# Innovation Ecosystem Dynamics, Value, Learning II: Can V&V Frameworks Tell Us More?

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**Abstract**. Can innovative system projects deliver faster, while also increasing earned confidence in the face of risk? This is not only a question of organizational paradigms, methods, and management—if we "push the envelope" far enough, it also begs the question of foundational limitations on underlying phenomena and capabilities of all systems of development, production, and other life cycle management, viewed as systems in their own right. Limitations on capabilities (including risks) of an engineered aircraft, bridge, or motor vehicle are ultimately constrained, through their designs, by underlying first principle phenomena. Is this perspective also applicable to phenomena of socio-technical innovation ecosystems?

This second paper in a series picks up where the first left off—with the underlying dynamics of systems of innovation, viewed through a Hamiltonian lens. That perspective showed how verification and validation (V&V) can be seen as more than the traditional "checks on the main work". Instead, they highlight *consistency gaps* which define the potential energy framework of the innovation ecosystem's Hamiltonian, driving the entire ecosystem.

But what happens when V&V frameworks, created in eras of pre-information technologies, are applied to engineering of cyber-physical systems? This paper summarizes results of a recent cross-disciplinary study of V&V frameworks of four technical societies, covering a range of engineered cyber-physical systems.

It may seem impractical to apply the mathematics of historical hard technologies to the human-intensive socio-technical systems of the supply chain ecosystem itself. But as a greater portion of such ecosystems are implemented in machine learning agents, the dynamics of such a hybrid human-IT socio-technical ecosystem, managing engineered cyber-physical systems, becomes a more attractive subject. Foundational limits don't just tell us what is impossible—they also tell us what is possible.

**Keywords.** Innovation Ecosystem, Verification and Validation, Cyber-Physical System, Hamiltonian, Machine Learning, Rapid Delivery, Risk Management

## Introduction

Both commercial and defense domains have pressing interests in dramatically improving the performance of innovation ecosystems—the socio-technical supply chain systems of development, production, supply and distribution, and other life cycle management. Such ecosystems are often described in terms of human-

performed technical and business processes, in the presence of risk and uncertainty, process stage gates, and including the subject matter of the INCOSE Systems Engineering Handbook. (Walden et al, 2023)

Is it possible for innovative system projects to deliver much faster, while also increasing earned confidence in the face of risk, formalizing related trade-offs? A refreshed perspective on these innovation ecosystems may be needed.

This paper begins with a brief review of its paper series predecessor, establishing the applicability of Hamiltonian mathematics to information systems and socio-technical systems, along with the Hamiltonian's potential energy role of supply chain project *consistency gaps*. These are related to verification and validation (V&V) frameworks.

The next section reviews the 2024 Rosetta Stone Project, in which members of four engineering technical societies have compared different standards-based V&V frameworks, and mappings between them. This informs the connection of the energy-based consistency gaps to V&V frameworks, but also shows the challenge that current standards-based V&V frameworks are not aligned with each other.

Next, attention is focused on how consistency management of models makes possible more effective, rigorous, and potentially automatable consistency management for V&V in general. This can also include exploitation of model-based patterns (configurable recurrent models).

Following that, the paper returns to foundational limitations on the performance of innovation ecosystems. Both speed and uncertainty are considered. Foundational limits also reveal what may be possible.

The paper concludes with implications for understanding and improving innovation ecosystem performance, and next steps within the INCOSE working groups pursuing related goals in support of FuSE.

## Innovation Ecosystem Hamiltonian: Energy from Inconsistency

The series predecessor to the current paper (Schindel, 2024) reviewed traditional issues and literature on approaches to improving the performance of innovation ecosystems. It then detailed some of Hamilton's mathematical contributions concerning energy-like characteristic functions and generalized momentum, and showed that these can be applied to information systems and socio-technical systems. The heart of that paper argued that the web of *managed consistencies* of an innovation ecosystem project provide state variables (consistency states) that describe the Hamiltonian's potential energy driving the project.

The consistency management perspective emphasizes learning and its application. Figure 1 illustrates the INCOSE Agile Systems Engineering Life Cycle Management (ASELCM) Pattern, used to plan or analyze any innovation ecosystem, and in which consistency management may be performed during a project. (Schindel, 2022) Figure 2 illustrates a segment of a *consistency thread* of such a project, in the context of the "Systems Engineering Vee Diagram" of technical processes familiar to systems engineers, described in the INCOSE SE Handbook (Walden et al, 2023) and ISO 15288 (ISO, 2023). These formalize the concepts of diverse consistency relationships between various information segments (information artifacts).

The example of Figure 3 reminds us that the set of consistency relationships for real projects is not just a one-dimensional linear *thread*, but instead of *web* of inter-artifact managed consistency relationships. This diagram includes notional *springs* whose stretching represents the degree of inconsistency between various information artifacts during the project. These springs and their stored energy become more than a mere metaphor when the managed inconsistencies are accounted for as the loss function to be minimized by the project. This is where the project's Hamiltonian enters the picture, as described in the predecessor paper.

