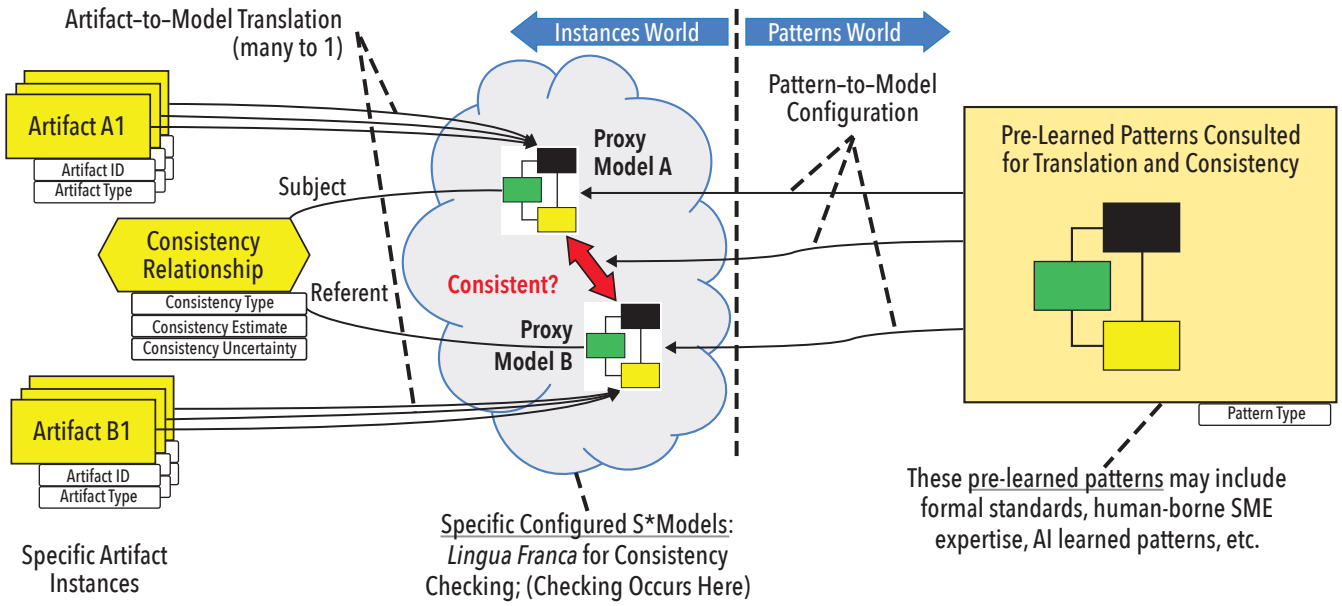
INSIGHT

This Issue's Feature:

Digital Engineering



Checking consistency of artifacts by translating them to proxy models that are consistency checked

Illustration credit: from the article *From Fragmentation to Federation: A Proposed Strategy for Advancing Digital Engineering Standards Development* by Celia S. Tseng, Joseph W. Marvin, William D. Schindel, Juan Carlos Mendo, and Terri W. Chan (page 11)

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From Fragmentation to Federation: A Proposed Strategy for Advancing Digital Engineering Standards Development

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■ **ABSTRACT**
The future of systems engineering depends on solving a pressing challenge: the fragmentation of data and models across engineering tools, enterprise systems, and lifecycle processes. While existing standards from the International Organization for Standardization (ISO), the Object Management Group (OMG), and other standard development organizations (SDOs) address specific domains and data exchange formats, no comprehensive framework exists to guide digital engineering (DE) across the full ISO/IEC/IEEE 15288 system lifecycle process—from technical and management processes to enabling and agreement activities. This disconnect limits organizations' ability to integrate, scale, and deliver consistent value across increasingly complex ecosystems.

This article examines the current gaps in interoperability standardization efforts and outlines opportunities for the International Council on Systems Engineering (INCOSE) to shape the future of digital transformation. It introduces the INCOSE agile systems engineering life cycle management (ASELCM) pattern as a foundation for aligning lifecycle processes with model-based technical exchanges through a federated digital thread. The authors call for INCOSE to adopt a strategic standardization role—working with other SDOs to define interoperability use cases, align lifecycle models, and model-based systems engineering (MBSE) standards, and develop a shared reference framework for interoperability. This collaboration is essential for enabling seamless, cross-enterprise interoperability—and for empowering organizations to realize the speed, scale, and economic advantage promised by digital transformation.

