised across scales. As listed in Table 2, as ICME maturity increases, readiness levels can “start lower” because ICME pushes decision-making down to lower length scales and earlier lifecycle phases while the maximum attainable readiness remains at 9, 10, or 7. This shift in decision readiness to lower achievable readiness levels is made explicit by bolding the lower readiness limits in Table 2

TABLE 2.—ICME CAPABILITY MATURITY AND DECISION INFLUENCE ACROSS EXISTING READINESS LEVELS

ICME CML	Decision character	Typical TRL range[a]	Typical MRL range[a]	Typical IRL range[a]	Interpretation
0	Historical/test-based authority	**7** to 9	**8** to 10	**6** to 7	Mature systems routinely fielded using legacy allowables, conservative margins, and corporate knowledge; no ICME decision authority
1	Sequential engineering	**6** to 9	**7** to 10	**6** to 7	Qualified materials and processes selected from established sets; materials and structures coupled sequentially
2	Expert-guided insight	**5** to 9	**6** to 10	**5** to 7	Expert-driven material/process tailoring for specific applications; insights are not scalable or repeatable
3	Predictive within validated regimes	**4** to 9	**4** to 10	**4** to 7	ICME begins influencing design trades within validated domains; decision authority remains limited
4	Optimization with managed risk	**3** to 9	**3** to 10	**3** to 7	ICME actively drives material and structural optimization; uncertainty is explicit and managed
5	Governed ICME decision authority	**2** to 9	**2** to 10	**2** to 7	ICME informs and constrains readiness progression across the lifecycle rather than merely reacting to it

[a] Readiness ranges indicate lifecycle regions where ICME may influence decisions; they do not prescribe required TRL, MRL, or IRL attainment, which remain governed by established readiness criteria.

This mapping reinforces that high TRL, MRL, or IRL values *do not imply high ICME CML.* Programs can reach advanced readiness levels while still operating at low ICME maturity, leading to late-stage redesigns, unexpected manufacturing challenges, or conservative overdesign. ICME CMLs therefore provide a missing but essential lens for assessing true decision readiness in complex aerospace systems.

5.0 DE Versus ICME: Infrastructure and Stress Testing

Many organizations invest heavily in DE expecting transformative outcomes yet see limited return because decision-making processes remain unchanged (Refs. 20, 24, and 26). Understanding the distinction between DE and Integrated Computational Materials Engineering (ICME) is essential to realizing meaningful transformation and ROI as the two serve fundamentally different roles within modern engineering enterprises. Therefore, clarifying this distinction is essential to avoiding misaligned expectations and unrealized ROI.

DE is an enterprise infrastructure. It focuses on the digital representation, management, and traceability of engineering information across the lifecycle, enabling configuration control, auditability, and continuity through the digital thread. DE answers the question: *How do we connect, manage, and trace engineering information so decisions are consistent and auditable?* Importantly, DE does not inherently require physics-based integration, iteration, or optimization. A digitally mature organization may possess extensive digital artifacts, models, and repositories while leaving its fundamental decision processes unchanged.

ICME, by contrast, is a closed-loop, physics-based, and data-informed engineering discipline whose explicit purpose is to *change engineering decisions*. ICME integrates processing, microstructure, properties, performance, durability, and uncertainty to enable optimization-driven choices to enable concurrent design of *fit-for-purpose* materials throughout structural applications/systems. Iteration, validation, and uncertainty management are not optional features of ICME; they are defining requirements.

This distinction leads to an essential asymmetry:

- *DE is not ICME*
- *ICME is a stress test for DE*

Higher levels of ICME capability place substantial and increasing demands on an organization's DE infrastructure, such that sustained execution of advanced ICME workflows is not feasible without a mature DE foundation. The reverse is not true. DE maturity is necessary but not sufficient for ICME, because DE alone does not ensure physics-based multiscale integration, governed scale handshakes, explicit uncertainty treatment, enterprise-scale optimization, or validation across regimes and scales. Accordingly, the presence of digital threads or digital twins should not be interpreted as evidence of ICME maturity in the absence of demonstrated decision authority and validation discipline (Refs. 2 to 5, 15, 20, and 21).

DE improves connectivity, accessibility, and governance of engineering artifacts across the lifecycle. Digital transformation, however, occurs only when validated, uncertainty-aware multiscale integration shifts decision authority upstream. ICME maturity becomes a stress test for transformation because it requires integration at multiple length and temporal scales that materially alters engineering decisions rather than merely digitizing documentation and data. Consequently, connectivity enables efficiency, but ICME maturity determines decision authority.

Further, in the context of ICME, it is essential to distinguish between *aleatoric* and *epistemic* uncertainty. Aleatoric uncertainty represents inherent variability in material behavior, processing conditions, or operating environments and cannot be reduced through additional knowledge. Epistemic uncertainty arises from incomplete understanding, limited data, or modeling assumptions and can, in principle, be reduced through improved experiments, models, and validation. Effective ICME practice requires that both forms of uncertainty be explicitly represented, propagated across scales, and reflected in engineering decisions. Failure to explicitly account for uncertainty (particularly when aleatoric and epistemic sources are not recognized or treated appropriately) often leads to misplaced confidence, over-conservatism, or invalid extrapolation beyond validated regimes.