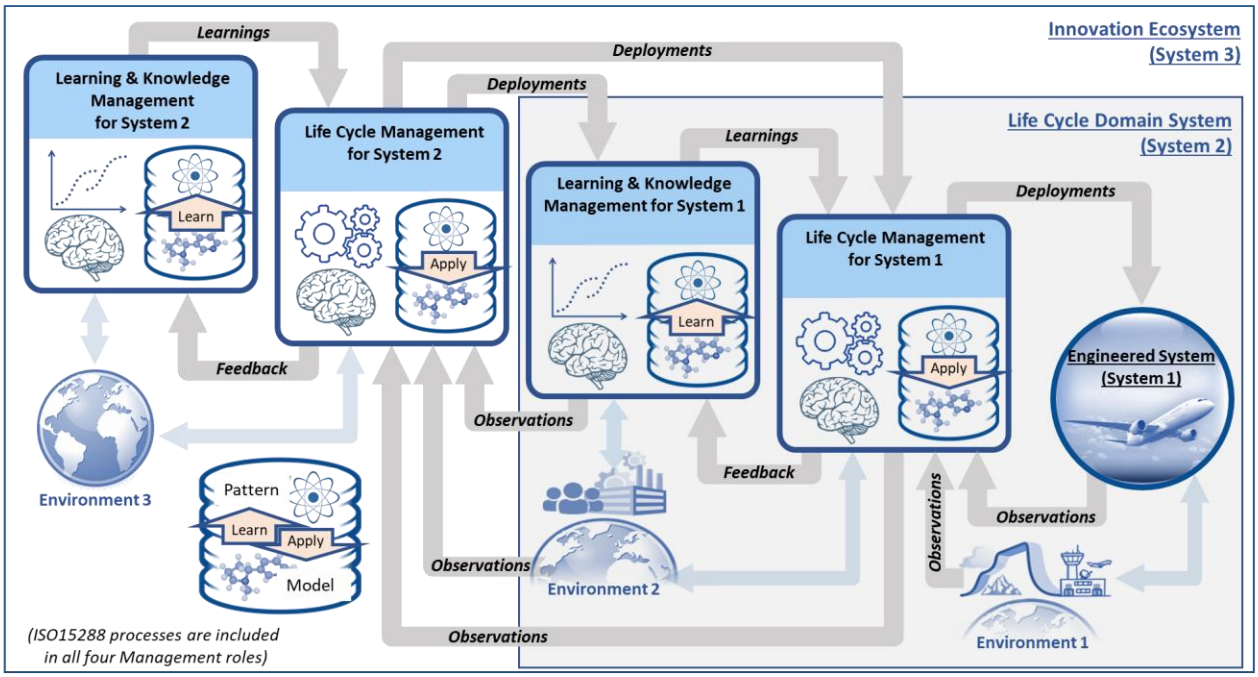



**Figure 1. INCOSE ASELCM Pattern, Level 1 View (the Innovation Ecosystem)**

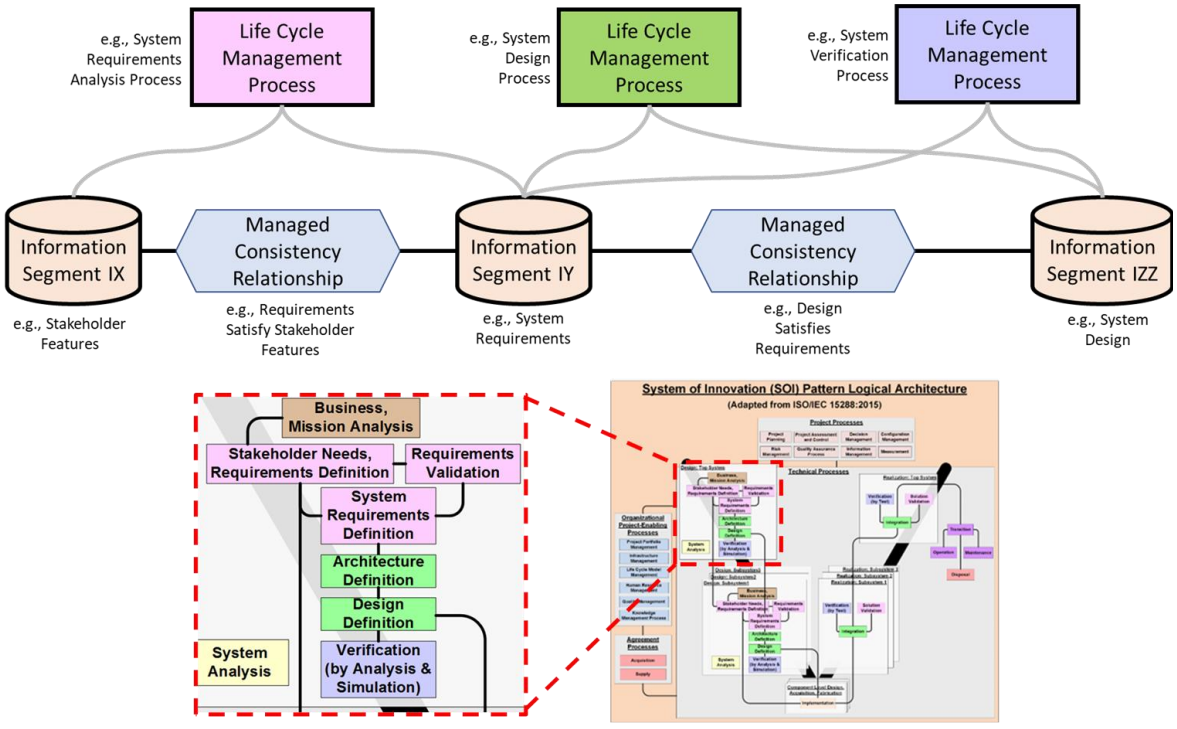



**Figure 2. Example of Section of Consistency Thread**

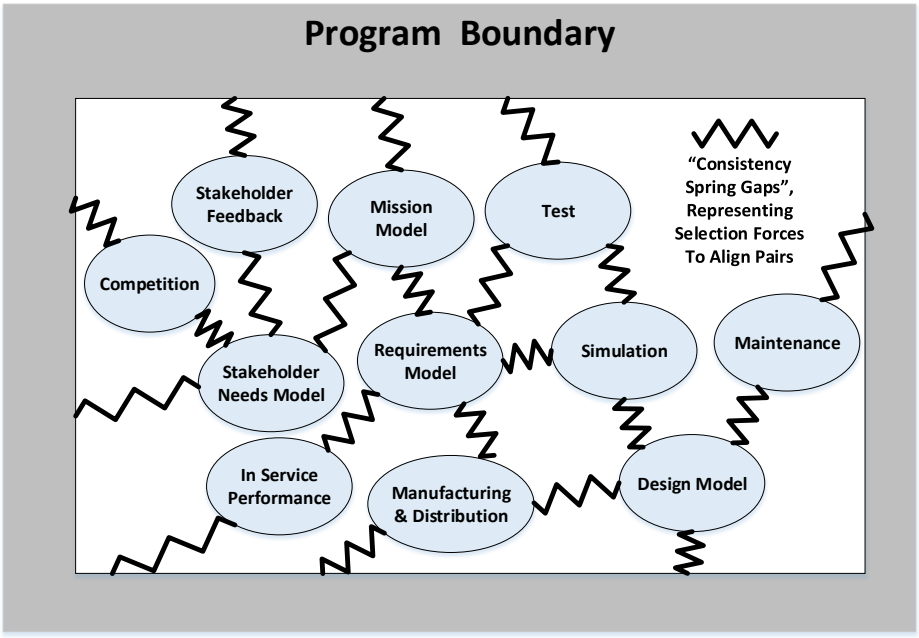



**Figure 3. Web of Managed Consistencies--Not Just a Thread**

When these collective consistency gaps are combined into an overall program consistency state, Figure 4 illustrates the idea that a well-managed program may discover (learn) over the course of the program to reduce overall inconsistency to an acceptable level. This diagram also shows what happens when a failing program's inconsistency diverges.

