INSIGHT

This Issue's Feature:

Systems Engineering in Early-Stage Research and Development: Bridging the Gap

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SEPTEMBER 2023
VOLUME 26 / ISSUE 3

INCOSE

A PUBLICATION OF THE INTERNATIONAL COUNCIL ON SYSTEMS ENGINEERING

INSIGHT

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About This Publication

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INCOSE's membership extends to over 20,000 members and CAB associates and more than 200 corporations, government entities, and academic institutions. Its mission is to share, promote, and advance the best of systems engineering from across the globe for the benefit of humanity and the planet. INCOSE charters chapters worldwide, includes a corporate advisory board, and is led by elected officers and directors.

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OVERVIEW

INSIGHT is the magazine of the International Council on Systems Engineering. It is published four times per year and features informative articles dedicated to advancing the state of practice in systems engineering and to close the gap with the state of the art. ***INSIGHT*** delivers practical information on current hot topics, implementations, and best practices, written in applications-driven style. There is an emphasis on practical applications, tutorials, guides, and case studies that result in successful outcomes. Explicitly identified opinion pieces, book reviews, and technology roadmapping complement articles to stimulate advancing the state of practice. ***INSIGHT*** is dedicated to advancing the INCOSE objectives of impactful products and accelerating the transformation of systems engineering to a model-based discipline.
Topics to be covered include resilient systems, model-based systems engineering, commercial-driven transformational systems engineering, natural systems, agile security, systems of systems, and cyber-physical systems across disciplines and domains of interest to the constituent groups in the systems engineering community: industry, government, and academia. Advances in practice often come from lateral connections of information dissemination across disciplines and domains. ***INSIGHT*** will track advances in the state of the art with follow-up, practically written articles to more rapidly disseminate knowledge to stimulate practice throughout the community.

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Publication Schedule. ***INSIGHT*** is published four times per year. Issue and article submission deadlines are as follows:

- December 2023 issue – 1 October 2023
- February 2024 issue – 1 November 2023
- April 2024 issue – 2 January 2024
- June 2024 issue – 1 March 2024
- August 2024 issue – 1 May 2024
- October 2024 – 1 July 2024
- December 2024 – 1 September 2024

For further information on submissions and issue themes, visit the INCOSE website: www.incose.org

 ISSN 2156-485X; (print) ISSN 2156-4868 (online)

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INSIGHT reaches over 20,000 members and CAB associates and uncounted employees and students of more than 100 CAB organizations worldwide. Readership includes engineers, manufacturers/purchasers, scientists, research and development professionals, presidents and chief executive officers, students, and other professionals in systems engineering.

Issuance	Circulation
2023, Vol 26, 4 Issues	100% Paid

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ADVERTISER INDEX September Volume 26-3

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FROM THE EDITOR-IN-CHIEF

William Miller, insight@incose.net

We are pleased to announce the September 2023 *INSIGHT* issue published cooperatively with John Wiley & Sons as the systems engineering practitioners' magazine. The *INSIGHT* mission is to provide informative articles on advancing the practice of systems engineering and to close the gap between practice and the state of the art as advanced by *Systems Engineering*, the Journal of INCOSE also published by Wiley. The issue theme is *systems engineering in early-stage research and development* (ESR&D): bridging the gap. Your editor attests to the successful ESR&D programs cited in the articles, having contributed in ESR&D programs and their transitions into the development, deployment, and fielding of systems as a practicing systems engineer, systems engineering functional manager, and chief systems engineer over several decades. We thank theme editors Michael DiMario and Ann Hodges, and the authors for their contributions.

Theme editors Michael DiMario and Ann Hodges lead off the issue addressing the phenomenon of a great many failures in early-stage research and development programs, referred to as the *valley of death,* that leads to enterprise hesitancy investing in ESR&D. Another phenomenon of ESR&D is an enterprise unwillingness to engage systems engineering in these programs because of the perception that systems engineering is heavily process oriented, adds unnecessary costs, and should be applied only to programs employing mature technologies. Their article cites examples where systems engineering was critical to the success of ESR&D that was foundational to the development and deployment of new systems at scale that advanced technologies to the benefit of humankind.

"A Bridge Blueprint to Span the Chasm Between Research and Engineering – A Framework for Systems Engineering in Early-Stage Research and Development" by Ann Hodges and Arno Grandos discuss the principles and foundational elements necessary for development and use of a framework for systems engineering applicable in ESR&D, including tailoring considerations associated with technology readiness levels (TRL) and stakeholder roles. They suggest metrics to enable evaluation and practical implementation of the framework for systems engineering innovation management at this phase of technology development.

"Systems Engineering in Technology Development" by Jaime Sly and David Crowne present a framework and guidance on systems engineering activities that add value and improve outcomes if applied during early stages of product development. Technology development in system development incorporates both scientific exploration and reduction to an engineered result. Applying systems thinking and systems engineering principles at this stage guide technologies to solve the right problems, progress the technologies to higher maturity levels, and implement workable architectures.

"An Approach to Bridging the Gap Between the Attainment of Research Objectives and System Application" by Susan Ruth provides a methodology and "language" that enables researchers and engineers to communicate more effectively to traverse the ESR&D valley of death. This methodology is the combination of established methods for communicating progress for a program combined with the development and application of domain assessments, called domain readiness levels (DRLs), specific to the domains relevant to the system of interest. DRLs are analogs to TRLs. The methodology enables two-way communication between the domain experts and the systems engineer, with the goal of effective incorporation of a technology. An example of the approach to bridge the valley of death is the development of a satellite composites optical support structure.

"Enhancing Early Systems R&D Capabilities with Systems – Theoretic Process Analysis" by Adam Williams demonstrates the benefit of systems–theoretic process analysis (STPA) for early system R&D strategy and development. The article describes diverse use cases for cyber security, nuclear fuel transportation, and US electric grid performance. The traceability, rigor, and comprehensiveness of STPA serves to improve R&D strategy and development. Leveraging STPA as well as related systems engineering techniques can be helpful in early R&D planning and strategy development to better triangulate deeper theoretical meaning or evaluate empirical results to better inform systems engineering solutions.

"Digital Engineering Enablers for Systems Engineering in Early-Stage Research and Development" by Arno Granados and Celia Tseng discusses

Industry 4.0, digital engineering (DE) transformation, and INCOSE working group efforts to illustrate how a systems engineering approach based on DE concepts facilitates rapid instantiation of key systems engineering process and elements in ESR&D projects. This approach is both enabling to foundational ESR&D efforts, and transformational in building a bridge across the valley of death to foster success in technology transition to product. An agnostic tool, standards-based framework is presented, and specific tools are used to illustrate ESR&D transformation.

"Incorporating Digital Twins In Early Research and Development of Megaprojects To Reduce Cost and Schedule Risk" by Christopher Ritter and Mark Rhoades quantifies how the incorporation of digital twin (DT) technology can reduce cost and schedule risk during ESR&D and later lifecycle stages in megaprojects. The Idaho National Laboratory demonstrated the application of DT in the Microreactor AGile Non-Nuclear Experimental Testbed (MAGNET) operations phase, showcasing the transformative potential of DT in both design and operation. These advances allowed real-time assessment of construction changes and their impact on project requirements. By focusing on the benefits of digital twinning, this article promotes a more positive attitude toward the incorporation of digital twin technologies in the early stages of R&D projects.

We hope you find *INSIGHT*, the practitioners' magazine for systems engineers, informative and relevant. Feedback from readers is critical to *INSIGHT*'s quality. We encourage letters to the editor at insight@incose.net. Please include "letter to the editor" in the subject line. *INSIGHT* also continues to solicit special features, standalone articles, book reviews, and op-eds. For information about *INSIGHT*, including upcoming issues, see https://www.incose.org/products-and-publications/periodicals#INSIGHT. For information about sponsoring *INSIGHT*, please contact the INCOSE marketing and communications team at marcom@incose.net. ■

INSIGHT Special Feature

Systems Engineering Management in Research and Development Valley of Death

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ABSTRACT

A failure of a great many early research and development programs is the result of encountering the traditional valley of death that shadows early research and technology development. The elements that create the valley of death leads to research and technology development high risk and poor return on investment for a great many research and development organizations. This leads eventually to avoiding research and technology development all together because the organizations cannot viably manage the outcome of their early-stage research and development (ESR&D) efforts. Unfortunately, there are few established frameworks and processes for enabling smooth transitions to avoid failure and manage risk across fundamental research, applied research, development, and productization. Many leaders, program managers, and scientists are unwilling to involve systems engineering because of the perception that systems engineering is heavily process oriented, adds unnecessary costs, and should be applied only to mature technologies. The value of systems engineering as applied to ESR&D is unclear to these key individuals. The unfortunate result is that systems engineering is not applied to ESR&D. This article discusses the potential of application of systems engineering to ESR&D to improve return on investment and decrease risk.

INTRODUCTION

Systems engineering in early-stage research and development (ESR&D), defined here as technology readiness levels (TRL) 1-5, is one of the most crucial phases in the design and early development process. It blends and blurs the lines between science and engineering, and requires a risk-based, disciplined, and graded approach to effectively manage scope, cost, and complexity of the final design and system. Many research and development (R&D) organizational leaders, program managers, and scientists are unwilling to involve systems engineering because of perceptions that systems engineering is heavily process oriented, adds unnecessary costs, and should be applied only to mature technologies. The value of systems engineering as applied to ESR&D in TRL 1-5 is unclear to these key individuals and stakeholders resulting in higher risk of failure due to not collecting the benefits of systems engineering (DiMario et al. 2021). This results in R&D efforts that fail outright, may solve the wrong problem, selected the wrong architecture, require fundamental rework, have difficulty transitioning maturity levels, result in higher R&D costs and extended development timelines, or creates a revolutionary technology but fails in product applications.

The formality of the systems engineering process and the architecture process is dependent on the reference architecture as well as the ESR&D objectives. This assumes that a high-level systems requirement or an operational concept exists. In most development organizations this process is relatively formal to the extent of the "largeness" of the system. In practice, systems engineers begin by asking for the requirements that are determined at an architecture level. The systems architecture and lower-level architectures and requirements are further refined in a cyclical manner. In this process, systems engineering artifacts and process begins with the architecture culture driving the process. However, the process of "architecting" does not imply formal systems engineering nor a formal process associated with formal architecting. For "garage shops" and many early engineering and research domains, a formal architecture process is absent and is based on specific domain or tribal knowledge. This is evident, for example, in the creation of the PC and the early work of Steve Wozniak and the Altair 8800 computer that eventually led to the Apple I computer and Windows-based computer technologies. This successful example is extremely rare and does not represent the majority of early technology development efforts.

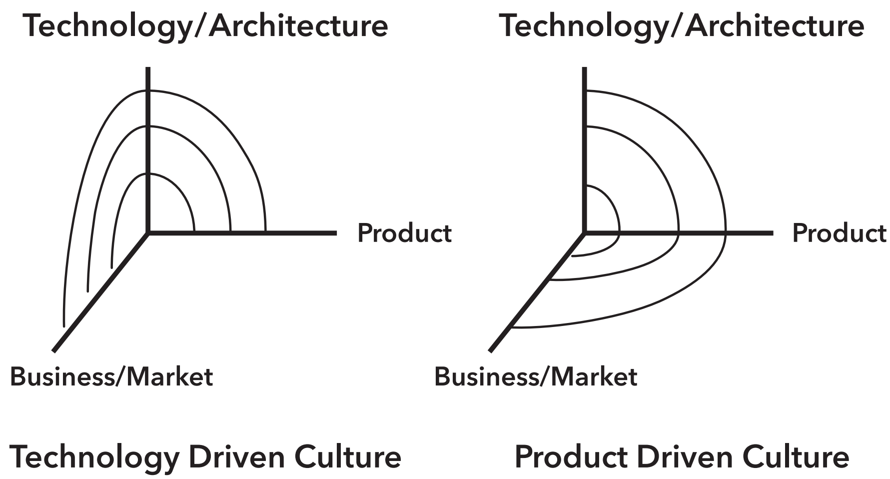

Figure 1. Technology and product driven cultures

The interplay between a technology-driven culture and a product-driven culture consists of holistic characteristics that may have a higher degree of innovation and technology research than strictly business results shown in Figure 1 (Gharajedaghi 1999, 135). What happens to the enterprising organization and what is the effect of the ecology of the R&D organization? Are risks incurred when technology is productized before the prototypes and experimentation is completed? Is the opportunity to compete for a dominant design in the marketplace not afforded since it was not ready to be accepted and evolve in the marketplace?

BIRTH OF SYSTEMS ENGINEERING IN RESEARCH AND DEVELOPMENT

The creativity of individuals and the supporting enterprise infrastructure process is critical for R&D, innovation, and systems engineering. Albeit, there are plenty of impediments to innovation and early R&D such as the infrastructure of the organization, creativity process as well as lack of funding (Christensen 2003a, 2003b, Ford et al. 2007, Georgescu 2022, Utterback 1996). It is viewed that systems engineering as a major infrastructure by program organizational leadership and researchers is an impediment. It is also viewed as an "imperialist" strategy by forcing a methodology onto organizations and R&D personnel and thus brings bureaucracy to R&D. Scientists and engineers have a view of systems management as being used by non-technical leaders with authority over them.

From a historical perspective regarding how and why systems engineering came to be, as early as 1950 Mervin Kelly, a research physicist who led the research of vacuum tube technologies and became president of Bell Telephone Laboratories 1951-1959 and director of the Sandia Corporation pioneered methods of how to be innovative, perform basic research, and successfully transition to commercialized products. His early methods included cross-disciplinary teams with close proximity between researchers and developers as well as the burgeoning engineering discipline called 'systems engineering' at Bell Laboratories in 1950 (Kelly 1950):

> *'Systems engineering' controls and guides the use of the new knowledge obtained from the research and fundamental development programmes in the creation of new telephone services and the improvement and lowering of cost of services already established. In determining the new development projects, 'systems engineering' considers the content of the reservoir of new knowledge awaiting application and the opportunities for its use in the interest of the telephone user.*

One of the first systems engineering seminal textbooks in 1962 describing systems engineering's use in R&D telecommunications technologies at Bell Telephone Laboratories, Arthur Hall (Hall 1962, 81) makes note of the importance of creativity using systems engineering:

> *A creative process is a time series of actions or events which leads to a novel system that satisfies the objectives of a group at some point in time.*

The Bell Laboratories systems engineering process constituted a creativity process as an inception of an idea and used a bounded innovation process resulting in system emergence. The various technical paths that followed considered disparate research and fundamental development became prominent through the use of systems engineering. Systems engineering also afforded the use of new knowledge and research by maintaining close association and blending of research and fundamental development. The early R&D process is the systems engineering process from high-level requirements through architectures to lower-level requirements to design.

A few examples of the use of systems engineering at Bell Laboratories in the late 1940s led to the creation and standardization of television transmission over coaxial cables, broadband microwave radio repeater communication system, an automatic message accounting system, a mobile radio subscriber telephone system, and a telephone subscriber set. The use of systems engineering determined performance criteria and first principles such as frequency bandwidth for voice transmission, circuit noise levels, cross-talk levels, noise interference protection, and distortion levels of speech currents (Kelly 1950, Georgescu 2022).

BELL LABS HISTORICAL CASE STUDY

An example of a successful bridging of research to development and eventual deployment, including the integration of sixteen Bell Labs' inventions, is the transition of Project Echo to Telstar – the first active telecommunications satellite. Arthur C. Clark is credited for the invention of the concept of a communications satellite in October 1945. However, John Pierce, a Bell Labs researcher is credited for the invention of active commutations satellites (Pierce 1955, Pierce 1959, US Patent 1950, US Patent 1962) whereby he created and engineered the early requirements and many key components for the design and deployment of an active communications satellite, called orbital relays.

Project Echo, led by John Pierce, was an experiment in passive orbital communications relays by reflecting a communications transmission from one coast to the other. Echo 1 satellite was launched August 12, 1960 – an aluminum mylar balloon that was expanded upon reaching low Earth orbit to 100 feet in diameter resulting in a successful coast-to-coast communications experiment. Based upon subsequent data and engineering analysis, a decision was made that low Earth orbit communications satellite would be preferred for voice communications versus Arthur Clark's concept of a geosynchronous satellite due to the uncomfortableness of voice time delays. This decision would create a more complex and expensive direction in the systems engineering and systems development as more ground stations would be required as well as more satellites to bridge the time when a satellite would be in view of a ground station.

Telstar was conceived by John Pierce, but the research and development of Telstar would be much different than a simple experimental demonstration. Telstar was the transformation of an idea to one of the most complex deployed products of its time with primary objectives to 1) demonstrate broadband microwave transmission through an active satellite to include 600 one-way telephone channels, limited number of two-way telephone channels, black and white television as well as color, 2) test the operation of a ground station with simultaneous transmitting, receiving, and tracking and 3) obtain space environment data and effect on the satellite (Dickieson 1963, Hoth 1963). This objective required the integration and interoperability of 3600 solar cells, guidance systems, 1000 solid state transistors, traveling wave tube to amplify a signal 10000 times, scaled horn antenna, and satellite spin stabilization. An active satellite was half of the system whereby the design and build of four large 3600 square foot aperture antenna horn ground stations would be required for European transoceanic communications.

The necessary research, design, development, and testing could not be performed by an individual or one group but required large groups of varied and skilled expertise as the concept and requirements were too variegated with integration of new technologies of which none were developed for space (Gertner, 220-222). Telstar 1, the first commercial active voice and television communications satellite was 170 pounds and 34.5 inches in diameter at 14 watts of power was launched July 10, 1962 to an elliptical low Earth 2.5-hour orbit providing the world with the first active transoceanic communications. Telstar 1 also introduced new venues of commercial ground stations and commercial NASA launch services. (NASA billed AT&T Bell Labs for the launch services and Thor-Delta launch vehicle.)

Systems engineering in early-stage R&D was performed by using the ground station assets, data and results of Project Echo coupled with Bell Labs innovations and technologies previously developed to fulfill the Telstar objectives. Active satellite plans and requirements comprising first principles and system parameters of the orbital relay, ground station, and launch vehicle transitioned from the mantra of research and solving interesting problems to developing a working experimental system focused on components to a world-wide communications system in the shortest amount of time–less than two years. (Crawford et al. 1963).

EARLY BEGINNINGS GOVERNMENT-REQUIRED SYSTEMS ENGINEERING

In the early 1960's, Robert McNamara, as Secretary of Defense, introduced phased planning for government control, with NASA and the Air Force intercontinental ballistic missile program being early promoters. In 1965, DoD established phased planning and systems concept as the cornerstone of its R&D regulations. Systems engineering development cycle consisted of feasibility studies, preliminary design, detailed design, manufacturing and test, production and operations of which configuration control and design reviews affected detail design through production (Johnson 2002a, 74; Johnson 2002b).

The systems engineering concept has its rudimentary beginnings as a solution to secure R&D and to move from idea to research to a production system. Systems management introduced rational control of researcher and early technology developer's expansionist thinking and culture or freedom to do whatever their whimsical ideas took them. Up to this time, platforms were not baselined and configuration control was absent of research to production. (Configuration management and control of engineering to production processes are well demonstrated of the US WWII manufacturing of aircraft and ships.)

A systems approach of reductionism brought order to engineering process chaos and complexity, and codified tribal knowledge by creating new engineering disciplines and managerial processes. The techniques of systems management provided proxies for technical progress such as cost measurement and design review approvals by management creating a hierarchy over technical teams through project management and configuration control. This is the origin of the term "management by the numbers." (Johnson 2002b). This new systems management and engineering discipline led to the success of the United States space program of the 1960s and 1970s from basic R&D to manufacturing and eventual launch to orbit and the Moon. The question for research and development organizations is what happens on the way from inception to objective?

EARLY-STAGE RESEARCH AND DEVELOPMENT AND RISK OF FAILURE

A situation that many large R&D organizations find themselves in are supporting their legacy systems and their customers (Christensen 2003a, Utterback 1996). All resources are applied to satisfy their customers and shareholders. Their products and technologies achieve market evolution through service and incremental product innovation due to their product-driven culture. While all this takes place, an outsider with a technology-driven culture enters the scene with a radical innovation or newly patented research supplanting the technology and products the established organizations have so endeared. In sufficient time, the wedding between the established organization and the customer ends as the replacing technology's performance and price points makes switching costs acceptable for the customer. The customer dumps the market established organization for the new market entrant innovative organization. The failure to innovate or conduct new research and early development by the former organization is because its capabilities and competencies that made it successful are now its liability.

For R&D organizations the risk of failure is extremely high with 90%-98% projects encountering the "valley of death" (VoD) characterized by research and subsequent technologies that are proven in principle fail to make their way in maturation to the developers, manufacturers, integrators, and product deliverers (Kampers et al. 2020, Natsheh et al. 2021).

Most organizations cannot afford the high investments and specialized competencies required. However, in technology research and development, the pace is swift and must plan to disrupt the marketplace or be disrupted. Many R&D organizations perform the research and sell it to larger firms to be integrated or matured. The product-driven culture of the established firm acquires the research from research firms or academia to avoid the risk and guarantee return on investment (ROI). The technology and product-driven cultures and firm priorities drive their risk behavior.

Systems engineering use for R&D is not a guarantee of successful technology and product maturation. However, there is a strong correlation of 80% of systems engineering use leads to successful programs with 8%-19% optimum system engineering program cost (Honour 2013). In all cases, the management of risk is utilized as the unforeseen cannot be predicted.

The management of risk is an important attribute as many studies reveal that risk is as important as traditional cost, performance, and schedule as shown in NASA's faster-better-cheaper (FBC) programs. In the years between 1992 and 2000, there were 16 FBC missions of which 6 had failed leaving a 63% mission success rate. A 63% success rate was acceptable since it indicated that NASA was not always "playing it safe." However, the year 1999 was an extremely troublesome year whereby 4 out of 5 spacecraft failed following 9 out of 10 successes in previous years (DiMario 2005). Risk is a measure of the potential inability to achieve overall program objectives within defined cost, schedule, and technical constraints. Risk management is broken into risk associated with planning, assessment, managing,

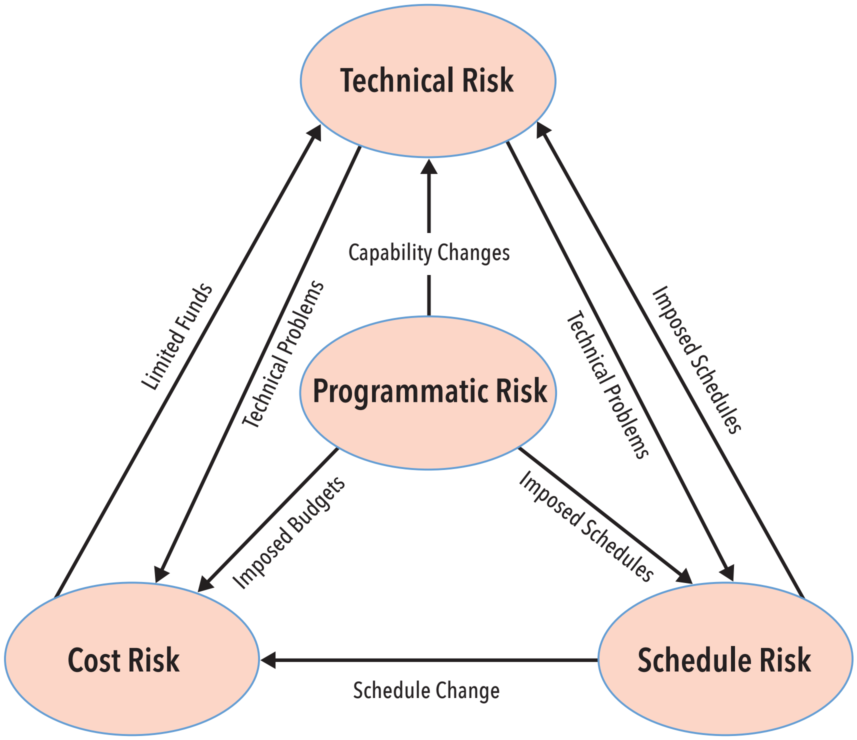

Figure 2. Programmatic risk interplay

and monitoring of achieving technical, cost, and schedule goals. Impact of risk of one programmatic element effects the others shown in Figure 2.

There is much risk within the maturation of research and technology to products or applications even if technical, cost, and schedule goals are managed well as evidenced in NASA FBC programs. All R&D organizations are well aware of the mountainous region between being technically proven and having a successful implementation as a product or application with a viable ROI. This difficulty in transitioning from research to a new technology resulting in the VoD typically occurs at TRL 5-6 after graduating through the previous TRLs referenced in Figure 3.

For many in the R&D community a technology is generally "proven" when it reaches TRL 6, in which it has achieved "prototype demonstration in a relevant environment." And once proven, there should be no reason why the product or application technology should not be available for use in its relevant application. This is hardly the case. The cost and risk are the first part of the VoD that makes it hard to transition a new technology or product to its relevant environment. Even if the risk is low, the new research and subsequent technology may not be as intended resulting in enormous cost and risk before successful implementation as a product or application.

THE VALLEY OF DEATH IN EARLY-STAGE RESEARCH AND DEVELOPMENT

The VoD occurs when appropriate funds are not present for transition or the technology and the product fails on its own accord. The funds are typically not present for many reasons, but one of the principal reasons is failure of the communities on opposite sides of the "valley" to communicate or "bridge" the requirements or expectations of what they are to be sharing (Ellwood et al. 2020, Ford et al. 2007). In traditional discussion of the VoD, the communities on opposite sides of the "valley" are early-stage R&D of academia, government research labs, small business research houses, and industry on the TRL 1- 5 side of the "valley," and the product development, integration, and delivery organizations on the TRL 6-9 side of the "valley." Academia and small research houses tend to focus on TRLs 1–4, whereas industry prefers to work with TRLs 7–9. An important traditional gap are levels 4–6 that represent a transition risk between research and industrial commercialization. This gap is traditionally the VoD that many new technologies reach TRL 4–6 and fall into a dark cavernous valley due to lack of funds because a transition from a research and technology push to a market or product pull was not bridged.

There is considerable data and reference to the US government research, development, test & evaluation (RDT&E) research and development budget and corresponding TRL levels. The RDT&E process can represent the commercial industry as a proxy example of ESR&D and product development in the discussion of the VoD of the US government RDT&E process. Research, development, test & evaluation budget activity 6.1-6.3 represents the science and technology (S&T) of basic research, applied research and advanced technology development equate to TRLs 1-5 (Sargent 2022). The S&T budgetary activities are generally managed by the government research labs while the budgetary activities 6.4-6.7 are managed by system program offices at TRL 6-9. On the one side of the "valley," the S&T community have a technology-push approach culture. Promising research and technologies are pursued on their own merits. The program office community, however, relies on a requirements-pull approach culture, with a product and relevant markets driving the applications and mission focus relating to the push and pull dynamics between these two groups.

In the US government Department of Defense FY 2020 budget, S&T accounted for 13.6% of the RDT&E budget while in FY 2024 the S&T budget shrank to 12.3% (Office of the Under Secretary of Defense (Comptroller) 2019, Office of the Under Secretary of Defense (Comptroller) 2023). (The RDT&E S&T budget percentages are determined by budget activities 6.1-6.3.

Stage	TRL	Definition
Basic Research	1	Basic Principles Observed
	2	Technology Concept Formulated
Technology Development	3	Experimental Proof of Concept
	4	Technology Validated in Controlled Environment
Technology Development / Technology Demonstration	5	Technology Validated in Relevant Environment
Technology Demonstration / System Development	6	Technology Demonstration in Relevant Environment
System Development	7	System Prototype Demonstration in Operational Environment
System Development / System Test and Operations	8	System Complete and Qualified
System Test and Operations	9	Actual System Proven in Operational Environment

Figure 3. Technology readiness level generic definitions

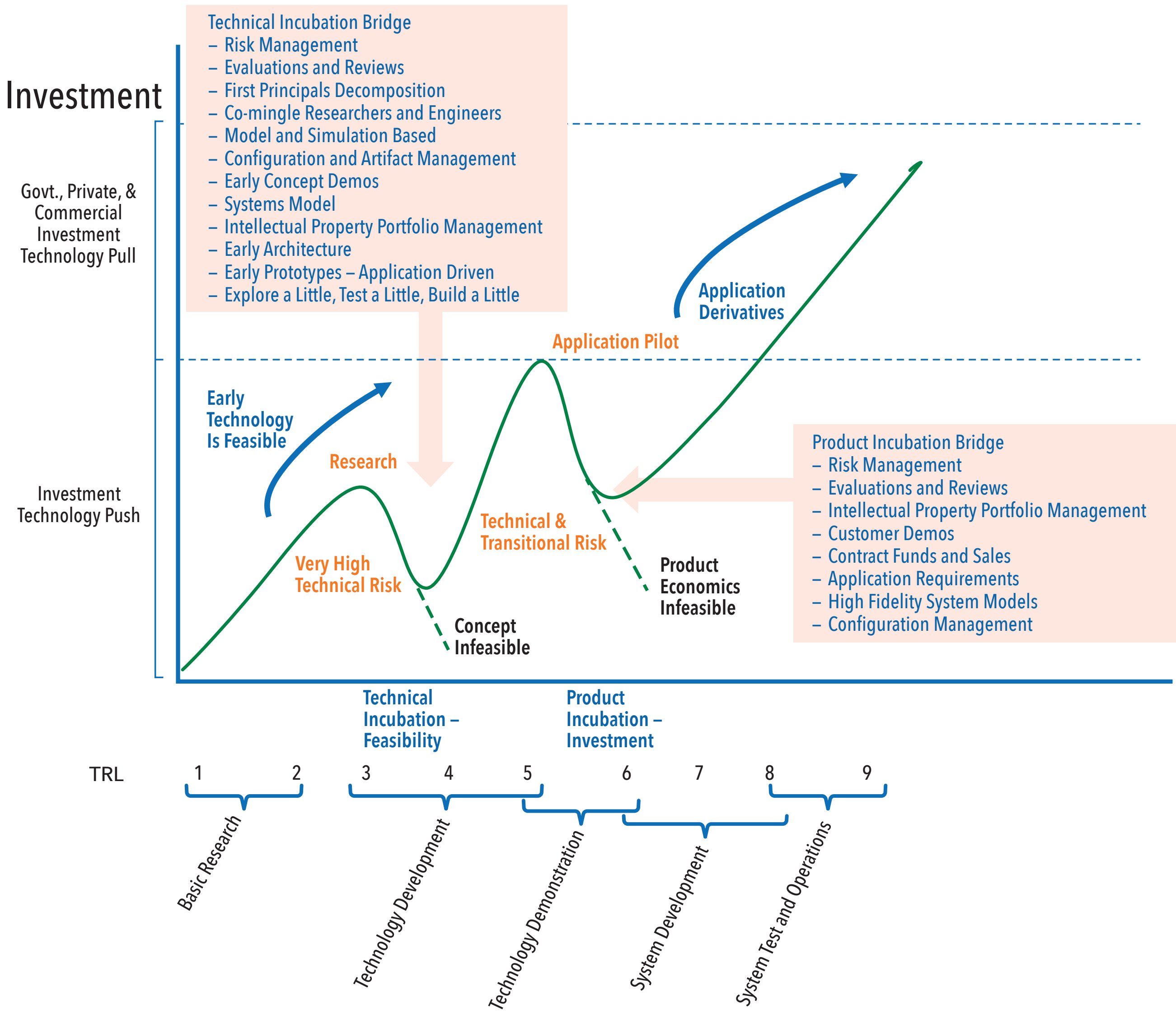

Figure 4. Technology and product maturation

The percentages may be higher due to S&T activity funds allocated in the classified RDT&E budget.)