■ **KEYWORDS:** digital engineering, interoperability, ontology, semantics, standards

INTRODUCTION

Achieving effective interoperability across the systems lifecycle remains a major challenge identified in the *Systems Engineering Vision 2035* (INCOSE 2021). Modern engineering spans multiple organizations, tools, and disciplines—each within its own evolving digital ecosystem—making the federation of data, processes, and tools essential for managing distributed, heterogeneous systems-of-systems. Despite numerous data standards such as SysML v2, FMI 3.0, STEP, and QIF, meaningful interaction across lifecycle processes remains fragmented (Powell 2025, Fischer et al. 2025).

Figure 1, excerpted from the *Systems Engineering Vision 2035*, highlights today's DE pain points. While the DE toolsets continues to grow, it is constrained by IT limitations and deeper system realities. Engineering tools—whether cloud or on-premise—typically access only the specific data they consume or produce, often in proprietary formats unique to each vendor. These tools perform critical functions but were not designed for the broad, interop-

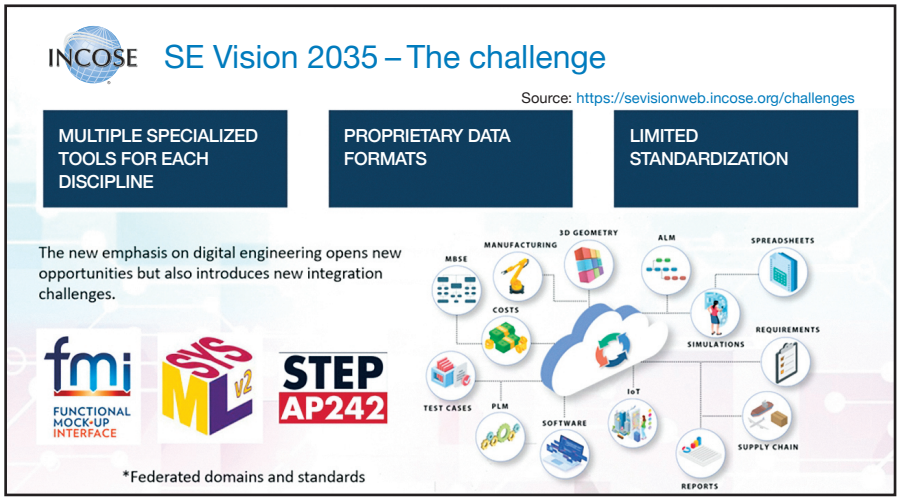


Figure 1. Systems Engineering Vision 2035 challenge

erable data access required for true DE. Standards to support this level of interoperability are only now beginning to emerge.

To achieve true interoperability, both syntactic and semantic interoperability must be addressed. Table 1 provides an overview of commonly used system engineering standards and their support for syntactic and semantic interoperability. Syntactic interoperability ensures that data formats, exchange protocols, and system interfaces are compatible, while semantic interoperability enables systems, machines, and stakeholders to interpret data meaningfully and consistently. This becomes especially important in model-based engineering, digital threads, and artificial intelligence (AI)-supported decision environments.

Each standard is assessed as having strong, partial, or indirect support in these two dimensions. A rating of strong indicates clearly defined data structures or formal logic-based semantics, enabling automated processing and integration. Partial support means the standard offers some structure or semantic clarity but lacks full formalization or consistency in application. Indirect suggests that while

Table 1. Systems engineering standards and interoperability support

Standard	Primary Domain	Syntactic Interoperability	Semantic Interoperability
ISO 10303 (Standard for Electronic Exchange of Product Data–STEP)	Product lifecycle, CAD/PLM	Strong	Partial
ISO 15926 (Industrial Automation Systems and Integration)	Process plants, lifecycle integration	Strong	Strong
ISO 15288/INCOSE Systems Engineering Handbook	Systems engineering lifecycle	Indirect	Indirect
OMG SysML v1.x	System modeling	Partial	Partial
OMG SysML v2.0	System modeling	Strong	Strong
ISO 42010	Architecture description	Indirect	Indirect
ArchiMate (TOGAF)	Enterprise architecture	Strong	Partial
DoDAF/MODAF/NAF/UAF	Enterprise architecture	Strong	Partial
OSLC (Open Services for Lifecycle Collaboration)	Cross-tool model traceability	Strong	Strong
W3C Semantic Web (OWL, RDF, SPARQL)	Cross-domain knowledge integration	Weak	Strong
ISO/IEC 11179	Metadata registries and vocabularies	Partial	Partial
LOTAR (EN/NAS 9300)	Product data archiving	Strong	Partial
ISO 14721 (OAIS)	General Digital Archiving	Strong	Partial
ProStep Digital Data Package (DDP)	Product data exchange	Strong	Partial
CASCaDE	Cross-disciplinary model-based collaboration	Strong	Strong
FMI	Simulation model exchange	Strong	Partial
QIF	Quality data exchange across manufacturing lifecycle	Strong	Partial