DE provides the infrastructure for engineering, but ICME determines whether that infrastructure actually changes decisions.

The distinction between DE and ICME highlights a broader principle relevant beyond materials engineering. Across modern engineering enterprises, technological capability, digital infrastructure, and analytical sophistication increasingly outpace the ability of organizations to confidently exercise model-informed decisions. The limiting factor is therefore not the availability of models or data, but the maturity of the ecosystem required to translate integrated technical knowledge into governed decision authority. In this sense, the ICME CML represent a domain-specific realization of a more general concept of *decision readiness*—the condition under which engineering predictions are sufficiently integrated, validated, traceable, and institutionally trusted to influence consequential decisions. While illustrated here through ICME, the underlying principle applies broadly to any discipline seeking to achieve true digital transformation rather than digitized workflow replication.

5.1 Two Defining Pillars of ICME: Handshaking and Optimization

5.1.1 Multiscale Handshaking as the Core ICME Challenge

A defining, and frequently underestimated, challenge in ICME is the handshaking between models and methods across length and time scales. In DE, integration often means transferring information between tools. In ICME, integration means defining how physics at one scale meaningfully informs behavior at another, with known assumptions, validity, and uncertainty. Handshakes across scales are inherently:

- Physics-dependent,
- Model-form dependent,
- Scale-dependent, and
- Often approximate or only partially validated.

The common simplification that “outputs of one scale become inputs to the next” is valid only when the translation is explicitly defined and its assumptions, limitations, and uncertainties are understood. In practice, uncertainty resides not only within individual models, but also within the cross-scale handshakes themselves. These uncertainties arise from model approximations at a given scale, mismatches in spatial and temporal resolution, fidelity differences between models, and regime dependence. Without governed and uncertainty-aware handshakes (potentially informed by multi-fidelity modeling and uncertainty quantification) ICME risks devolving into disconnected multiscale modeling rather than functioning as an integrated engineering discipline.

A familiar example of such a governed scale handshake exists in continuum constitutive modeling. Continuum constitutive models embed lower-scale mechanisms into structural response through internal state variables and evolution laws, translating microstructural physics into engineering-scale predictions via mathematically defined scale transitions. At lower scales, ICME necessarily relies on hierarchical, reduced order, or surrogate representations that manage, not eliminate, uncertainty.

5.1.2 Optimization as a Defining Requirement

ICME is inherently iterative and optimization driven. Consequently, models, cross-scale handshakes, and the ICME workflows that orchestrate them must be:

- Computationally efficient,
- Stable under repeated evaluation, and
- Robust across the design space.

This requirement explains why surrogate models, reduced-order methods, and AI/ML accelerators are essential: not as replacements for physics, but as enablers of repeated, uncertainty-aware multiscale optimization. However, acceleration alone does not confer maturity. As optimization cycles become increasingly automated and data-driven, rigorous attention to model pedigree, training domain, validation regime, and uncertainty quantification becomes even more critical—particularly for AI/ML components whose extrapolation behavior may be poorly bounded. Without explicit traceability of model lineage, applicability limits, and uncertainty treatment, accelerated workflows risk amplifying error rather than enabling trustworthy decision authority.

Accordingly, higher ICME capability levels require not only optimization efficiency, but also governed integration of models and surrogates within a traceable digital ecosystem. Optimization, not mere connectivity, is the discriminator between descriptive digital workflows and decision-transforming ICME practice; and optimization that lacks validated handshakes, uncertainty awareness, and governance discipline does not constitute higher maturity. Table 3 provides a concise contrast between the various aspects involved in DE and ICME.

As ICME capability matures, optimization increasingly involves high-dimensional, multi-objective trade spaces spanning multiple scales and disciplines. Emerging artificial intelligence and machine learning techniques may assist human decision-makers by guiding trade-space exploration, prioritizing design alternatives, and identifying regions of interest, while preserving human judgment (i.e., human-in-the-loop), physics-based modeling, and explicit uncertainty treatment within the optimization loop.

TABLE 3.—CONTRASTING ECOSYSTEM ROLES OF DE AND ICME, ILLUSTRATING PROGRESSION FROM DIGITALLY ENABLED INFORMATION MANAGEMENT TO GOVERNED, MODEL-INFORMED DECISION AUTHORITY

Aspect	DE	ICME
Primary role	Digital backbone (infrastructure + traceability)	Decision workflows (materials-structural decision authority)
Iteration	Enabled (not required)	Required (closed-loop iteration)
Optimization	Optional / use-case dependent	Core requirement (fit-for-purpose)
Physics depth	Representation-focused	Physics-informed
Multiscale integration	Optional	Required
Uncertainty	Often implicit / unevenly treated	Explicit decision driver
Automation	Data and workflow execution	Orchestrated decision workflows
Outcome	Better-managed decisions	Better decisions (within stated bounds)

As shown in Figure 2 and Tables 1 and 2, ICME maturity simultaneously constrains decision authority and places stringent demands on DE infrastructure. ICME exposes weaknesses that DE alone can obscure, including brittle tool interoperability, missing or inconsistent metadata, undocumented assumptions, untracked uncertainty, and poor knowledge retention. For this reason, ICME CML serve a dual role: they measure an organization's ability to perform ICME and indirectly reveal the maturity and robustness of the underlying DE ecosystem. When viewed through this lens, the ICME capability maturity framework provides a unifying bridge between DE initiatives and engineering outcomes. It explains why digitization efforts often fail to deliver ROI, and why true digital transformation, where decision-making workflows themselves are changed, only emerges at higher ICME capability levels.