The vast majority of RDT&E funding is spent by the system program offices, characterized by minimal risk tolerance. However, as the S&T FY2024 budget experienced a shrinkage the total RDT&E budget increased 39% from FY2020. One would hope that with the significant increase in program office RDT&E budget, post S&T transition bridging mechanisms would be a strong enabler for successful S&T transitions and afford early communications and soft requirements as a transition process is implemented and the technology moves from a "push" to a "pull" venue."

There is a myriad of reasons for the existence of the VoD due to failed research and technology project bridging (Natsheh et al. 2021). The projects succeeded on their own merit but failed to transition from R&D to acquisition. The two sides of this valley have their own independent cultures, vocabulary, management structures, and technical practices. The R&D and acquisition sides of the bridge need to recognize this and account for continued failure of systems engineering process adoption within the early-stage R&D. Bridging the VoD also requires more than tailorable systems engineering processes as it requires broad understanding and cooperation of both sides of the bridge to provide necessary funding and maintain ROI.

General discussion focuses on one VoD occurring at TRL 5-6 where S&T fails to transition to acquisition or commercialization (Natsheh 2021). However, technology management experience proposes there are two VoDs shown in Figure 3. In addition to the transition failure at TRL 5-6, the first VoD occurs at approximately TRL 3-4 whereby the research and technical incubation prior to product or application fails to transition to technology demonstration. The lower TRLs are characterized by technology push whereby it is viewed that they must succeed on their own merits. Thus, there are two VoDs whereby the first is a technology VoD occurs as a result of a transition failure from research to a viable technology due to failed bridging of managing risks and the second at transition to commercialization due lack of bridging to mitigate technical and product transition risk. There are many examples whereby the original research intent is not satisfied but that other successful opportunities evolve (Brock 2023). The alternative opportunities can be viewed as a rescue from the valley's depths, however extremely rare.

It is problematic for research and early technology of TRLs 1-5 to mature and to succeed on their own merits via a technology "push" mantra with no venue for a technology pull of TRLs 6-9. The bridge will not be present unless both sides of the potential VoD build a necessary scaffolding to facilitate the transition from research to engineering – for example, activities and deliverables that are rigor appropriate.

Examples of bridging actions for the two bridges are shown in Figure 4. These steps or any actions are tailorable to meet the needs of the culture and technology, but to not have transitional remedies in place and executed by both sides of the bridge results in a VoD. This is most important in the case of ESR&D whereby technology incubation must maturate successfully to reach product incubation. The freedom and an expansionist culture of research and early technology development is ma intained with simple and tailored systems management techniques, shown in Figure 4 as technical incubation bridge, which includes looking forward to what may be required in future maturation levels and potential bridging activities.

A classical remedy for avoiding or providing a shallow VoD in government and business sectors is to provide large sums of financial aid that inherently builds the necessary bridge (Gill 2022). The VoD has two peaks on each side. One peak is the research or technology origin and the other is the technology transition or product commercialization. Technologies or products are rescued from the VoD due to a late recognition of their intrinsic value comprising of only 2%-10% of projects. This rescue is typically due to application of funds which assumes remedies the needs of both sides of the valley versus addressing why the valley is present. Unless funds originate from the "pull side" of the valley, it is not clear how a bridge may be sustained. There are numerous examples by which tailored systems engineering process, techniques, and tools properly used may avoid the VoD or at a minimum applied to both sides of the valley, satisfying the forces of "push and pull" to build a bridge to avoid the VoD without large ingestion of funds (Dykes 2011).

This is not to say that all basic and applied research should succeed. There may be reasons why the maturation of basic research and technology fail whereby the early concept is infeasible or the product economics are infeasible. It is better to fail early and fail cheaply and learn from the failure than to expend large sums of capital and continue because large sums have been expended – "the project has become too expensive to terminate." A fundamental step proposed by the US Department of Defense is to promote technology prototyping to overcome the VoD (Office of the Under Secretary of Defense for Research and Engineering 2022). This is an important step, albeit not the only action that should be taken. Technology and product demonstrations are already required in the TRL 5-6 and a prototype is typically how it may be done. However, this guide may be employed on both sides of the valley at TRL 3-4 and TRL 5-6. This would certainly help build a bridge, avoid the VoD all together, and provide for a healthy ROI.

SUMMARY AND CONCLUSIONS

Systems engineering management and principles came to be first reported in the early 1950s to expedite and successfully maturate technology from basic and applied research. These principles were quickly adapted by government agencies to develop and manage complex technologies in the 1950s and 1960s to meet the needs of the US Department of Defense and NASA. A perceived systems management bureaucracy grew from the use of systems management and engineering, albeit successful in its usage, to the level of disdain by the very stakeholders and researchers that promoted its use in earlier times. This disdain has led to a lack of systems engineering use by basic and applied researchers in order to sustain a sense of research freedom.

The sense of research freedom and research philosophy of "build-it and they will come" results in a VoD where technology and products permanently die or large sums of funds are required to save the research or technology from ultimate failure. By building the necessary bridges for research and early technology development in ESR&D and later product maturity, funding and a sustained ROI may be maintained leading to full maturity of research to product or applications. Research freedom is easily maintained with tailored systems management and engineering principals and frameworks with emphasis on avoiding a future VoD, the very reason systems engineering came to be. The necessary VOD bridges in the research and technology maturation will improve the probability of pure and applied research maturation to product and commercialization from the current 2-10% without throwing large sums of capital onto a systemic-avoidable problem and hoping a product blooms. ■

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Ann Hodges retired after 48 years of service at Sandia National Laboratories and was a distinguished member of technical staff. She was the Mission Services Division's systems engineering lead for the systems engineering part of the project and product delivery system (PPDS) at Sandia National Laboratories and was a project manager and systems engineer for a complex exploratory-phase project. She is a primary author of the risk-informed graded approach to the application of project management, systems engineering, and quality management which is one of the key aspects of the PPDS. She obtained a BBA and an MS in computer science from the University of New Mexico, and holds CSEP, SAFe SPC4, and CMII certifications. Ann has held leadership positions in the INCOSE Enchantment Chapter including director-at-large 2011-2012, president-elect and acting secretary 2013, president 2014-2015, and secretary 2015-present. She is the co-chair of the INCOSE Systems Engineering for Early-Stage R&D working group.

A Bridge Blueprint to Span the Chasm Between Research and Engineering — A Framework for Systems Engineering in Early-Stage Research and Development

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ABSTRACT

Researchers and funding organizations often do not understand the value of systems engineering in early-stage projects (technology readiness levels TRL 1-5), during which systems engineering may be viewed as an unnecessary cost, and as a process heavy effort applicable only for mature technologies. This may result in a relative lack of engineering rigor and lack of understanding of innovation context which often contributes to failures in the "valley of death" between fundamental research and applied development.

We argue there is more than one pathway for crossing the valley of death, and that relevant application of systems engineering implemented at an appropriate level of rigor provides a foundation for transition and use of technical innovation. This article discusses the principles and foundational elements necessary for development and use of a framework for systems engineering applicable in early-stage research and development (ESR&D), including tailoring considerations associated with TRL and stakeholder roles. Associated framework metrics are suggested to enable evaluation and practical implementation of the framework for systems engineering innovation management at this phase of technology development.

INTRODUCTION

There are many potential obstacles to fielding innovations resulting from research. Anton (2022) lists a wide range of over 40 of these barriers. Figure 1 shows an affinity diagram of the barriers identified in Anton (2022).

A framework that bridges the "valley of death" between research and engineering needs to eliminate or at least attenuate the barriers depicted in Figure 1. DiMario et al. (2021, 11) posed some important questions, which the framework should also address:

- Can the framework address the types of projects of interest?
- Does the framework address the cultural gap between systems engineering and ESR&D?
- Does the framework support the range of internal and external stakeholders?
- Can the framework support different funding levels and funding allocation strategies?
- What is an acceptable level of process documentation, tools, and templates required by the framework?

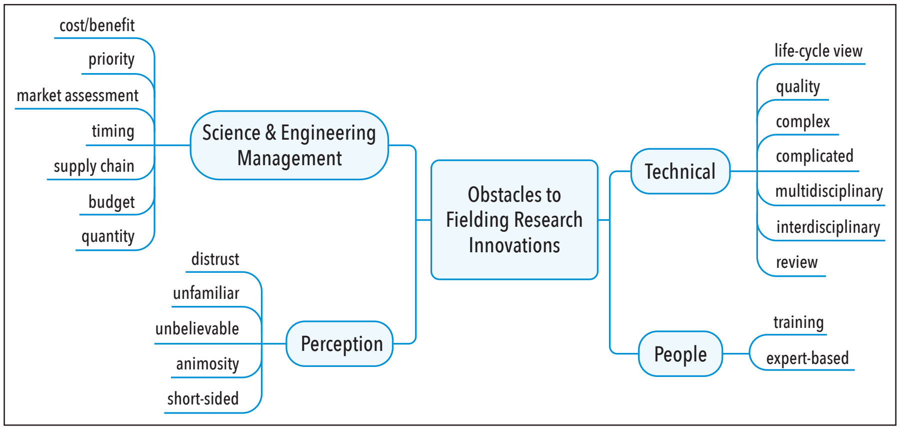

Figure 1. Affinity diagram of challenges for bridging research and engineering

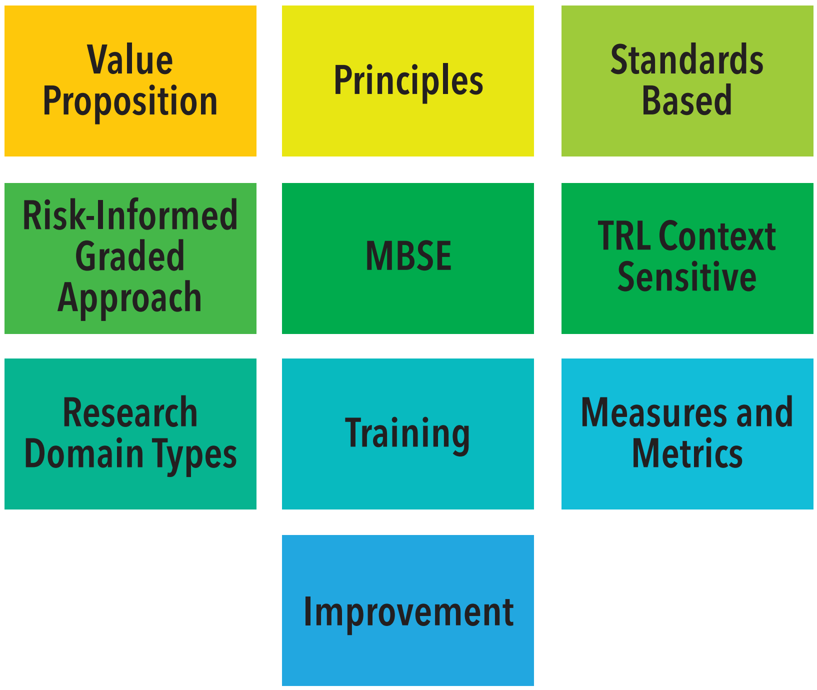

Figure 2. Elements of the systems engineering in the ESR&D framework

- Will the framework support the transition to more formal systems engineering should the effort move beyond the TRL level for ESR&D?

This article provides a framework blueprint that addresses these barriers and points. The framework blueprint consists of the following elements shown in Figure 2 which are described in the remaining sections.

VALUE PROPOSITION

It is well established in literature that eliminating defects early in the product life cycle is far less costly and magnifies efficiency, as shown in Figure 3. However, this value proposition is not compelling to researchers or funding organizations because of a lack of understanding about the value of systems engineering which is viewed as being heavily process oriented and applicable only for mature technologies. Systems engineering is often not applied to early stages of R&D, resulting in the research, problem, or early prototype being developed incorrectly, insufficiently, or inadequately preserved which incurs greater risk in the inability to transition to higher TRLs.

According to McKinsey & Company, "The age of the insular R&D organization is over. To serve as a company's innovation engine, R&D strategy needs to be equipped for today's fast-moving world…Innovation cycles are accelerating. The growing reliance on software and the availability of simulation and automation technologies have caused the cost of experimentation to plummet while raising R&D throughput. The pace of corporate innovation is further spurred by the increasing emergence of broadly applicable technologies, such as digital and biotech, from outside the walls of leading industry players". (Brennan et al. 2020) Systems engineering is a critical enabler in four key areas identified by McKinsey & Company: accelerating innovation cycles, connecting to the customer stakeholder, having accountable metrics, and reallocation of existing R&D portfolios to new endeavors.

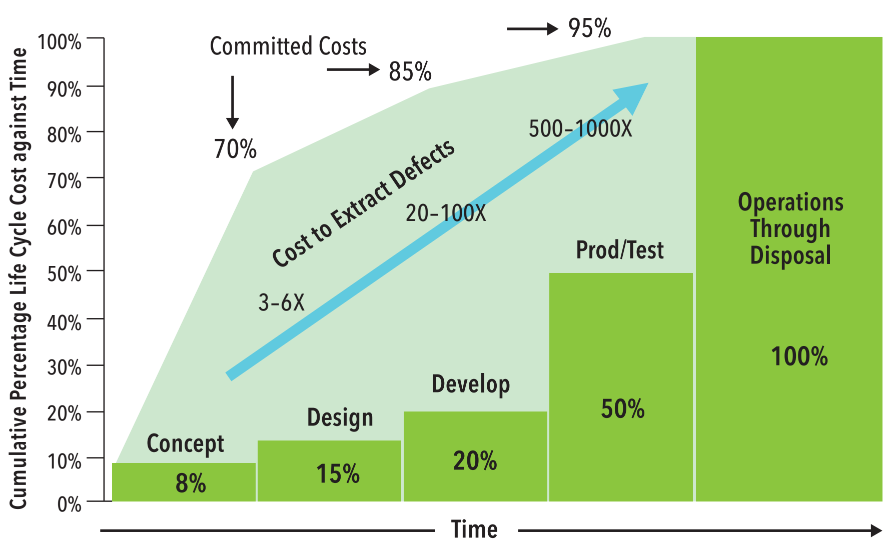

Figure 3. INCOSE's value proposition for applying systems engineering early (Walden et al. 2015, 14 Figure 2.4)

The value proposition needs to be expressed in terms that are meaningful and compelling for both the research community and the business. A more convincing benefit to this community is that applying systems engineering to research activities early assures quality of the research products throughout the project life cycle and provides a foundation for future technical maturation. The result is research deliverables that meet the stakeholders' needs and requirements, increases the credibility of the research, and makes it more likely that the research will survive peer review, cross the valley of death while still achieving the goal of avoiding the time-consuming and costly rework implied in the INCOSE value proposition.

From the business perspective, *systems engineering adds value when it meshes with business to enable an R&D strategy that is a comprehensive guide for the organization, involves stakeholders both inside and outside the R&D group*, from scientists and principal investigators to sponsors and finance officers. *Systems engineering works across the R&D effort to define capabilities, technologies, talent, and assets which become more granular as the strategy is instantiated at differing levels of the R&D organization, or as level of rigor increases.*

From the researcher perspective, *right-sized systems engineering provides value to research activities to provide credible research results that deliver a foundation for future technical maturation.*

FRAMEWORK PRINCIPLES

According to Merriam-Webster (2023), a principle is "a comprehensive and fundamental law, doctrine, or assumption; a rule or code of conduct", a belief that influences actions and/or explains the nature or workings of something. The set of principles provide a foundation for a framework for systems engineering in ESR&D – provide

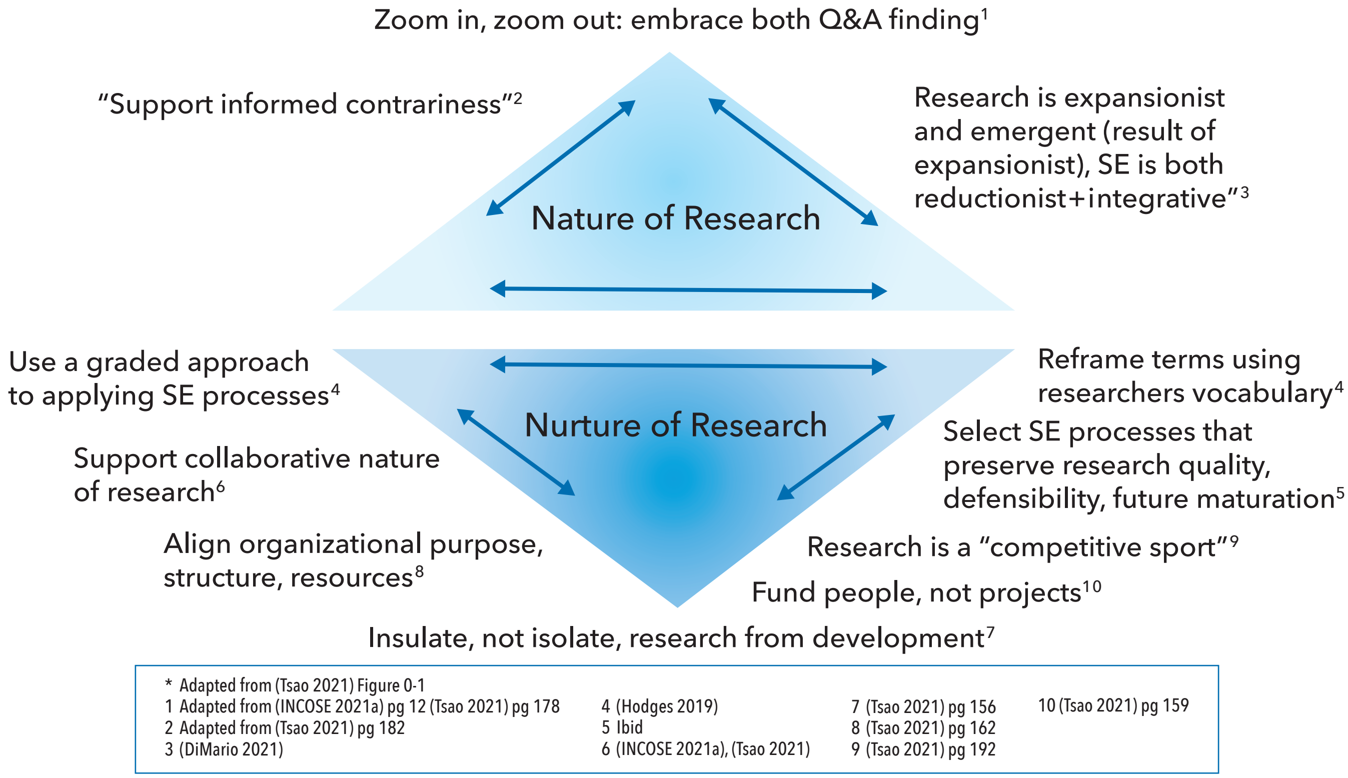

Figure 4. Principles for a framework for systems engineering in ESR&D

guidelines, processes, and tools for the "right" and "right-sized" tailored systems engineering activities and deliverables to support ESR&D projects. The principles should be general enough to apply to a wide variety of research organizations, even if the missions differ, which include industry, academia, and government. The framework principles:

- need to be sensitive to the nature of R&D – both culture and goals,
- reframe systems engineering wording for the R&D culture,
- enhance the integrity and repeatability of the R&D products, and
- are consistent with the value proposition for applying systems engineering early for ESR&D.

The set of principles for the framework is summarized in Figure 4. The interested reader is referred to the source references for more information about each principle.

STANDARDS BASED

Industry standards reflect best practices and provide a foundation for the framework's recommended practices and deliverables. The set of standards can provide increased credibility and confidence in the research process and results for both the external stakeholders as well as an organization's internal stakeholders. The framework's set of standards considers the broadly accepted standards for systems engineering, more narrowly focused domain standards, and standards important to the stakeholders such as WHO (2011) and ASME (2019).

The set of process standards that provide a foundation for how systems engineering is performed is shown in Figure 5. Applying these to the creation of an ESR&D framework's standards requires critical thinking and is not meant to be a simple checklist as there is no complete general set of standards for all domains. The researchers need to identify the standards and guidelines that are applicable to the relevant research domain(s). The research, systems engineering, and associated project manager practitioners have to carefully collaborate and come to consensus on the general and more specific processes that are relevant to the research activity. The processes need to be rigor-appropriate for ESR&D and the terminology reframed to be understandable to the research community.

RISK-INFORMED GRADED APPROACH

Applicable rigor should be informed by the risk of the research and the project. An approach adapted from Hodges (2013) to determine the relevant rigor includes consideration of intrinsic characteristics of both the research and the project, including:

- the consequence/impact of failure
- characteristics that increase the likelihood of failure:

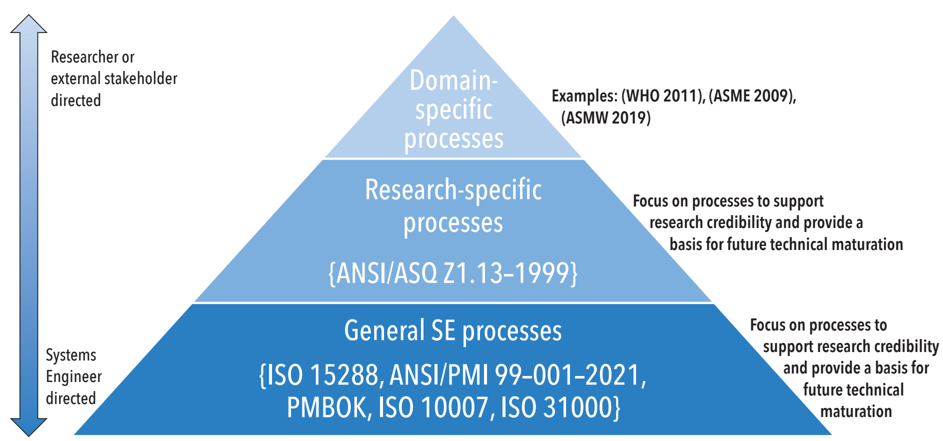

Figure 5. Set of standards for the systems engineering in the ESR&D framework

Table 1. Roles and responsibilities for activities and deliverables

Process Area	Principal Investigator	Project Manager	Systems Engineer	Science/Engineering Domain Lead	Sponsor
Requirements Definition and Management	Responsible, Accountable	Supporting	Responsible	Supporting	Accountable
Architecture Definition	Accountable, Responsible	Informed	Supporting	Responsible, Supporting	Informed
Verification and Validation (V&V)	Accountable, Responsible	Informed	Supporting	Responsible, Supporting	Supporting
Project Planning: Proposal/Charter	Supporting	Responsible	Supporting	Supporting	Accountable
Project Planning: Milestone Definition	Responsible	Accountable	Responsible	Responsible	Informed
Project Planning: Work Breakdown Structure (WBS) Definition	Supporting	Responsible, Accountable	Supporting	Consulted	Informed
Project Planning: Budget Definition	Supporting	Responsible	Supporting	Consulted	Accountable
Configuration Management	Accountable	Consulted	Responsible	Supporting	Informed
Risk Management	Accountable	Responsible	Responsible	Supporting	Informed
Issues/Action Item Tracking	Accountable	Responsible	Responsible	Supporting	Informed
Measuring and Test Equipment Management	Accountable, Responsible	Supporting	Consulted	Responsible	Informed
Project Tracking and Oversight	Responsible	Accountable	Supporting	Consulted	Informed

- urgency of research deliverable(s)
- research objectives/requirements stability
- reliance on maturity level of underlying technology and/or manufacturing
- complexity of the technical, organizational, or procurements to support the research
- presence of and availability of infrastructure (experimental, laboratory, test facilities)
- stakeholder expectations.

Generally, for research projects the combination of the consequence of failure and likelihood of failure is low. However, a higher consequence of failure of the research (for example, a "grand challenge" or "moon shot" project) will result in a higher rigor recommendation.

MODEL-BASED SYSTEMS ENGINEERING (MBSE)

Traditionally, system engineering is document-based. but many systems being developed today are too elaborate to manage with documents alone. Behaviors and interfaces are increasingly complex, entangled, and full of exceptions and dependencies, making document-based approaches inadequate to capture architecture, behavior, and interactions. The framework described in this article is generally agnostic to the implementation approach, for example, document based, DOORS tools, or MBSE. However, the authors recognize and encourage the industry-wide "digital transformation" and use of MBSE.

Model-based system engineering builds a project using models to describe all the different subsystems and elements. Information that would usually be included in documents is expressed in a more structured and digitally processable way – as diagrams and tables, for example, rather than as words. Most importantly, modern MBSE tools interface with other science and engineering tools so that models are more than boxes and lines on a picture. Tools that implement SysML though application programming interfaces (APIs) allow for integration with other tools. This allows information to be more connected and processed by computers and used within different software tools.

MBSE is not only for production systems. R&D programs can likewise benefit from models being developed, reused, and extended. And like the transition from analogue to digital, the transition from documents to models will enable projects to be much more efficient. Refer to Granados & Tseng (2023) for more details on digital engineering enablers for ESR&D.

As an example, the Japanese Aerospace Exploration Agency's (JAXA's) Engineering Test Satellite-9 is a demonstration satellite that aims to achieve next generation geostationary satellite communication. The project team is applying MBSE to manage the complex operations of the satellite. More generally, JAXA's R&D Directorate is using and accumulating knowledge in MBSE to support future projects (Yuta Nakajima and Fukatsu, 2020).

TRL CONTEXT SENSITIVE GUIDANCE ROADMAP

The roles and their respective responsibilities on a research project are described in Table 1 using RASIC (Responsible, Accountable, Supporting, Informed, Consulted) categories. The activities and deliverables in Appendix A Table 3 are typically fulfilled by the roles as outlined in Table 1.

As described in DiMario and Hodges (2023), there are two valleys of death in technology maturation:

- TRL 3-4 resulting from failure to transition from research to a viable technology, and
- TRL 5-6 resulting from failure to transition to commercialization.

The guidance for systems engineering activities and deliverables therefore focuses on TRLs 1-6 which is contained in Table 3 in Appendix A. Note that the artifacts listed in the table comprise the initial set of items for a digital thread for product development.

There are several assumptions for the content in Table 1 and Table 3:

- It is impossible to cover all research domains and application areas, and the guidance is general enough to address all scientific research, such as materials science, device physics, and quantum computing.
- Each applicable domain for the research project will have its domain-specific architecture and design definition. There may also be TRL-specific requirements for each relevant domain.
- The activities and deliverables require a trans-disciplinary team consisting of the principal investigator (PI), project manager, systems engineer, science/engineering domain lead, and sponsor.
- For higher-risk research, for example, a grand challenge moon shot-level project or external stakeholder expectations, increased rigor should be used:
  - Increased formality: Deliverables should be described using increased formality and more detail. For example, develop a more formal plan instead of rather than a one-page approach description. Use more formal tools, such as a configuration management tool that supports a digital thread description instead of relying on a shared drive with naming conventions.
  - Increased scrutiny: Deliverables will likely require more review and evaluation. Although the PI is responsible for reviewing the experimental process including the approach, plans, results, analyses, and reports, an external review panel comprised of domain experts may be necessary to help ensure research quality and increase stakeholder confidence.
  - Increased monitoring: Tracking and oversight, both internally and externally, will be more frequent. More formal status reporting on performance, cost, and schedule could take place monthly, with periodic program reviews.
- The activities in Table 3 are based on the standards in Figure 4. The processes in the domain-specific standards provide a basis for bridging the terminology into more general systems engineering activities and deliverables.
- The table focuses on planning and oversight of activities, and assumes that implementation occurs.

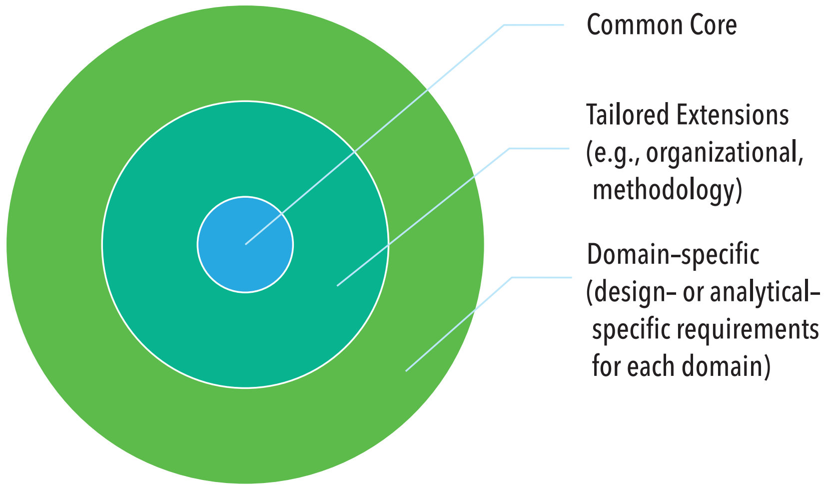

Figure 6. Leveraging and integrating practices, deliverables, and terminology across domains (adapted from Long 2023 slide 23)

Table 3 in Appendix A provides a roadmap of activities and deliverables for research teams that supports the preservation of the integrity of results, transparency in how results were achieved, and provides a foundation for further maturation for ESR&D projects. Table 3, along with the associated RASIC in Table 1, is a "job aid" in applying systems engineering early in R&D projects which serves to attenuate risks leading to the two valleys-of-death described in DiMario (2023) and is the scaffolding to bridge research and engineering domains.

RESEARCH DOMAIN TYPES

There may be multiple domains that contribute to the scientific results in a research project. For each domain, there is likely terminology, design and analysis artifacts, and tools that are utilized in the technical maturation journey. For example, as depicted in Figure 5 there are domain-specific standards that may need to be addressed. Appendix A Table 3 contains TRL-specific guidance for practices and deliverables. Many of these items are common across domains, such as "specify approach for capturing and managing research objectives, performance parameters, and derived requirements" contained in the requirements definition and management TRL 1 roadmap. This represents the "common core" shown in Figure 6. A research project may utilize specific approaches (such as agile) which is represented as the "tailored extensions" layer. Table 3 in Appendix A references domain-specific considerations, such as "specify TRL-specific domain requirements for the relevant domain(s)", also in the requirements definition and management TRL 1 roadmap. This is depicted as the "domain-specific" layer in Figure 6.

The TRL roadmap can be instantiated with specific examples of practices and deliverables for a specific domain, which provides more targeted guidance within an organization or industry which provides support for research domain types. Similarly, there are domain-specific measures and metrics that provide insight into technical maturation.