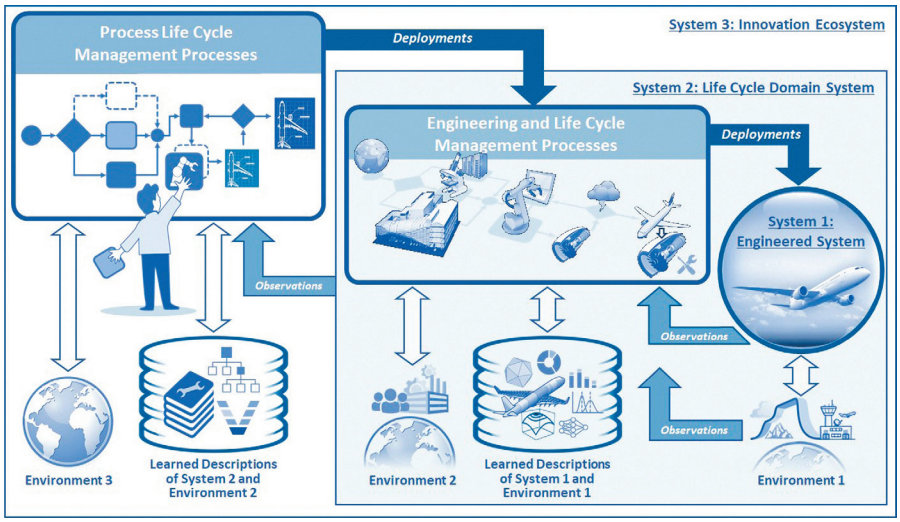


Figure 2. INCOSE ASELCM level 1 reference model

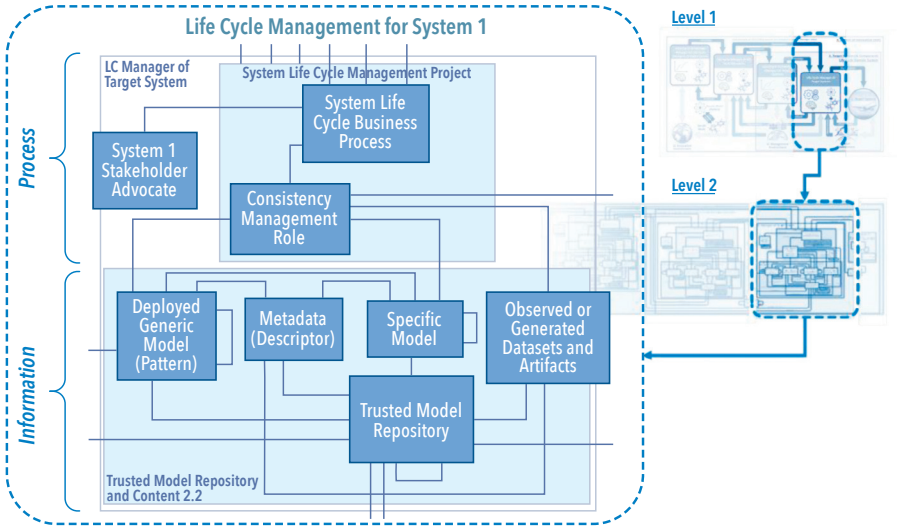


Figure 3. INCOSE ASELCM level 2 reference model

the standard may not directly address syntax or semantics, it can contribute when combined with other frameworks.

These assessments reflect both the intended purpose of each standard and how it is applied in practice, highlighting current strengths and gaps in achieving full lifecycle interoperability for model-based and digital engineering. While many standards support data exchange at the technical level, they often fall short in enabling semantically consistent communication across systems and stakeholders. The core issue is semantic heterogeneity—the lack of shared meaning across tools, models, and organizational contexts. As a result, information may be exchanged syntactically but misinterpreted semantically. Standards like ISO 15288 and the INCOSE *Systems Engineering Handbook* define what information is produced and consumed at each lifecycle stage, but they do not offer a theoretical foundation to ensure that these exchanges lead to aligned, collaborative outcomes.

The ASELCM Pattern (Figure 2) — particularly level 2 shown in Figure 3 — provides a system-theoretic framework for identifying where interoperability is essential across technical, technical management, agreement, and enabling processes (AIAA 2023). This framework helps analyze real-world use cases in which effective collaboration depends on aligned semantics and shared models. Interoperability is a prerequisite for consistency management—the ability to detect, assess, and reconcile discrepancies between models across disciplines (Schindel 2021). For instance, interoperability enables a change in a system requirement to automatically flag consistency issues in linked architecture models, test plans, or configuration data, helping teams maintain alignment across stakeholders and tools. Without this, organizations face late discovery of issues, miscommunication, redundant work, costly rework, and regulatory noncompliance—challenges that cannot be solved with isolated internal data alone. By establishing robust interoperability, organizations can maintain a traceable, version-controlled digital thread that supports faster decisions, stronger collaboration, and more predictable system outcomes (AIAA 2023).