For organizations, the ICME capability levels provide a realistic lens through which to assess current state, identify barriers to advancement, and align investment with desired decision authority. It discourages premature claims of transformation and encourages deliberate progression.

For software tool ecosystems, the framework clarifies where infrastructure investment enables ICME and where ICME imposes requirements on infrastructure. It distinguishes between tools that support digitization and capabilities that enable transformation, helping to guide product roadmaps, integration strategies, and customer expectations.

Organizations often underestimate ICME not because the physics is hard, but because maintaining decision credibility across evolving models, data, and requirements is harder.

5.2 ICME Within the DE Ecosystem

ICME capability must be interpreted within the broader context of DE maturity. Digital maturity frameworks emphasize interoperable data environments, configuration management, model governance, and enterprise-level digital integration. These elements are essential enabling conditions for sustained ICME capability, particularly when predictive results influence high-consequence decisions (Ref. 25).

However, digital infrastructure maturity alone does not establish predictive authority. As decision consequence increases—particularly for requirement-relevant or life-limiting assessments—the rigor of multiscale validation, uncertainty quantification, traceability, and governance must increase correspondingly. ICME maturity therefore scales not merely with technical sophistication, but with evidentiary burden and decision consequence.

Within a DE ecosystem, ICME operates both as a consumer and a stress test of digital maturity. It depends on interoperable tools, authoritative data sources, traceable model workflows, and governed configuration management. At the same time, cross-scale materials-structural decision authority exposes weaknesses in data lineage, uncertainty management, and digital governance structures. Digital engineering provides the lifecycle digital backbone. ICME provides materials-structural decision authority that leverages (and rigorously tests) that backbone. The disciplines are therefore complementary but distinct.

6.0 Implications for Certification, Airworthiness and Technical Authority

From an FAA, DoD, and NASA perspective, ICME maturity is fundamentally a question of *technical authority and decision credibility*, not modeling sophistication. Certification and airworthiness authorities do not approve tools or models in isolation; they accept engineering decisions supported by traceable assumptions, validated evidence, and clearly defined limits of applicability.

Traditional certification pathways accommodate low ICME capability by relying on conservative design margins, extensive testing, accumulated service experience, and heroic individuals. These approaches are well understood and effective, but they shift cost, schedule risk, and learning late into the program lifecycle and can slow progress when key personnel depart. Higher ICME capability levels offer the potential to redistribute certification evidence upstream by enabling validated, uncertainty-aware, physics-based predictions to inform material qualification, design allowables, and structural substantiation.

Importantly, only ICME capabilities at *Levels 4 and 5* approach *certification-relevant decision authority*, where model-informed evidence may credibly supplement or partially replace traditional test-based artifacts. At lower ICME levels, models can provide insight and risk awareness but should not be used as primary certification evidence.

For regulatory acceptance, ICME workflows must be governed, auditable, and transparent. This includes documented model assumptions, validated cross-scale handshakes, explicit uncertainty treatment, and digital traceability from requirements to decisions. In this sense, ICME capability maturity aligns naturally with FAA, DoD, and NASA expectations for disciplined engineering practice rather than attempting to circumvent established certification principles. In nonregulated domains, the analogous Level-5 threshold is requirement-relevant decision authority for safety-critical, mission-critical, or contractually binding decisions, where evidence, traceability, and governance must meet the applicable stakeholder acceptance criteria.

Documenting model assumptions, limitations, and applicability is essential for technical credibility; however, ICME maturity also requires that such information be presented at appropriate levels of abstraction for different stakeholders. More mature ICME systems distinguish between detailed technical documentation intended for model developers and reviewers, and higher-level, decision-focused representations suitable for engineers, managers, and certification authorities, while maintaining traceability between them. Emerging capabilities in artificial intelligence and large language models may play an important enabling role at higher ICME capability levels by assisting in the synthesis, summarization, and contextualization of complex model documentation, assumptions, and evidence for different stakeholders. When appropriately governed and traceable, such tools can help bridge the gap between detailed technical artifacts and decision-relevant insight, without breaking the digital thread or replacing physics-based models, validation, or human judgment.