TRAINING

The goal of training in the context of systems engineering in ESR&D is to provide enough knowledge and skills to the research team so that systems engineering activities can be understood and performed, not to turn the researchers into systems engineering experts. Similarly, the PI and other research team leads provide the systems engineer with enough domain knowledge to tailor the systems engineering practices to support the project. Given this goal, adopting a coaching and mentoring approach for applying the systems engineering framework described in this paper is recommended. "Coaching is a non-directive form of development aiming to produce optimal performance and improvement at work. It focuses on specific skills and goals … The process typically lasts for a defined period. Mentoring is a

Table 2. Goals and related questions for systems engineering in the ESR&D roadmap

Goals/Questions, Measures-Metrics	Preserve research integrity, credibility	Provide foundation for future technical maturation
Are requirements defined and managed? • % requirements in compatible format for more formal requirements mgt (goal 100% as approach TRL 4) • # requirements change over a time period (stability)	X	X
Is architecture defined and managed for each relevant research domain? • % architecture defined for relevant domains		X
Is a verification &validation (V&V) approach defined and used? • % coverage of requirements, architecture for V&V planning items • % planned V&V conducted • % "pass" results • # of incomplete or incorrect items identified (implies technical debt)	X	X
Are technical and programmatic items to be configuration managed identified? Are those configuration items version controlled? • % items to be configuration managed version controlled	X	X
Is a change management approach specified and used? • # changes that fall under the criteria for change management over some specified time period are requested, implemented, verified	X	X
Is a risk management approach specified and used? • risk register exists, updated within some specified time period • # severe and high technical and programmatic risks over some specified time period • trend of severe and high technical and programmatic risks over some specified time period	X	X
Is an issues/action item tracking approach specified? • # of issues by severity level • trend of higher severity level issues over some specified time period	X	X

relationship where a more experienced colleague shares their greater knowledge to support development of a less experienced member of staff" (INCOSE 2018, 52 Competency Area — Professional Coaching and Mentoring description).

The PI and systems engineer are key in defining the details in Table 3 in Appendix A. The systems engineer coaches the PI, explaining the motivation and lower-formality approaches for achieving the processes' goals. The PI coaches the systems engineer on the terminology the research team will understand, what tools the team uses to plan, conduct, capture, and analyze experimental results. The domain leads provide details on their domain to include in the roadmap to the PI and systems engineer. This roadmap acts as both a training and facilitation tool, providing guidance on the core set of activities and deliverables that will help assure producing and delivering quality research results as well as defining and communicating the expectations that the research team is to follow in their activities. Because the research team contributed to the roadmap specifications, the content will be more complete and, because the approach is participative, there will be more support on the part of the team and knowledge about how to incorporate systems engineering into their activities.

The systems engineer's involvement with the research team ranges from strategic to tactical levels. At the strategic level, the systems engineer coaches the research team – to identify the rigor level (low or medium), the specification of details for the systems engineering roadmap – and helps establish templates and other infrastructure for the activities and deliverables. At the tactical level, the systems engineer facilitates the execution and monitoring of the activities in support of the PI, acting more as a mentor to the PI.

MEASURES AND METRICS

Measures and metrics can be useful in assessing current performance, set goals for improvement, and to forecast potential outcomes given the current context. (A "measure" is a value of something, such as temperature. A "metric" is comparing a value to some threshold, for example, a body temperature of 100 degrees F is a fever because it is above the normal 98.6 degrees F reading.) Assessment with respect to research objectives provides more effective and relevant information to support research success. The "goal/question/measure-metric" approach shown in Table 2 is used as an example, with the goals based on the value proposition for systems engineering in ESR&D defined earlier in this paper, and questions related to the systems engineering roadmap activities contained in Table 3 in Appendix A. (Questions are posed to provide insight to assess status of the associated goal. Measures or metrics provide qualitative or quantitative data to address the associated question.) Note that there are likely measures/metrics that are focused on the scientific exploration of the research project, for example, key performance parameters or the project's specific research objectives.

IMPROVEMENT

There are multiple facets that can identify opportunities for improvement.

- Measures and metrics trends can provide insight into gaps in technical progress, issues and risks. Identifying and addressing these gaps is crucial

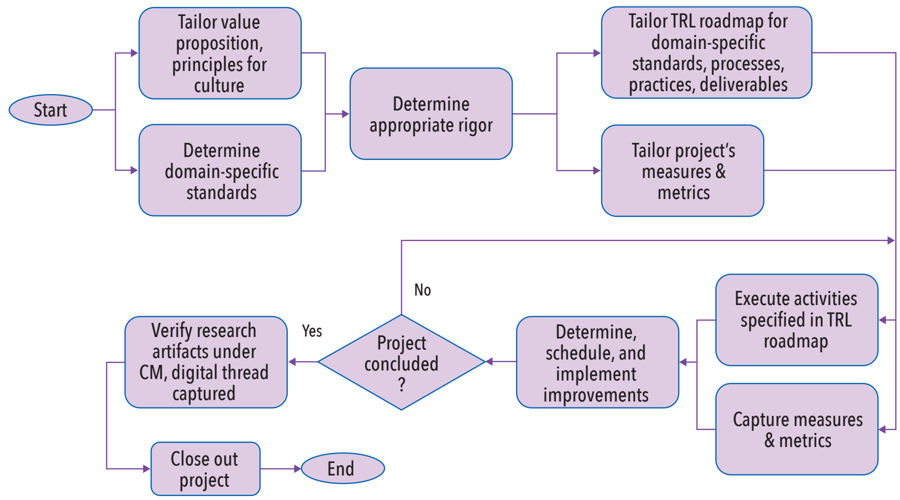

Figure 7. Using the systems engineer in ESR&D framework elements

in helping to assure the success of the research project.

- If the measures and metrics are not providing the transparency needed for assessing progress, determine what changes are needed to improve the transparency.
- Domain-specific TRL requirements/definitions may need to be adjusted as more knowledge is gained from the research analyses.

SUMMARY

This article presented a blueprint for the principles and foundational elements necessary for development and use of a framework for systems engineering applicable in ESR&D. An approach for defining framework metrics is suggested to enable evaluation and practical implementation of the framework for systems engineering innovation management at this phase of technology development. Figure 7 shows a recommended order for how these elements can be utilized. Note that coaching and mentoring between the systems engineer and PI (and other domain experts) occurs throughout the duration of the research project, more intensely at the outset of the project and decreasing as knowledge and skills are obtained by the project team.

The introduction section posed some challenges that the framework should address. This article described an approach for responding to each challenge.

Can the framework address the types of projects of interest? Yes – domain-specific tailoring and a risk-informed graded approach is included in the framework. Additionally, developing templates for the TRL roadmap for research domain types provide increased efficiency and effectiveness in applying systems engineering in ESR&D.

- Does the framework address the cultural gap between systems engineering and ESR&D? Yes – a trans-disciplinary approach is emphasized in utilizing the framework.
- Does the framework support the range of internal and external stakeholders? Yes – for example, stakeholder expectations are a key consideration for determining the appropriate level of rigor.
- Can the framework support different funding levels and funding allocation strategies? What is an acceptable level of process documentation, tools, and templates required by the framework? Yes – these questions are addressed by the risk-informed graded approach to determine appropriate rigor, and rigor-level considerations (formality, timing, and scope).
- Will the framework support the transition to more formal systems engineering should the effort move beyond the TRL level for ESR&D? Yes – focus on providing an infrastructure for preserving research integrity and knowledge capture (for example configuration management, foundational to developing a digital thread) provides a basis for further technical maturation and therefore providing a bridge from research to engineering.

Many of the challenges for bridging research and engineering summarized in Figure 1 are overcome by the framework:

- Technical – Increased awareness of the life cycle perspective included in the systems engineering activities and deliverables in Table 1 and the multidisciplinary approach facilitates inter-transdisciplinary mindfulness.
- Science and engineering management – Budget is better informed by the life cycle view, and includes earlier consideration of the potential market and supply chain issues.
- People – Mutual training/coaching between the PI and SE is emphasized.
- Perception – Increased potential for tackling some of the perception issues due to increased confidence and credibility in the relevant standards, the research approach, vetting, and the ecosystem supporting the research activity.

Future activities include applying the framework, obtaining feedback, and addressing gaps. ■

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Ann Hodges retired after 48 years of service at Sandia National Laboratories and was a distinguished member of technical staff. She was the Mission Services Division's systems engineering lead for the systems engineering part of the project and product delivery system (PPDS) at Sandia National Laboratories and was a project manager and systems engineer for a complex exploratory-phase project. She is a primary author of the risk-informed graded approach to the application of project management, systems engineering, and quality management which is one of the key aspects of the PPDS. She obtained a BBA and an MS in computer science from the University of New Mexico, and holds CSEP, SAFe SPC4, and CMII certifications. Ann has held leadership positions in the INCOSE Enchantment Chapter including director-at-large 2011-2012, president-elect and acting secretary 2013, president 2014-2015, and secretary 2015-present. She is the co-chair of the INCOSE Systems Engineering for Early-Stage R&D working group.

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APPENDIX A: ROADMAP OF SYSTEMS ENGINEERING ACTIVITIES AND DELIVERABLES FOR TRLS 1-6

Table 3. Roadmap of systems engineering activities and deliverables for TRLs 1-6

TRL Level Activities & Deliverables / Process Areas	BASIC RESEARCH 1 - Basic principles observed and reported	BASIC RESEARCH 2 - Technology concept and/or application formulated	TECHNOLOGY DEVELOPMENT 3 - Analytical and experimental critical function and/or characteristic proof-of-concept	TECHNOLOGY DEVELOPMENT 4 - Component and/or breadboard validation in laboratory environment	TECHNOLOGY DEVELOPMENT/ DEMONSTRATION 5 - Component and/ or breadboard validation in relevant environment	TECHNOLOGY DEMONSTRATION 6 - System/ subsystem model or prototype demonstration in relevant environment
Requirements Definition and Management	• Identify research objectives, sponsor key performance parameters • Specify TRL-specific domain requirements for the relevant domain(s) • Specify approach for capturing and managing research objectives, performance parameters, and derived requirements • Implement the management approach	• Refine research objectives, performance parameters, TRL-specific domain requirements based on experimental results • Research→ engineering transition(s) defined and requirements considered • Identify figures of merit, trade studies, relevant simulations and needed fidelity, considering all life-cycle phases • Conduct trade studies, simulations, analyze results for refining research objectives and identifying derived requirements • Manage changes to research objectives, requirements	• Refine research objectives, performance parameters, TRL-specific domain requirements based on experimental results • Refine figures of merit, trade studies, relevant simulations and increased fidelity • Conduct updated trade studies, simulations, analyze results for updating research objectives, derived requirements and architecture alternatives • Manage changes to research objectives, requirements • Specify requirements management approach • Specify research objectives, performance parameters, TRL-specific domain requirements and other derived requirements in a format compatible for import into an MBSE tool	• Continue the first 4 activities from TRL 3 • Implement the requirements management approach • Import research objectives, performance parameters, TRL-specific domain requirements and other derived requirements in a format compatible for import into an MBSE tool	• Continue the first 4 activities from TRL 3 • Continue refining the requirements in an MBSE tool	• Continue the activities from the previous TRL
Architecture Definition		• Identify initial use case model for potential application of research outcome • Specify context diagram of potential application of research outcome • Identify potential architectural components • Initiate development of domain-specific models • Architecture-related research →engineering transition(s) defined	• Refine use case model • Refine context diagram • Refine domain-specific models based on experimental results and analyses • Specify architecture alternatives of potential research application - interfaces, major components (e.g., block diagram, sequence diagram, state machine diagram)	• Continue the first 3 activities from TRL 3 • Refine architecture of potential research application selecting leading architectural candidates from alternatives • Create relevant system models (e.g., describe phenomenology, behavior models [e.g., activity diagram, parametric diagram]) or simulations • Create prototype that demonstrates relevant/ key characteristics	• Continue the first 2 activities from TRL 4 • Enrich subsystem/ component models, simulations or prototypes to demonstrate sufficient behavior in the relevant environment	• Continue the first 3 activities from TRL 4 • Increase scope of subsystem/ component models, simulations or prototypes with increased aggregation of phenomenology in the relevant environment
Verification and Validation (V&V)	• Specify V&V approach, relevant reviews/reviewers • Specify evaluation approach (e.g., test, demonstrate, analyze) for each TRL-specific requirement • Conduct reviews of TRL 1-related artifacts • Identify issues and risks from V&V activities • Deliver V&V report artifacts as indicated in the V&V approach	• Perform V&V on experimental plans, analyses and reports • Specify evaluation/ test approach scenario for each TRL-specific requirement • Review TRL-specific evaluation/test approach • Perform V&V of artifacts related to this TRL • Identify issues and risks from V&V activities • Deliver V&V report artifacts as indicated in the V&V approach • V&V approach for addressing TRL transitions	• Continue V&V activities from previous TRL	• Continue V&V activities from previous TRL	• Continue V&V activities from previous TRL	• Continue V&V activities from previous TRL

Table 3. Roadmap of systems engineering activities and deliverables for TRLs 1-6 (continued)

TRL Level Activities & Deliverables / Process Areas	BASIC RESEARCH 1 - Basic principles observed and reported	BASIC RESEARCH 2 - Technology concept and/or application formulated	TECHNOLOGY DEVELOPMENT 3 - Analytical and experimental critical function and/or characteristic proof-of-concept	TECHNOLOGY DEVELOPMENT 4 - Component and/or breadboard validation in laboratory environment	TECHNOLOGY DEVELOPMENT/ DEMONSTRATION 5 - Component and/or breadboard validation in relevant environment	TECHNOLOGY DEMONSTRATION 6 - System/ subsystem model or prototype demonstration in relevant environment
Project Planning: Proposal/ Charter	Document the research scope, relevant domains, multi-disciplinary team (including systems engineers), relevancy of research, identify equipment/ laboratory/ facilities needed to support research, appropriate rigor (likely Low, Medium for "grand challenge" or "moon shot"), include references to milestones, WBS, budget					
Project Planning: Milestone Definition	• Specify start and end, relevant way-point milestones to provide insight for progress • Research → engineering transition strategy defined	• Organize milestones using the WBS structure • Refine milestones to assess progress • Specify dependencies between milestones	• Refine milestones to assess progress • Create a more formal schedule: Specify major tasks and dependencies for major milestones	• Refine milestones and schedule as needed	• Refine milestones and schedule as needed	• Refine milestones and schedule as needed
Project Planning: Work Breakdown Structure (WBS) Definition	• Specify decomposition of research objectives (e.g., domain based) in WBS • Specify activities related to research infrastructure in WBS including safety of experimenters, equipment, materials/"products"; requirements management; CM; risk management; issue/ action item tracking; M&TE management; waste stream disposal	• Organize milestones into WBS • Refine WBS given experimental insights	• Refine WBS as needed given experimental insights	• Refine WBS as needed given experimental insights • Update WBS to include planning for market analysis, production, supply chain	• Refine WBS as needed given experimental insights, market analysis, production	• Refine WBS as needed given experimental insights, market analysis, production
Project Planning: Budget Definition	Specify time-phased budget for the research project's "period of performance" to address the WBS, with research → engineering transition considered	• Update budget needs based on the issue and risk mitigations • Request budget changes as needed	• Update budget needs based on the issue and risk mitigations • Request budget changes as needed	• Update budget needs based on the issue and risk mitigations • Request budget changes as needed • Research → engineering transition needs met	• Update budget needs based on the issue and risk mitigations • Request budget changes as needed	• Update budget needs based on the issue and risk mitigations • Request budget changes as needed
Configuration Management (CM)	• Specify programmatic (for example proposal, milestones, WBS, budget, tracking, risk management artifacts, issues management artifacts, records (e.g., experimental equipment calibration, schedule/cost actuals, briefings, reports)) and technical (for example experimental plans, experimental results, V&V results (including reviews), risks, issues, requirements) items to track — "configuration items" • Specify the approach for how changes will be managed for those configuration items (include impact analysis for performance, cost and schedule) • Specify how programmatic and technical items will be version controlled and tracked to support trend analysis and preserve integrity of results • Version control the identified configuration items • Implement the change management approach	• Refine configuration management approach as needed based on project experience • Perform change management • Perform version control	• Continue identified activities in previous TRL for this process area	• Continue identified activities in previous TRL for this process area	• Continue identified activities in previous TRL for this process area	• Continue identified activities in previous TRL for this process area

Table 3. Roadmap of systems engineering activities and deliverables for TRLs 1-6 (continued)

TRL Level Activities & Deliverables / Process Areas	BASIC RESEARCH 1 - Basic principles observed and reported	BASIC RESEARCH 2 - Technology concept and/or application formulated	TECHNOLOGY DEVELOPMENT 3 - Analytical and experimental critical function and/or characteristic proof-of-concept	TECHNOLOGY DEVELOPMENT 4 - Component and/or breadboard validation in laboratory environment	TECHNOLOGY DEVELOPMENT/ DEMONSTRATION 5 - Component and/ or breadboard validation in relevant environment	TECHNOLOGY DEMONSTRATION 6 - System/ subsystem model or prototype demonstration in relevant environment
Risk Management	• Specify risk management approach (identify, analyze, treatment options, mitigation plans) • Specify risk register attributes and tracking approach/tool • Implement risk management (approach and supporting infrastructure)	• Refine risk management approach as needed based on project experience • Continue performing risk management, considering risks beyond up to and beyond TRL 6	• Refine risk management approach as needed based on project experience • Continue performing risk management, refining/ updating risks from prior TRLs	• Refine risk management approach as needed based on project experience • Continue performing risk management, refining/updating risks from prior TRLs • New research → engineering transition risks considered	• Refine risk management approach as needed based on project experience • Continue performing risk management, refining/updating risks from prior TRLs	• Refine risk management approach as needed based on project experience • Continue performing risk management, refining/updating risks from prior TRLs
Issues/Action Item Tracking	• Specify approach for tracking issues and action items resulting from research activities, technical exchanges, problems with experimental infrastructure, V&V • Implement issue tracking (approach and supporting infrastructure)	• Refine issue and action item tracking approach as needed based on project experience • Continue performing issues/action item tracking	• Refine issue and action item tracking approach as needed based on project experience • Continue performing issues/action item tracking	• Refine issue and action item tracking approach as needed based on project experience • Continue performing issues/action item tracking	• Refine issue and action item tracking approach as needed based on project experience • Continue performing issues/ action item tracking	• Refine issue and action item tracking approach as needed based on project experience • Continue performing issues/ action item tracking
Measuring and Test Equipment (M&TE) Management	• Determine availability of and calibration needs of equipment identified in the proposal • Perform calibration and maintenance on identified equipment • Identify gaps in availability, track issues using the issue tracking approach	• Update availability of and calibration needs of equipment identified in the proposal • Continue other identified activities in previous TRL for this process area	• Update availability of and calibration needs of equipment identified in the proposal • Continue other identified activities in previous TRL for this process area	• Update availability of and calibration needs of equipment identified in the proposal • Continue other identified activities in previous TRL for this process area	• Update availability of and calibration needs of equipment identified in the proposal • Continue other identified activities in previous TRL for this process area	• Update availability of and calibration needs of equipment identified in the proposal • Continue other identified activities in previous TRL for this process area
Project Tracking and Oversight	• Specify approach for comparing planned (e.g., budget) to actuals, analyzing variances, addressing variances and reporting • Implement tracking and oversight approach	• Refine tracking and oversight approach as needed based on project experience • Continue performing project tracking and oversight	• Refine tracking and oversight approach as needed based on project experience • Continue performing project tracking and oversight	• Refine tracking and oversight approach as needed based on project experience • Continue performing project tracking and oversight • Transition oversight coordinated with transition receiver	• Refine tracking and oversight approach as needed based on project experience • Continue performing project tracking and oversight	• Refine tracking and oversight approach as needed based on project experience • Continue performing project tracking and oversight

Systems Engineering in Technology Development

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ABSTRACT
Technology development is the crucial first step in designing new products and systems. It is a unique phase of product development in that it incorporates both scientific exploration and reduction to an engineered result. Too often, systems thinking and systems engineering principles aren't applied at this stage, leading to technologies that solve the wrong problems, inability to progress to higher maturity levels, and unworkable implementation architectures. In practice, this means higher development costs, extended timelines, and failed technology development projects.This article presents a framework for and provides guidance on systems engineering activities that add value and improve outcomes if applied during early stages of product development.

INTRODUCTION

The failure rate for projects transitioning from early technology readiness levels (TRLs) to viable products is high across all industries. Failure rates are even higher in highly regulated industries like medical devices and aerospace or where new technology integrates into complex product solutions.

Industry has long recognized a general maturity model that categorizes a product or system on a TRL 1-10 scale (Straub 2015). This paper discusses projects that fall within the definitions of TRLs 1-6. Systems engineering practices are often ignored at this stage and many organizations treat systems engineering as an unwarranted burden rather than helpful guidance.

This paper presents a systems thinking framework and set of systems engineering activities that better inform the technology maturation process. These include: The complete capture of mission objectives, decoupling of the problem from the implementation, risk informed iterations, a method to track performance against key design drivers, and effective operational demonstrations.

The result is a framework and set of artifacts and architectural views to drive the appropriate solutions to the identified need or problem. We present some practical antidotes in the form of a framework that incorporates systems thinking to envision the final product and the rigor of systems engineering to focus the development effort and improve the probability of delivering the right solution.

CURRENT STATE AND COMMON PROBLEMS

While most organizations hold their processes for technology development under a tight, proprietary umbrella, groups like INCOSE provide some relevant guidance on this topic and describe the current state of the art.

Mature research organizations (such as national labs) apply systems engineering in a staged approach, determining the applicability based on several criteria including complexity, safety criticality, regulatory oversight, application of multiple disciplines, and others. They may require a partial set of the system vee activity to be performed as early as TRL3. This guidance only seems to provide indication of the rigor required and doesn't specifically tailor the activity for a technology development, only stating that it needs to be performed.

At some businesses, the method for developing technology is based on a proposed solution to a stakeholder need, a set of validation criteria, and a stair-stepped approach of increasing maturity prototypes and validation tests against the stated criteria. A non-advocate assessment of the validation criteria and data is reviewed and then the overall system TRL is advanced to the next stage.

The process works well for a combination of well understood problem statement, simple system solution, and experienced team members with a strong background in designing si milar products. Many of the traditional systems engineering steps are intuitively captured within the validation criteria and in the selection of the validation tests.

As the complexity of the system increases, the ability of even an experienced team to properly focus on the core problem becomes more and more difficult. Thus, it becomes tempting to jump to intuitive conclusions under the pressure of wanting to get something done. Flyvbjerg and Gardner (2023) note that this pressure drives premature selection of an implementation architecture concurrent with developing prototype demonstrations and processes that may have never been done, with the magical hope that the technology, desired functionality, and final design all mature in parallel. He notes this was the case for the Sydney Opera House, a design marvel that ruined the architect's reputation and nearly bankrupted the city.

Another common pitfall is that the development team, often composed of scientists who do not possess strong systems engineering skills, may spend inordinate time implementing functions that are not critical or do not contribute to the technical breakthroughs necessary to field a final product.

Finally, Beasley and Ingram (2020) concluded that there are five main traps for innovators that commonly derail research and development initiatives. These are:

- Inability to identify that the market and competition have changed, and a new, better product-market fit is possible
- Inability to identify that the collaborating systems and partners we rely on have changed, or have conflicting goals we can no longer support
- Inability to separate out current products, firm's competences, and market, leading to inappropriate future planning
- Neglecting to identify, understand and plan for appropriate collaborating systems and/or realization system
- Neglecting to think about sustaining systems, resulting in an inability to scale up.

In the author's own organization and based on an internal survey, two additional traps were identified:

- Inability to produce a technology within the timeframe appropriate to support a go-to-market strategy
- Significant, latent technical risks implementing the technology within a product line strategy.

APPLYING A SYSTEMS DRIVEN APPROACH

An effective framework must address common problems experienced by organizations that develop new products and systems employing new technology. Therefore, it should address the current state described above and include countermeasures to the innovation traps. We propose the following attributes to improve technology development outcomes. While not a 1:1 map, they will result in more deterministic results if rigorously applied:

1. A way to elicit a full understanding of the problem space and context
2. A way to establish clear success criteria based on all stakeholder inputs
3. A method that allows for innovation in a fluid solution space
4. A method to assess technical maturity in its architectural context
5. A way of handling ambiguity in requirements
6. A way of handling ambiguity in external interfaces and system knowledge
7. A method for eliciting and evaluating feedback from stakeholders
8. Forcing functions that clearly tie to market strategy
9. A method for managing both known and unknown risk.

A systems-centric framework takes the current process of staged, TRL reviews and refines it into an iterative, architectural process that invokes systems thinking and systems engineering principles upfront to increase confidence that the right solution will be developed.

The solution is focused on system needs, is validated through concept of operation (ConOps) scenarios, forces most of the iteration and work into the functional architecture development phase, and encourages building minimal purpose prototypes implementing only critical functions and designed to answer fundamental questions.

The readiness level definitions become architectural attributes of the system instead of process drivers. The process driver then becomes a systems validation plan based on the system functional architecture and prioritizing criticality and maturity attributes.

The process becomes more scalable as system complexity increases. Recommended systems activities are described in the next sections.

Develop a System Needs Definition

The first point where systems thinking and systems engineering process can add value to a technology development project is in the very beginning. Technology development projects often start with an idea or an awareness of an emerging technology. That may not be fully formed or documented. Applying systems thinking inherently addresses criteria 1 and 2 above.

A problem or need statement can be driven by any stakeholder internal or external to the organization. These start as a verbal request or statement or may be driven by a market trend or strategy discussion. Distilling this statement into a true system needs definition is an often missed or under scoped task.

An effective method for establishing the problem domain and effectively invoking systems thinking (Arnold and Wade 2015) is documenting the concept of operations. The concept of operations is agnostic of the solution and identifies key scenarios, functions, and interactions to better frame the problem space.

The US Department of Defense Architectural Framework (DoDAF) and INCOSE provide excellent guidance on how to perform a concept of operations. The concept of operations will identify all life cycle needs, establish a context boundary, identify all stakeholders, establish a business case, and inform an early functional architecture.

As different use scenarios are defined, key statements will become obvious to measure the success criteria of the solution. These are called measures of effectiveness (MoE) (Roedler & Jones, 2005) and they are defined as the "operational" measures of success that are most closely related to the achievement of the mission or operational objective being evaluated, in the intended operational environment, under a specified set of conditions.

MoEs are effective for providing key indicators of achieving the mission needs for a system across the full life cycle and will likely serve as a standard of acceptance for the technical solution.

A set of MoEs can be informed by the concept of operations, input from the stakeholders, early market strategy, and lessons learned. A reasonable number of MoEs should be captured to focus the problem. For example, a recent technology development project led by the authors produced around 30 MoEs. MoEs can be thought of as quasi-requirements. They can be less prescriptive and more performance-based, which is helpful during technology development.

When using an MBSE approach and environments like SysML, the ConOps and MoEs can be captured within the model as a series of use case, activity, and sequence diagrams. These define high level functions that need to be performed and can be captured as functional blocks. This can be the basis for a functional architecture.

A concept of operations and set of MoEs become a system needs definition that explains the problem domain. This system needs definition establishes scope and expectations for both the organization and the technology development team and provides a platform for evaluating different technical approaches.

Perform a Concept Trade Study

An organization may have a set of technical capabilities available that can be evaluated against the high-level functions defined by the ConOps. These may take the form of features from past development projects, technology developed internally but not yet deployed or acquired intellectual property and technology. One or more concept trade studies should be performed to evaluate existing capabilities and technologies against functions identified in the ConOps.

The top level ConOps functions, the MoEs, and a defined set of technologies and capabilities, as well as an initial assessment against the MoEs will need to be available. Forced ranking of the MoEs for a particular application may be necessary and helpful,

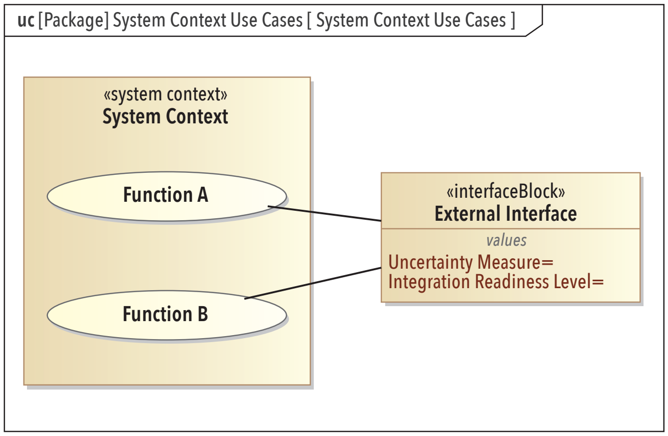


Figure 1. ConOps function identification

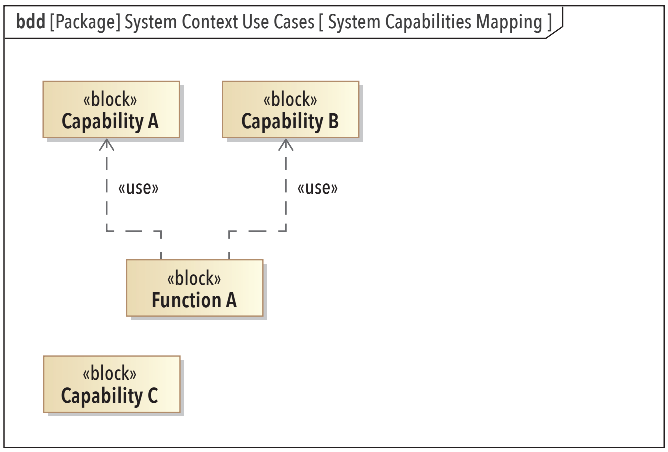


Figure 2. Relating capabilities to functions

especially in cases where a solution may fit multiple markets.

The MoEs should be used to drive the capability trade studies and market feedback used to weight the MoEs for a particular application. A risk register should be generated to capture technical concerns related to the selected capabilities or technologies.

The preferred capabilities and technologies should then be mapped to the high-level functions identified by the ConOps. Example capabilities may include existing internal products, existing external products, and particular technologies. The following figure shows a basic system context from the ConOps and two identified functions.

Capabilities may be combined to support a function, but the act of relating the capabilities to the top-level functions establishes the intent.

When this activity is done, it becomes very clear that there are two distinct triggers for updating the trade study(s). The first is a change in ConOps, which can be triggered at any time the stakeholders alter their acceptance criteria or intended use of the system. This can be discovered through frequent demonstration directly to the stakeholders.

The second is a change in capabilities. This could come from external sources (for example, competitors), large step changes in technology capability, business case, or newly available internal products. These can be discovered through market monitoring, intellectual property (IP) surveys, and other means.

The output of this process is a set of selected capabilities that are mapped to a top-level functional architecture. The trade study and mapping exercise provides the user a strong understanding of capability assessments against the MoEs as well as guidance towards a preferred set of capabilities and technologies to investigate.

Investigate the Solution Concept

The goal of investigating the solution concept is to quickly identify whether proposed technologies/capabilities are capable of meeting mission goals. This phase creates a system validation plan that focuses on the critical and high risk, high unknown behavior, and assesses the performance against the MoEs.

In investigating the solution concept, the first activity should be to fully decompose the functional architecture from the high-level version generated for the ConOps. Each function can be decomposed into its inputs, outputs, and transfer function. The ConOps scenarios can be used to validate the functional architecture, identifying missing functions and interfaces to support all stakeholder needs.

The functional architecture should include the full problem domain, accounting for not only the system of interest (within the context boundary), but also any external, behavioral interfaces. The following diagram demonstrates a generic functional decomposition that shows the problem domain, external interfaces, system context, and a decomposition of functions.