HOW SPECIFIC MUST AN INTEROPERABILITY FRAMEWORK BE?

Interoperability frameworks must strike a balance between generality and domain specificity. In ontology hierarchies, general-to-specific layering is well understood, but expressing multiple models—such as subsystem specifications, industrial or internal reference architectures, or system-level designs—within the same framework does not ensure we can evaluate whether they (1) contradict each other or (2) align with known facts about their domain. The key question is: Is the framework specific enough to support the kind of consistency checking the stakeholder requires?

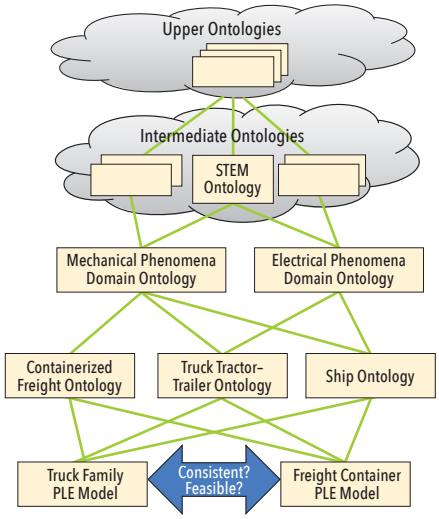


Figure 4: How specific must an ontology be?

For example, consider MBSE models of a semi-trailer truck family that must now accommodate containerized freight lifted by cranes for intermodal shipping (Figure 4). Even if both truck and container models are valid in SysML, their interoperability alone doesn't reveal whether their assumptions about crane, trailer, and ship interactions are logically or physically consistent. This isn't a failure of SysML—it's a matter of whether the reference ontology is specific and expressive enough to capture the semantics of those interactions.

Figure 4 also underscores a deeper issue: engineering ontologies should be grounded in the physical sciences. Generalized STEM principles, such as Hamilton's Principle, underlie all technical domains (Schindel 2024). Omitting these foundations from digital engineering ontologies risks weakening their ability to support real-world reasoning and innovation.

EXAMPLE STANDARDIZATION APPROACHES TO ADDRESS INTEROPERABILITY CHALLENGES:

Addressing interoperability in digital engineering requires strategies that handle both the structure and the meaning of exchanged information. Traditional standardization has emphasized shared syntactic structures and fixed terminologies—effective in static, bounded domains but insufficient for today's distributed, evolving, and heterogeneous ecosystems. As enterprise-scale systems grow more dynamic and cross-disciplinary, more agile approaches are emerging to support interoperability standardizations at scale. Three such approaches are outlined below:

1. Shared Terminology Approach (Common Meta-Standards)

   The most common interoperability strategy is to define a shared terminology in a standard—such as STEP, SysML, or QIF—to which all participating systems must conform. When applications use different internal vocabularies, human specialists create transformation mappings to align them (Bittner 2006).

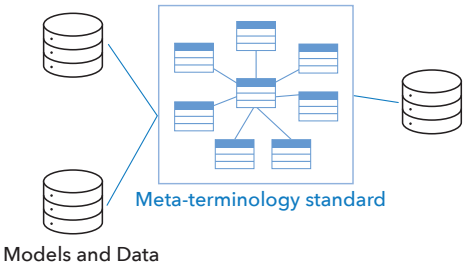


Figure 5. Shared terminology standards approach

   This approach has advanced syntactic interoperability but relies on static semantics that are rigid and brittle amid domain diversity and evolving technologies (Bittner et al. 2006). Because semantics are often implicit or narrowly defined, mismatches must be resolved manually, limiting scalability and hindering dynamic cross-domain collaboration or rapid tool integration.