6.1 Validation: The Dominant Cost and Risk Driver in ICME

The implications of ICME capability become most consequential when certification, validation, and regulatory acceptance are considered. Verification and validation play distinct roles in ICME. *Verification* establishes that models and workflows are implemented correctly and perform as intended numerically. *Validation* establishes that the models represent physical reality with sufficient fidelity for their intended use. For certification relevant applications, validation, not verification, is the dominant cost driver and primary source of risk. This distinction between verification and validation, and the need to establish model adequacy for an intended context of use, is foundational to modern verification, validation, and uncertainty quantification practice (Refs. 27 to 32). In this context, epistemic uncertainty reflects lack of knowledge that may be reduced through additional data or improved models, whereas aleatory uncertainty represents inherent variability that cannot be eliminated, only characterized (Ref. 28).

Validation in ICME is commonly underestimated and is often the dominant cost and risk driver in achieving credible decision authority. To establish such decision authority, ICME workflows must be validated across:

- Multiple length scales,
- Multiple coupled physics (e.g., mechanical, thermal, environmental),
- Multiple loading modes (e.g., static, cyclic, creep, fatigue), and
- Inherent variability in material and process response.

Some scales, states, and interactions are partially or fundamentally intractable to measure directly through experiment. Successful ICME programs therefore adopt *tiered validation strategies*:

- Validate where experimental data exist,
- Quantify uncertainty where data are limited or unavailable, and
- Define explicit bounds on model use and extrapolation.

Note that all validation is necessarily bounded; however, higher ICME capability levels require that model applicability limits, uncertainties, and validation evidence be *explicitly* defined, propagated across scales, and aligned with the intended decision context.

Without this discipline, ICME outputs can appear precise yet be dangerously misleading. High ICME CML is not achieved by eliminating uncertainty, but by making uncertainty explicit, traceable, and decision relevant. Note this paper does not advocate replacing established certification, airworthiness, or qualification processes with ICME-based methods. Rather, it positions ICME CML as a framework for understanding when and how model-informed evidence may credibly support engineering decisions within existing regulatory structures.

At low ICME CMLs, traditional certification artifacts—such as conservative design margins, extensive testing, and service experience remain essential and appropriate. At higher ICME CMLs, validated and uncertainty-aware ICME workflows may inform material qualification, design allowables, and structural substantiation, provided their assumptions, limitations, and domains of applicability are explicitly documented and auditable.

Consistent with FAA, DoD, and NASA expectations, ICME maturity does not eliminate the need for testing, verification, or validation. Instead, it enables a more deliberate and transparent exploration and allocation of certification evidence and uncertainty-awareness, potentially shifting some learning earlier in the lifecycle while preserving regulatory rigor, traceability, and safety.

It is important to note that partial or context-limited validation is not unique to ICME; it is common practice across engineering disciplines to validate models within a narrow set of conditions and implicitly extend their use beyond those bounds. ICME does not eliminate this reality, but instead makes validation assumptions, applicability limits, and uncertainty explicit and traceable across scales and tools.

As a result, the initial development and validation of ICME models and workflows can require significant upfront investment, particularly when integrating disparate tools, experiments, and expertise distributed across multiple individuals or organizations. However, when properly governed, this investment is not incurred repeatedly at the same scale. As ICME capabilities mature, validated models, data, and workflows can be reused, extended, and incrementally refined across projects, reducing the marginal cost of subsequent validation activities while increasing confidence and decision authority over time.

Given the cost and complexity of validation, it is reasonable to ask why ICME should be pursued at all. The answer lies in the nature of the decisions being made. When the objective is limited to selecting from existing, qualified materials, traditional approaches remain effective. However, when the goal is to design new materials and processes that are fit for a specific engineering application (rather than merely acceptable across broad envelopes) ICME becomes essential. At this level, ICME is not a cost-saving measure in isolation; it is an enabling capability that allows classes of materials, process, and performance decisions to be made that are otherwise inaccessible using traditional methods.

6.2 Consistency Management and Lifecycle Evolution in ICME

As ICME matures from an analytical capability to a decision-authoritative framework, the dominant challenge shifts from model development to consistency management across the digital lifecycle. ICME workflows do not exist at a single point in time. Requirements evolve, models mature, data sets expand, and digital twins transition from exploratory artifacts to operational assets and transition between digital representations and digital twins (i.e., representative of a physical asset) over time. As a result, the credibility of ICME-informed decisions depends not only on the quality of individual models, but on the ability to actively manage consistency across models, data, assumptions, requirements and decisions over the system life cycle.

Importantly, ICME does not imply that immature materials or models are granted design or certification authority prematurely; rather, it provides a structured mechanism to explicitly track evolving evidence, uncertainty, and applicability limits, enabling decisions to be defended, revisited, bounded, or deferred as new information becomes available. In this respect, ICME makes risk visible earlier rather than hidden, allowing organizations to identify unfavorable material behavior sooner, better target resources to key drivers of uncertainty, and adjust design decisions before irreversible commitments are made.

From an industry and certification perspective, the preference for established, qualified material over unqualified fit-for-purpose alternatives is entirely rational. ICME does not seek to bypass material qualification or certification processes. Rather, at higher maturity levels, ICME enables certification considerations to be integrated into material and process design from the outset, such that evidence generation, validation planning, and applicability limits are explicitly aligned with anticipated certification requirements as materials mature. In this way, ICME supports the development of fit-for-purpose materials whose path to qualification is intentionally designed, rather than deferred or discovered late in the lifecycle. At no point does ICME imply that unqualified materials should be deployed operationally; rather, it provides a disciplined framework for accelerating learning while preserving certification rigor.