Typical functional architecture analyses can be performed to make sure that any missing functions or missing interfaces are identified. Applying the scenarios identified in the ConOps to the

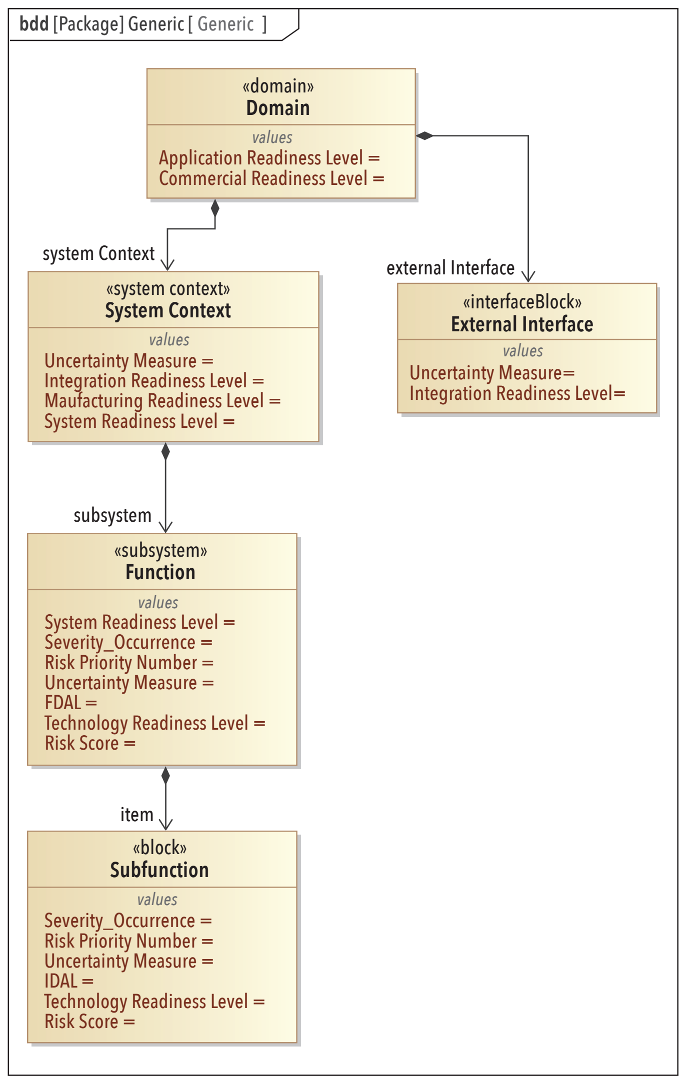
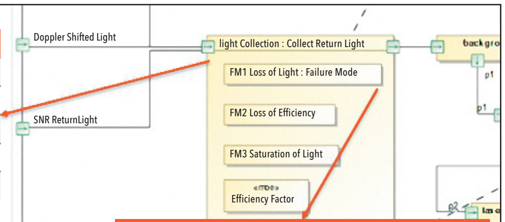


Figure 3. Functional decomposition

Light Collection	Collect Return Light
SO (worst case)	81
RPN (worst case)	162
Uncertainty	1
TRL	4
Risk	15



Light Collection	FM1 Loss of Light
Severity	9
Occurence	9
Detection	2
SO	81
RPN	162

Figure 4. Example failure mode attribute scoring

functional architecture will validate that all required functions, interfaces, and ranges are captured. Any new functions or interfaces added should be mapped to a capability.

Minimum attributes should then get an initial assessment for each function, depending on its level within the hierarchy. Assuming the domain represents a Level 0 of the hierarchy, the recommended attributes are described below. Note that at this phase, some of these attributes may be default values.

Level 0 — Domain Level

Application readiness level – An assessment of the solution's readiness for the application or ConOps that's been defined. Since this process generally uses the ConOps scenarios for validation purposes, the progression of the application readiness level will follow the system readiness level assessment closely.

Commercial readiness level – An assessment of the solution's readiness for widespread commercial acceptance. For the scope of technology development, it's unlikely this value will progress beyond a 5 before the product is transitioned to a more traditional product development cycle. Refer to ranking tables for detailed checklists.

Level 1 — System Context and External Systems Level

(External systems, system context) Integration readiness level – An assessment of the interface and sufficiency of detail and understanding to allow a full characterization of the relationship, compatibility, and understanding of availability.

(External systems, system context) Uncertainty measure – The level of representative data, over the operating range that validates the behavior.

(System context) System readiness level – A combination of the technology (or system) maturity assessments for the components and interfaces that make up the system, assessment that emergent behavior has been accounted for and is well understood.

(System context) Manufacturing readiness level – An assessment of the system's maturity and ability to support manufacturing processes.

Level 2/Level n — System Functions/ Subfunctions

System readiness level – A combination of the technology (or system) maturity assessments for the components and interfaces that make up the system, assessment that emergent behavior has been accounted for and is well understood.

Technology readiness level – A standard maturity assessment for a particular function or capability.

Uncertainty measure – The level of representative data, over the operating range that validates the behavior. (Knight, 2002)

Risk score – A normalized score based on known, captured risks that are allocated to that function. The risk score is based on multiplying the probability times the effect. Each system is a sum of its own risks and the risks of all its subsystems/functions. The results can be either normalized or averaged over the number of risks.

As an initial functional architecture is built and related to capabilities or technologies, the MoEs may be decomposed further into measures of performance (MoPs). These are measures that characterize the functional attributes relating to the system operation, estimated under specified environmental conditions. These can also represent physical attributes, but during this phase only the functional attributes should be identified.

The output of this activity are the required functions, information transformation, and interfaces that accomplish the ConOps. Additionally, the initial capabilities are mapped to each function and any gaps are identified.

The goal of building a complete functional architecture is ultimately to understand the required interactions and criticality as they relate to the ConOps and MoEs identified by the key stakeholders. This provides a clear understanding of the problem space and context as well as any missing capabilities.

Mature the Solution Concept

To mature the solution concept, additional detail and views are applied to the functional architecture to produce a prioritized system validation plan and full set of MoPs and KPPs.

For safety critical systems an important architectural feature is function criticality. A streamlined version of a systems design and failure mode and effects analysis (DFMEA) (SAE 2009) is an appropriate analysis that can identify critical functions (SAE 2009).

To perform this, assess each function's possible failure modes. If the failure modes are not known, basic modes such as loss of function and erroneous output of function can be assumed. Each failure mode should be assigned a severity, occurrence, and detection score based on SAE (2009). Each function can then be assigned the following attributes representing the worst-case failure mode score for:

Severity/occurrence value (SO) – The severity score multiplied with the occurrence score. Provides an assessment of the criticality of the function based on both the severity and probably occurrence of its worst failure mode.

Risk priority number (RPN) – This score is calculated by multiplying the SO value from above with the detection score. The ability to detect a failure effectively can reduce or increase the criticality of a particular function.

Figure 4 shows an example of these detailed attributes and the scores associated with them.

Combining SO, RPN, and uncertainty scores provides insights that might not otherwise be obvious.

Using this method, if the SO score of the function is high, then the development team should treat that function as critical as they develop the technology. If the uncertainty score is also high, it may indicate that insufficient validation testing has been performed for that function.

This method thus constrains unknown risk, ensuring it is addressed early and not left to emerge late in the technology development program. Countermeasures in the form of early or additional testing can then be planned accordingly. In the worst case, this approach may point out that the technical approach is fundamentally flawed, saving the organization time, resources, and money.

The SO score of a function will also immediately identify areas of the architecture that are ripe for establishing key performance parameters (KPPs). KPPs are defined as those performance parameters

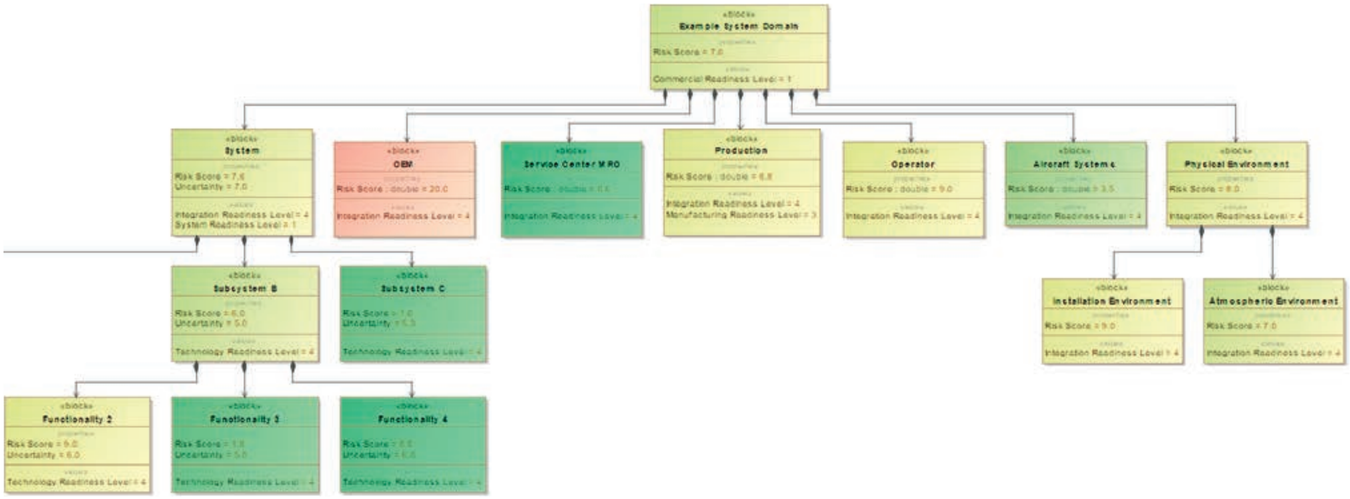


Figure 5. Example maturity view

are so significant that failure to meet the threshold value of performance can be a cause for the concept to be reevaluated or the project to be reassessed or terminated.

The readiness level attributes can then be applied more thoroughly, resulting in a top-level architectural maturity view, as depicted in the example below.

Several key inputs to the system validation plan can be extracted from this view. Validation activities can be categorized roughly as:

1. High uncertainty functions – may indicate validation activities that are focused on reducing uncertainty such as design of experiments etc.
2. High criticality functions – may highlight key functions that will require frequent demonstration and additional scrutiny from the customer and/or certification authorities.
3. High risk functions – multiple risk mitigation methods can be applied.

More importantly, this view highlights areas of the architecture that may not need significant focus early in the technology development. For example, this architecture includes a function to provide sensor status. All the attribute scores indicate that the overall maturity of this function is higher than others. Work could be deferred on this function until its relative scores eventually highlight it as being critical. This will happen later in the program when the other, more critical functions have been developed and matured.

The output of this activity is a prioritized system validation plan and updated MoPs and KPPs.

This activity produces a system validation plan that encourages high-value testing. Low maturity components are tested first. Frequent, smaller scoped and minimal purpose prototypes are built to answer more specific questions. The method focuses on both functions and interfaces, including external interfaces and behaviors. Finally, the plan highlights un-implemented functions and rationales for those.

Produce a Minimum Viable Product

Further refinement of the capabilities that map to the functional architecture will produce an implementation architecture. Subsets of this implementation architecture can be built and tested based on the system validation plan.

Each of the functions will map to critical capabilities that are decomposed into implementations. This provides a clear traceability to a minimal purpose prototype. Each capability will have clear MoPs and these will be further refined. When a final implementation architecture is selected these will become the basis of that system's requirements.

The functional maturity view for that prototype can also inform make/buy decisions. For example, a lower risk subfunction could be implemented with a commercial-off-the-shelf solution instead of a custom design. A combination of minimal purpose prototypes will inform the minimal viable product. This product can implement the ConOps identified by all stakeholders.

This activity produces a set of validation data that can aligns with the ConOps of the system and is focused on low maturity aspects of the system. The focus is on designing and maturing critical functions, validating high risk and high uncertainty items against the ConOps, and allows for a more modular approach to building the prototypes.

Monitor Concept Progress

Depending on the size and complexity of the system, all the MoPs could be monitored or the KPPs identified based on the criticality of the functions. The KPPs will be a critical subset of the MoPs. Additionally, the architectural maturity view is an input to this activity.

Frequent demonstrations using minimal purpose prototypes provide a set of data against MoPs that can be tracked through industry standard metrics tracking methods. This process produces that critical data. In the example shown in Figure 6, the values and the planned thresholds were based on market input for specific RFPs. Simulation prototypes and real hardware prototypes were separated in this case. The example shows a stoplight status of red based on the trendline.

In addition to these monitors, with presented with the context of the functional maturity view, further action can be discussed in context. For example, is the uncertainty of the related function very low? If so, there may be reason to focus further on that function and continue to investigate in case the demonstrated performance is a result of some key deficiencies in the prototype. Alternatively, if this trend has been consistent with several demonstrations, it may be time for the program to re-evaluate its market strategy. In this case, platform X is probably not a feasible launch platform.

While the example shows a single KPP, the dashboard should include a number of KPPs so the holistic project view becomes clear. All other KPPs may be green which also indicates that a reassessment of the strategy (and ConOps) could still produce a viable product from the development, but without this or with reduced capability in this function.

The output of this activity is a technical performance measure (TPM) dashboard, ideally displayed in real-time to keep the team focused on the critical timeline, maturity, and goals of the program.

The maturity view (which can easily be

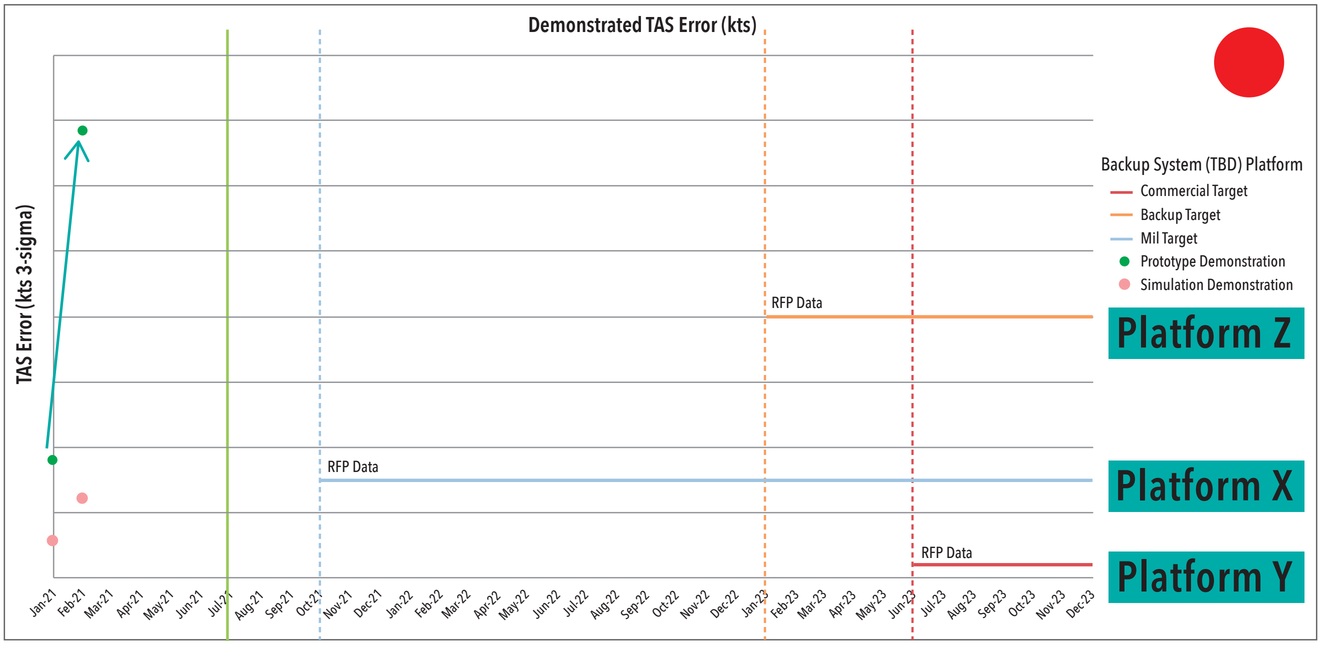


Figure 6. Example monitoring dashboard

Table 1. Framework summary

Current Process			Revised Process			Value
Inputs	**Activity**	**Outputs**	**Inputs**	**Activity**	**Outputs**	
• Problem or need statement • Technology and product portfolio	**Perform a concept trade study**	• Selected solution concept • Risks	• Problem or need statement	**Develop a system need definition**	• Conops • MOE's • Risks	• No predetermined solution • Understanding of problem space and success criteria
			• MOE's • High Level Functions and Interfaces • Capabilities	**Perform a concept trade study**	• Selected capabilities mapped to top level functional architecture	• Understanding of multiple accessments against MOE's • Initial guidance toward a capability
• Risks • TRL Validation criteria	**Review TRL**	• Updated risks • Incremental prototypes • Validation data • Candidate solution that might solve problem	• Top level functional architecture • Selected capabilities	**Investigate a solution concept.** Decompose a Functional Architecture and exercise Conops scenarios to identify gaps	• Required functions, information transformation, and interfaces	• Clear understanding of problem space, missing requirements, clear context • Optimized architecture based on Conops • Capability gaps
			• Detailed functional architecture mapped to capabilities	**Mature a solution concept.** Perform maturity and failure mode analysis on architecture	• Prioritize system validation plan • MOPs, KPPs	• Prioritized validation plan • Clear indication of maturity • Candidate solution functionally established and likely to solve the problem
			• System validation plan • Functional architecture views	**Produce an MVP:** Map high priority functions to implementation elements (refinement of concept) and execute validation to Conops	• Validation data • Minimal purpose prototypes	• Focus on designing critical functions • Validation of high risk/uncertainty items against Conops • Modular approach to MVP
			• TPMs • Validation Data • Maturity View	**Monitor Concept Progress**	• TPM control tower • Maturity View	• Clear readiness measures of components • Clear indication of external dependencies, risks, and uncertainty

color-coded based on the set of attributes) provides a clear readiness level of the system as well as the components that are driving it. Since the functional architecture also includes external interfaces, this will also highlight external dependencies and uncertainty that may be affecting the ability of the system to be right timed for the market. The TPM dashboard provides a progress meter for the validation of the system against KPPs and MoPs, highlighting potential trends and giving insight into the likelihood of the system to achieve operational objectives. Finally, these views change real-time so that the assessments can change as the solution evolves.

CONCLUSIONS AND FUTURE WORK

Most traditional systems activities aren't set up to foster innovation and are not typically right sized for a technology development program. When a program has a very low maturity level, how can traditional systems engineering practices help to develop a validation plan that answers the questions that need to be answered in an efficient way?

The proposed framework combines a few traditional systems engineering analyses into an architectural maturity view that helps focus validation efforts on the most important problems. Additionally, the framework removes the rigor around requirements development and focuses instead on validation criteria using MoEs and MoPs.

Some key attributes such as guidance on complexity measures based on uncertainty and functional impact are provided. The framework is intended to be flexible and scalable. Additional architectural views and analyses could be performed based on the type of product. While not strictly required, the framework is optimized for agile project management techniques and model-based systems engineering (MBSE) techniques.

A general summary of the framework is provided in Table 1. ■

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An Approach to Bridging the Gap Between the Attainment of Research Objectives and System Application

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ABSTRACT

The aerospace industry has widely adopted the use of technology readiness levels (TRLs), (NASA) which describe the maturity of a technology from earliest stages of research through the operational system. In using TRLs, it has been observed that bridging the gap between research on a technology and its incorporation by engineers into a system is challenging. Nominally, the transition from TRL 4, defined as a component and/or breadboard validation in a laboratory environment, to TRL 7, defined as a system prototype demonstration in an operational environment, is a programmatic gap known as the "valley of death." The valley of death is a schism whereby the component that incorporates the new technology fails to meet the eventual system requirements. The goal of this paper is to provide a methodology and "language" that enables the researchers and engineers to communicate more effectively to traverse this gap. The basis for this methodology is the combination of established methods for communicating progress for a program combined with the development and application of domain assessments. Domain readiness levels (DRLs), analogs of the TRLs, are specific to the domains relevant to the system of interest. Specifically, the methodology is intended to enable two-way communication between the domain experts and the systems engineer, with the goal of effective incorporation of a technology. This paper will use an example of the approach to bridge the "valley of death" targeted on the development of a satellite composites optical support structure that must stay in focus across the temperature range of 77-323 degrees Kelvin. In this example, the communication will use two relevant domains, materials and processes, to illustrate the methodology.

INTRODUCTION

The incorporation of a new technology into a system is undertaken when the risk is low enough and the potential reward significant enough to undertake the risk. Assessments of risk and reward are context dependent, but once the decision to invest in and incorporate a new technology has been made and accepting potential risk, the reward is the successful incorporation of the technology for the purpose of the system. The inability to mature a technology sufficiently for a program, that is, crossing the "valley of death", led to a US Department of Defense program requirement that a technology readiness assessment (TRA) shall be conducted for all critical technologies incorporated in the program. The technology readiness level (TRL) of these critical technologies shall be 6 to be a part of the program baseline (DR&E 2009). However, this approach doesn't provide any guidance for executing the maturation process.

It is the thesis of this paper that the language of a domain engineer is different from the language of the systems engineer, even when they use the same words. It is the goal of this paper to provide methods to bridge this communication gap. Further, if a domain engineer understands the full context of the intended use of the technology, it is more likely that this will both guide the domain engineer's execution and provide an early warning of a potential shortfall in time to adjust the program with minimal overall impact. Likewise, if a systems engineer or a program manager is aware of the scope of what the domain engineer views as the "technology" then modifications can be made to the development effort to concurrently obtain the data necessary to show maturity.

The options provided herein include conventional communication methods such as roadmaps, TRLs (see Table 1), and Gantt charts. In addition, to supplement these methods 1) a summary sheet of data to support the TRL level 6 assessment, 2)

Table 1. Technology readiness levels as defined by NASA

TRL	NASA DEFINITION
1	Basic principles observed and reported
2	Technology concept and/or application formulated
3	Analytical and experimental critical function and/or characteristic proof-of concept
4	Component and/or breadboard validation in laboratory environment
5	Component and/or breadboard validation in relevant environment
6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
7	System prototype demonstration in a space environment
8	Actual system completed and "flight qualified" through test and demonstration (ground or space)
9	Actual system "flight proven" through successful mission operations

two domain-specific assessments, "domain readiness levels" (DRLs) for the illustrative example domains (materials and processes), and 3) incorporation of a "degree of difficulty." In various combinations, these are intended to improve understanding between the program manager/systems engineer point of view and the domain expert point of view.

BRIEF DESCRIPTION OF A HYPOTHETICAL SYSTEM USED FOR ILLUSTRATING METHODOLOGY

Since the thesis for this paper is that improved domain-to-program communication is the key to crossing the "valley of death", this hypothetical and simplistic technology development will be used to show how the elements of communication may be used. The technology development for this program is the development of satellite low 0 coefficient of thermal expansion (CTE) struts, which are to be incorporated into a composites optical support structure that must stay in focus across the temperature range of 77-323 degrees Kelvin. The structure supports a mirror approximately 1 meter in diameter that must maintain focus over a wide temperature range after all ground handling, installation, and launch.

The domains relevant to the technology development for the purposes of illustration are the domains of materials and processes but may not be the only relevant domains. To achieve the support struts for the space-based optical support mount, several material families were evaluated. The selected material was carbon fiber-based composites. At the assumed state of development for this paper, it had been shown analytically that specific resin-fiber geometries have the ability to achieve a near 0 CTE over a wide temperature range and could be designed to have mechanical properties of strength and stiffness for this application. Based upon the confidence of the domain experts in building such struts via filament winding and the significant advantages, a technology development program was created (Ozaki 2008).

For the purposes of illustration, the program is divided into projects as follows:

- Project A – Demonstrate that there is composite configuration combining a carbon fiber with a negative lengthwise CTE and a resin with a positive CTE that will achieve the CTE over the temperature range of 77-323 degrees Kelvin that can be made into struts with a near 0 CTE between the two ends of the strut. This is the research that is intended to mature a technology.
- Project B – develop or adapt a method for combining the struts and mounting the mirror so that the focal point of the attached mirror fulfills system requirements, is stable and is structurally sound enough to withstand environments, notably the launch environment.
- Project C – A method to test the struts and then the optical mounting structure to be sure it, as a subsystem, will achieve the system objectives.
- Project D – Define the final design of the optical mount, the associated manufacturing and quality aspects such as including repeatability and margin, and build a working prototype of the subsystem.
- Project E – Build and incorporate the subsystem into the satellite system and perform qualification testing.

GENERAL APPROACH FOR COMMUNICATION

Several artifacts are used in combinations to communicate program/project-level perspectives with domain specialists and program managers. While the roadmap, Gantt chart, and TRL are in common usage, the level 6 TRA, DRLs, and degree of difficulty were created to better incorporate the domain point of view (Ruth 2001).

1. Roadmaps – provide a high-level view of the program and the projects, that together, make up the program; these can be implemented in Gantt charts to show more detail
2. TRLs – provide a high-level assessment of maturity
3. TRA for TRL 6 data capture
4. DRLs – describe the maturation process similar to the TRLs but from the domain's perspective
5. Degree of difficulty – a domain assessment for elements of a project to be used to communicate to program levels

ROADMAPS

Roadmaps are a high-level depiction of a program and often include multiple projects that are constructed to be related via physical and temporal logic

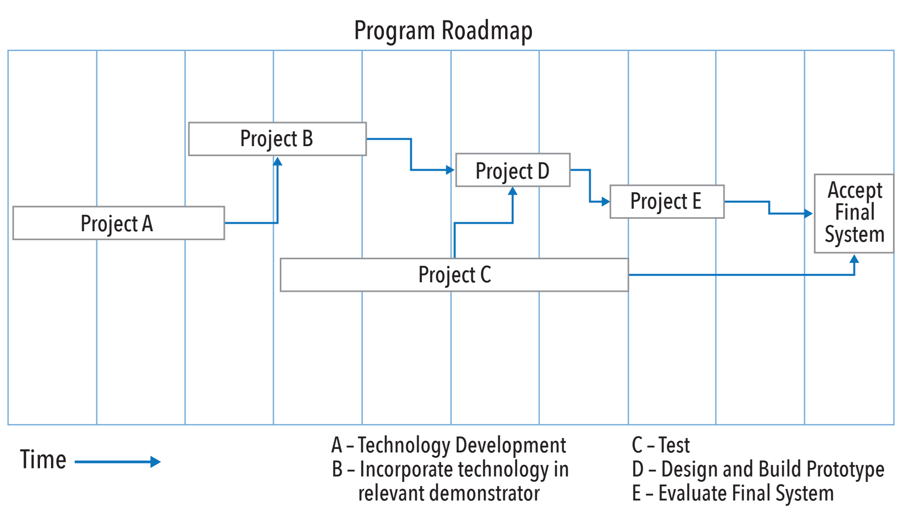

Figure 1. Program roadmap showing temporal relationship with constituent projects

as illustrated in Figure 1. The value is a high-level view of the program as well as showing where a technology development project fits into the overall program. When the technology development is planned as part of a program, it will often be one of the earliest projects on the roadmap and in fact, may precede the program.

For the purposes of illustration, the roadmap will be used to show how to incorporate detailed assessment into a program view. Depending upon the complexity of the program and what is to be communicated, there may be several versions of the roadmap with varying levels of detail. The roadmap depicted is for a hypothetical system described below, but only includes the projects that mature the technology to the system level.

Logic for the temporal relationships among the projects described is as follows:

1) The technology development (A) precedes all but the beginning of the project B that incorporates it. No point in starting B until there is reasonable confidence that A will be successful and to what degree.
2) The testing (project C) is a parallel effort that applies to both the testing for the optical mount (B) and the higher-level testing (D) with some potential adaptation for qualification testing (E). In this example, testing the struts alone is built into project A. Determining how to manage the extreme temperatures and do the evaluation is why the project is separate.
3) Projects B, D, and E are sequential. This is conventional practice. There are gaps between them to accommodate the timeline of project C, providing schedule margin, if needed.

Any temporal chart such as this roadmap, can be converted to a Gantt chart if there is a need to communicate at a lower level of detail illustrated in Figure 2.

TECHNOLOGY READINESS LEVELS

For the purposes of this paper, the technology readiness levels are as defined by NASA and shown in Table 1. An approach for objectively performing a technology readiness assessment to support the assertion that the TRL is at 6 or above is illustrated in Figure 3. The basic approach is to describe all of the requirements that the technology must meet in the system of interest. Each row can be updated as more data becomes available, thus communicating status and progress, in this case towards TRL 6. Moreover, this simple construct can be expanded to capture progress towards the details at lower and higher maturities.

Figure 2. Roadmap with added detail in Gantt chart format

Item	TRL	Basis of Assessment
TRL	TRL=	Description of item and what is driving the TRL goes here
Environment		
Pre-launch environments (with time)		
1- Weather (cold, hot, wet, dry, humid)		
2- Contamination		
3- Mechanical connections		
4- Electrical connections		
5- Communication connections (including data)		
6- Electromagetic spectrum (lighting, sunlight, etc.)		
Launch environment-external		
1- Pressure (changing pressure, venting)		
2- Temperature (heating e.g., due to aerodynamic drag)		
3- Gravity (acceleration)		
4- Vibration		
5- Structural loads		
Launch environment-internal		
1- Temperature (e.g., cryogens, combustion)		
2- Temperature gradients		
3- Corrosion		
4- Behavior of model or prototype in interfacing environment (e.g., software running on hardware)		
Operational Environment		
1-Lifetime (e.g., engine run time, moving mechanical assemblies, batteries, anything with a wear-out mechanism		
2- Duty Cycles/Transients (e.g., engine restarts		
3- Complex dynamic behavior (examples include flow and pneumatics, typically impacting performance, e.g., thrust ISP, etc.)		

Figure 3. Template for capturing data to support a technology readiness assessment (TRL6)

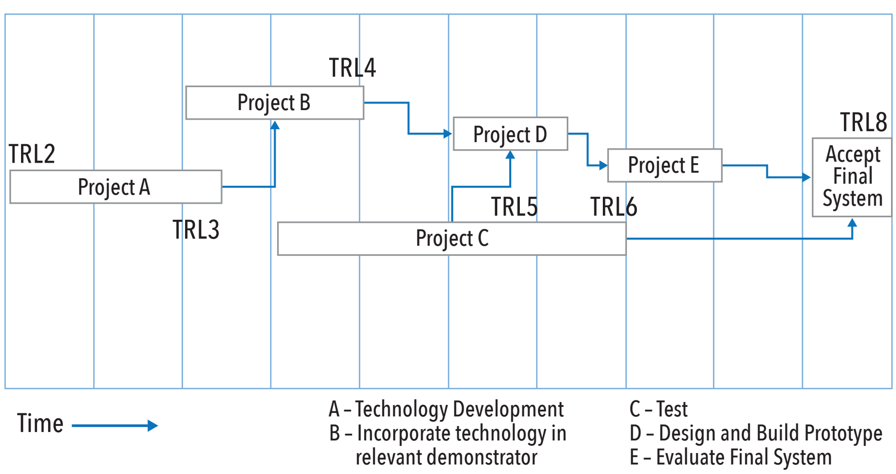

Figure 4. Addition of TRLs to the roadmap

TRLs can also describe the planned maturation of the technology on the program roadmap by adding TRLs where possible at the beginning and end of each project as shown in Figure 4.

Note that using the logic in the hypothetical project 1) not all of the maturation is in project A, 2) not all of the beginnings and endings of projects were able to be assessed and 3) going from project A to project B, the TRL actually requires ancillary engineering, thus identifying a potential gap. Project A is for the low CTE struts and project B is for the mount that uses the struts. The mounting scheme in this program has been assumed to be mature. This type of assessment helps identify additional data and related work needed to cross the "valley of death."