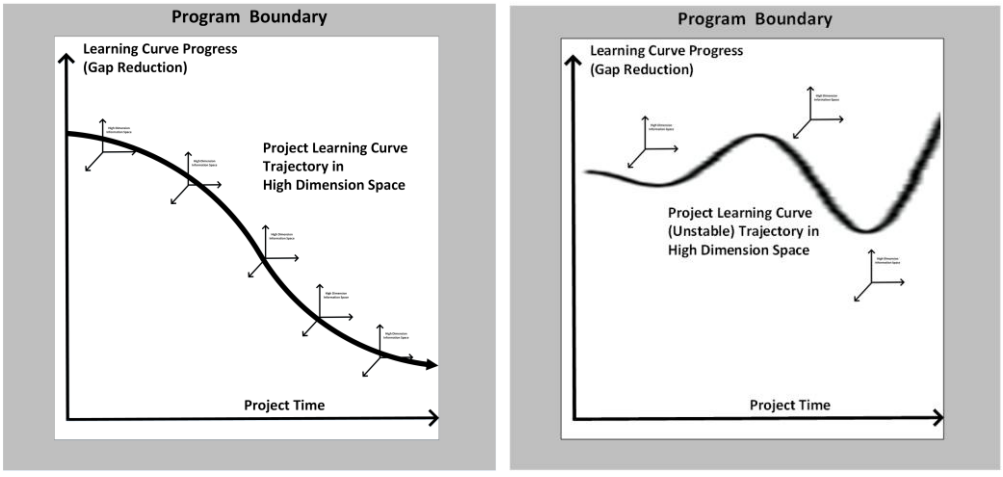



**Figure 4. Combined Program Consistencies Status of Converging and Diverging Projects**

Figure 5 illustrates an example consistency web segment of information artifacts in a manufacturing product program, involving a vehicle program spread across Tier 1 and supplier enterprises in a combined supply chain. This diagram should not be viewed as flow of information, but rather as a web of consistencies being managed, in which the lines connecting artifacts represent managed consistency relationships.

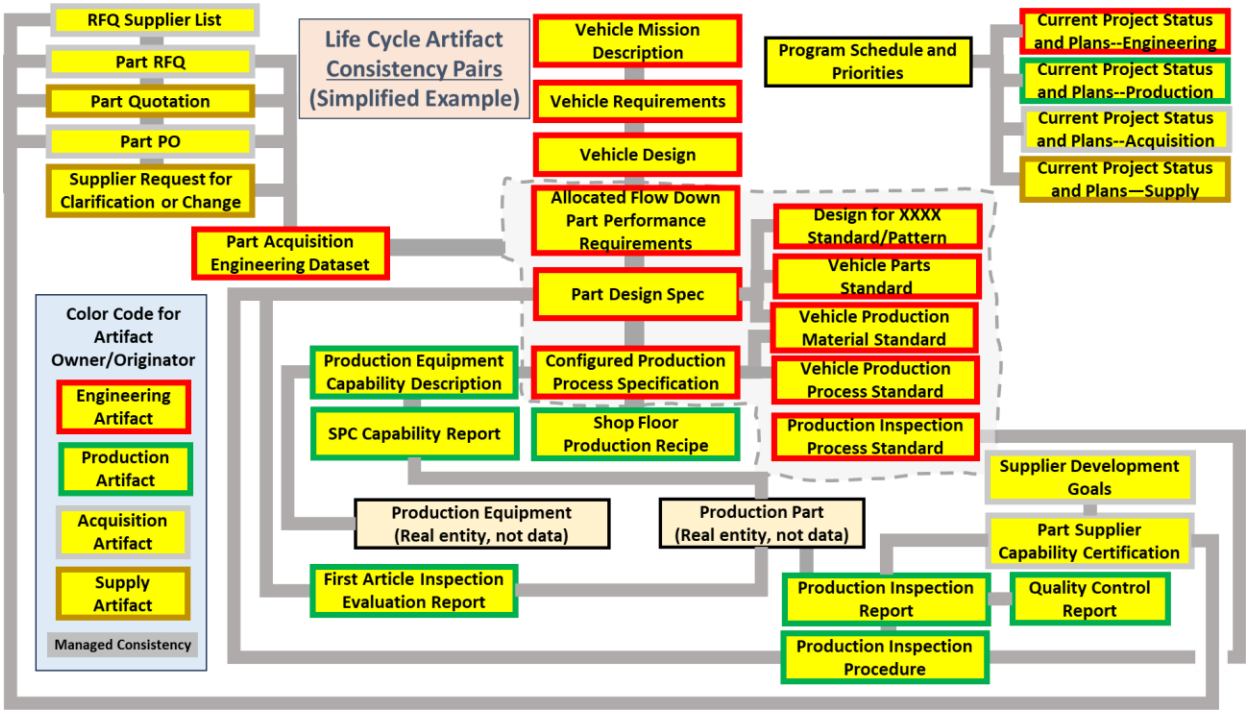



**Figure 5. Segment of an Example Manufacturing Product Consistency Web of Artifacts**

Those diagrams are intended to emphasize an expanded *consistency management* view of verification and validation, in which the full collection of consistencies being managed is *more than just a check on the main work* of the project. If we view consistency management as detecting and reconciling inconsistencies, then such *consistency management becomes the main creative technical and management work* of delivering the product, viewed from an information perspective.

Instructively, such a view of detection and reconciliation is also aligned with the internal algorithms of machine learning and its generative applications, whether we intend to apply AI technologies or not. (LeCun, Bengio, Hinton, 2015). This is an expanded view of V&V, whether performed by human labor and expertise, or by AI assistants, or a hybrid of both. It reminds us that, even though a program may be grounded in the work of people, equipment, laboratories, manufacturing lines, physical prototypes, and test beds, all that activity is really about learning a combination of information segments which fit together with acceptable levels of consistency.