The challenge of maintaining consistency across evolving requirements, models, data, and assumptions over the system lifecycle is well recognized in digital thread and digital twin literature, which emphasizes configuration control, traceability, and governance as foundational enablers rather than optional capabilities (Refs. 2 to 5). Within an ICME ecosystem, however, consistency management extends beyond traditional configuration control, requiring explicit tracking of:

- Evolving requirements and objectives,
- Model versions and uniquely identifiable realizations (e.g., tagged, archived, or otherwise reproducible instances), along with assumptions and domains of validity,
- Experimental data provenance and relevance,
- Scale-to-scale handshakes and information transformations, and
- Decision context and intended model use.

In this context, version identification alone is insufficient; ICME maturity requires that models and workflows referenced in decisions remain accessible and reproducible by others over time. Without this discipline, ICME results rapidly lose relevance as upstream or downstream elements change.

Consistent with the AIAA Digital Thread definition (Ref. 3), ICME imposes some of the most demanding consistency requirements of any DE activity, as it couples multiscale physics, experimental data, and optimization-driven decisions across organizational and temporal boundaries. As ICME capability increases, so too does the burden placed on the digital infrastructure to:

- Maintain authoritative sources of truth,
- Preserve traceability between scales and disciplines,
- Propagate uncertainty and credibility metadata, and
- Prevent silent divergence between models, data, and decisions.

In practice, sustained high-level ICME capability is not viable *without a mechanized digital thread* capable of managing these relationships continuously (Refs. 16 to 19, and 33 to 37). ICME-driven digital twins further amplify these demands. Unlike descriptive digital twins, ICME-based twins are frequently *decision-bearing*, supporting model-based property determination, material qualification, structural trade studies, and certification-relevant assessments. As highlighted in the AIAA Digital Twin implementation paper (Ref. 5), digital twins must be intentionally planned, validated, and evolved with clear purpose and operational boundaries.

When ICME is used to inform or optimize material and structural behavior, the digital twin effectively becomes a *living embodiment* of ICME capability. Maintaining its credibility therefore requires continuous consistency management across physical testing, model updates, and operational feedback.

Consistency management in ICME is fundamentally a *technical governance problem*, not an information technology problem. While digital infrastructure enables traceability and configuration control, engineering leadership must define authority, responsibility, and acceptance criteria for model updates, data relevance, and decision reuse. Without explicit governance, even well-designed digital threads will degrade over time. Note failures associated with loss of configuration control and model–data inconsistency across lifecycle phases are repeatedly cited as root causes in retrospective assessments of DE and model-based initiatives (Refs. 2 to 5, and 8).

The illustration shown in Figure 4 is therefore not intended to suggest that high ICME capability implies complete knowledge or the elimination of unforeseen behavior. The emergence of new regimes, coupled physics, or unanticipated failure modes is an inherent feature of scientific and engineering progress. Rather, the failure illustrated in Figure 4 arises when an ICME framework lacks the governance, traceability, or adaptability to recognize that assumptions have been exceeded, to incorporate new evidence, and to propagate the implications of that evidence back through models, handshakes, and decisions. In a mature ICME environment, such discoveries should trigger targeted investigation, model refinement, and updated validation, thereby accelerating learning rather than undermining confidence. In other words, in high-maturity ICME, discovering new behavior is not a failure, whereas failing to adapt the framework in response is.

Illustrative Failure Mode: Misidentified ICME Maturity

Consider a program that claims ICME capability based on the use of multiscale material models, a digital thread, and a modern engineering toolchain. While the program achieves TRL 6 to 7 and MRL 7 using traditional qualification testing, ICME results are used informally to justify reduced margins and accelerated design decisions.

Late in development, discrepancies emerge between predicted and measured durability under combined thermal-mechanical loading. Investigation reveals that scale handshakes were undocumented, uncertainty was implicit, and validation was limited to a narrow loading regime. As a result, certification authorities require additional testing, eroding schedule and cost benefits while undermining confidence in the ICME approach.

This outcome reflects not a failure of individual modeling tools, but a breakdown of the integrated ICME ecosystem and an overstatement of achieved ICME maturity. Without an explicit validation strategy, governed scale handshakes, and decision authority aligned with intended requirements, ICME outputs may appear precise yet provide insufficient evidence to support requirement-relevant decisions. The risk therefore lies not in using ICME, but in exercising decision authority beyond the maturity actually achieved.

Figure 4.—Example of potential failure mode associated with misidentifying ICME maturity.

7.0 Summary and Call to Action

This paper argues that the absence of a clear ICME capability maturity framework has hindered both DE initiatives and ICME adoption. By introducing explicit levels tied to decision authority, engineering integration, and validation rigor, the proposed framework:

1. Clarifies the difference between digitization and true digital transformation.
2. Provides a missing readiness dimension that complements TRL, MRL, IRL, SRL, and TML frameworks.
3. Anchors ICME roadmaps in demonstrable capability rather than aspirational intent.
4. Guides software ecosystem investments toward enabling transformation, not just tooling.
5. Helps prevent years of duplicative efforts, misaligned expectations and unrealized ROI.