DOMAIN READINESS LEVELS

To supplement the other level readiness scales (technology, manufacturing, system readiness levels), DRLs were created to enable a domain engineer to capture and communicate an assessment of maturity from the context of the domain, roughly corresponding to the TRLs (Ruth 2011). The premise for DRLs is that every domain expert knows the natural progression to maturity is for their domain. By developing and using the DRLs it is possible to standardize the communication from the domain perspective. DRLs are at a very immature state of development consisting of a limited use of the two in this paper with the possibility of extending the concept to other domains. Note that the language of the DRLs is general for the purposes of communication with others outside the domain, including program managers.

For the hypothetical system, the domains of materials and processes were chosen and DRLs were developed. The rationale for these two is that a) they are this author's domains of expertise, b) they are the two domains that are fundamental to all hardware, and c) progress in advancing maturity is correlated between the two.

The DRLs for both materials and processes, are described in Figure 5. Note that readiness level, or maturity, for materials starts at "material family identified". This assumes that the various materials are already known though does not assume commercialization or even the data needed to support the application. This scale terminates when a material is a commodity. Processes have been treated similarly, with a starting point of a process being in existence with the highest maturity when a process is in high volume production.

While there are earlier stages of materials research not shown in this DRL, a program is unlikely to incorporate a project that uses

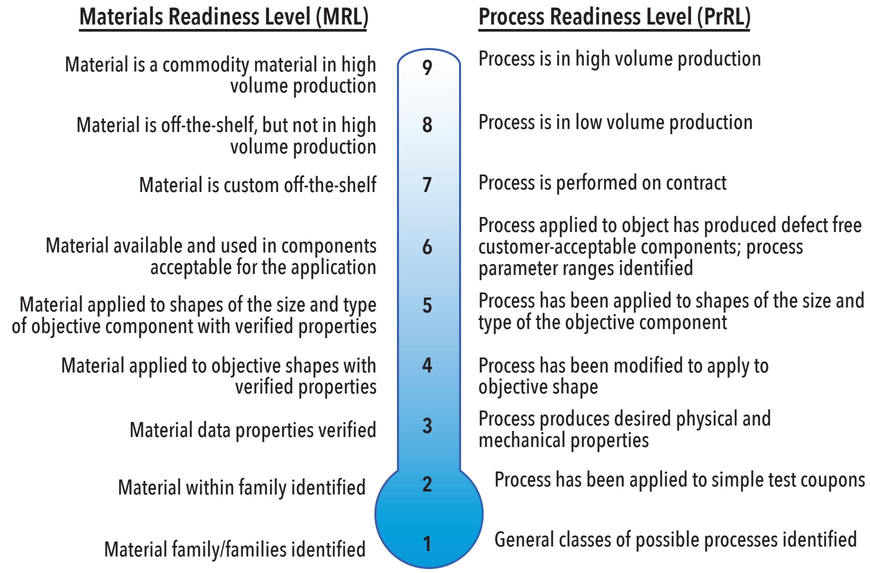

Figure 5. Domain readiness levels for materials and for processes

a material that has not been developed.

The materials readiness level (MRL) scale (not to be confused with manufacturing readiness level which is also abbreviated "MRL") is designed to aid a materials engineer in communicating in a consistent way the amount of data and information that exists relevant to the intended application. The assessment can be the basis for additional dialog, for the program to construct queries relevant to managing the program and the domain specialist for both responding to the program queries and for keeping the research targeting the intended application.

Process readiness levels (PrRL) also start with the lowest maturity that a program would consider and there is more basic research that resulted in identifying general classes of processes that might be used. Similar to the MRLs, the scale is designed to have objective measures of the applicability of the process to the technology development component in the system of interest.

For this application, what was known before project A was undertaken were carbon fibers have a negative CTE in the axial direction while resins have a positive CTE. Together in a composite, they exhibit a hybrid CTE as long as the resin and fibers stay bonded. For space systems, there are a limited number of resins that are suitable for application to space systems. Therefore, project A started with a material readiness level of 2 and as a part of project A will be matured to show it is acceptable for the application.

Likewise, the filament winding process for this application is already quite mature at PrRL 5, but the limited number of units needed means the maturity only has to be shown to result in reproducible units as typical of low-rate production such as PrRL 7.

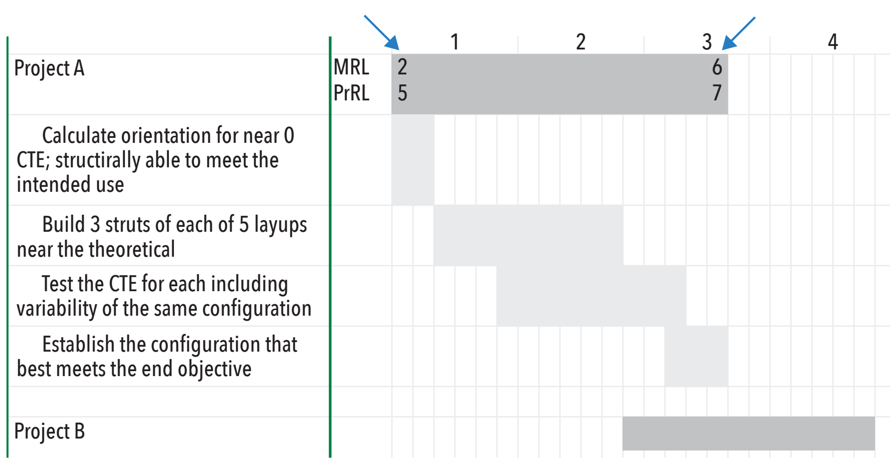

Figure 6. Approach to communicating DRLs At the beginning and end of the planned work

DRLs can be included on schedules like a Gantt chart to show the maturation with respect to the domain shown in Figure 6. Note that these DRLs are only applicable to project A and they are not the only DRLs to be considered. DRLs are not helpful at higher TRL levels for this particular application. The application is a single satellite, so high volume production is not required in this case.

DRLs for every relevant specialty domain can be developed and used similarly. For this application, a thermal DRL and a structural DRL for project A are likely companions to the ones described.

DEGREE OF DIFFICULTY

To supplement the domain's communication, some of the steps along the path to the project objective may range from easy to extremely difficult depending on the combination of characteristics required to yield the intended result. The systems engineer usually has perspective on the overall intent of the end item and the needed combination of characteristics, including those through end-of-life. The domain engineer usually has the perspective (or will acquire it as part of their work) of how difficult it will be to achieve and demonstrate the desired combination of characteristics in their domain(s). Having an assessment of the difficulty enables identification of when and for what purpose additional resources might be needed to achieve the system objective.

Degree of difficulty can be associated with any level of detail and is the perspective of the domain engineers responsible for execution. The project level assessment for difficulty is shown in Figure 7. Note that in this example, project C is actually assessed as the most difficult. However, not all lower-level activities are equally difficult. To communicate the aspects of a project that are difficult, a Gantt chart with lower-level activities can be used as shown in Figure 8 which shows the anticipated difficulty for the steps of project C, the most difficult project.

The difficulty arises from the need to test to the dimensions of CTE (10^{-6} m/m per degree Kelvin) which requires both very fine measuring capability as well as temperature control of the unit under test. Thus, program management is informed as to what the domain specialists are anticipating as a complementary view to the DRLs.

SUMMARY

The proposed methods for communication incorporate both overview level and detail level options and provides methods for combining them into a common view. The overview is assumed to be the purview of the systems engineer, who also includes the TRL assessment. The DRLs and degree of difficulty are envisioned as additions by the domain experts.

The detailed assessments including developing all of the data necessary for

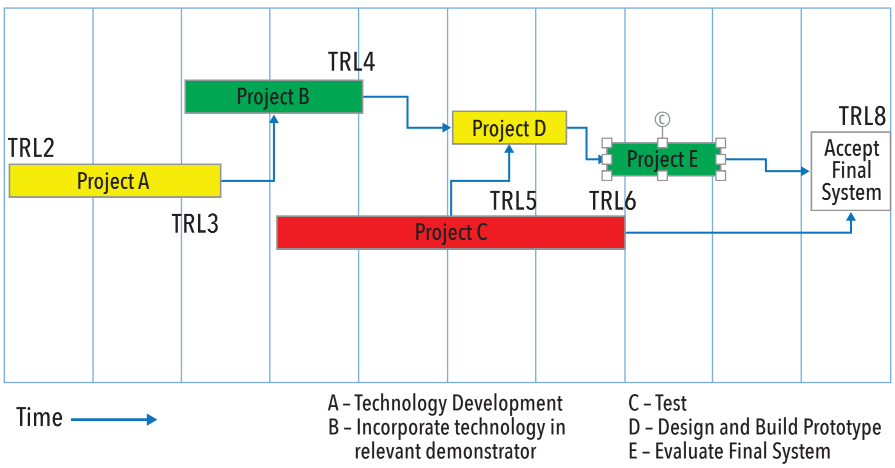

Figure 7. Adding degree of difficulty to a roadmap

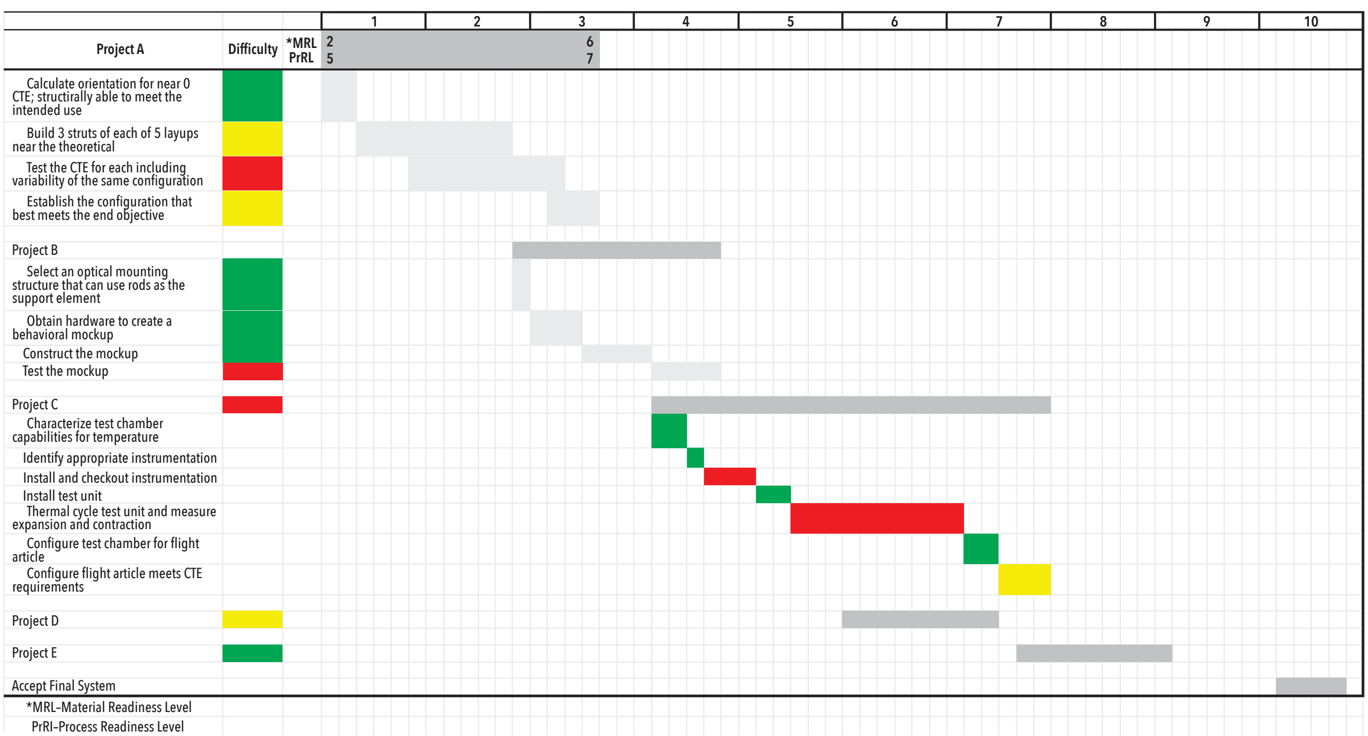

Figure 8. Adding degree of difficulty to more detailed plans

application in the system. The detailed communication of what is needed is the purview of the systems engineer, but making sure all of the data is acquired is the purview of the domain experts. This includes the details that are needed to show how TRL levels have been attained.

Together, these communication tools are proposed to provide a way to communicate more effectively among the program leadership, the project managers, the systems engineers, and the domain specialists. The communication tools at the program level, generally the purview of the systems engineer, tend to be fully mature and those for detailed communication from the domains, the purview of engineers and scientists are significantly less mature. While not yet rigorously tested, this suite of tools and techniques are proposed as an approach to cross the "valley of death", TRLs 4-6. ■

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ABOUT THE AUTHOR

Susan Ruth is retired after more than thirty years at The Aerospace Corporation, where she began her career by using her expertise in material and processes as applied to space systems. Subsequently, with a Master's degree in systems architecture and engineering, she was able to combine the "top down" approach of systems engineering in conjunction with her heritage domain expertise. For Aerospace, a part of her position was to assess projects with technical objectivity. She has used the combination of domain (bottom up) and technology (top down) readiness levels to assess both potential risk and to more effectively describe maturity of a project from both perspectives.

Enhancing Early Systems R&D Capabilities with Systems—Theoretic Process Analysis

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■ **ABSTRACT**
Systems engineering today faces a wide array of challenges, ranging from new operational environments to disruptive technological—necessitating approaches to improve research and development (R&D) efforts. Yet, emphasizing the Aristotelian argument that the "whole is greater than the sum of its parts" seems to offer a conceptual foundation creating new R&D solutions. Invoking systems theoretic concepts of emergence and hierarchy and analytic characteristics of traceability, rigor, and comprehensiveness is potentially beneficial for guiding R&D strategy and development to bridge the gap between theoretical problem spaces and engineering-based solutions. In response, this article describes systems–theoretic process analysis (STPA) as an example of one such approach to aid in early-systems R&D discussions. STPA—a 'top-down' process that abstracts real complex system operations into hierarchical control structures, functional control loops, and control actions—uses control loop logic to analyze how control actions (designed for desired system behaviors) may become violated and drive the complex system toward states of higher risk. By analyzing how needed controls are not provided (or out of sequence or stopped too soon) and unneeded controls are provided (or engaged too long), STPA can help early-system R&D discussions by exploring how requirements and desired actions interact to either mitigate or potentially increase states of risk that can lead to unacceptable losses. This article will demonstrate STPA's benefit for early-system R&D strategy and development discussion by describing such diverse use cases as cyber security, nuclear fuel transportation, and US electric grid performance. Together, the traceability, rigor, and comprehensiveness of STPA serve as useful tools for improving R&D strategy and development discussions. Leveraging STPA as well as related systems engineering techniques can be helpful in early R&D planning and strategy development to better triangulate deeper theoretical meaning or evaluate empirical results to better inform systems engineering solutions.

INTRODUCTION

Systems engineering today faces a wide array of challenges, ranging from increasingly complex operational environments to new and novel interdependencies to dynamic (r)evolutionary technological changes to fluidly shifting roles of human actors. In response, research, and development (R&D) efforts have focused on developing solutions to address these challenges. Yet, R&D projects aimed to address interdependencies may struggle with managing uncertainty in the analysis, possibly resulting in overly narrow hypotheses or suffering "unintended consequences." Or R&D efforts attempting to capture the pace of technological change may suffer from scope creep and get stuck in a seemingly never-ending cycle of revising research objectives to align with the newest technological breakthrough. When R&D efforts venture into this arena, identifying the appropriate level(s) of complexity to address, particularly when applied to real systems, is of utmost importance.

If "the action of working artfully to bring something about (INCOSE 2023)," then there is a need for adequately addressing these challenges in early-systems R&D. Systems theoretic concepts that underpin systems engineering approaches, founded on the Aristotelian argument that the "whole is greater than the sum of its parts," offer a conceptual foundation for better understanding how to transition from theoretical problem spaces toward practice, engineering-based solutions. Revisiting two classic concepts from general systems theory, of hierarchy and emergence, is informative in this endeavor. If there are fundamental differences and relationships between levels of complexity within a system (Von Bertalanffy 1950), then hierarchy is a concept by which to identify what generates, separates, and links each level. Once identified, the dynamics between and within hierarchical levels can be described as higher-ranking components and influences constraining the range of possible behaviors of components and influences at lower levels leading to a structure designable toward optimized performance. Consider, for example, between digital valve controllers communicating constraints on physical behaviors within nuclear power plant cooling systems.

Likewise, emergence describes the phenomenon wherein behaviors at an observed level of complexity are irreducible to and cannot be explained by the behavior or design of its subordinate components (Von Bertalanffy 1950). Once irreducibility is acknowledged, invoking emergence helps capture how observed system behaviors are, at least in part, driven by interactions within conditions, settings, and circumstances of system operations. For example, consider how risk for transporting spent nuclear fuel internationally relates to successfully executing combinations of technical, administrative, and procedural requirements. Taken together, hierarchy and emergence suggest that systems can be designed to leverage interactions toward desired system performance. Introducing these concepts into R&D project discussions can orient efforts toward exploring both individual component reliability and collective component interactions each offering the potential to improve protection schemes and resilience for the US electric grid.

These systems theoretic concepts introduce additional characteristics potentially beneficial for connecting the theoretical problem space to engineering-based solutions. First, consider traceability as the ability to track behavior or status during movement through a process. A better ability to track changes in or responses to R&D decisions can better help develop projects. Second, the quality of being thorough and accurate, or improved rigor, can help ensure that R&D strategies are optimal reflections of the problem being investigated. Lastly, consider comprehensiveness as the ability to include all elements of a process, activity, or mechanism. Here, the extent to which the entire set of considerations are included will improve the impacts of R&D design and development.

Such characteristics seem helpful for adding structure to connect the theoretical problem space to potential engineering-based solutions, which also suggests similar applicability for scoping systems engineering R&D projects. In support of early systems R&D, this article offers systems-theoretic process analysis (STPA) as an example of an approach that has guided the development of R&D projects in such diverse use cases as cyber security, nuclear fuel transportation, and US electric grid performance. Leveraging STPA can be helpful in early R&D planning and strategy development to better triangulate deeper theoretical meaning or evaluate empirical results to better inform systems engineering solutions.

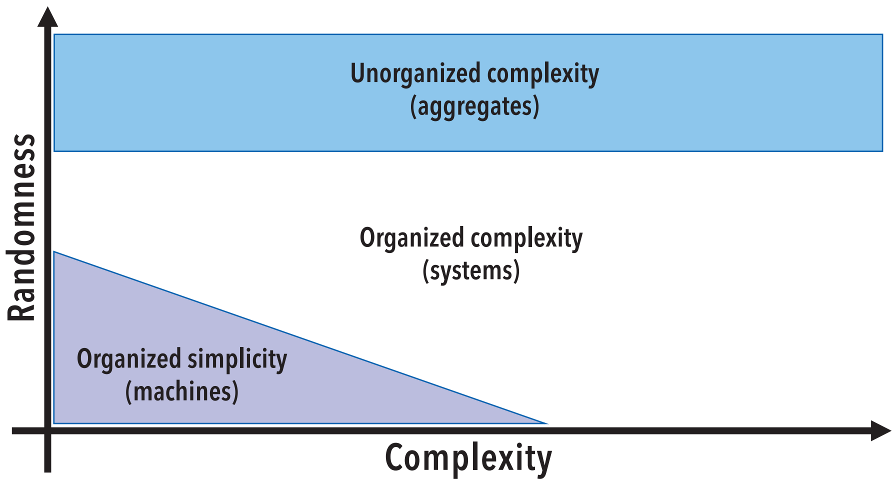

Figure 1. Comparison of zones of randomness and complexity, recreated from (Weinberg 1975)

FROM THEORY TO PRACTICE

Expanding on the common Aristotelian argument, general systems theory provides the conceptual foundation for describing how observed performance is not always explainable by the behavior(s) of its constituent parts. For example, Figure 1 illustrates one way to explain system performance. Traditional R&D development practices are well-suited for using deterministic frameworks for addressing the zone of "simplicity" and stochastic approaches for addressing the zone of "unorganized complexity." Conversely, systems theoretic concepts and systems engineering techniques are uniquely suited to address the zone of "organized complexity", defined by Weaver (1948) as those "problems which involve dealing simultaneously with a sizable number of factors which are interrelated into an organic whole."

Beyond simply recombining components in attempts to describe real-world behaviors, systems engineering offers analysis technique and mental models to capture the non-statistical, non-random logic observed in the realm of organized complexity addressing the role of interactions, nth-order effects, and dynamism in understanding observed performance. Systems-theoretic process analysis (STPA) utilizes these concepts of emergence and hierarchy to provide traceability, rigor, and comprehensiveness in understanding of observed performance for complex engineering projects.

STPA is based on a causality model that defines safety of complex systems as the ability of a system to maintain a state that eliminates losses resulting from systems migrating into hazardous states and experiencing extreme external events (Leveson and Thomas 2018). Rather than emphasizing failure prevention, this framework analyzes safety as the avoidance of hazards and hazardous system states in terms of three fundamental-and controllable-concepts:

- **Constraints**, goals or set points by which higher levels within a hierarchy exhibit control of activities at lower levels based on the current understanding of the system being controlled
- **Control structures**, hierarchical model whereby the entire socio-technical system send commands and feedback signals to enforce constraints and avoid undesired system states
- **Process models**, abstracted representation of how a controller (for example, human or automation)

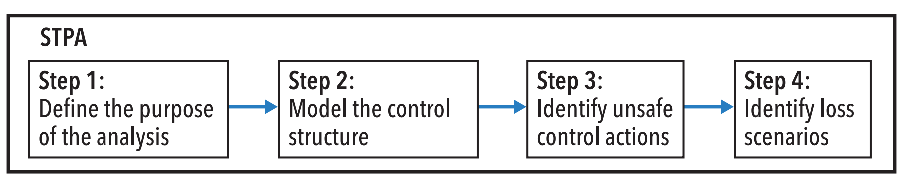

Figure 2. STPA process illustration, recreated from Leveson and Thomas (2018)

Table 1. Subset of UCAs for autonomous H-II transfer vehicle (HTV) operations, recreated from Appendix C in (Leveson and Thomas 2018)

Control Action (from ISS Crew)	Not providing causes hazard	Providing causes hazards	Too Early, Too Late, Order	Stopped Too Soon/ Applied Too Long
Abort	ISS crew does not provide Abort Command when emergency condition exists [H-1]	ISS crew provides Abort Command when HTV is captured [H-1] ISS crew provides Abort Command when ISS is in Abort path [H-1]	ISS crew provides Abort Command too late to avoid collision [H-1] ISS crew provides Abort Command too early before capture is released [H-1]	N/a
Capture	ISS crew does not perform Capture when HTV is in capture box in free drift [H-1]	ISS crew performs Capture when HTV is not in free drift [H-1] ISS crew performs Capture when HTV is aborting [H-1] ISS crew performs Capture with excessive/ insufficient movement (can impact HTV, cause collision course) [H-1]	ISS crew performs Capture too late, more than X minutes after HTV deactivated [H-1] ISS crew performs Capture too early before HTV deactivated [H-1]	ISS crew continues Performing Capture too long after emergency condition exists [H-1]

processes and understand the process being controlled, including information regarding variable relationships, current system state, and the processes that can change the state of the system

Based on the logical analysis of this causality model, the goal of this analysis technique is to identify as many hazards as possible, thereby expanding the potential solution space to improve safety and providing decision-makers and designers with additional information to achieve desired complex behaviors (Leveson 2012). More specifically, STPA consists of four broad steps (Figure 2).

Where STPA was originally developed to support systems safety and hazard analysis, Step 1 offers a chance to explore other emergent systems properties including security, vulnerabilities, and risk. Based on the hierarchical control structure model of the system of Step 2, STPA uses control actions and feedback signals to illustrate communication between controllers whether physical, digital, or human and a controlled process (for example, normal nuclear power plant (NPP) operations). In this manner, STPA uses this set of desired control actions as a baseline for identifying a comprehensive set of logical violations for each. These logical violations are the analytic core of Step 3, and include:

- Necessary control commands *are not issued*;
- Unnecessary control actions (UCAs) *are issued*;
- Potentially correct control actions are *provided too early or late*; or,
- Potentially control actions are *stopped too soon (or too late)*.

The traditional language of STPA uses the phrase "unsafe" control actions — again, based on it's original development for systems safety. In this article, STPA is expanded to a broader set of potential emergent properties, suggesting the term "undesired" control action is more applicable.

The resulting undesired control action table, provided as an example in Table 1 illustrates how STPA can identify flawed interactions, mis-timed engineering activities, or incomplete communication structures, as well as component malfunction and hazards that occur when all components behave as expected. In general, identifying loss scenarios of Step 4 focuses on a more detailed description of why an undesired control action may happen.

STPA of Steps 1-3 provides a useful structure for guiding early R&D strategy and project development discussions. For example, STPA provides a high degree of traceability. More specifically, by linking component controls and constraints to system states of concern, STPA affords opportunities to not only identify where potential propagation of undesired behaviors could occur but can also map how potential design decisions matriculate throughout the hierarchical control structure model. Similarly, STPA is a rigorous process. By evaluating each component and their interactions in the hierarchical control structure model of Step 2 according to the logical violation categories the define undesired control actions of Step 3, STPA offers strict process for an exhaustive set of outputs. Lastly, STPA's logic paradigm suggests a comprehensive set of analytical outcomes. By defining desired system behaviors in terms of enforcing controls and constraints without prioritization, STPA inherently captures a wider range of realistic and plausible opportunities for undesired system performance.

Together, the traceability, rigor, and comprehensiveness of STPA serve as useful tools for bridging theoretical problem spaces with engineering-based solutions. Where STPA logically highlights how and where undesired control actions may manifest in a system, it provides opportunities to either define experiments to better understand the impacts of violated control actions on system behavior or guide development of novel solutions. Similarly, the hierarchical control structure model of STPA is uniquely suited to visualize — in a robust, yet clear manner — key interactions between components in a system that may (or may not) significantly impact overall system performance. Thus, the logical structure of STPA can be repurposed to help generate empirical designs, investigate theoretical underpinnings of performance, or explore the efficacy of novel technologies to better inform systems engineering R&D efforts.

APPLYING PRACTICE TO RESEARCH

Though traditionally applied for evaluating safety operations in more mature or deployed systems, elements of STPA have successfully used to improve safety early in the system design life cycle (Fleming 2015) suggesting a similar ability to guide early R&D development and strategy discussions. For additional explanation, the following three use cases offer examples of STPA usage.

Use Case #1: Investigating the efficacy of evaluating hazards for digital instrumentation and control systems in nuclear power plants:

While the US Nuclear Regulatory Commission (NRC) mandates nuclear power plants prepare a cyber security plan, the lack of a consensus approach resulted in different plants taking different approaches to meeting this requirement. Traditional approaches focused on identifying critical digital assets and mapping them to safety-based risk assessment. Yet, the large number of probable cyber hazards, however, challenge the efficacy of deterministic approaches. This suggested a need to develop a risk-informed approach to explore possible hazards in digital components and systems in nuclear power plants (Williams and Clark 2019).

Invoking STPA, this project leveraged the concept of emergent systems behaviors as an organizing principle for better characterizing cyber security as an element of desired nuclear power plant operations that emerged from analog process components, digital systems, and operator actions. Accounting for the importance of these interdependencies between digital, physical, and human components within desired nuclear power plant operations is another key insight generated from STPA. Further, the (un)desired performance of nuclear power plants are described in terms of control action and feedback interrelationships between components in a control structure model.

The logical construct of STPA provided several key insights for this R&D project. First, the hierarchical control structure approach allowed for the creation of a hybrid model capturing both piping and instrumentation diagrams (P&ID) and digital network topologies shown in Figure 3. Though typically evaluated separately, merging these two descriptions of the nuclear power plant into a single diagram offers a more complete mapping of desired, and potential (un)desired, behaviors. Second, the logical foundation of undesired control actions is conceptually like basic events in fault trees, an insight gained from applying the STPA hazard analysis approach and comparing those results against more traditional fault tree-based analysis for nuclear power plant safety. This resulted in the project incorporating undesired control actions into fundamentally new models called "systems-theoretic informed fault trees," or SIFTs. SIFTs utilize key systems theoretic concepts to expand upon traditional fault trees by incorporating (1) the uniqueness and complexity of digital components and (2) newly identified causes of hazards, including those from component interactions and that still result with no component failure occurring.

Including STPA-generated undesired control actions into SIFTs provides enhanced traceability in two manners.

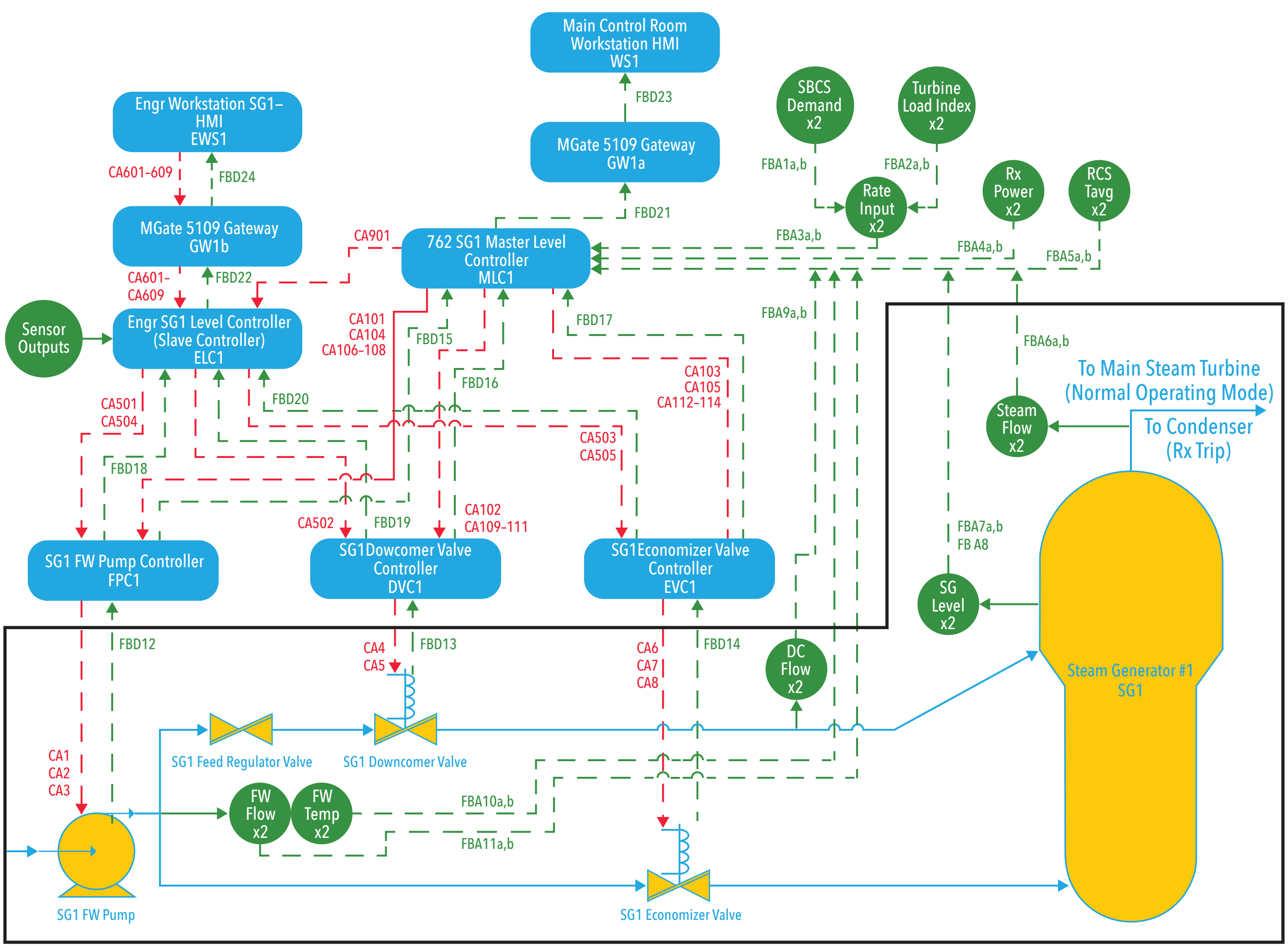

Figure 3. Notional main feedwater control digital and physical systems modeled as a hybrid STPA-related hierarchical control structure, from Williams and Clark (2019). Blue elements are controllers (in the STPA sense) which execute control actions (via red dashed lines) and green circles are sensors within the system which report various types of feedback (via green dashed lines—both of which are mapped onto a more traditional P&ID (the bottom portion that is blocked off). Describing notional nuclear facility system in this manner helped highlight several key features for improving cyber security.