Extending the historical concept of document trees found in systems engineering management plans (SEMPs), when configured for a specific project, the ASELCM Pattern can be used to auto-generate the plan for an artifact web of consistencies pairs, such as illustrated by Figure 5. It does so by using the segment of the Level 2 ASELCM Pattern shown in Figure 6. The complete web so generated becomes a form of *credibility assessment framework* (CAF). (Kaizer, 2018 ) (Rhodes, 2020)

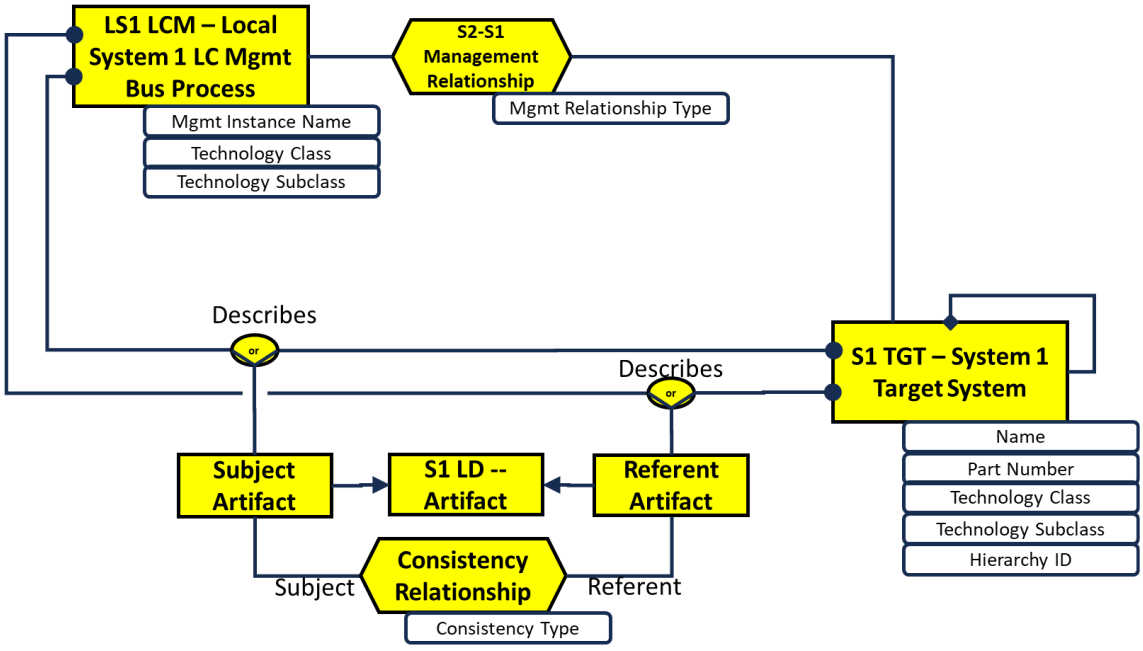



**Figure 6. Segment of ASELCM Pattern Level 2, Used to Auto-Generate Consistencies Plan**

This leads us to turn to how existing formal standards frameworks for verification and validation are aligned for this use, and especially when they are applied to complex cyber-physical system products.

## Standards-Based V&V Frameworks: The Rosetta Stone Project

Verification and validation (V&V) have long histories in the practice of delivering products, including their treatment in the INCOSE Systems Engineering Handbook and the ISO 15288 standard upon which it is based. Of particular interest for this paper are the ISO15288 explicit notes to the effect that verification and validation can apply to any of the artifacts of the life cycle management processes. While it is common to see those V&V terms applied to certain traditional artifacts, applying them to all artifacts is less common (unless perhaps we count "signing off" as performing V&V). Whatever may be current practice, it is notable that this primary INCOSE reference explicitly calls out the option of applying V&V to potentially all artifacts—a form of consistency management summarized by the previous section.

Some of the specific details of V&V necessarily depend on the types of information artifacts, the types of artifact-described components and technologies, and the types of consistencies being checked. ISO 15288 is by intention a generalized framework applicable to systems and technologies of any type, so we must turn to more specialized references when seeking technology-specific details of V&V. Two related questions are of particular interest in this paper:

1. Model-Based Simulations: What do V&V standard frameworks that are specific to V&V of computational models and simulations have to say about technology-specific aspects of V&V?

2. Integrated Cyber-Physical Systems: When a system contains an integrated combination of information technologies and other (e.g., mechanical, electronic) technologies, how are different technology-specific V&V frameworks performed to gain confidence in the overall integrated system?

The rise of information technology in these spaces drove need for standard frameworks to support shared understanding and confidence. (Thacker et al, 2004). Several technical societies have published important standards specifically for V&V of computational models, for engineering or scientific purposes, including NAFEMS (Rogers et al, 2020), ASME (Moorcroft, Mahadevan, et al, 2022), (Moorcroft et al, 2019), (Coleman et al, 2016), (Morrison et al, 2018), and AIAA. (Mehta et al, 1998). These describe numerous details of V&V that are specific to computational models, including those related to numerical methods, iteration, convergence, finite element considerations, software quality assurance, and other details.

Since ISO 15288 describes V&V in general terms for systems, independent of their technologies, one might expect to find that the specialized standards for V&V of computational models would be special cases of the more general ISO 15288 standard's V&V provisions, but provide enhanced details specific to computational model V&V. In other words, the specialized standards would be consistent with the ISO 15288 V&V, but more specialized in their detailed aspects unique to computational models. However, this is not the case for some very fundamental aspects:

1. Verification and validation of systems under the ISO 15288 framework are grounded in requirements. This includes not only verification and validation of systems with respect to their requirements, but validation of the requirements themselves, among other things.
2. Verification and validation of computational models under the ASME VVUQ standards framework (as summarized by ASME VVUQ-1) are focused on characterizing the quantitative accuracy of a computational model, but not with respect to application-specific requirements on that accuracy.

So, even a term as basic as "validation" means something quite different in these two frameworks. When planning the verification and validation of an integrated cyber-physical system, how are the different discipline practitioners to satisfy V&V standards applicable to technology specific components, subsystems, and the integrated system in such a way as to maintain rigorous understanding and confidence in the overall system? An example illustrating this challenge is the integration, into a complex machine tool product, of intelligent software-based models predicting tool bit wear. How is confidence in the overall resulting system established through V&V, as described in the various applicable standards frameworks?

In order to better understand the current landscape of V&V framework standards related to computational models compared to systems in general, in early 2024 members of four technical societies began the Rosetta Stone Project (Fischer et al, 2025). The goal of this one-year collaboration was to establish an initial *mapping* between the existing V&V standard and guideline frameworks of ISO 15288 standard (ISO, 2023) frequently used by INCOSE, the NAFEMS ESQMS Engineering Simulation Quality Management System Standard (Rogers et al, 2020), the ASME VVUQ-1 definitional standards for computational models (Moorcroft, Mahadevan, et al, 2022), and the AIAA G-077 V&V Guide for V&V of Computational Fluid Dynamics Models (Mehta et al, 1978). Analogous to how the historical Rosetta Stone enabled an understanding of three different written human languages describing a common subject (Rosetta Stone History, 2024), this project focused on how the four different standards describe V&V of systems in general or computational models in particular.