While illustrated in an aerospace context, the maturity framework is applicable to any engineering domain requiring cross-scale materials–structural decision authority. Ultimately, engineering maturity is meaningful only to the extent that it alters consequential decisions. By focusing on the integrated ICME ecosystem (models, methods, data, digital infrastructure, governance structures, and workforce competencies) as a unified decision-support capability this framework provides a more complete and operationally relevant assessment than evaluating tools, infrastructure, or cultural adoption in isolation.

The authors recommend that organizations engaged in DE and ICME adoption, use this framework as a common reference for assessment, roadmap development, and governance. Standards bodies and professional societies are encouraged to consider this framework as a foundation for future guidance on ICME implementation and assessment.

7.1 Organizational Culture as a Limiting Factor in ICME Adoption

Although ICME capability maturity is assessed at the level of a decision-specific ecosystem, the cultural environment of the organization in which that ecosystem operates strongly influences whether higher maturity levels can be achieved, sustained, and trusted. Experience across government, industry, and academia consistently demonstrates that *organizational culture* is often *the rate-limiting factor* that determines whether ICME-enabled ecosystems can achieve, sustain, or exercise higher levels of decision authority, regardless of technical sophistication. Many organizations continue to struggle with foundational digital practices, including data stewardship, model governance, and cross-disciplinary collaboration, even as advanced modeling tools and digital infrastructure become increasingly available. As a result, ICME capability maturity ultimately emerges not from technical tools alone, but from the combined alignment of technical rigor, digital infrastructure, and the cultural practices that enable those capabilities to influence engineering decisions.

The NASA Vision 2040 (Ref. 1) effort explicitly recognized this reality, concluding that while most technical challenges are ultimately solvable, cultural challenges (such as resistance to change, risk aversion, and misaligned incentives) are significantly more difficult to overcome. As succinctly captured during that effort by the statement, "*culture eats strategy every time*."

Although organizational culture is not defined as a separate maturity axis in this framework, it is implicitly embedded within the ICME capability levels themselves through the behaviors they require. Within organizations whose cultural practices support only limited integration, ICME-enabled ecosystems typically operate at Levels 1 and 2, permitting the use of digital tools and models primarily within traditional discipline-siloed workflows and conservative decision frameworks. Ecosystems operating at Level 3 make predictive authority explicit and bounded, meaning ICME-informed results are trusted only within clearly defined regimes, assumptions, and decision contexts. This allows ICME to inform decisions without extending authority beyond validated applicability limits.

At Level 4, ecosystems demonstrate sufficient confidence in model validation, uncertainty management, and governance to enable optimization of materials and designs rather than relying exclusively on conservative margins as the primary risk-management mechanism. At Level 5, ecosystems operate within organizations that are culturally prepared to allow ICME-informed evidence to influence requirement-relevant decisions, subject to appropriate validation, governance, and regulatory acceptance. Even at Levels 3 and 4, however, organizations may still default to conservative decision-making when uncertainty is poorly characterized, may be unwilling to institutionalize ICME results beyond individual programs, or may deliberately restrict ICME-informed decisions from supporting requirements compliance or certification due to governance, trust, or liability concerns.

In this sense, ICME maturity reflects not only the technical capability of an ecosystem but also the willingness of the surrounding organization to change how engineering decisions are made, reviewed, and trusted. Without this cultural foundation, organizations may invest heavily in ICME tools, data, and digital infrastructure yet remain effectively constrained to lower capability levels, unable to realize the transformational benefits that ICME promises.

Consequently, organizations should be deliberate in evolving their culture toward one that not only accepts digitization, but actively embraces digital transformation across engineering processes, practices, and the product lifecycle. Such a cultural evolution is essential for enabling ICME-enabled ecosystems to progress toward higher capability maturity levels. Further, advancing ICME capability levels requires not only tools and infrastructure, but sustained investment in workforce skills spanning materials science, computational modeling, data governance, and systems engineering.

7.2 Assessment and Evidence Requirements

ICME capability maturity should *not be self-asserted*. Self-assessment without objective evidence is insufficient, particularly when maturity claims are used to justify investment, schedule compression, or requirement-relevant decisions. Robust assessment requires *demonstrable artifacts* (validated model use, documented scale handshakes, explicit uncertainty treatment, and traceable decision records) reviewed with rigor commensurate with decision consequence. Consistent with established predictive capability maturity practices in the modeling and simulation community, assessment should explicitly distinguish between assessed maturity and the maturity required for intended use (i.e., assessed ICME CML versus required ICME CML), with documentation, governance, and review formality scaled to decision risk and consequence (Refs. 22 to 24).

To avoid overstatement and confirmation bias, organizations are strongly encouraged to conduct ICME capability assessments through *independent review*, either by a separate technical authority within the organization or by an external, technically qualified party. Independent assessment reinforces credibility, exposes hidden gaps, and aligns ICME maturity claims with actual decision authority.