Table 2. Summary of STPA-generated states of increased risk for a representative set of control actions for international SNF transportation, from Williams (2018). The middle column illustrates the benefit of invoking STPA early in R&D to help identify novel undesired versions of control actions—namely the 3S control actions not linked to a safeguards, safety, or security control action (last two rows). early in the (middle column). The right-hand column demonstrates the traceability from undesired versions of control actions to a range of states of increased risk (SIR)—where SIRs are not prioritized but labeled for categorial purposes.

Control Action	STPA Label / 3S STPA Label	State of Increased Risk (SIR) [STPA hazard type]
Transmit GPS location of SNF cask	Safeguards Control Action1	SIR10 [NNP1,2]
	3S Control Action1	SIR10, SIR12 [NNP1,2]
Submit confirmation of removing SNF from inventory within 48 hours to IAEA	Safeguards Control Action2	SIR10, SIR11 [NNP] SIR10 [PNN2]
	3S Control Action2	SIR10, SIR11, SIR12 [NNP] SIR10, SIR12 [PNN2]
Physical assessment of cask contents in appropriately sealed facility	Safety Control Action1	SIR1, SIR2 [NNP2] SIR1, SIR2 [PNN1,2]
	3S Control Action3	SIR12 [NNP1] SIR1, SIR2 [NNP2] SIR1, SIR2, SIR5, SIR7 [PNN1,2]
Stop acceleration once at 55 mph	Safety Control Action2	SIR4 [NNP1]
	3S Control Action4	SIR4 [NNP1] SIR8 [Too early]
Engage rail car immobilization mechanism	Security Control Action1	SIR5, SIR6 [NNP] SIR5, SIR7 [PNN1]
	3S Control Action5	SIR5, SIR6 [NNP] SIR5, SIR7 [PNN1] SIR2 [PNN2]
Communicate the process for transferring armed security responsibility	Security Control Action2	SIR9 [NNP] SIR7, SIR9 [PNN1]
	3S Control Action6	SIR5, SIR9, SIR10 [NNP] SIR5, SIR7, SIR9 [PNN1]
Harmonize concepts of operations across safety, security, and safeguards	3S Control Action7	SIR3, SIR12 [NNP1] SIR1, SIR2 [NNP2] SIR1, SIR2, SIR5, SIR7 [PNN1,2]
Coordinate between safety, security, and safeguards during emergency plans	3S Control Action8	SIR3, SIR12 [NNP1] SIR1, SIR2 [NNP2] SIR1, SIR2, SIR5, SIR7 [PNN1,2]
STPA Hazard Types: NNP = "needed, not provided"; PNN = "provided, not needed"; Too early = "provided tool early" Subscripts denote a particular conditional description for a violated control action aligned with a given state of increased risk		

First, the inherent ability of STPA to identify potential propagation of undesired behaviors could occur, and associated potential to map how design decisions matriculate, is enhanced by the additional structure given to undesired control actions in the fault trees. The second element of traceability relates to mapping the fault tree cut set solutions into the following categories: random component mechanical failures, combinations of mechanical and undesired digital control actions, only undesired digital control actions. The fact that the SIFTs identify new types of cut sets is indicative of the rigor offered by invoking STPA. These categorical cut sets also speak to both the comprehensiveness of this R&D particularly considering that the cut set category "random component failures" matches solutions of traditional fault tree analysis. The end result of this STPA-inspired research project is the hazards and consequences analysis for digital systems (HAZCADS) analysis technique (EPRI 2018) currently being implemented to improve cyber security in US nuclear power plants.

Use Case #2: Examining the dynamics of safety, security, and international safeguards for international spent nuclear fuel transportation:

Real-world observations and expected operational realities illustrate increasingly complex challenges transporting spent nuclear fuel successfully and without incident. Yet, traditional analysis methods struggle to capture dynamics related to such anticipated challenges as overlaps in risk mitigation responsibilities, conflicting regulatory objectives, increases in transfers between transportation modes, and multi-

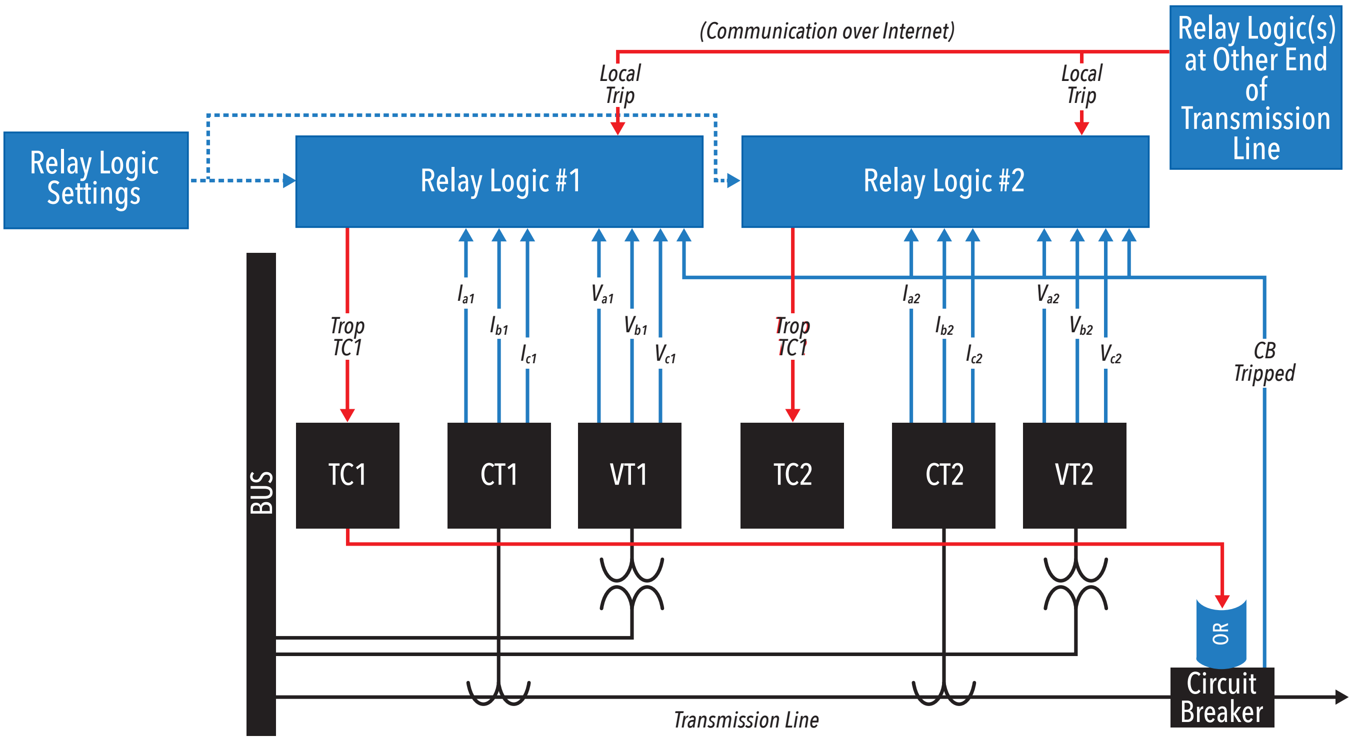

Figure 4. Notional .S grid transmission line protection systems modeled as a hybrid STPA-related hierarchical control structure. The blue boxes are modeled as STPA controllers (which execute control actions via the red arrows) and the black boxes are system elements and sensors feeding back signals on the state of the system (via the blue arrows)—both of which are overlaid on a black block diagram tracing electricity transmission. Describing the system in this manner helped identify key insights to improve grid protection and resilience.

ple geopolitical or maritime border crossings. In response, a research project was initiated to explore an analytical solution capable of evaluating challenges to safety (for example, preventing an accidental radiological release), security (for example, protecting against intentional malicious acts) and safeguards (for example, averting state-sponsored diversion of nuclear material) of spent nuclear fuel transportation (Williams 2018).

The core concepts of hierarchy and emergence inherent within STPA helped guide project planning discussions, particularly in terms providing a framework for appreciating the (in)direct relationships between hazards, threats, and risks to spent nuclear fuel transportation in complex globalized environments. STPA evaluates the ability for the spent nuclear fuel (SNF) transportation system to achieve its mission to physically move SNF from an origin facility to a destination facility without disruption of selected and approved routes, timelines, and operations. The underlying logic of STPA suggests that, if the system migrates into any of these potential states of increased risk, whether a safety, security, or international safeguards-focused risk, one additional external event could result in one of these unacceptable losses. For example, STPA argues that unauthorized access to the spent nuclear fuel during the transport results in a state of increased risk. The specific cause or contributing factors to the unauthorized access can range from the intentional use of explosives or a cask breach from an unintentional derailment. From the STPA perspective, the goal is not to prevent these causes but to design technical, administrative and systemic controls to keep the cask from experiencing unauthorized access and thereby entering the state of higher risk. Between combined hierarchical control structures and joint undesired control action analysis shown in Table 2, STPA guided the project discussion toward identifying a range of designed controls to mitigate the risks and unacceptable losses of international spent nuclear fuel transportation.

Introducing an STPA-based approach provided a high degree of traceability from undesired control actions to their associated states of increased risk and unacceptable system performance losses when evaluating safety, security, and international safeguards risk for international spent nuclear fuel transportation. Tracking propagation of undesired control actions also highlighted key areas of interdependence between safety, security, and international safeguards mitigations. For example, even though a security design decision can prevent unauthorized access to the cask, a violated security control could also result in an unplanned radiological release, a large safety hazard or a loss of continuity of knowledge that is a safeguards issue. In terms of rigor, applying STPA illustrated the importance of the "provided, not needed" control action violation where interdependence between safety, security, and international safeguard control actions existed including identifying states of increased risk missed by more traditional approaches. The ability for this research to identify additional states of increased risk that not directly aligned with desired levels of safety, security, and international safeguards performance indicates a more comprehensive solution. STPA inspired insights and results from this research project have produced an analytical framework more aligned with the real-world, multi-modal, and multi-jurisdictional nature of ensuring adequate safety, security, and international safeguards during international spent nuclear fuel transportation.

Use Case #3: Exploring approaches to improve resilience-based and risk-informed decision making for project the US electric grid:

Recent events, including a 2014 shotgun attack on an electrical substation in California, the 2021 cyberattack on the Colonial pipeline in Texas, and the 2023 suspected domestic terrorist plot to attack substations in Maryland demonstrate the need to re-evaluate resilience analysis for the US electrical grid. This suggests a need to build scientific and logical arguments for analyzing potential vulnerabilities to craft more robust and comprehensive strategies to mitigate risk and increase resilience in the electric grid. Typical protections observed across the US electric grid are a mix of common baseline protections augmented by piecemeal, bespoke efforts that tend to be poorly coordinated. Further, many of these protections emphasize preserving individual grid components, which often results in shutting a component down, perhaps prematurely which may then cause downstream components to pass performance thresholds and cause rolling brown/black outs. The fact that the US electric grid consists of three major regions and more than 120,000 miles of lines operated by 500 companies is an additional challenge to improving resilience.

In response, asserting that risk, resilience, and vulnerabilities are emergent properties hypothesizes that STPA based thinking can evaluate how the electrical grid would recover following unknown, but anticipated, perturbations. Further, if vulnerabilities are conceptualized as opportunities to create undesired consequences, then resilience can be conceptualized as using control actions to ensure desired performance levels in STPA. The logic underpinning hierarchical control structure models can help illustrate the range of controls necessary to ensure generation, distribution, and transmission functions are maintained at desired performance levels, shown in Figure 4, as well as offer insights for characterizing spatial elements of risk and resilience. Similarly, the STPA undesired control action can help capture transient and dynamic interactions between resilience phases, with the last two undesired control action categories identifying temporal elements of risk and resilience.

The STPA basis for this research project allowed the inherent traceability to better specify connections between nodes in grid networks. In addition, the hierarchical control model provided the scaffolding on which to investigate both temporal and spatial elements of grid resilience. Even with the preliminary work in this project focusing on more simplistic representations, STPA demonstrated the ability to describe an exhaustive set of undesired control actions that directly challenge the resilience of the electric grid, which also suggests a similar level of rigor for higher fidelity grid descriptions. The STPA-generated hierarchical control structure approach also affords an opportunity to create template models for commonly occurring subsets of nodes within the US electric grid. By extension, undesired control actions associated with each template can be identified more quickly and novel interactions highlighted more efficiently as the template models are connected in ways to capture more comprehensively larger, more realistic grid (sub)systems. Ultimately, the traceability, rigor, and comprehensiveness of STPA will continue to drive the research to develop new and novel protection schemes to improve the resilience of the US electric grid.

CONCLUSIONS AND IMPLICATIONS

As demonstrated in the three use cases described in the previous section, STPA provides a logical foundation and analytical framework for connecting theoretical problem spaces to potential engineering-based solutions to aid in scoping systems engineering R&D projects. Hierarchical control structure models demonstrated traceability and comprehensiveness in evaluating cyber security for nuclear power plants and risk analysis for international spent nuclear fuel transportation. STPA derived undesired control actions illustrated rigor in identifying interdependent risks in international spent nuclear fuel transportation, as well as in characterizing temporal and spatial risk elements challenge US electric grid resilience.

Retuning again to the logical and theoretical foundations for STPA, invoking the phenomena of hierarchy and emergence provide useful guide rails for early-systems R&D discussions. STPA's hierarchical control structure models help capture—and simplify—the complexity in modern systems by abstracting them in a manner that both emphasizes the importance of component performance and the various interactions between them. Likewise, the emphasis on maintaining emergent system performance within a desired range offers a mechanism for exploring the flexibility of potential control actions or the range of possible redesigns to expand that desired operational space. Together, STPA can help inform either experimental design, hypothesis generation, system redesign options, or the characteristics necessary for novel, next-generation solutions.

Challenges experienced in bridging theoretical problem spaces with engineering-based solutions have both persisted and necessitated new approaches and potential solutions. As Von Bertalanffy eloquently stated in 1972:

> Modern technology and society have become so complex that the traditional branches of technology [and analysis] are no longer sufficient; approaches of a holistic or systems, and generalist and interdisciplinary nature become necessary (420).

The ability of STPA to provide holistic, generalist, and interdisciplinary solution to these challenges have also been demonstrated in a range of domains including aerospace (Fleming and Leveson 2014), medical (Pawlicki, et. al. 2016), automotive (Placke Duo 2015), port security (Williams 2015), and cyber security (Bakirtzis, et. al. 2017) in addition to the three use cases demonstrated in this article. To the extent that logical and analytical characteristics of other techniques are like STPA, then similar benefits for scoping and guiding R&D strategies can be anticipated. Ostensibly, this suggests that STPA based approaches, and perhaps broader systems engineering at large, provide a bridge for applying "artful will of bringing something to fruition" to improve early systems engineering R&D efforts. ■

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Digital Engineering Enablers for Systems Engineering in Early-Stage Research and Development

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ABSTRACT
Robust systems engineering is perceived as an unnecessary cost and schedule burden when the goal is proof of concept in an early-stage project (TRL 1-5). In reality the majority of industry, as opposed to academic, early-stage research and development (ESR&D) efforts are generally not "pure research", but instead focus on technology development for the purpose of technology transition to applied development and technology insertion into new or existing products. To overcome the barriers, an early and active end-user focused system engineering approach is needed to build the use cases to support the transition from fundamental research to applied development. Digital engineering (DE) enablers can lower the transition investment cost through the use of agile methodologies, reference architectures, and model-based design and manufacturing capabilities. End-to-end digital continuity from ESR&D to manufacturing and sustainment facilitates early discoveries of transition risks, which enable informed decision-making to mitigate pitfalls leading to the "valley of death."

This article leverages efforts associated with Industry 4.0, digital engineering transformation and INCOSE working group efforts to illustrate how a systems engineering approach based on DE concepts facilitates rapid instantiation of key systems engineering process and elements in ESR&D projects. This approach is both enabling to foundational ESR&D efforts, and transformational in building a bridge across the valley of death to foster success in technology transition to product. An agnostic tool, standards-based framework is presented, and specific tools are used to illustrate ESR&D transformation.

INTRODUCTION

Systems engineers are versed in the Vee model, architecture, traceability, writing good requirements, and other systems engineering principles. If you're reading this article, hopefully you also know something about digital engineering tools and process enablers such as model-based systems engineering (MBSE), end-to-end digital traceability, and agile methods.

Before digital tools, scientists and system engineers working in ESR&D relied on paper and spreadsheets to document their research, record experiments, and track their results. This approach is no longer sufficient as research topics become more complex, generating an exponential volume of data for analysis. Additionally, complex research topics often involve a large multidisciplinary team across locations and organization boundaries, which introduce communication and data sharing challenges with using document-centric methods. A model-based and data-driven approach to ESR&D reduces the risk of human error, enabling a distributed team to collaborate experiments and share results. Model-based design of experiments enables researchers to automate workflows and processes for rapid simulated results, supporting decision making and bringing new solutions to market faster.

The focus of this article lies not in the use of specific tools, but rather in the value add of using these concepts and tools in an integrated digital ecosystem. While each tool or concept can add value on their own, the connectivity of a digital ecosystem generates emergent value: the connected whole is greater than the sum of the parts. These digital enablers possess applicability beyond aerospace or high-volume production programs; they are equally applicable to small to medium programs as well. This article illustrates how systems engineering and agile enabled teams working in early-stage R&D can readily leverage these concepts. This article is divided into sections that address the following: agile methodologies, architectures enablers, and model-based design and manufacturing. The benefits of end-to-end digital continuity in a digital ecosystem are illustrated throughout the article.

AGILE METHODOLOGIES

In today's complex and dynamic markets,

companies must increase their ability to sense and respond to the changing customer needs. To address complex research topics, researchers realized the need to conduct research and experiments with a set of digitally connected partners and collaborators across distributed locations. To respond to these challenges, 32% of R&D organizations have reported to have adopted agile practices (Digital.ai 2022). Adopting agile methodologies for R&D projects can help organizations become more efficient, effective, and responsive to customer needs, leading to greater innovation and competitive advantage. It helps organizations mitigate the risk of "valley of death," which refers to the challenges in transitioning a product or solution from R&D phase to production phase of the systems engineering lifecycle.

Agile methodology is based on a set of principles outlined in the Agile Manifesto (Beck, et al. 2001), which values individuals and interactions, working software, customer collaboration, and responding to change over following a strict plan or process. It involves breaking down development into small, manageable iterations or sprints, each of which delivers a working product or solution. The development process is typically collaborative, with team members from different functional areas, such as development, testing, and design, working together to deliver the solution.

Agile methodologies can help mitigate the "valley of death" in several ways:

1. Collaboration and communication: Agile methodologies prioritize collaboration and communication between R&D, production, and end users: feedback on the usability, feasibility, and manufacturability of new products or solutions is obtained early. This can help identify potential issues early on, reducing the risk of costly mistakes during production or user deployment.

   Use of collaboration tools can help geographically distributed teams work together effectively, which may include project management software, social communication tools, and shared modelling environments. An example is the Dassault System's 3DEXPERIENCE platform program excellence solutions in Figure 1, which provide comprehensive enterprise program management, social collaboration, and a common environment for managing digital artifacts in real time.
2. Early testing and validation: Agile methodologies emphasize early and continuous testing and validation by emphasizing the importance of developing a minimum viable product (MVP) early and iteratively. This means that each iteration of the agile development process should produce a working solution that can be tested and validated. By validating the feasibility and marketability of new products or solutions early in the development process, R&D can reduce the risk of investing in solutions that may not meet customer needs or be successful in the market.

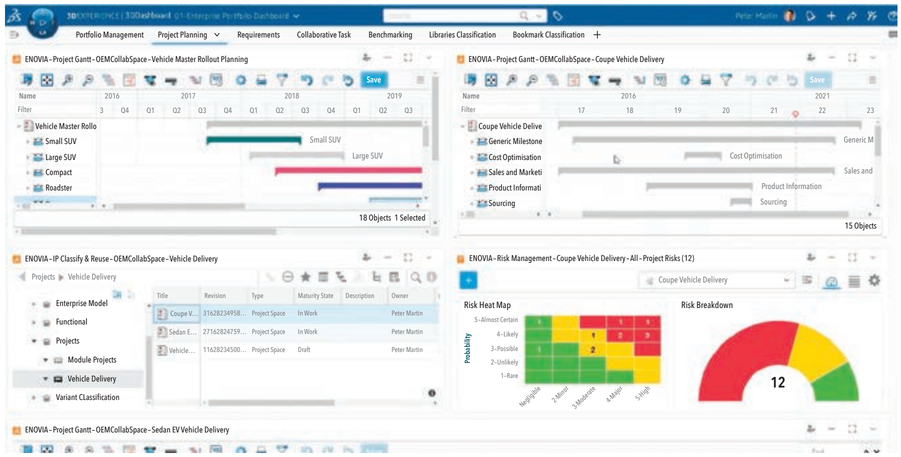

Figure 1. 3DEXPERIENCE program excellence for collaborative program planning and development

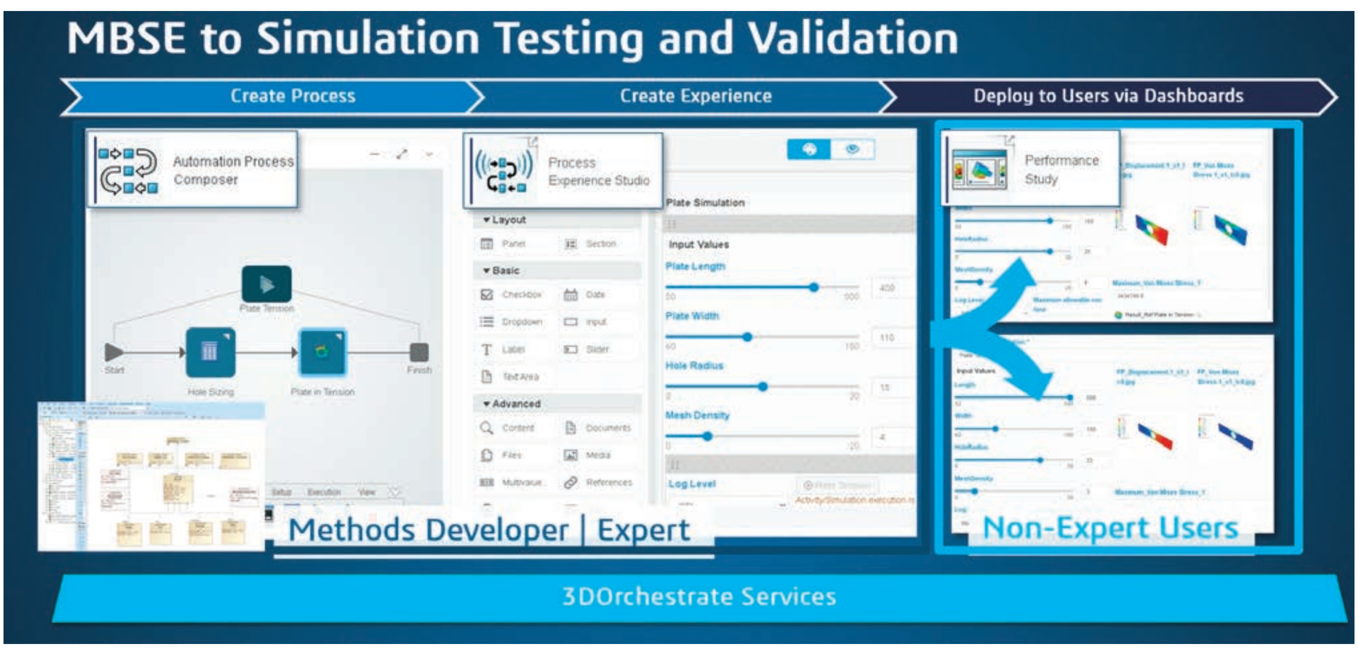

Figure 2. MBSE model as part of integrated MDAO

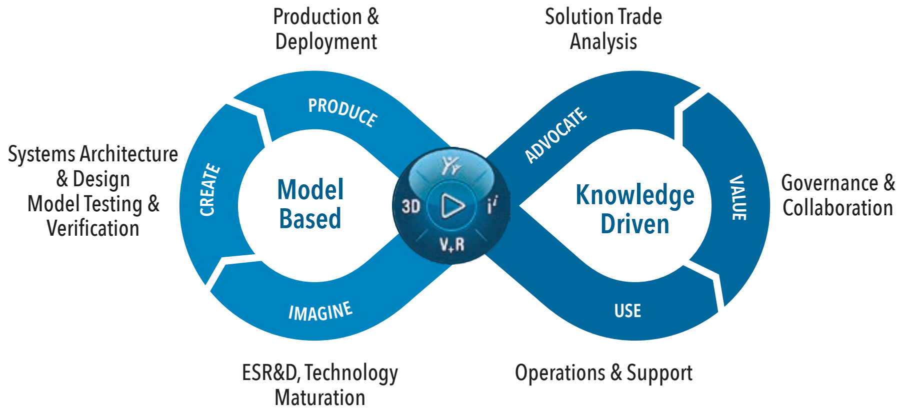

Figure 3. 3DExperience "IFWE"" loop for continuous improvement

This can help ensure that products or solutions are aligned with customer needs and have a better chance of success in the market.

There are several tools available to support continuous integration and continuous testing. These tools typically help automate the testing and validation process, provide real-time feedback on design change impacts on requirements, and improve overall test management and efficiency. An example of an integrated tool suite in 3DEXPERIENCE platform is using Cameo Systems Modeler with SIMULIA Process Composer to conduct multi-domain analysis and optimization (MDAO) illustrated as Figure 2.

3. Continuous improvement: Agile methodologies encourage a culture of continuous improvement. By delivering validated working solutions early and often, teams can gather feedback from customers and stakeholders and make adjustments as needed. By regularly reflecting on project outcomes and processes, teams can identify opportunities for improvement and make adjustments to reduce waste, increase efficiency, and improve product or solution quality.

   Agile project management tools and retrospective tools can help teams visualize the development process, identify bottlenecks and gather feedback for improvement. An example is the 3DEXPERIENCE IFWE loop in Figure 3, which is a collaboration framework and tool to enable everyone involved in an innovation project – from the research lab to the factory to the consumer – to interact and work together. As a result, it empowers innovators to design and test consumer experiences, from the idea to market delivery and usage, before actually producing them.

Agile methodology is a customer-focused, collaborative approach to development that prioritizes flexibility, responsiveness, and delivering working solutions quickly and frequently. Although agile methodology originated in the software development industry, it can be applied to ESR&D to increase speed to market while decreasing the risk of "valley of death".

ARCHITECTURE ENABLERS

Systems engineering typically defines and uses three primary types of system architectures: functional, logical, and physical/solution as shown in Figure 4:

> **Functional architecture** is a definition of all the functions necessary to complete the requirements needed for the system to perform. A typical example of this would be through development of use cases and functional requirements.
>
> **Logical architecture** (LA) comprises system functions that support customer needs, encompassing requirements, desired capabilities and high-level operational activities. It ensure design solution flexibility and adaptability by existing independently of and without imposing design decisions. This would typically be allocation of activities within use cases to system logical groupings; the LA shows which logical element performs which functional activity.
>
> **Physical/solution architecture** is a definition of the physical makeup of the system and align with an engineering or manufacturing bill of materials (EBOM/MBOM).

While digital enablers can generally expedite aspects of developing and capturing this classical trio of architecture, two key concepts that are digital enablers which can create emergent value are reuse through establishment of a reference architecture (RA), and connected traceability (CT).

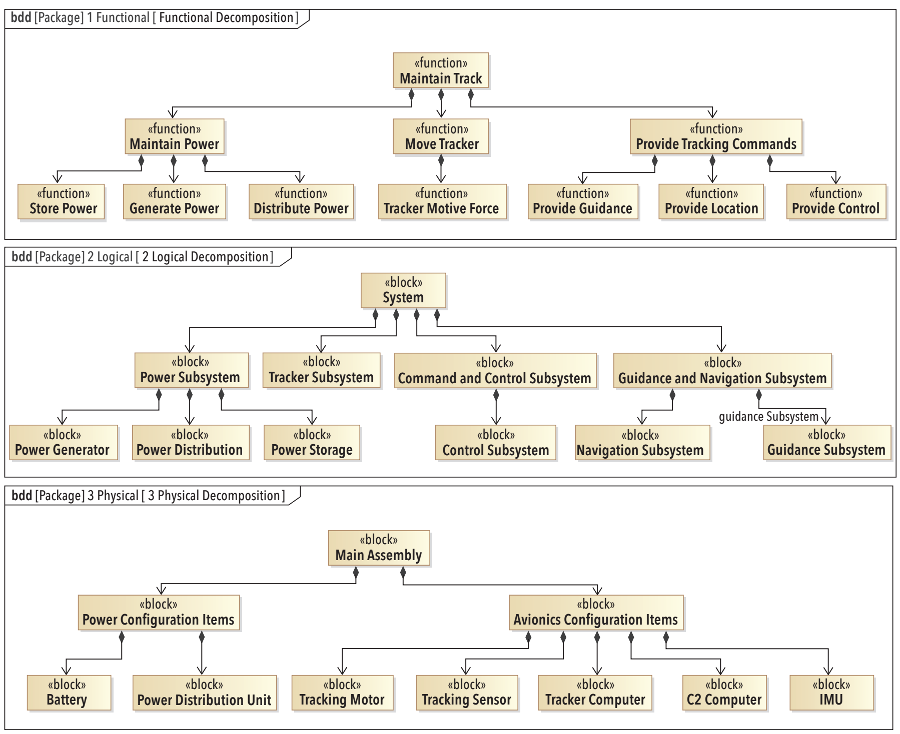

Figure 4. Simple example (top to bottom) of functional, logical, and physical/solution architecture

THE REFERENCE ARCHITECTURE

An RA is more commonly known in software; however, the concept is equally applicable to hardware-based or software intensive systems. The key aspect of an RA is that it provides a solution template for an architecture for a particular domain at a particular level of abstraction functional, logical, or physical. The RA is in effect a “previous solution”, which generalizes and extracts from previous successful implementations.