The Rosetta Stone comparison mappings are elaborations based upon a much earlier representation of simulation model credibility terminology in (Schlesinger, 1979), implied by the graphic of Figure 7. Much has changed since that time (Oberkampf and Roy, 2010), but a core representational idea is preserved in the 2024 Rosetta Stone diagrams. The historical Figure 7 showed three information sources: Reality (to be simulated), a Conceptual Model (at that time, a general conceptual model including mathematics, representing what is known or hypothesized about the Reality of interest), and the Computerized Model, an executable model that generates simulation data intended to simulate aspects of interest of the Reality of interest (and can be validated against it). Three connecting lines are shown in Figure 7, representing what were (in 1979) proposed standard terms for three kinds of consistency checks: Model Qualification, Model Verification, and Model Validation:

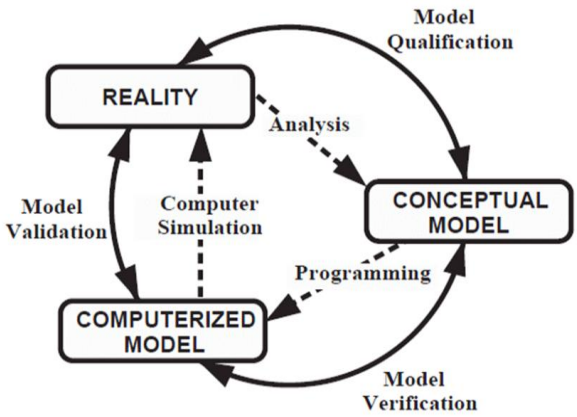



**Figure 7. Early Representation of Computational Model V&V Terms (Schlesinger, 1979)**

V&V for computational models has evolved since 1979, but the 2024 Rosetta Stone mapping diagrams still represent forms of V&V as checks of the consistency of line-connected information pairs. Figure 8 illustrates aspects of the Rosetta Stone mapping between V&V in ISO 15288 (ISO, 2023) shown in red, versus ASME VVUQ-1 (Moorcroft, Mahadevan, et al, 2022). Figure 9 similarly compares ISO 15288 to NAFEMS ESQMS (Rogers et al, 2020). Figure 10 similarly compares ISO 15288 to AIAA G-077 (Mehta, 1978).