Practical application of independent ICME maturity assessment must recognize legitimate intellectual property and proprietary constraints. Organizations are rarely able to expose full model formulations, data assets, or internal workflows for external inspection. Accordingly, credible maturity evaluation does not require disclosure of proprietary technical content, but rather demonstration that appropriate governance, validation discipline, traceability, and decision controls exist. Assessment may therefore rely on evidence of discipline process rather than exposure of proprietary content. Examples include documented validation strategies, configuration management practices, controlled model lineage, uncertainty treatment procedures, review records, and decision traceability artifacts. Independent reviewers need not access underlying intellectual property to determine whether ICME-informed decisions are exercised within governed and reproducible frameworks.

This distinction mirrors established practices in certification, quality assurance, and safety-critical engineering audits, where confidence arises from disciplined processes and accountable governance rather than unrestricted visibility into proprietary technical implementations.

Consistent with this philosophy, related efforts have proposed pragmatic, tool-focused maturity and credibility aids for ICME, including verification/validation checklists and TML guidance coupled to risk-versus-consequences assessment to judge whether a model/tool is sufficiently mature for a specific application (Ref. 23). Such efforts reinforce the need for evidence-based maturity claims and intended-use-bounded credibility assessments. The present framework extends this concept from tool-level maturity to decision-centric ICME capability maturity across scales and workflows.

7.3 How to Use the ICME Capability Maturity Framework

This framework is not intended as a compliance standard, certification shortcut, or maturity scorecard, but as a decision-centric diagnostic and planning tool. Its primary purpose is to help organizations assess where ICME meaningfully influences engineering decisions today, identify gaps that limit decision authority, and align future investments in models, data, experiments, and digital infrastructure with clearly articulated objectives.

Effective use of the framework begins by selecting a specific decision context (for example, material selection, process optimization, durability prediction, or certification substantiation) and assessing the highest ICME capability level that can be credibly demonstrated for that decision. The assessment should be grounded in demonstrable evidence, including validated model use, documented handshakes across scales, explicit uncertainty treatment, and traceable decision artifacts.

When applied in this way, the framework helps organizations distinguish between exploratory modeling, engineering insight, and decision-authoritative ICME. It also provides a common vocabulary for communicating expectations between technical teams, program leadership, and stakeholders, reducing the risk of overstated capability claims and misaligned ROI expectations. Table 4 provides illustrative examples of how different ICME activities align with capability levels.

TABLE 4.—EXAMPLE ICME ACTIVITY ALIGNMENT WITH CAPABILITY LEVELS

ICME use case	Typical ICME level	Rationale
Digitized material databases and handbook allowables	1	Information is digitized but not coupled across scales
Physics-based material models used to interpret test trends	2	Insightful analysis without decision authority
Multiscale ICME linking processing to microstructure to properties for a bounded application[a]	3	Predictive capability within validated regimes
Optimization of material architecture considering material and manufacturing variability	4	ICME drives design decisions with managed uncertainty
ICME-informed material-structural qualification or certification substantiation	5	Certification-relevant decision authority demonstrated

[a] See the Aurora D8 ICME project in Reference 5 as it demonstrates multiscale coupling and optimization yet still relies on bounded validation.

It is important to emphasize that ICME capability is *decision-specific, not organizationally uniform*. A single organization may simultaneously operate at different ICME capability levels across programs, disciplines, or decision types. For example, an organization may employ Level 4 ICME practices for material optimization while relying on Level 1 or Level 2 approaches for certification substantiation. Recognizing this reality is essential for honest self-assessment, realistic planning, and effective prioritization of ICME and DE infrastructure investments.

At the same time, organizations may exhibit a stable baseline ecosystem maturity, reflecting sustained technical rigor, governance discipline, and cultural integration developed over time. Such baseline capability represents the highest level of decision authority that can be exercised within validated regimes. However, exercised authority for any specific decision remains bounded by context of use, consequence, and uncertainty tolerance. Ecosystem maturity therefore defines what is possible; decision context determines what is exercised.

Finally, ICME capability maturity is best understood as decision-specific, evidence-based, and governed rather than a static organizational attribute. While this paper establishes the conceptual structure and decision-centric philosophy of ICME maturity, practical implementation requires structured assessment constructs, measurable attributes, and governance-aligned evaluation tools. Operationalizing ICME maturity therefore requires evaluating the integrated ecosystem that enables decision authority, including models, workflows, digital infrastructure, governance practices, and workforce readiness. A companion implementation methodology and supporting assessment constructs are therefore envisioned to operationalize these maturity levels into quantifiable assessment scoring rubrics that organizations can use to evaluate current capability, identify limiting factors, and guide strategic investment.

8.0 Decision Readiness in the Evolution of Engineering Maturity

The ICME capability maturity levels (CMLs) framework can be viewed within the broader historical evolution of engineering readiness constructs. Technology readiness levels (TRLs) established a common language for assessing scientific feasibility and technological maturity. Subsequent frameworks, including manufacturing readiness levels (MRLs), system readiness levels (SRLs), and Integration Readiness Levels (IRLs) approaches, expanded this perspective to address producibility, operational performance, and system and subsystem interoperability. More recently, Digital Engineering maturity models have emphasized information integration, authoritative data environments, and lifecycle traceability.