2. Logic-Based Ontology Approach (Semantic Interlingua with Refence Ontology)

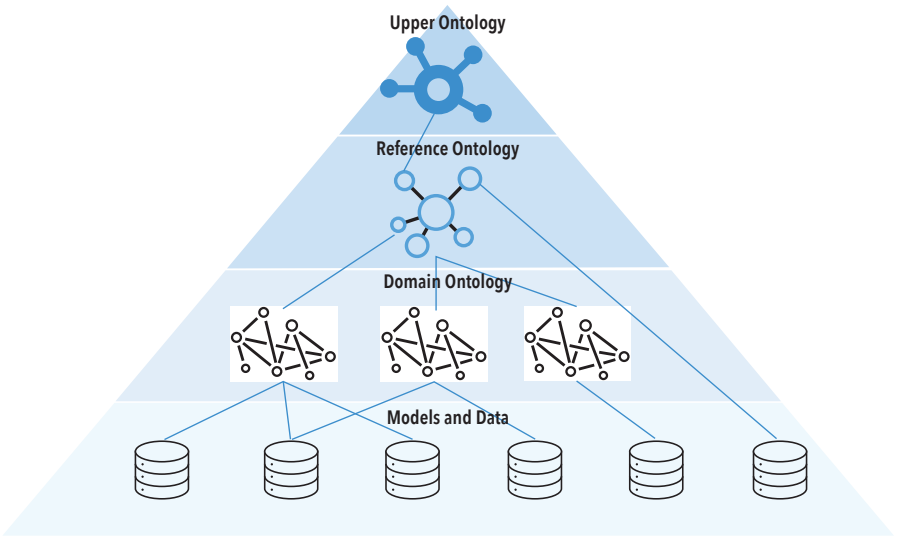


Figure 6. Logic-based ontology standards approach

   A more agile and scalable strategy uses logic-based ontologies to formally define the semantics of each application's terminology. Systems retain their internal ontologies but map them to a shared reference ontology—an interlingua defined in formal logic (Bittner et al. 2006). This enables automated transformation via inference engines, preserving meaning across tools with different coordinate systems, measurement conventions, or modeling assumptions. Standardized upper-level ontologies such as the basic formal ontology (BFO) ISO/IEC 21838-2 (ISO 2021) and common core ontologies (CCO) (Rudnicki 2019) are available to serve as these references for aligning disparate domain ontologies in systems engineering—though they currently lack a STEM-focused ontology foundational to all engineering disciplines. This approach is applied by the INCOSE Digital Information Exchange Working Group (DEIX WG) to develop a digital engineering ontology (Gregory et al. 2025). In the manufacturing domain, the Industrial Ontologies Foundry (IOF) core ontology—grounded in BFO—enables interoperability across manufacturing, supply chain, and MBSE collaborations (Drobnjakovic et al. 2023).

3. Adaptive Multi-Semantics Approach to Consistency Management

   In large programs, artifacts and data sources frequently employ different semantics, and true uniformity may be impractical. Ongoing system evolution and new phenomena drive paradigm shifts that continually alter semantic frameworks (Schindel 2020). Rather than enforcing a single standard, this approach tolerates multiple coexisting semantics, using explicit consistency