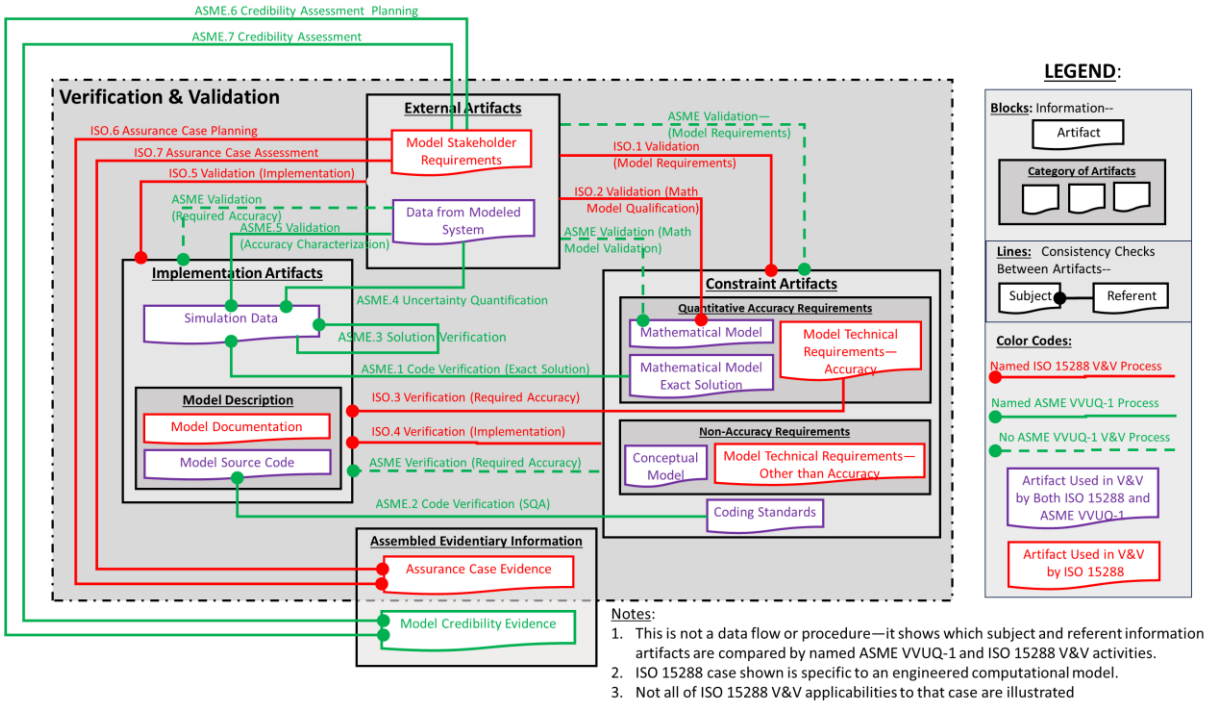



**Figure 8. V&V Standards--A Comparative Mapping for ISO15288 and ASME VVUQ-1 (Adapted from (Fischer et al, 2025))**

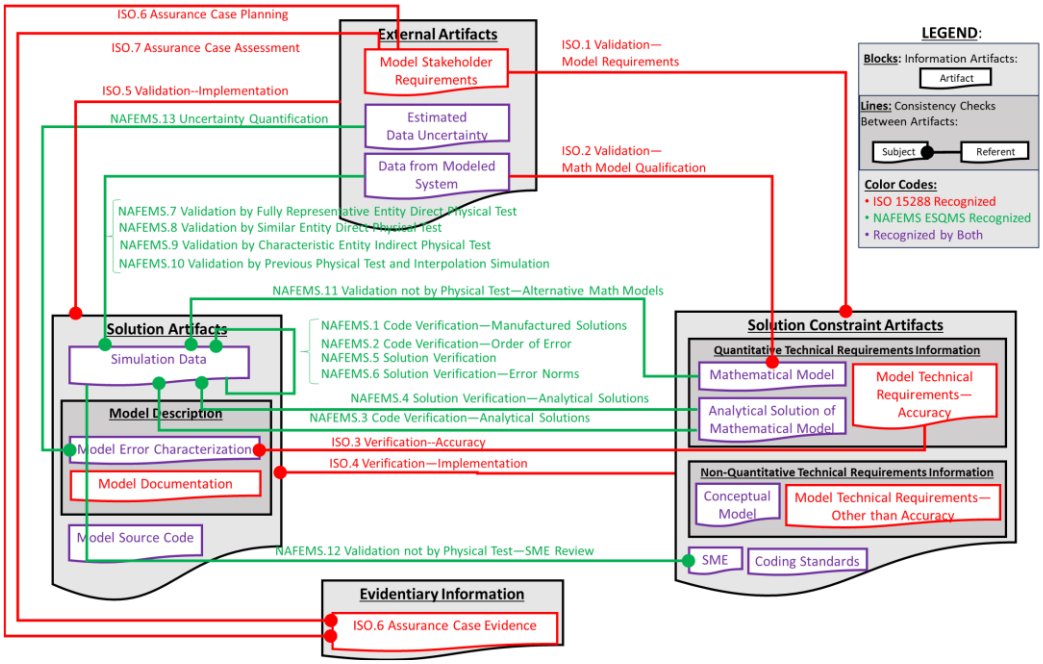



**Figure 9. V&V Standards--A Comparative Mapping for ISO15288 and NAFEMS ESQMS (Adapted from (Fischer et al, 2025))**

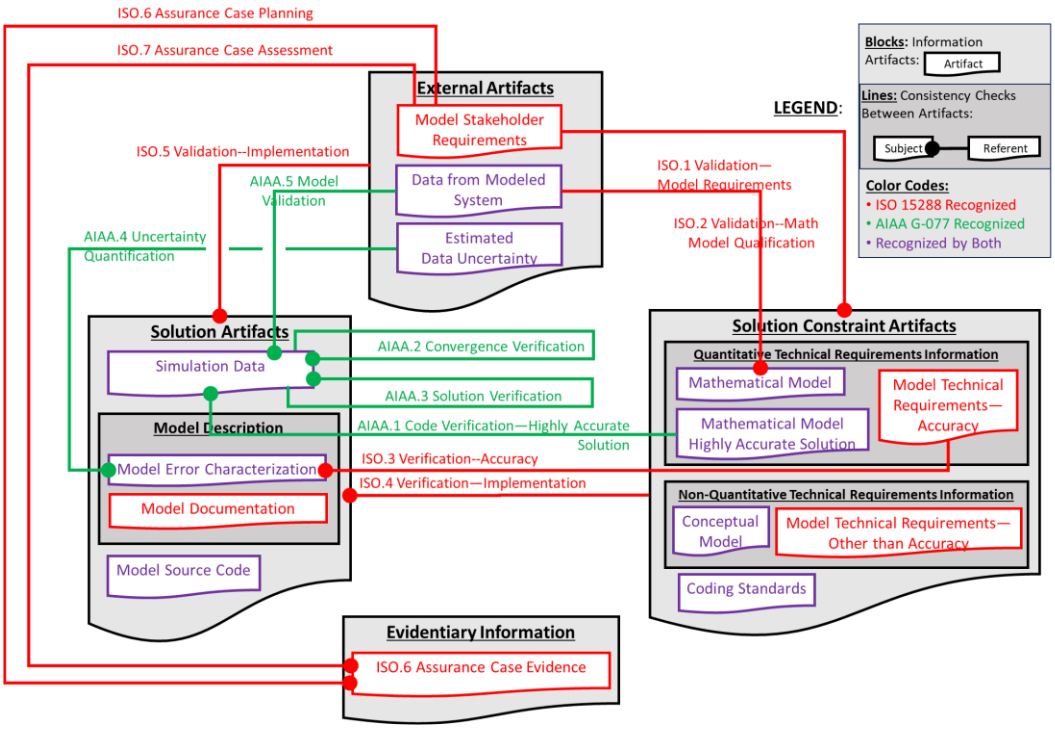



**Figure 10. V&V Standards—A Comparative Mapping for ISO 15288 and AIAA G-077 (Adapted from (Fischer et al, 2025)**

Definitions of the above are provided in (Fischer et al, 2025). Examples of V&V for computational models are provided in (Freitas et al, 2012) for structures and (Morrison et al, 2018) for medical devices.

# Verification and Validation of Models

For students of the INCOSE SE Handbook and ISO 15288, the targets of V&V are systems of all types. However, V&V of computational models has a special value significance.

## *Explicating the Information: Consistency Management of Models*

In current practice, managing the content consistency of information artifacts involves significant human-supplied subject matter expertise and effort. Some of that expertise is technology-specific, but there are other types of human expertise also required, including base natural language fluency, application domain-specific knowledge, project-specific or company-specific knowledge, and in some cases simple ability to even access the information to be managed, which may in part be outside of tangible information artifacts, spread across people. If models are used for some of those artifacts (such as descriptive Model-Based Systems Engineering (MBSE) models or computational models for simulation of system performance or production) then literacy in the modeling languages, conventions, or simulations may also be required.

Those are usually very significant barriers to both rigorous consistency management (managed uncertainty) and desired project schedules (managed speed). Any plan to pursue increased (and ultimately even continuous) consistency management must include a bridge across those historical barriers of required human effort and expertise. There are two powerful aids for creating such a bridge, and they can be combined:

1. After decades of development, the use of large language model (LLM) based artificial intelligence (AI) agents to analyze prose, diagrams, and other media has caught the attention of business and public. Generative extensions and applications of this technology have heightened that interest. How can this technology best be employed with confidence to improve consistency management?

2. Artifacts that are in the form of structured models are potentially more rigorously inspectable for their consistency with each other or with shared alignment patterns—particularly if the models are well-structured and coordinated. Current model-based practices are not that mature across industry. However, there is a significant history and literature of semi-automatic model consistency management in the case of model-based software (frequently UML). Some of these practices provide options for *light weight checks* (fast, easier screening, but incomplete) and *rigorous checks* (more costly but more complete). A sampling of that literature has been included following the main text References section. (Model Consistency Management Literature, 2004-2019)

An attractive option is a combination of (1) and (2) above, shown in Figure 11:

1. The use of LLM technology to semiautomatically translate today's varying document and description artifacts into well-structured S*Models (Schindel, 2011), (INCOSE Working Group, 2024b, d) that are more rigorously expressive.

2. The use of semiautomatic inconsistency detection, applied to the generated models. This can include generation of estimated uncertainties, as does a Kalman Filter.