RA can be defined at different levels of abstraction. A highly abstract RA might align with functional architecture and a collection of use cases or functions. A mid-level RA might align with a logical architecture and demonstrate the interactions of procedures or methods within a system defined to perform a very specific task. This is effectively using the logical architecture for execution of a use case.

Reference architecture can act as a digital enabler by:

1. Accelerate solution development: A reference architecture provides a starting point for solution development. This can help organizations to accelerate their solution development timelines and reduce time-to-market.
2. Improve solution quality: A reference architecture provides a standardized set of guidelines and best practices for solution development. This can help to improve solution quality and consistency, reducing the risk of errors, and ensuring that solutions are more reliable and maintainable over time.
3. Support interoperability: A reference architecture helps to establish a common language and set of standards for solution development, which can facilitate interoperability and integration between different systems. This can help organizations to avoid the development of siloed solutions and achieve greater efficiency and effectiveness across their technology landscape.
4. Enable scalability and flexibility: A reference architecture can help organizations to build solutions that are more scalable and flexible, enabling them to adapt to changing business needs and technology trends over time. This can help organizations to avoid the need for costly and time-consuming re-architecture efforts down the line.

The value for ESR&D is the cost and schedule savings associated with reuse. An appropriate reference architecture accelerates delivery through the reuse of an effective domain space, and can also enable consistent application of technology use within an organization. For organizations that are new to the idea of adopting DE and MBSE, the challenge usually referenced is that there is significant effort to create the original architecture in the first place; one cannot reuse what one does not have. What is often overlooked, especially in ESR&D environments, is that spending the time to capture information provides the same return on investment (ROI) benefit as doing systems engineering in the first place, with the additional value of refactorable reuse.

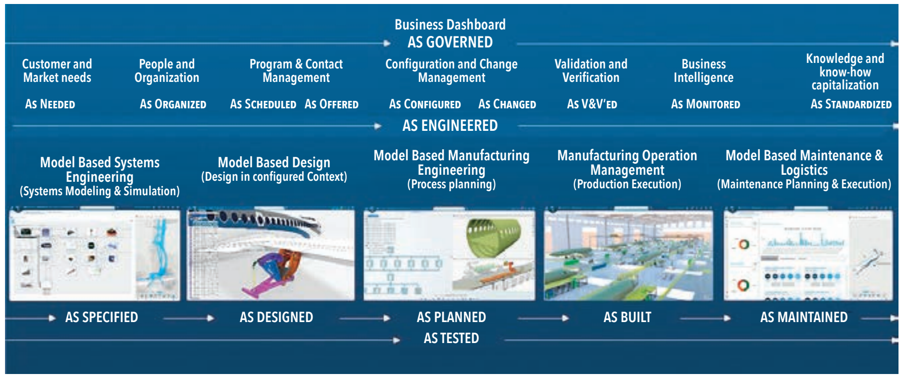

Figure 5. End-to-end digital traceability across system life cycle

There are a variety of tools that can support reference architecture development. These include model-based system architecture tools, which provide a platform for developing and visualizing reference architectures. These tools can be supported by collaboration tools to facilitate joint development with multiple stakeholders and organization, which ensure all parties are aligned to the architecture goals and objectives. Simulation tools can also be used with system architecture tools to simulate the behavior of the reference architecture and test different use case scenarios. This provides early validation of the reference architecture and identify potential issues before implementation. Lastly, integration of a requirement tool with the system architecture tool helps ensure that the reference architecture aligns with stakeholder requirements.

END-TO-END DIGITAL TRACEABILITY

Digital engineering implementation is characterized by the use of data and models throughout the system engineering lifecycle. As an organization increases its adoption of models and digital technologies, 72% of companies reported that data volumes are growing faster than their ability to manage them (MarketPulse Research by Foundry Research Services 2023). As a result, 64% of companies rank implementation of a data governance program their top objectives to achieve business value from data. There is also cultural resistance to data sharing, with more than 50% of companies indicating their functional departments are hesitant to

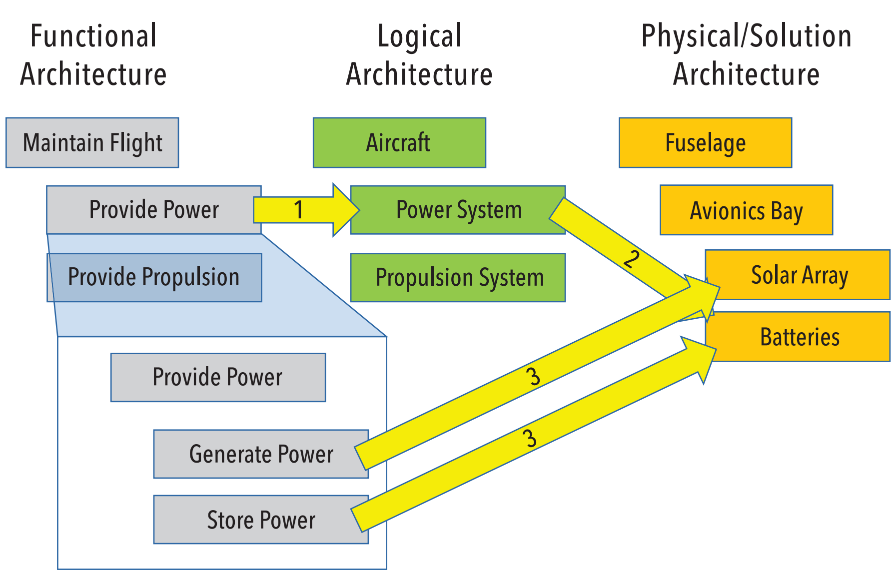

Figure 6. Architecture relationships

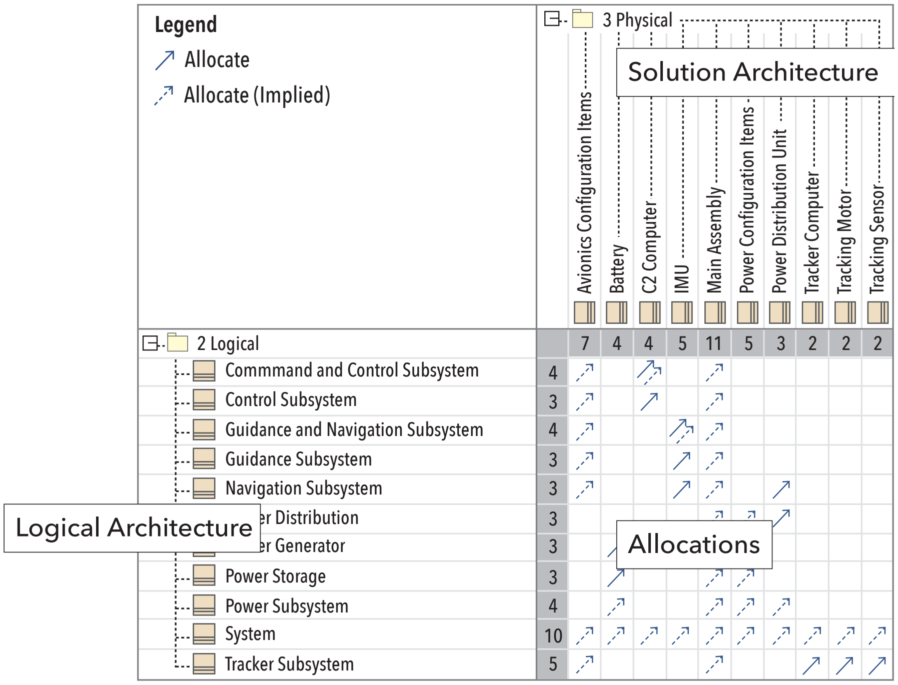

Figure 7. Logical to physical allocation

break down silos and share data across the enterprise. The causes of cultural resistance can be attributed to conventional practices that values individual achievement and fosters the reporting of work after it is finished. This cultural practice limits the realization of the full value of digital engineering, as it encourages functional teams to manage pieces of information from their engineering domain without considering its logical interdependencies until late in its development.

End-to-end digital traceability, as illustrated in Figure 5, seeks to eliminate siloed development by integrating models and data across functional domains and system development lifecycle. Digital traceability formalizes the link between business needs and product development, allowing companies to evaluate promising research with potential market-fit. The connected data model assists stakeholders in exploring and qualifying options, leading to informed actionable decisions. Moreover, end-to-end digital traceability is a key enabler for effective agile execution according to 58% of respondents in the 2022 State of Agile Survey (Digital.ai. 2022). Digital traceability enable efficient information and knowledge management, by increasing the visibility of data and facilitate multi-disciplinary collaboration and innovation.

ARCHITECTURAL RELATIONSHIPS

Consider the common approach of “document centric engineering” to determine and convey traceability between levels of architecture as illustrated on Figure 6.

Engineering effort is made to allocate function to logical architecture to solution, and eventually to procurement items. In document-centric engineering, the effort is made but is only usable when processed visually by an engineer as a “human-in-the-loop.” In a digital ecosystem utilizing MBSE and other tools, these tools not only guide a methodology, but also capture relevant metadata. This metadata supports model-based analytical metrics, enabling an understanding of the complete context for the solution space and establishing a definition of done. Once the logical architecture is established, allocations captured in digital enablers, shown in Figure 7, represent the design implementation of the logical architecture element. This also enables early identification of commonality as well as solution gaps.

DESIGN AND TRADE SPACE

The transition from logical to solution architecture is the node point for trade space exploration, enabling a key system engineering capability of basing design decisions on data for cost implications. The same nodes shown on Figure 8 also enable identification of trades for future proofing and impacted/allocated systems. This is a critical consideration for ESR&D, particularly when future capability growth considerations are critical to advance beyond an MVP without necessitating a complete redesign.

EARLY DESIGN CONCEPT VALIDATION

A digitally enabled engineering space provides a linked and traced solution

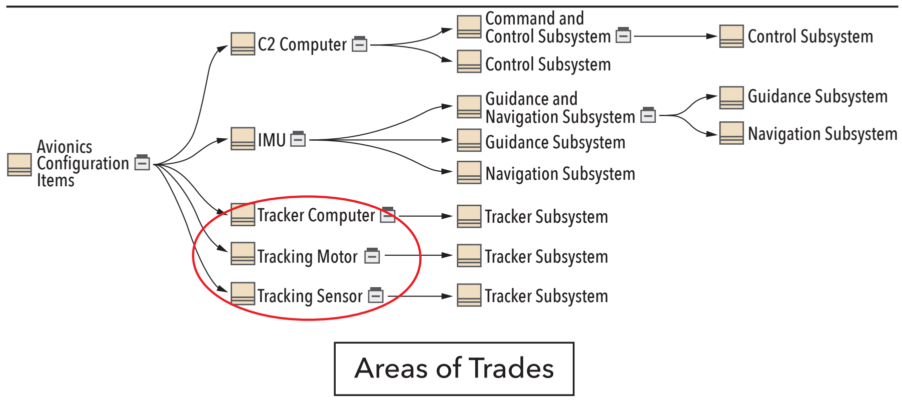

Figure 8. Logical to solution architecture allocation

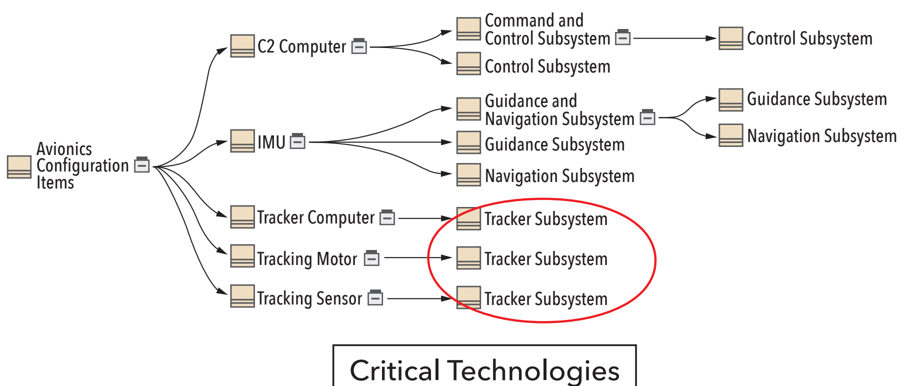

Figure 9. Relation map

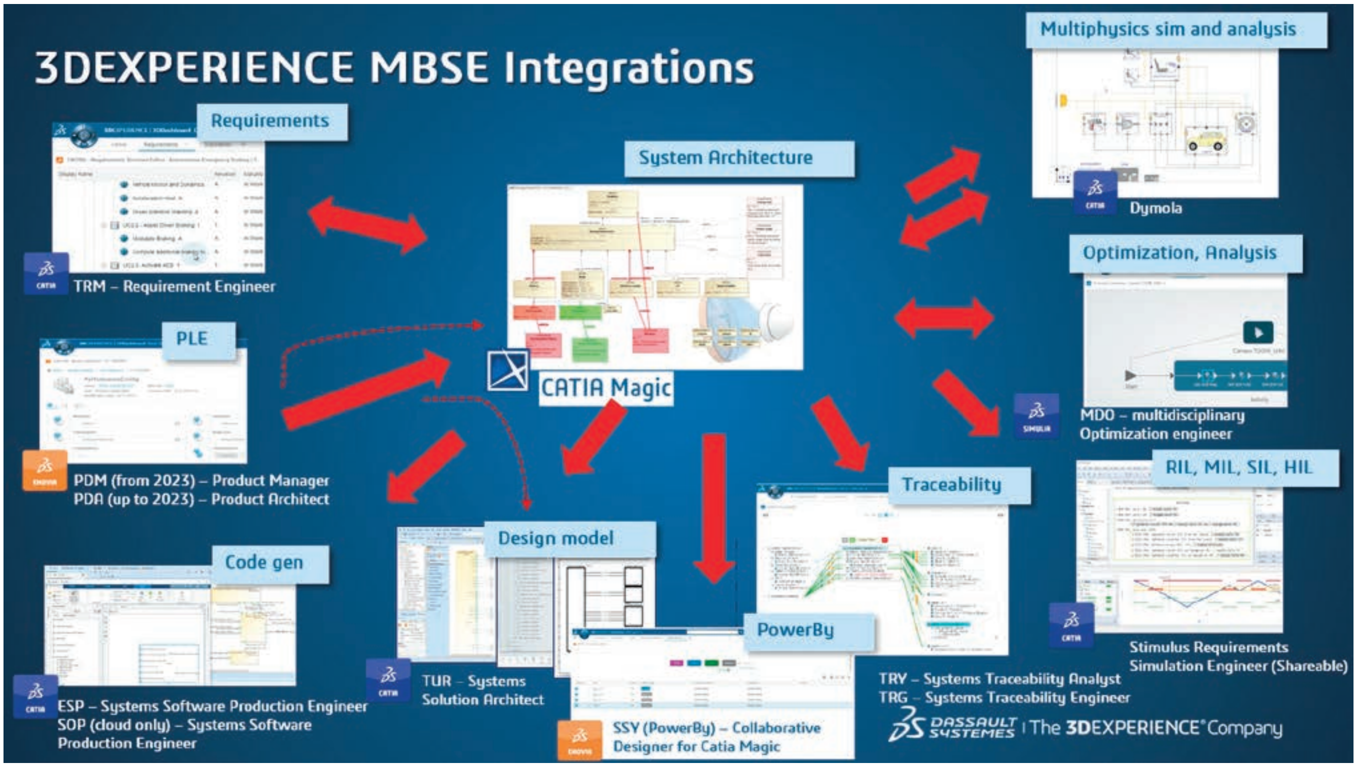

Figure 10. MBSE integration and traceability within DE ecosystem

architecture, which can be used to assess technology and business risk areas for the design. The digital model simultaneously contains both the broad logical architecture and the key design aspects of the solution architecture enabling one to "deep dive" into the detailed design while maintaining connectivity to the higher-level architecture. Critical technologies and vertical cuts through the design space are visible and the aforementioned model reuse enables architecture maturation across programs, including early assessments of critical elements and reuse (Figure 9). The human–in-the-loop is required to assign criticality where additional information or elaboration in engineering/design space is required, for example, an architecture risk reduction prototype, or a safety critical item.

ECOSYSTEM CONNECTIONS: TRACEABILITY

Traceability is the formal identification of the relations between engineering artifacts, rationale for design choices and constraints, or provenance of information associated with engineering artifacts, and is a primary method used to tame the complexity of modern systems. End-to-end digital traceability is becoming increasingly important in engineering, particularly in industries such as aerospace, automotive, and medical devices, where safety and regulatory compliance are critical. Traceability is mandated for compliance in all safety-related processes: DO-178, DO-254, ISO 26262, IEC 61508, and derivatives.

By providing a complete digital record of the product lifecycle, end-to-end digital traceability can help organizations to:

1. Ensure product quality: By capturing and linking all data and information generated throughout the product lifecycle, end-to-end digital traceability can help to ensure that products meet quality standards and regulatory requirements.
2. Improve efficiency and reduce costs: End-to-end digital traceability can help to identify inefficiencies and bottlenecks in the product lifecycle, allowing organizations to streamline their processes and reduce costs. By analyzing data trends throughout the product lifecycle, end-to-end digital traceability can identify patterns and correlations that may indicate inefficiencies. For example, if a particular test phase consistently takes longer than expected, this may indicate a problem that can be addressed. End-to-end digital traceability can provide valuable insights for continuous improvement efforts, helping organizations to identify areas for optimization and innovation.
3. Shared authoritative source of truth: By providing a shared digital record of the product lifecycle, end-to-end digital traceability can help to facilitate collaboration between different teams and stakeholders, improving communication, facilitate knowledge management and reducing the risk of errors from having different records in disconnected systems.

The ecosystem connections of traceability enable our understanding of complex system relationships, and thereby increase the speed and improve the quality when a project needs to respond to change. An impact analysis conducted in a connected engineering ecosystem identifies the parts of the engineering effort that may need to be changed in order to respond to a requested or mandated change. This is above and beyond a simple "where used" in a product lifecycle management (PLM) repository where product design models are stored and managed, as seen in Figure 10.

Traceability between systems modeling lanuage (SysML) model elements is illustrated on Figure 11. Note that stereotypes are used in the model for common systems engineering artifacts of: risks, technical performance measures (TPM), and hardware configuration items (HWCI).

The real emergent value of a digital approach is when we extend relationships to elements that are outside of the SysML model repository. Most SysML tools available today provide an application programming interface (API) which

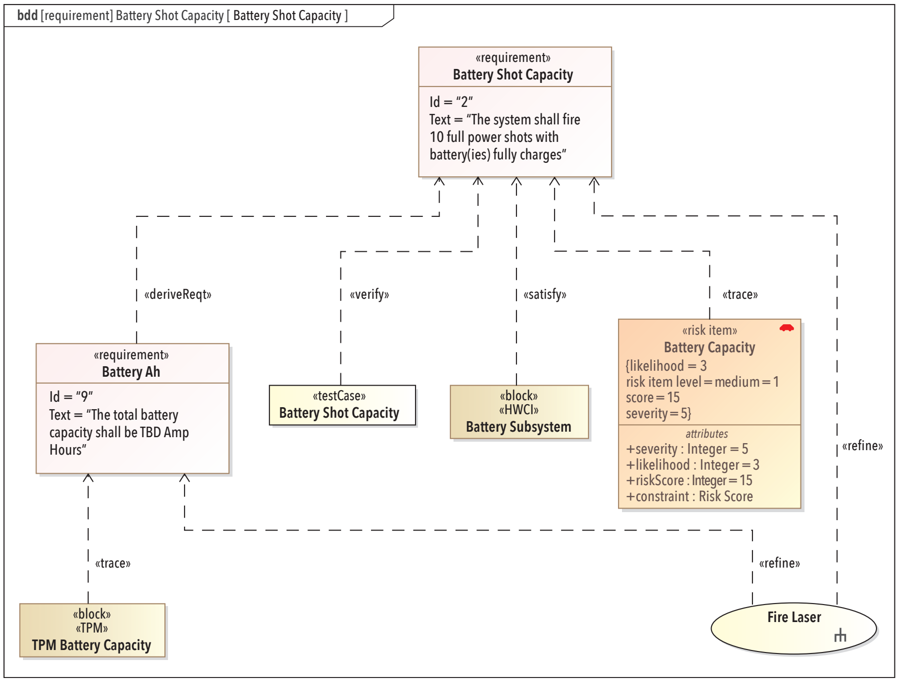

Figure 11. Example of requirement-centric traceability

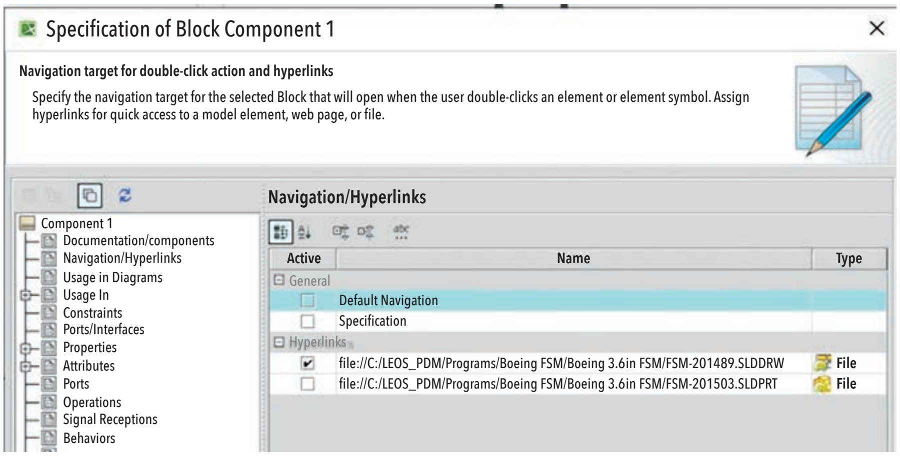

Figure 12. Built-in hyperlink navigation

can be used for connectivity to external repositories. Some tools provide specific tool extensions or interfaces to other tools. For ESR&D, a relatively simple and low-cost approach could even leverage for example, a basic URL hyperlink provided interface that connects model elements with files, documents, or other tool elements through an API such as URLs or JavaScript. The example shown on Figure 12 is from Dassault Systems' Cameo System Modeler, where a model element specification can include a URL to connect the element to an external item. The URL can be a file location, web address, or in the case illustrated, a file URL from a SOLIDWORKS PDM installation.

Traceability can be achieved in both directions with our current tool example because the Cameo tool also provides a model element URL which can be used in an external repository. If ESR&D is equated to a lower level of rigor, then an overly elaborate engineering tool environment is not required. If primary tools are chosen which at minimum enable/provide URL information both into and out of the respective repositories, then traceability can be established and maintained relatively easily. There is a need for an appropriate level of rigor from a configuration management perspective, which is supported and enabled by the traceability of the previously discussed impact analysis of connected artifacts.

There are a wide variety of tools that can support end to end digital traceability. The use of specific tools will depend on the specific needs of the organization and the system being developed. End-to-end digital traceability can be achieved by utilizing a platform to connect and integrate various applications that collect and store data throughout the product's lifecycle. Here are some steps to connect the tools to enable end-to-end digital traceability:

1. Identify the enabling capabilities needed to support the development of the system of interest, then identify tools and systems that are involved in the system's lifecycle. This may include tools for product design, development, testing, manufacturing, supply chain management, and customer support.
2. Determine the data that needs to be collected and stored in each tool and system. This may include data such as product specifications, requirements, test results, manufacturing parameters, and customer feedback. Developing a data reference architecture enables digital traceability by providing a blueprint for organizing and managing data across the system lifecycle. A data reference architecture defines the data requirements, data flows, data models, and data management processes needed to ensure that data is accurate, complete, and consistent.
3. Create data integration points between the different tools and systems. This may involve setting up a central integration platform such as 3DEXPERIENCE, or leveraging APIs and other methods of exchanging and transforming data between systems. Using a data reference architecture provide a standard framework for data interoperability requirements between different systems and tools, reducing the risk of large data integration between systems.
4. Establish data governance policies to ensure the accuracy, completeness, and consistency of the data across all the tools and systems. This may include continuous testing and monitoring of data quality requirements and standards, ensuring that data is accurate, complete, and consistent. It includes considerations for security requirements and standards, ensuring that data is protected from unauthorized access or tampering. Integrated analytics and visualization tools can enable stakeholders to analyze and understand the data throughout the product lifecycle. This ensures that data can be trusted and relied upon.

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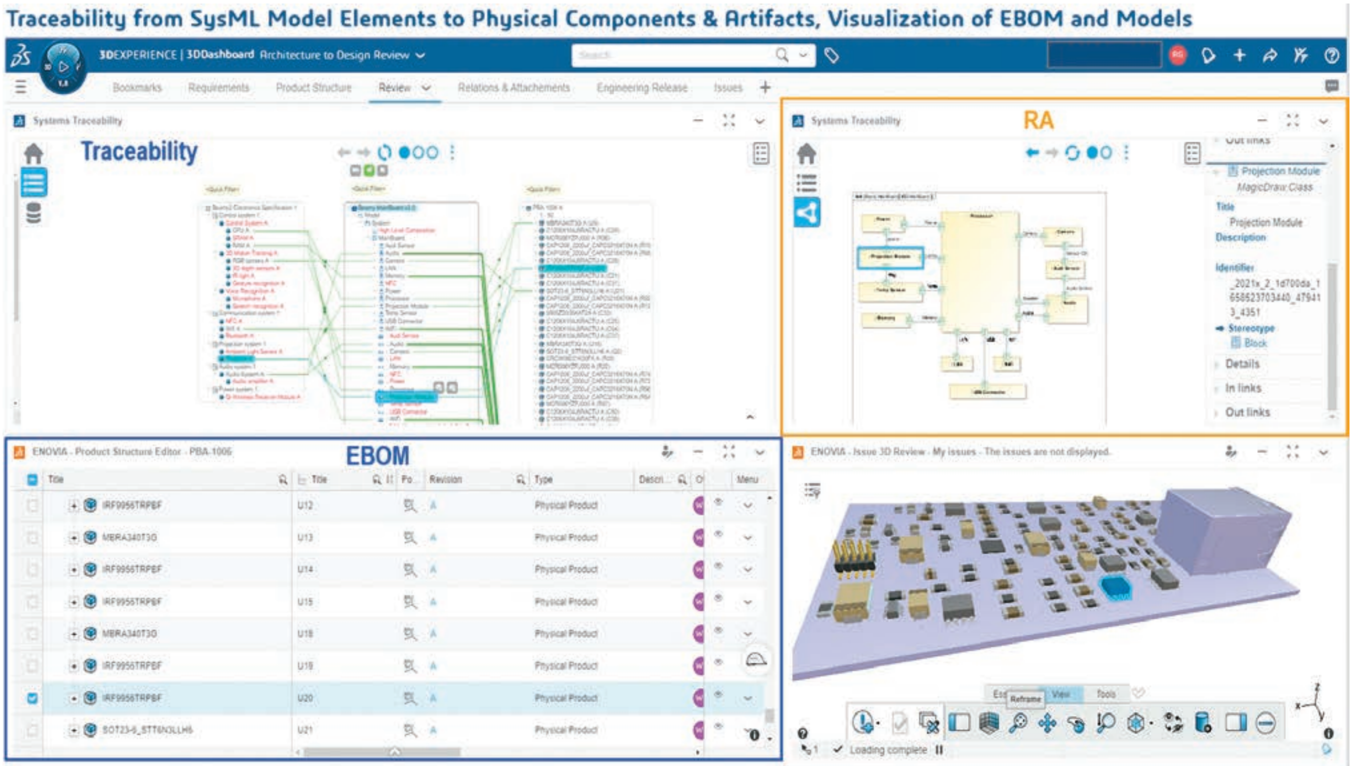

Figure 13. RA model traceability to design and EBOM

MODEL-BASED DESIGN AND MANUFACTURING

The emergent value of digital enablers for ESR&D for model-based design and manufacturing is an extension of traceability. When ESR&D and systems engineering is disconnected from manufacturing, it results in a siloed work environment that exacerbates quality issues such as compromised product manufacturability, increased defects and rework cycles, and escalated cost. This is often a consequence of designing the system before fully understanding the requirements, driving engineering to a "procurement architecture" approach. A procurement item, in this context, refers to a tangible object that is either procured or manufactured. From an ESR&D perspective, what is needed for effective use of any architecture is connection with traceability from the procurement architecture, through a logical architecture, to the functional architecture, and vice-verse. The benefits of digital traceability continue into use of a procurement and manufacturing architecture. With a model-based approach, a model, or an RA that has been extended, can be mapped from system engineering to physical design models, and to engineering bill of materials (EBOM) for procurement, as illustrated in Figure 13.

Additive manufacturing (AM) programs are an example of pioneering the establishment of agile/digital supply chains in the US Air Force (USAF). AM, or 3D printing, uses computer-generated designs to create 3D objects layer-by-layer, making it an additive process. It has the unique value of generating physical components directly from design models without special tooling requirements, which reduces the need for spare-part inventories by enabling on-demand product of items from digital models in operation environments (Mckinsey 2022). ESR&D were the early adopters of AM due to its potential for rapid prototyping and experimentation opportunities. At the implementation level, lingering perceptions around cost and speed limitations have slowed adoption beyond prototyping applications. Digital enablers can be used to leverage domain expertise to identify, analyze, and prototype components suitable for AM. As an integrated approach with model-based design, digital techniques drive innovative and rigorous process including data mining, 3D model-based technical data creation, engineering analysis, and digital sustainment.

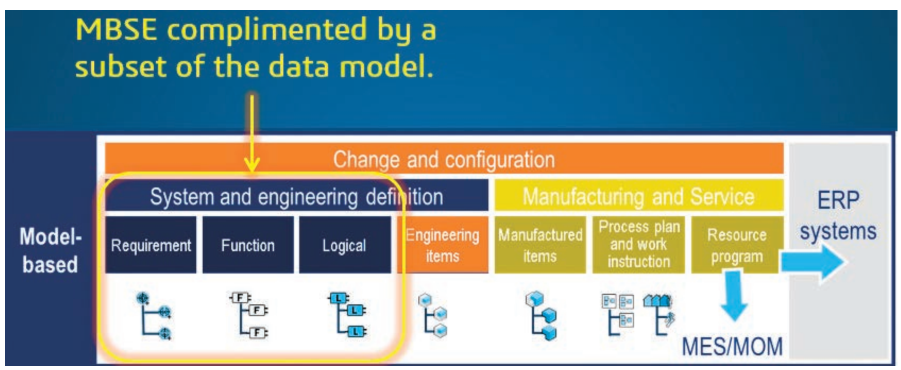

Figure 14. MBSE data model traceability to manufacturing data model

To enable successful implementation of AM, an end-to-end digital approach, shown in Figure 14, is required to implement a modernized supply chain, through the digitalization of previously mechanical processes. From developing digital twins with model-based engineering to integrating artificial intelligence and machine learning, methods can inject model-based verification early in the process, expediting ESR&D through more complete testing and qualification from the outset. Components entering the supply chain as prototype or production parts do so with the necessary standards and certifications to ensure their suitability against requirements and measures of effectiveness (MOE).