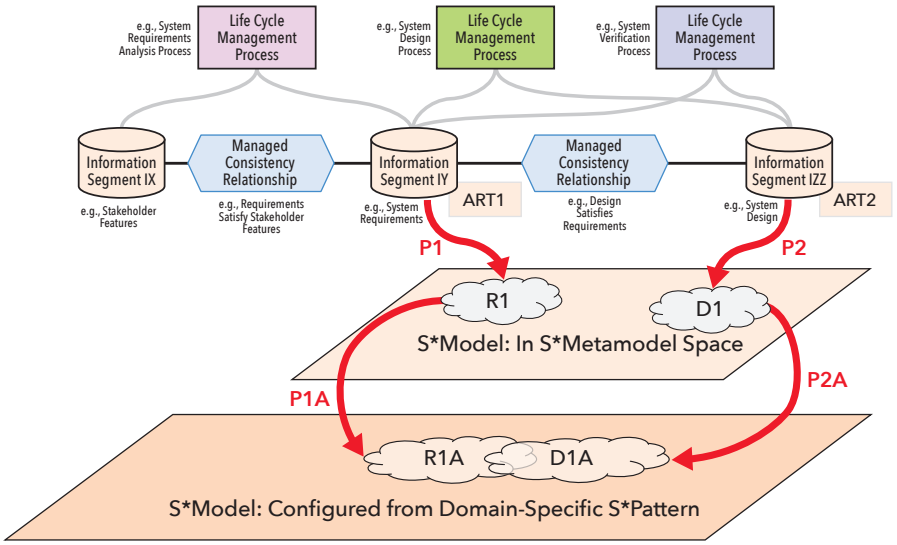


Figure 7. Understanding automated conversion as projections in vector sub-spaces

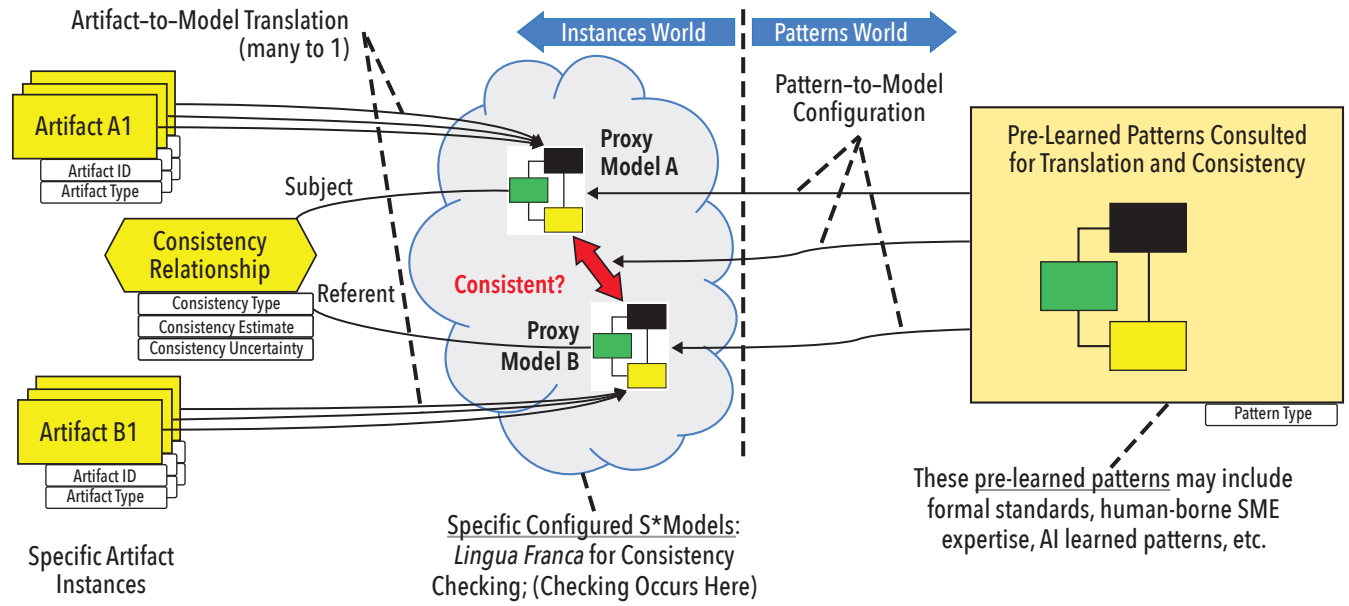


Figure 8. Checking consistency of artifacts by translating them to proxy models that are consistency checked

management to align them (Schindel 2021). The INCOSE MBSE Patterns Working Group is developing methods for machine-assisted translation of artifacts into standardized MBSE "proxy models" (Schindel 2025), based on the S*Metamodel as a STEM-based ontology (Schindel 2016 Patterns WG 2025). These proxies represent the original artifacts for cross-framework consistency checks, enabling dynamic interoperability across heterogeneous ecosystems (Figures 7 and 8).

Each of the three approaches—shared terminology, logic-based ontology, and adaptive multi-semantics—offers unique strengths depending on the use case. Shared terminology provides broad syntactic interoperability but lacks flexibility in rapidly evolving domains. Logic-based ontologies enable precise, automated semantic interoperability but require investment in semantic modeling. Adaptive multi-semantics accepts real-world variability, enabling pragmatic consistency management across diverse frameworks. No single approach is universally best; effective strategies often blend these methods to suit specific technical, stakeholder, and lifecycle needs. INCOSE and partner SDOs have an opportunity to combine these approaches to bridge technical standards and lifecycle models, advancing toward a federated, semantically robust ecosystem aligned with the *Systems Engineering Vision 2035*.

PROPOSED INTEGRATION STACK FOR INTEROPERABILITY STANDARDS

To support both syntactic and semantic integration, we propose a layered approach: an integration stack for interoperability standards (see Table 2 and Figure 9). This framework defines six layers: (1) infrastructure, (2) syntactic exchange, (3) semantic annotation, (4) domain ontology, (5) reference ontology, and (6) upper ontology. Each layer serves a specific role in enabling meaningful, structured, and scalable information exchange across systems and organizations. For systems