Note that the approach of Figure 11 does not imply or require replacement of the project artifacts, which may be repeatedly translated to S*Models as they progress during the project, each consistency check cycle:

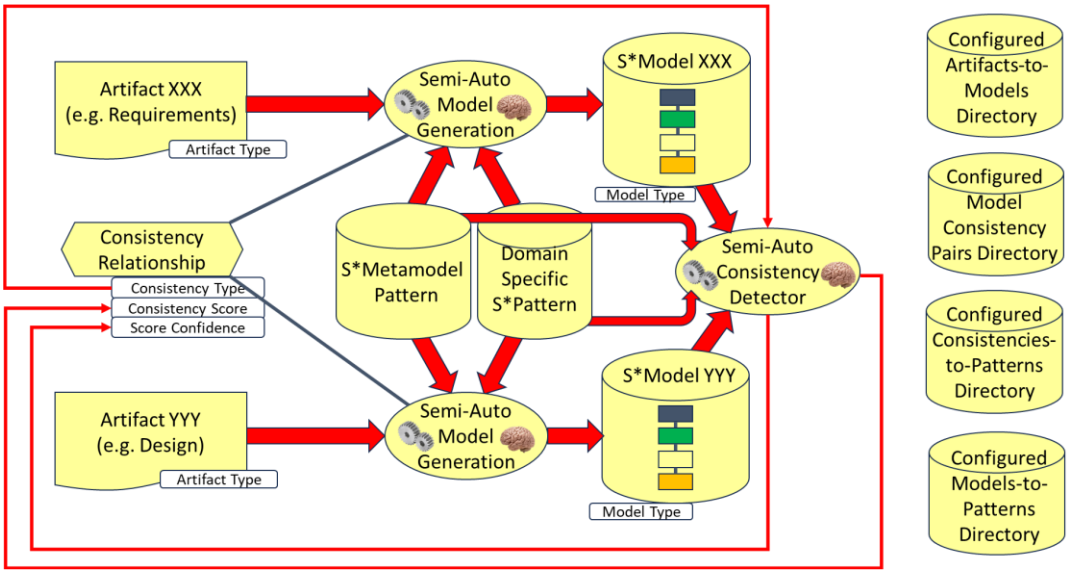



**Figure 11. Enhanced Inconsistency Detection by Translation to Explicit Models**

## *Using Model-Based Patterns in V&V Consistency Management*

*S*Models* are models in any tooling or modeling language that have been mapped to the S*Metamodel. So, an S*Model is any model satisfying the S*Metamodel. (INCOSE Working Group, 2024b)

*S*Patterns* are generalized S*Models of system families, and can be rapidly and semi-automatically configured to populate specific S*Model instances without requiring the modeling skills necessary to originate such a model de novo. Refer to Figure 12. S*Patterns may describe families of domain-specific engineered products, manufacturing systems, engineering processes, product lines, natural systems, or other systems. (INCOSE Working Group, 2024c) Those model-based S*Patterns are the focus of the work of the INCOSE Patterns Working Group, with examples. (INCOSE Working Group 2024a).

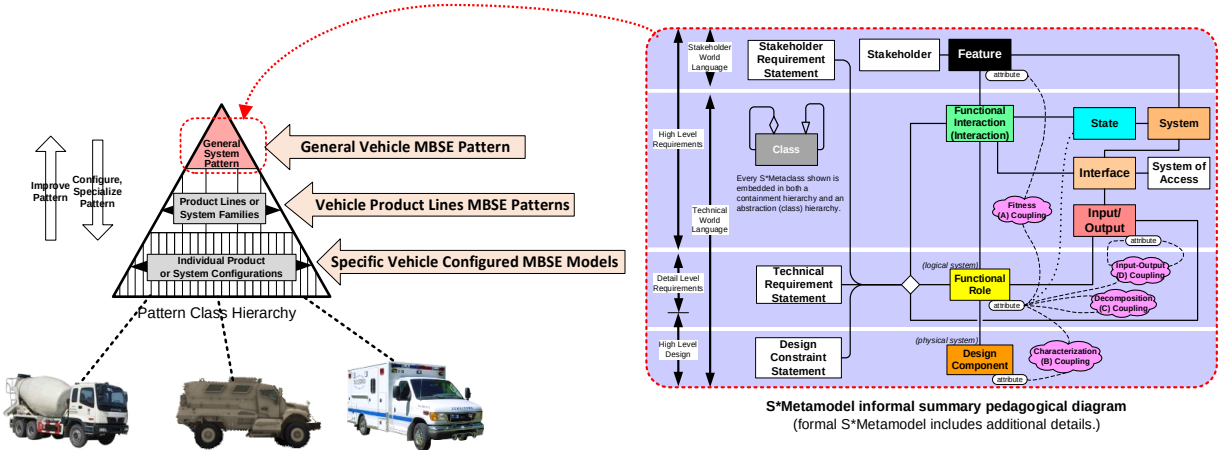



**Figure 12. S*Models Can Be Auto-generated from S*Patterns**

S*Patterns play several different roles in the consistency management scheme of Figure 11. In general, they reduce needs for human SME labor by capturing and sharing subject matter expert knowledge:

1. The Semi-Automatic Model Generation process is enhanced by consulting S*Patterns:

    a. The S*Metamodel formally defines the pattern of general semantics of all S*Models, including those to be distilled from Artifacts. This reduces the need for human subject matter expertise in S*Models basic to generating the S*Models.

    b. Domain-specific S*Patterns (if available) provide additional domain specific semantics that can specialize or constrain additional aspects of these models, such as names. This reduces need for human domain subject matter expertise in generating the S*Models. Human SME input is provided where such S*Patterns are not available.

2. The Semi-Automatic Consistency Detector process is enhanced by consulting S*Patterns:

    a. The S*Metamodel formally defines the pattern of consistency checks inherent for all S*Models, including those model pairs to be consistency checked. This reduces the need for human subject matter expertise in S*Models basic to consistency checking the S*Model pairs.

    b. Domain-specific S*Patterns (if available) provide additional domain specific consistency checks that specialize or constrain the consistency checks. This reduces the need for human domain subject matter expertise in consistency checking the model pairs. (It is important to understand that checking the consistency of two models with each other will frequently call upon domain knowledge not present in either of the two models being checked against each other. Knowledge of science, technology, engineering, or mathematics (STEM) belongs here. For example, whether a particular material in a part design satisfies the requirements for a part's performance calls upon pattern knowledge from material science.) Human SME input is provided where such S*Patterns are not available.