SUMMARY RECOMMENDATIONS

Digital engineering can enable ESR&D by providing tools and techniques to model, simulate, and analyze complex systems and phenomena, and by enabling more efficient and effective collaboration between researchers and developers. From startups to large enterprise, digital ecosystem brings previously siloed organizations together and create emergent value by leveraging the network effects of collaboration and knowledge sharing. Metcalfe's law, popularized by Ethernet pioneer Robert Metcalfe, states that the value of a network to its users grows as the square of the total number of its connected users (n^2) (Wikipedia). Therefore, each member of the digital ecosystem adds emergent value to the business. When fully implemented, the digital ecosystem enables a positive virtuous cycle where each additional model connection enables more sophisticated analytics, which generates more value for all participants in the ecosystem.

When system engineering extends its architecture models outside of the SysML model repository, it creates linked connections that generates emergent value. The end-to-end digital ecosystem traceability enable our understanding of complex system relationships, and thereby increase the speed and improve the quality when a project needs to respond to change. This framework for digital engineering emphasizes the use of models and digital enablers across the lifecycle, facilitating the development of solutions to problems associated with complexity, uncertainty, and rapid change in deploying and using concepts and products. It provides a more agile and responsive development environment, better informed decision making, enhanced communication, increased understanding of and confidence in the system design, and a more efficient engineering process. ■

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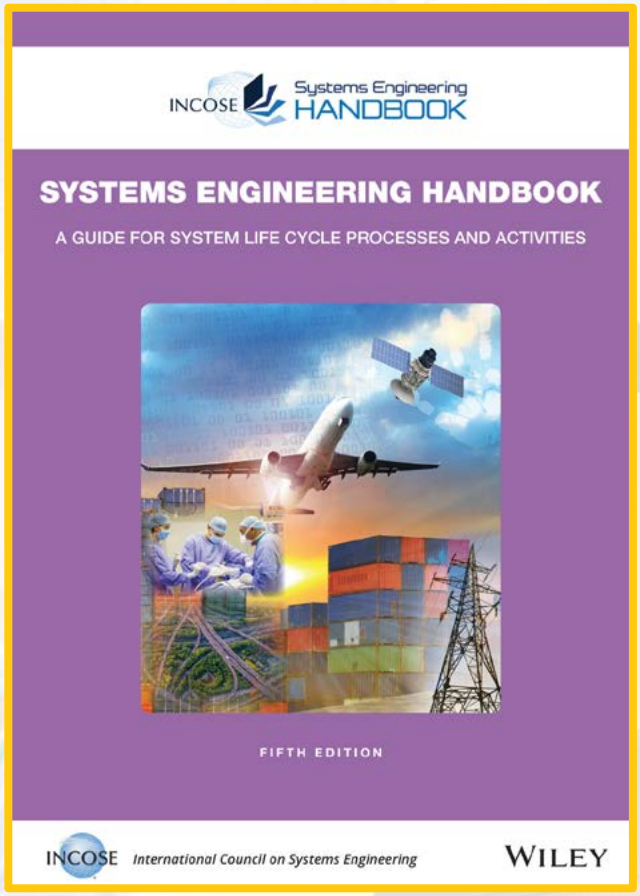

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Incorporating Digital Twins In Early Research and Development of Megaprojects To Reduce Cost and Schedule Risk

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ABSTRACT
Early-stage research and development (ESR&D) plays a vital role in the product development lifecycle, necessitating innovative approaches to address the complex challenges faced during this phase. This article quantifies how the incorporation of digital twin (DT) technology can reduce cost and schedule risk during ESR&D and later lifecycle stages in megaprojects. The Idaho National Laboratory demonstrated the application of DT in the Microreactor AGile Non-Nuclear Experimental Testbed (MAGNET) operations phase, showcasing the transformative potential of DT in both design and operation. These advances allowed real-time assessment of construction changes and their impact on project requirements. By focusing on the benefits of digital twinning, this article aims to promote a more positive attitude toward the incorporation of digital twin technologies in the early stages of R&D projects.

INTRODUCTION

To meet future energy needs, a significant number of new hydroelectric and nuclear energy powerplants need to be constructed, especially since those two sources produce large amounts of energy without producing carbon. An intergovernmental panel on climate change (IPCC) report recommended that "nuclear energy would have to more than double" to limit global warming by the 1.5°C objective (Poneman 2019).

Many hydroelectric and nuclear power projects exceed $1B and are classified as megaprojects. In his *Industrial Megaprojects* book, Edward W. Merrow classifies a megaproject as a failure if it exceeds its planned schedule or planned budget by 25% or fails to meet the originally defined objectives within 1 year after construction. Using these criteria, Merrow found only 35% of megaprojects were considered successful (Merrow 2011).

Digital twins (DTs) are virtual living models of real-life systems. They can help project managers and engineers understand and predict how the system will behave in different situations, making it possible to find problems and test solutions. DTs offer the potential to reduce schedule and provide greater insight into development and planning activities thereby reducing cost risk in powerplant design through the life cycle but planning and staffing for the DT must be done during early-stage research and development. This paper explores how DTs can improve the success rate of megaprojects in these industries. This paper analyzes the current state of the hydroelectric and nuclear construction industries as compared to historical averages, investigates a typical nuclear powerplant construction schedule with application of Monte Carlo simulations, and presents a fault tree approach to identify potential schedule risk reductions using DT technologies.

MEGAPROJECT SCHEDULING

While nuclear powerplants are the majority of US carbon-free power generation, each type of powerplant is studied independently and oftentimes considered distinctly different from one another. There are many commonalities between the development of hydroelectric and nuclear powerplants. These commonalities include regulatory bodies (Nuclear Regulatory Commission and Federal Energy Regulatory Commission in the US), construction using large amounts of poured concrete, unique site criteria, the requirement for in-depth engineering processes, and large budgets which classify these projects as megaprojects. These commonalities allow for a larger reflection on the state of megaprojects regarding power generation

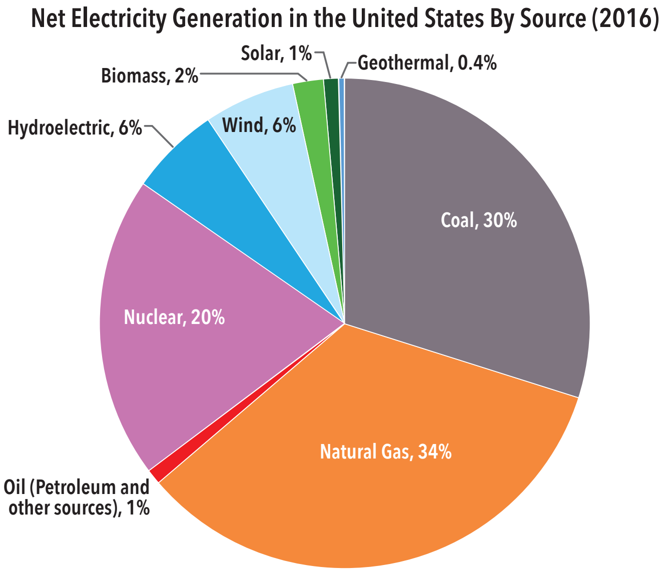

Figure 1. US electricity generation sources (EPA n.d.)

and whether issues are unique to a particular power generation source or endemic to the entire power production construction industry. A comparison of hydroelectric and nuclear projects pre and post 1979 is presented.

Pre-1979 Hydropower Construction Schedules

In the early 20th century, the United States completed many historic hydroelectric projects from the Hoover Dam on the Nevada border to the Oroville Dam in California. These earlier projects still account for the majority of U.S. carbon-free electricity as seen in Figure 1.

Much of the data on hydroelectric construction is historic, not tracked publicly, and thus difficult to source. A table of existing hydroelectric powerplants crowd sourced on Wikipedia was used as a starting point of all hydroelectric powerplants over 100 MW in the United States (Wikipedia n.d.). Data was mined from each hydroelectric powerplant article where both a construction start and end date was available. If either date was unavailable, a search across historic data sources and power electric databases was performed. This yielded a construction start and end date for 91% of hydroelectric powerplants. Likewise, data from the Comerford, Bad Creek, Gianelli, Great Lakes, Salina, and S. C. Moore were omitted from this study as both starting and ending construction data could not be readily sourced. These data points

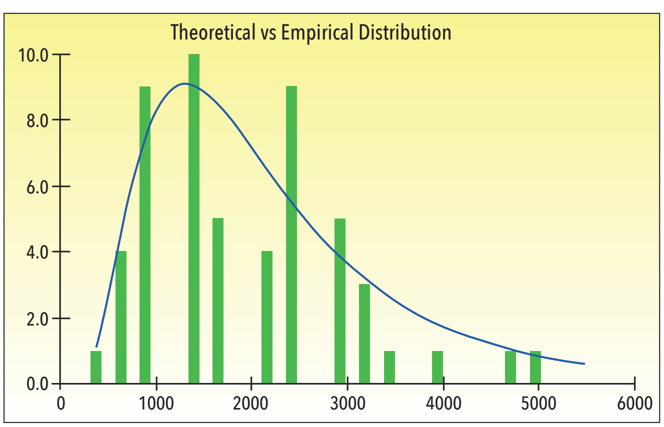

Figure 2. Hydropower pre-1979 distribution (construction days)

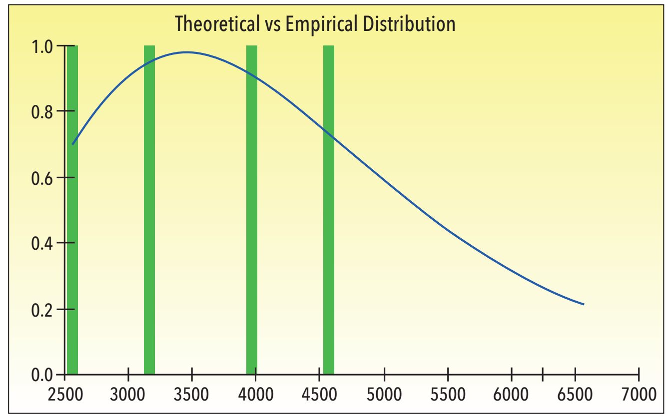

Figure 3. Hydropower post-1979 distribution

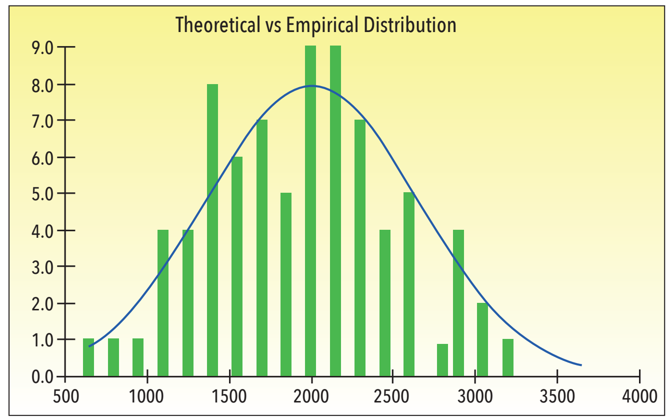

Figure 4. Nuclear power pre-1979 distribution

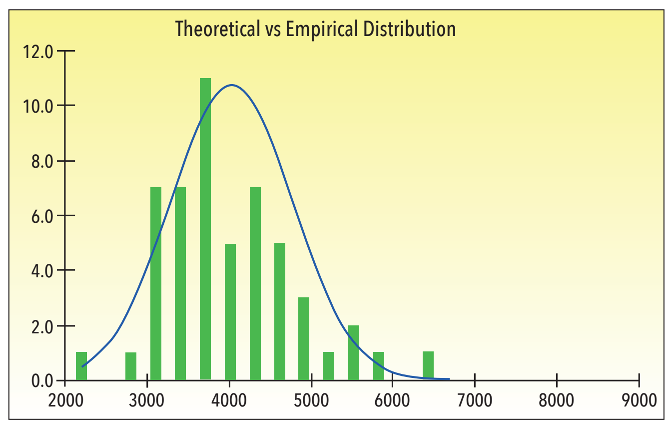

Figure 5. Nuclear power post-1979 distribution

were plotted and fit with a lognormal distribution. Data points for pre-1979 hydroelectric powerplants were plotted and fit with a relatively lognormal distribution as seen in Figure 2. The large degree of variation is due to differing reservoir site geography and local conditions associated with constructing dams. Prior to 1979, hydroelectric powerplants had a mean construction duration of 2,308 days or 6.32 years.

Post-1979 Hydropower Construction Schedules

In the 1970s, several safety accidents occurred across the power industry from the Idaho Teton Dam breach in the 1970s to the Three Mile Island incident in 1979. These incidents brought new oversight and regulations in large engineering projects. Using 1979 as a pivotal year, the same approach of utilizing crowd-sourced Wikipedia data, combined with historical searches, was used to identify construction schedules. As with the pre-1979 data, the post-1979 data was plotted and fit with a log normal distribution, as seen in Figure 3. Only four hydroelectric dams over 100 MW were constructed after 1979, and the mean of these projects was 4,229 days or 11.6 years. Notably, this represents an 83.4% increase in schedule duration for hydroelectric construction projects from the pre-1979 values.

Pre-1979 Nuclear Construction Schedules

Like hydropower, the early 20th century was a landmark time for nuclear energy. From the first nuclear electricity generation near Idaho Falls, Idaho (EBR-1) in a small research powerplant to the successful construction of facilities producing gigawatts of energy in Illinois (Dresden Nuclear Power Station). The nuclear power industry constructed over 80 powerplants in less than 25 years, bringing carbon-free energy to many large U.S. population centers. The International Atomic Energy Agency (IAEA) publishes data on every commercial power plant in the world, including each plant's construction date and grid connection date. This data was mined from IAEA's public report to plot and fit nuclear construction schedules prior to 1979 as seen in Figure 4 (International Atomic Energy Agency 2021).

Nuclear construction follows a normal distribution. The mean schedule duration was 2,004.75 days or 5.49 years from construction start to grid connection. These projects represent most of the carbon-free electricity available in the United States today.

Post-1979 Nuclear Construction Schedules

Unlike hydroelectric power, over 50 nuclear plants have been brought online since 1979, however, few since 1996. The Vogtle units 3 and 4 represent the only power generation units under active construction currently and are planned to be online in 2023 (World Nuclear News 2022). This dataset included the Vogtle plant construction data, even though construction is ongoing as the plants are in the final year of construction, and thus, the data is considered accurate. One datapoint is omitted, the Watts Bar unit 2, as construction was paused for ~30 years, and it is thus difficult to extrapolate raw construction time. Again, the data post-1979 was plotted and fit with a normal distribution in Figure 5 (International Atomic Energy Agency 2021). Nuclear power plants demonstrated a 4,029 day mean schedule duration or 11 years. This is an increase in duration of 101%. Nuclear projects are getting longer, similar to hydroelectric power.

Table 1. Schedule delay categories

Country	Contractor	Client	External
Saudi Arabia	0.06	0	0
Nigeria	0.63	0.6	0.53
Hong Kong	0.19	0.67	0.13
Egypt	0.13	0.13	0
Indonesia	0.13	0.07	0.07
Turkey	0.13	0.13	0
Thailand	0.38	0.33	0.33
South Africa	0.06	0.07	0.13
Botswana	0.06	0	0
Malaysia	0.13	0	0
India	0.19	0.27	0
Jordan	0.06	0.07	0.2
Average Risk of Each Category	0.18	0.20	0.12

SCHEDULE RISK COMPARISON

Schedule risk within construction projects is initiated from three primary sources: the contractor performing the construction activity, client (owner/operator), and external factors. Dr. Hendrik Prinsloo of HPM Consultants analyzed risk factors originating from 17 studies across construction projects globally (Prinsloo n.d.). These risk categories from contractor, client, and external factors were averaged and represent the probability of schedule delays.

Across these 17 studies, Prinsloo found 46 different initiating events causing a schedule delay. It is noteworthy that while these items appear independent, there may be some dependency and interaction among the sources of problems. Each initiating event with its calculated probability of occurrence is presented in (Prinsloo n.d.). These events were utilized to develop fault trees as seen in Figure 6 to Figure 9.

The fault trees, as drawn from Lucid Chart, were calculated using formulas from the *Probabilistic Risk Assessment Procedures Guide for NASA Managers and Practitioners* (Stamatelatos and Dezfuli 2011). This analysis resulted in a 72.72% likelihood of having a schedule delay, which is consistent

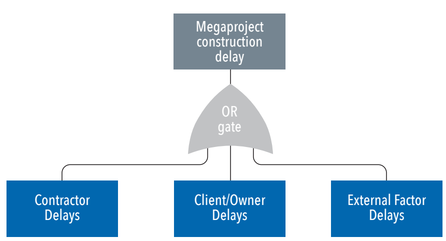

Figure 6. Parent megaproject construction delay fault tree

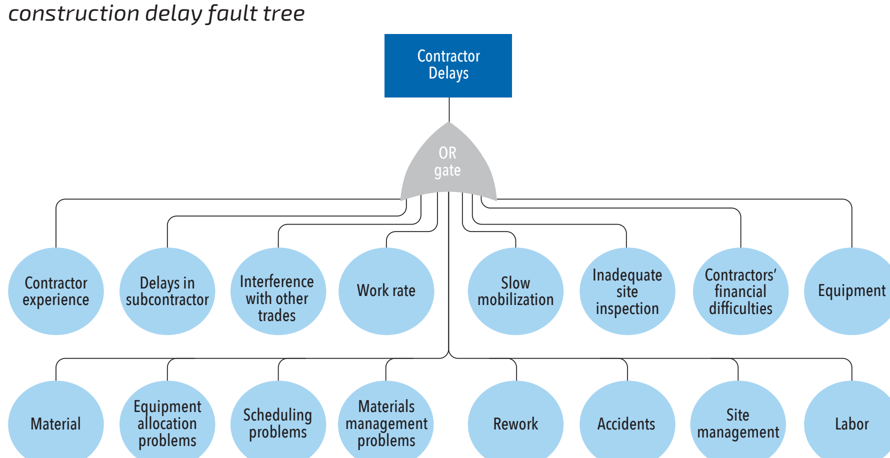

Figure 7. Contractor delays fault tree

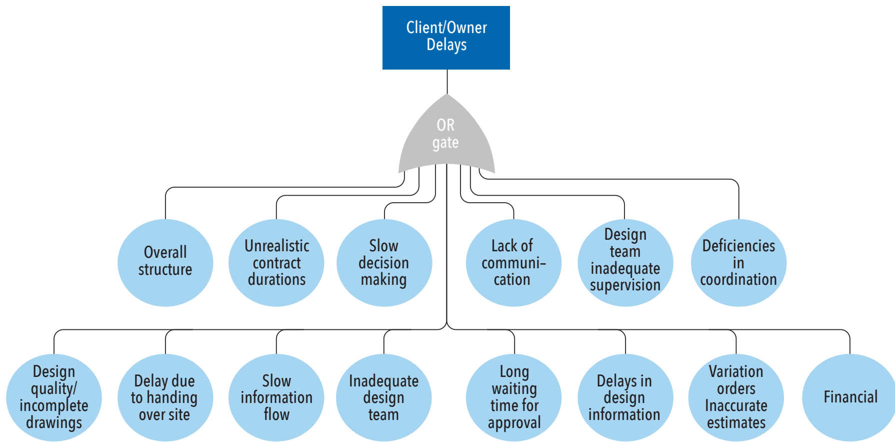

Figure 8. Client/owner delays fault tree

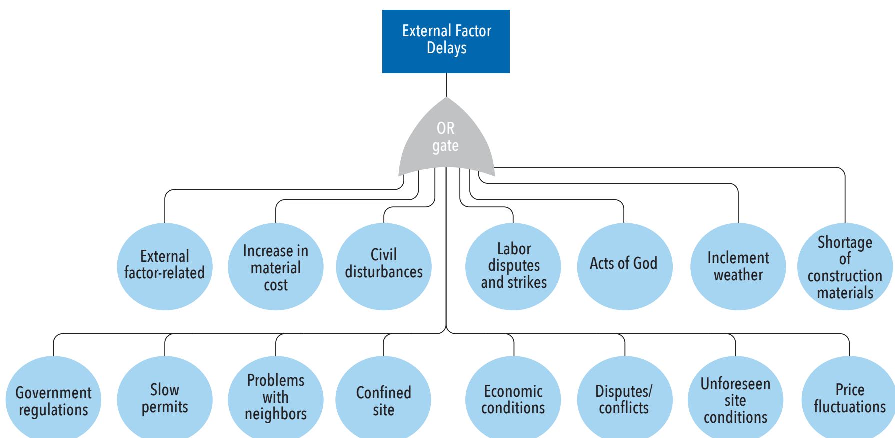

Figure 9. External factor delays fault tree

with an independent study from Arizona State University that also found a 72% probability of construction schedule delay (Rivera et al. 2017).

Risk Mitigation With A Digital Twin Approach

DTs are virtual, living models that can mirror a physical asset from its initial conceptual design through its eventual operation. These models typically begin as architecture models using model-based systems engineering (MBSE) tools and descriptive 3D models. This basic architecture/DT modeling can begin during early-stage research and development and help explore the trade-space of alternatives (Tao et al. 2018).

This DT approach is the next step of early product lifecycle management (PLM) techniques that leverage advancements in increased computing power and data integration, creating a digital thread to achieve fundamental breakthroughs in megaproject development. Risk is commonly defined as the product of likelihood and consequence. Through a more detailed exploration of the various trade-spaces, improved analysis of construction and assembly processes, and geometry assurance of the system's components, the likelihood of schedule delays can be reduced, thus reducing risk (Söderberg et al. 2017).

A quantitative exploration of how using a DT approach impacts a megaproject was completed. Each initiating event identified above was traced to a cited study, academic paper, and/or news article demonstrating a quantifiable DT benefit to reduce the probability of a hazard. Expectedly, some factors, including many external factors, do not have a mitigation that can be resolved with a DT approach. The results of the DT benefit, including a cited source of data, are presented in Prinsloo (n.d.).

The adjusted-DT events calculate to a 51.71% chance of schedule delay, reducing from a previous unmitigated 72.72%. This demonstrates a significant benefit of utilizing DTs to reduce construction risk, but notably, does not reduce all probability of schedule delays. For example, DTs cannot mitigate "acts of God" nor hire qualified teams of engineers and designers. A limitation of this analysis is that while the probability of delay can be reduced by ~20%, it is unknown what effect this would have on schedule distributions. It is likely, from the above tables, that DTs would reduce variance in schedule delays and, given the interaction of failure events is complex, provide other insights into processes that could reduce construction risk. See Tables 2–4.

Digital Twin Human Reliability Examples

Understanding the benefit of applying DTs can be difficult to fully comprehend. The concept of DTs is still maturing with varying definitions of what a DT must include. Recovery factor formulas, obtainable from the *Probabilistic Risk Assessment Procedures Guide for NASA Managers and Practitioners* (Stamatelatos and Dezfuli 2011), are used to calculate any potential benefit of a DT.

$$HEP = \sum_{i=1}^{I} [(BHEP_i) \prod_{j=1}^{J} RF_{i,j}]$$

Figure 10. Human reliability recovery factor formula (Stamatelatos and Dezfuli 2011)

Vogtle units 3 and units 4 utilize a Westinghouse AP1000 design. Another AP1000 design, V. C. Summer, was under construction in parallel in South Carolina. This project was ultimately unsuccessful. A review from Bechtel found that the project was issuing over 600 change orders per month. Engineering change orders are a knowledge-based task and thus with a traditional design change process have a rather high 7.63% error rate. Using DT, one is much more likely to discover errors earlier, while still in the design and development stage because one needs to gather detailed information to create the digital twin thus forcing higher fidelity planning. After the DT is built, one can perform analyses using DT to provide additional insight not previously available using traditional methods. If one adds artificial intelligence to review the analyses, further errors may be discovered and can be corrected. The error rates based on the traditional process are captured in Table 5 as the basic human error probable (BHEP) values. The effect of using DT and AI is captured as recovery factors (RF1 and RF2) in the table. Better understanding of the physics and construction is captured as RF3. The revised error probability per task is calculated by multiplying the BHEP by the RFs.

By implementing a DT-enabled change process using a combination of known

Table 2. Contractor delays

Cause	Adjusted	DT	DT Benefit
Contractor experience	0.0143	0.0143	0
Delays in subcontractor	0.0143	0.0086	0.4 (de la Boulaye et al. 2017)
Interference with other trades	0.0143	0.0143	0
Work rate	0.0448	0.0358	0.2 (Slepneva, Chernysheva, and Zaitseva 2021)
Slow mobilization	0.0143	0.0072	0.5 (McKinsey and Company 2022)
Contractors' inadequate site inspection	0.0143	0.0122	0.15 (Avanade Insights 2022)
Contractors' financial difficulties	0.0591	0.0372	0.37 (Gurumurthy, Schatsky, and Camhi 2022)
Equipment	0.0448	0.0022	0.95 (B2W Software n.d.)
Material	0.0305	0.0228	0.25 (Wyman n.d.)
Equipment allocation problems	0.0143	0.0072	0.5 (Hulett 2017)
Planning and scheduling problems	0.0448	0.0224	0.5 (Hulett 2017)
Materials management problems	0.0448	0.0224	0.5 (McKinsey and Company 2022)
Rework	0.0143	0.0046	0.68 (Saunders n.d.)
Accidents	0.0143	0.0086	0.4 (Chua 2022)
Site management and supervisions	0.0753	0.0376	0.5 (McKinsey and Company 2022)
Labor	0.0448	0.0358	0.2 (Slepneva, Chernysheva, and Zaitseva 2021)

Table 3. Client/owner delays

Cause	Adjusted	DT	DT Benefit
Overall structure	0.0332	0.0332	0
Unrealistic contract durations	0.0156	0.0078	0.5 (Hulett 2017)
Slow decision-making	0.0332	0.0099	0.7 (Berruti et al. 2017)
Lack of communication	0.0156	0.0016	0.9 (Sanchez, Hampson, Vaux 2016)
Design team inadequate supervision	0.0156	0.0156	0
Deficiencies in coordination	0.0156	0.0047	0.7 (Berruti et al. 2017)
Design quality/incomplete drawings	0.0644	0.0064	0.9 (Sanchez, Hampson, Vaux 2016)
Delay due to handing over site	0.0156	0.0156	0
Slow information flow	0.0332	0.0232	0.7 (Berruti 2017)
Inadequate design team	0.0332	0.0332	0
Long waiting time for approval	0.0644	0.0193	0.7 (Berruti 2017)
Delays in design information	0.0332	0.0099	0.7 (Berruti 2017)
Variation orders	0.1131	0.0362	0.68 (Saunders n.d.)
Inaccurate estimates	0.0156	0.0016	0.9 (Sanchez, Hampson, Vaux 2016)
Financial	0.0644	0.0450	0.3 (Slepneva, Chernysheva, and Zaitseva 2021)

Table 4. Contractor delays

Cause	Adjusted	DT	DT Benefit
External factor-related	0.0093	0.0093	0
Increase in material cost	0.0093	0.0093	0
Civil disturbances	0.0093	0.0093	0
Labor disputes and strikes	0.0093	0.0093	0
Acts of God	0.0093	0.0093	0
Inclement weather	0.0197	0.0197	0.5 (SciJinks n.d.)
Government regulations	0.0093	0.0093	0
Slow permits	0.0197	0.0197	0
Problems with neighbors	0.0093	0.0093	0
Confined site	0.0093	0.0093	0
Economic conditions	0.0093	0.0093	0
Disputes/conflicts	0.0093	0.0093	0
Unforeseen site conditions	0.0197	0.0197	0
Price fluctuations	0.0197	0.0197	0
Shortage of construction materials	0.0290	0.0145	0.5 (McKinsey and Company 2022)

Table 5. Contractor delays

Task	BHEP	RF1	RF2 (AI)	RF3 (Physics)	Product	Source
Classic Change						
Requirements	0.04	0.22			8.80E-03	(Hougie 2019; Jones 2011)
Design	0.45	0.15			6.75E-02	(McConnell 2004; Jones 2011)
					7.63E-02	7.63%
DT Change						
Requirements	0.04	0.22	0.3075		2.71E-03	(Hougie 2019; Jones 2011; Hao 2020)
Design	0.45	0.15		0.05	3.38E-03	(McConnell 2004; Jones 2011; OpenLearn n.d.)
					6.08E-03	0.61%
Classic Design						
Requirements	0.06	0.22			1.29E-02	(Langenfeld 2016; Jones 2011)
Interfaces	0.06	0.22			1.29E-02	(Langenfeld 2016; Jones 2011)
Design	0.03	0.15			3.75E-03	(Autodesk n.d.; Jones 2011)
					2.96E-02	2.96%
DT Design						
Requirements	0.06	0.22	0.3075		3.98E-03	(Langenfeld 2016; Jones 2011; Hao 2020)
Interfaces	0.06	0.22	0.3075		3.98E-03	(Langenfeld 2016; Jones 2011; Hao 2020)
Design	0.02	0.15		0.05	1.20E-04	(Autodesk n.d.; Jones 2011; OpenLearn n.d.)
					8.08E-03	0.81%

artificial intelligence and first principal techniques, it is expected that the error rate probability will be cut to less than 1% as seen in Table 5.

NATIONAL LABORATORY USE CASE

In the design phase of the versatile test reactor (VTR) project, digital engineering using models/data instead of documents and integration of data across models helped realize significant risk reduction on construction cost and schedule. A 3D model of VTR was developed in the first 3 months of the project–10 times faster than similar past efforts. For VTR, North Carolina State University developed a method to automate mesh creation for 3D modeling. To capture integrated 2D and 3D models of the plant, VTR uses a virtual design construction and building information management (BIM) tool from conceptual design through construction. A nuclear ontology (DIAMOND) connects object types across the nuclear construction discipline, allowing real-time access to how changes in construction will affect requirements. For example, project managers were able to conduct near real-time reviews of how construction changes could affect the plant. A tool that uses data to generate documentation has driven a culture change. The requirements information management (RIM) tool helps ensure the requirements process is based upon essential information needs. The tool captures requirements, codes, and standards in a fully integrated database to understand the whole impact of changes. Research is ongoing at Idaho National Laboratory (INL) to apply these technologies across INL's broad portfolio of microreactor and nuclear test bed programs.

In the operations phase, the INL team recently demonstrated a transformative microreactor DT of the Microreactor AGile Non-Nuclear Experimental Testbed (MAGNET). MAGNET utilizes a set of electrical heating elements to physically test reactor core thermal behavior, heat exchanger performance, and passive decay in a non-nuclear physical test. The DT was able to issue autonomous control commands based on forecast predictions up to 10 minutes into the future while providing the operator real-time information using mixed reality. This early-stage research proves it is possible to achieve digital engineering objectives broadly in both design and operation.

CONCLUSION

The use of DTs in developing and managing megaprojects has demonstrated significant potential to reduce construction risk and schedule delays. By providing a virtual representation of a project from its initial conceptual design through its eventual operation, DTs can help identify and address potential issues early in the development process.

The application of DTs in various case studies, such as the VTR project and the MAGNET, has showcased the benefits of digital engineering in reducing error rates and improving overall project efficiency. Furthermore, the integration of artificial intelligence, data management, and real-time analyses enabled by DTs provides valuable insights for better decision-making, leading to more streamlined and cost-effective megaprojects.

While DTs cannot mitigate all risks associated with complex projects, their implementation can substantially reduce the likelihood of schedule delays and promote a more efficient, data-driven approach to project management. If one considers the massive investments required for a megaproject, even small improvements in the design and development process yield significant savings and justify the additional effort and expense building the DT. As technology continues to advance and mature, the adoption of DTs is expected to improve how megaprojects are designed, constructed, and operated, paving the way for more successful outcomes in the future. ■

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