Table 2. Integration stack for interoperability standards

Layer	Purpose	Standard Categories	Example Standards
6. Upper Ontology Layer	Foundation for shared logic and cross-domain alignment	Upper-level, formal logic ontologies	BFO, DOLCE, SUMO, ISO/IEC 21838
5. Reference Ontology Layer	Provides shared interlingua for mapping domain models	Mid-level ontologies derived from upper ontologies	Common Core Ontologies (CCO), Industrial Ontologies Foundry (IOF) Core
4. Domain Ontology Layer	Encodes domain-specific semantics	Formal or semi-formal ontologies for engineering, manufacturing, etc.	CASCaDE Ontology, DEIX Ontology
3. Semantic Annotation Layer	Provides contextual meaning for data/model elements	Standards for annotation, semantic linking	RDF, OWL, SKOS, OSLC Resource Shapes, DEIX DVM concepts
2. Syntactic Exchange Layer	Structures how data is exchanged across tools and services	File formats, data schemas, exchange protocols	XML, JSON-LD, STEP (AP242/239), ReqIF, XMI, FMI, QIF, DEIX DVM
1. Infrastructure Layer	Transport and messaging	Network, transport, and API protocols	REST, HTTP, MQTT, OSLC Services, GraphQL

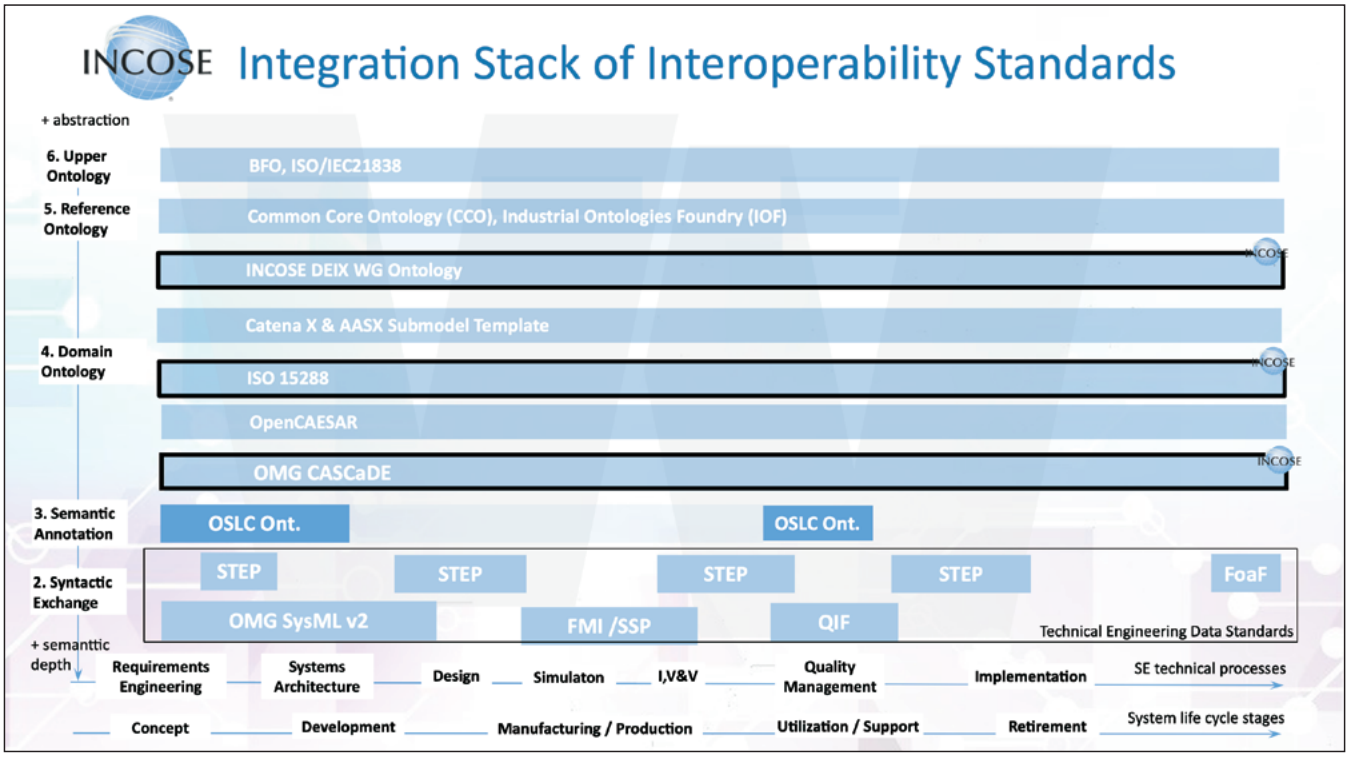


Figure 9. Integration stack of interoperability standards across system technical and management processes

engineers, it preserves data structure and meaning—supporting consistency, analysis, and decision-making. For tool providers, it offers a modular integration path that supports innovation within individual layers while aligning to a broader digital engineering ecosystem. This integration stack approach creates a flexible, scalable foundation for connecting diverse tools and standards across technical and management processes.