## Foundational Limits Also Describe Foundational Possibilities

Understanding foundational limitations imposed by underlying phenomena does not just tell us what cannot be done—it also tells us what may be possible, as in thermodynamics history. Returning to the capabilities of the Innovation Ecosystem, we can return to the introduction's questions about its speed and risk.

### *Speed: Parallelizing The Innovation Processes*

We have an interest in whether the underlying innovation process is inherently serial and must repeat hierarchically, versus whether it may be *parallelized for iteration*. This interest applies in both manually-performed and automated cases.

Traditional system decomposition provides an example. During the innovation process, at a given system decomposition level, once decomposition at that level has occurred and requirements flowed to system components, much work on separated system components can proceed in parallel. This may lead to feedback that impacts the decomposition plan and in turn other system components. Real or simulated integration of the decomposed elements may likewise uncover issues impacting the decomposition plan. If we add consideration of effects such as external sourcing and internal manufacturing, more cases of this feedback are seen. "Shifting left" in the systems engineering "Vee" diagram, by more "left side" analysis and simulation has been a popular way to reduce the surprise of late "right side" discoveries. However, even with a heavy and successful shift to the left (also hierarchical) side, there are still multiple loops of iteration up and down the left side.

Is there a way for enhanced V&V to further parallelize the innovation process, as consistency management? Referring to Figure 11, the use of Domain Specific Patterns for hierarchical consistency checking is such a step. This depends upon managing past learning as intellectual asset patterns to be applied in future projects. Part of managing that learning is the management of uncertainty, whose quantification returns us to the subject matter of VVUQ of models. Improving the alignment of standards-based V&V frameworks for models is a part of the journey to that destination. V&V is itself a generator of uncertainties.

## *V&V Confidence: Uncertainty, Kuhn's Essential Tension, and Diversity*

Discovery and learning never end--even models with a high degree of earned confidence are only "right" until they are "wrong". So, consistency management must provide for evolution in the referents to which subjects are compared. The INCOSE Agile Systems Engineering Life Cycle Management (ASELCM) Pattern (also known as the Innovation Ecosystem Pattern) of Figure 1 provides an enterprise level reference model emphasizing evolutionary learning—whether the learned patterns are in the heads of subject matter experts or in the formally recorded patterns learned by the enterprise and its machine learning assistants.

This reference pattern for group learning helps us analyze, plan, or implement improvements for any innovation ecosystem. It recognizes learned patterns, whether in the heads of human SMEs or the computers of their automated assistants. The feedback loops and learning provide a place to address a fundamental balance of both technical systems and human life, referred to by Thomas S. Kuhn as "The Essential Tension" (Kuhn, 1977).

Engineered systems for optimal estimation and control have demonstrated previously unimagined triumphs in communication and navigation (Voyager, 2024), (Cassini-Huygens, 2024), by optimizing against fundamentals. A leading example is the Kalman Filter (Kalman Filter, 2024), with Bayesian inference history tracing to Rev. Thomas Bayes (Bayesian Inference, 2024). This leads to balancing the influence of previous belief (extracted from past experience) versus responding to new information. Rudolf Kalman addressed that balance as a mathematical optimization of Bayesian estimation in the presence of uncertainty arising from lack or corruption of perceived signals (epistemic uncertainty) versus random variation in the real behavior of systems (aleatory uncertainty). In a Kalman Filter, this leads to optimizing ratios of certain filter gain (weight) parameters (on past knowledge versus new signals) and Kuhn's Essential Tension. For an example, see (Schindel, 1972). For a human facing potentially shifting patterns in the presence of uncertainties, it is described by Kuhn as "…the ability to support a tension that can occasionally become almost unbearable is one of the prime requisites for the very best sort of scientific research." (Kuhn, 1977)

The ASELCM Pattern of Figure 1 is concerned with representing innovation ecosystems' balancing of those two: What we have learned in the past (as learned patterns) and what we are newly encountering. Like other perceived foundational constructs, this perspective both tells us about limits to what can be achieved, while also encouraging us to strive to reach those limits.

Diversity offers another fundamental resource. Even optimally balanced models for V&V may still present too much uncertainty or risk. When a program must rely upon systems whose V&V uncertainty is too large, alternate approaches, redundancies, and fail-safes may be used to reduce combined uncertainty, as long as the probability distributions of the sources of uncertainty are believed to be sufficiently independent.

# Conclusions, Implications, Next Steps

1. The Innovation Ecosystem Pattern and Hamiltonian mathematics tell us that the potential energy driving a program forward comes from the consistency gaps of its framework of (potentially expanded) verification and validation artifact pairs. (This conclusion was an input to this paper, from its series predecessor, now seen in a V&V context.)

2. Although ISO 15288 provides a generalized standard system & software framework for verification and validation, there are other V&V frameworks standardized by other technical societies, including those for computational models. For innovation projects targeting cyber-physical systems that embed computational models, gaining cross-discipline coordination across those V&V frameworks is vital to their integrated management for the combined system V&V.
3. Shrinking consistency management gaps during a program does not always need to occur in serialized stage-gate sequence, when pre-learned configurable model-based patterns are available for at least some aspects of the system problem and solution spaces. In those cases, consistency management of subsystem and component models against the pre-learned pattern can then be parallelized, replacing top-down serialized stage gates with faster, middle-out consistency management against the pre-learned pattern.
4. In addition to other benefits cited for model-based methods, models also enable V&V consistency detection that can be more rigorous as well as more automated. But the models themselves require V&V.
5. For enterprise programs whose artifacts are not model-based, this approach can semi-automatically translate the available artifacts into S*Models for use in semi-automatic V&V consistency checking, without forcing the adoption of models; it can also optionally accelerate the adoption of S*Models.
6. For enterprise programs lacking model-based patterns, human SME-borne patterns allow implementation of this approach, which can accelerate as the patterns are explicated as S*Patterns.
7. As S*Patterns become available, the V&V process can come closer to continuous V&V.
8. As S*Patterns become available, the development process can come closer to parallelization for speed.
9. The V&V process is still the arbiter of uncertainty, which is not eliminated by models or patterns. Balancing the "Essential Tension" of adaptation rate versus adherence to pattern is still fundamental. However, it provides options when defense or market crisis requires taking greater risk to achieve greater speed.
10. When V&V uncertainty-implied risk is judged to be too high but speed is nevertheless required, diversity can also be employed to reduced overall risk, provided the related probability distributions are sufficiently independent of each other.
11. A related joint project has been initiated by the INCOSE System Sciences Working Group and INCOSE Patterns Working Group, in support of the INCOSE Future of Systems Engineering (FuSE) Initiative.

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