Despite these advances, a persistent gap has remained between demonstrated capability and consequential engineering decision-making. Technologies may be mature, manufacturable, and digitally integrated, yet organizations may still lack sufficient confidence, governance structure, or institutional alignment to rely on predictive results in design, programmatic, or certification decisions.

The ICME Capability Maturity framework addresses this gap by characterizing the conditions under which integrated modeling, data, and organizational practices collectively achieve *decision readiness*—the state at which model-informed predictions can be responsibly exercised as governed engineering decision authority. In this sense, ICME CML represents a material–structural realization of decision readiness within complex engineering ecosystems.

Historical parallels can be observed in the evolution of aviation safety, where improvements arose not solely from advances in technology, but from the institutional acceptance of predictive engineering supported by validated models, integrated information management, and disciplined governance. Safety gains accelerated only after predictive capability achieved sufficient organizational trust to influence certification and operational decisions. Viewed through this broader lens, ICME maturity does not merely describe advancement in modeling sophistication or digital infrastructure adoption. Rather, it reflects the progression by which engineering organizations transition from analytical capability to trusted, governed, and institutionally exercised decision authority. This work introduces the concept of a *decision readiness level* (DRL) as a unifying lens for understanding maturity across diverse engineering domains, extending beyond ICME while remaining grounded in its materials–structural origins.

Engineering transformation ultimately occurs *not when* capability exists, but when capability becomes *decision ready*.

Appendix A.—Condensed Readiness Metric Summaries

This appendix provides condensed summary tables of: TRLs 1 to 9, see Table A.1; MRLs 1 to 10, see Table A.2; IRLs 1 to 7, see Table A.3; SRLs 1 to 5, see Table A.4) These tables are included to emphasize how ICME capability levels complement—rather than duplicate—existing readiness assessments by explicitly addressing decision readiness across scales. Full details of these different readiness levels can be found in References 8 to 12.

The condensed IRL definitions (Table A.3) are reconciled with widely cited IRL formulations in the systems engineering literature and emphasize increasing interface definition, control, information exchange, and validation.

SRLs (Table A.4) assess overall system maturity by combining technology, integration, and manufacturing considerations across the lifecycle.

TABLE A.1.—CONDENSED TRLs

TRL	Short definition	Interpretation
1	Basic principles observed	Scientific research begins; no application context.
2	Concept formulated	Potential applications identified.
3	Proof of concept	Analytical and experimental validation of critical functions.
4	Lab validation	Components validated in laboratory environment.
5	Relevant environment validation	Components validated in relevant environment.
6	System/subsystem demonstration	Prototype demonstrated in relevant environment.
7	System prototype demonstration	Prototype demonstrated in operational environment.
8	System complete and qualified	Flight-qualified or production-representative system.
9	System proven in operation	Technology used successfully in mission operations.

TABLE A.2.—CONDENSED MRLs

MRL	Short definition	Interpretation
1	Manufacturing implications identified	Manufacturing acknowledged; basic research only.
2	Manufacturing concepts identified	Candidate materials/processes identified.
3	Manufacturing proof of concept	Lab experiments validate concepts.
4	Laboratory manufacturing capability	Processes demonstrated in lab.
5	Prototype components (relevant environment)	Key processes demonstrated on components.
6	Prototype system/subsystem capability	Preliminary design accepted; processes largely defined.
7	Production-representative capability	Detailed design nearly complete; processes proven.
8	Pilot line / LRIP[a] ready	Stable design; pilot line demonstrated.
9	Low-rate production demonstrated	Ready for full-rate production.
10	Full-rate production	Lean, stable, continuous production.

[a]LRIP: Low-rate initial production wherein limited-rate manufacturing is used to validate production capability prior to full-rate production.

TABLE A.3.—CONDENSED IRLs

IRL	Short definition	Interpretation
1	Interface identified	An interface between technologies is identified with sufficient detail to characterize the relationship.
2	Interface specified	The interaction between technologies is defined with increasing specificity.
3	Compatible interaction	Technologies are compatible and can integrate and interact in an orderly manner.
4	Integration quality defined	Quality, assurance, and integrity of integration are defined.
5	Controlled integration	Integration can be established, managed, and terminated in a controlled manner.
6	Information exchange enabled	Integrated technologies can accept, translate, and structure information for intended use.
7	Integration verified and validated	Integration is verified and validated to a level sufficient for actionable decisions.

TABLE A.4.—CONDENSED SRLs

SRL	Lifecycle phase	Interpretation
1	Concept refinement	Initial concept refined; system strategy defined.
2	Technology development	Technology risks reduced; candidate technologies selected for integration.
3	System development and demonstration	System capability developed; integration and manufacturing risks reduced.
4	Production and deployment	Operational capability achieved and fielded.
5	Operations and support	System sustained cost-effectively over its lifecycle.

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