Figure 9 illustrates the layered integration stack for interoperability standards against the systems engineering technical and management processes, reflecting syntactic and domain-specific standards across all lifecycle stages. The standards shown in Figure 9 represent commonly used and developing systems engineering standards today. In the future, this mapping will continue to evolve and refined in alignment with INCOSE's standard development strategy to address emerging needs in model-based and digital engineering.



Figure 10. INCOSE strategic objective: advance system engineering as the world's trusted authority

PROPOSED INCOSE STANDARD DEVELOPMENT METHODOLOGY WITH SDOS

INCOSE is positioned to play a strategic role in shaping the future of systems engineering standards—an emphasis reinforced in the INCOSE Strategic Plan (Figure 10) (INCOSE 2024). To address interoperability challenges, INCOSE can continue and expand partnerships with SDOs such as ISO, OMG, and IEEE. Acting as an "independent broker," INCOSE can help integrate and govern changes to standards developed by multiple SDOs (see Figure 11).

INCOSE has initiated a MBSE–DE Integration Forum to align and scale the work of individual INCOSE WGs by coordinating users, vendors, researchers, and multiple WGs to identify ISO 15288-linked use cases, apply the interoperability stack, and surface standards gaps. Current examples include the Tool Integration and Model Lifecycle Management (TIMLM) Working Group, which is developing use cases for MBSE architecture co-development between OEMs and suppliers using diverse tools. The MBSE Patterns Working Group is addressing consistency management across lifecycle processes, while the DEIX Working Group is advancing use cases for digital artifact exchange using viewpoint models and ontologies. INCOSE also contributes use cases to OMG's CASCaDE, connecting standards from ISO, OMG, and Modelica. Maintaining a curated

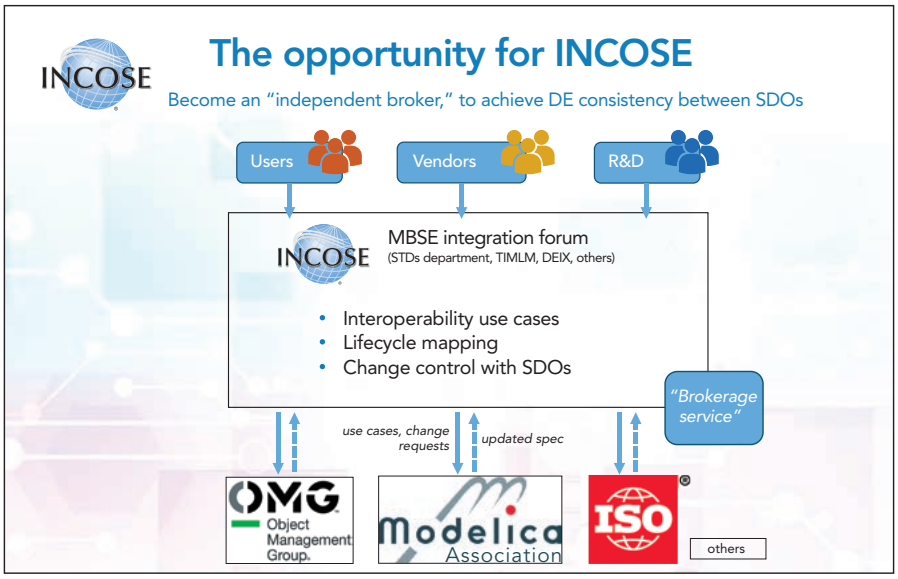


Figure 11. Proposed INCOSE standard development framework

catalog of interoperability use cases and lifecycle mappings would guide SDO collaboration, enabling iterative standards improvement and reinforcing INCOSE's leadership in building agile, standards-based DE ecosystems.

CONCLUSION AND PATH FORWARD

Interoperability is essential to the future of model-based, digitally connected systems engineering. While advances like SysML v2 represent major progress, significant gaps remain—particularly in achieving seamless, semantically aligned integration across tools, domains, and organizations. INCOSE can play a unique leadership role by identifying high-impact interoperability use cases and collaborating with SDOs to close these gaps.

We recommend applying a design science research (DSR) methodology, anchored in the ASELCM Pattern, to ensure emerging standards address real-world lifecycle needs. Consistency management should be the foundation for enabling digital thread continuity and cross-organizational collaboration. The Industrial Ontologies Foundry (IOF) in manufacturing illustrates how logic-based ontologies can enable scalable interoperability and digital twin innovation, but systems engineering still needs a STEM-informed ontology to fill critical foundations.

INCOSE has launched a standards task force to define its long-term standards strategy. Beginning with coordinated working group efforts at INCOSE IW 2026, this initiative will work toward an open, scalable, and semantically robust interoperability framework—advancing the vision set out in the *Systems Engineering Vision 2035*. ■

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