Research Report

N. PETER WHITEHEAD, THOMAS LIGHT, ADRIAN LUNA, JIM MIGNANO

A Framework for Assessing the Costs and Benefits of Digital Engineering

A Systems Approach

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About This Report

Since 2006, the U.S. Department of Defense (DoD) has employed a policy for architecting weapon systems that emphasizes model-based systems engineering (MBSE). In 2018, the scope of MBSE was expanded into digital engineering, described by the U.S. Navy as "an integrated, computation-based approach that uses authoritative sources of system data and models across disciplines to support life cycle activities from concept through disposal."[1]

Motivated by the need to balance digital engineering utility with digital engineering activity costs, the purpose of this project was to develop decision support frameworks for assessing the costs and benefits of digital engineering in defense weapon system programs. In addressing this objective, we looked extensively at prior work in this area, at established DoD cost-benefit analysis (CBA) approaches, and at systems engineering in defense and commercial practices. We determined over the course of our analysis that relative costs and benefits of digital engineering cannot be determined without addressing rigor and risks in the practice of digital engineering policy, and so we also addressed those issues. The result is a set of two decision support frameworks: one using established norms of CBA and one using established practice of systems engineering. This report also provides analysis into the rigor and risks aspects of digital engineering practice, along with a set of recommendations.

The scope of the research documented here spans DoD, all the services leveraging digital engineering and MBSE, the primary weapon system contractors, the systems engineering technical assistance contractors, the university-operated academic research centers, and the federally funded research and development centers that participate in the DoD acquisition and systems engineering ecosystem. The intended audience for this report is program engineers, program systems engineers, contracting officers' representatives, program managers, program executive offices, service acquisition offices and commands, and DoD systems engineering policymakers.

This report documents research and analysis conducted as part of a project entitled *Digital Engineering Cost-Benefit Framework* sponsored by the Systems Engineering and Architecture Division of the Office of the Under Secretary of Defense, Research and Engineering.

The research reported here was completed in December 2023 and underwent security review with the sponsor and the Defense Office of Prepublication and Security Review before public release.

RAND National Security Research Division

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[1] Naval-LIFT, "Naval Digital Engineering Body of Knowledge," Naval DEBoK, Naval-LIFT Wiki, 2023.

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Summary

Our task was to understand the costs and benefits of digital engineering in the U.S. Department of Defense (DoD) and develop a decision support framework for digital engineering activities in weapon system programs. To prepare, we reviewed the literature and interviewed stakeholders to understand the current state of digital engineering practice and prior efforts to assess costs and benefits of digital engineering and model-based systems engineering (MBSE). We then developed decision support frameworks incorporating (1) established DoD cost-benefit analyses approaches and (2) established systems engineering decision methodologies. Along the way, we noted critical issues with rigor and risks in the practice of DoD digital engineering and added that aspect to our study.

Our research suggests that cost-benefit decision support for digital engineering is possible at any stage of a weapon system program life cycle if program data have been collected accordingly or if goal-based systems engineering principles are leveraged. Calculating definitive costs and benefits of digital engineering is imperfect because no analyst will have access to an identical weapon system program developed without digital engineering—the counterfactual scenario.

Although many authors claim MBSE and digital engineering benefits, empirical data supporting those claims remain rare. Claimed or aspirational benefits expressed in such general terms as *better* and *easier* defy assessment but might nevertheless have been factored in program decisions. Cited references for most published studies on digital engineering and MBSE derive from software development practices. Therefore, they have limited relevance in practical applications of weapon system engineering. Despite long-standing expressed intent for DoD to adopt more industry-type development and innovation methodologies, return-on-investment justifications that industry generally requires have not also taken root in DoD culture.

Our first framework builds on established cost-benefit analysis practices familiar to economists and DoD analysts. In line with those practices, we developed an approach tailored to implementations of digital engineering being pursued by DoD programs.

The second framework leverages the systems engineering goal definition process codified in Joint Capabilities Integration and Development System and acquisition laws pertaining to DoD. Focusing on the key performance parameters and the key system attributes, we establish quantifiable units of benefit for a digital engineering approach: indexes of performance. Using a logic-model approach, alignment of corresponding risks, and a cost breakdown matrix of cost categories provides a trade-study means to compare and choose from multiple digital engineering activity options as they might affect the defined weapon system goals.

Next, we consider issues with rigor and risk in digital engineering—leverage points where focused policy could improve development and acquisition outcomes through digital engineering. We conclude with a summary of our findings, recommendations for dealing with the issues of rigor and risk, and a presentation of the two frameworks.

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CHAPTER 1

Introduction

> We know a tremendous amount about how the world works, but not nearly enough. Our knowledge is amazing; our ignorance even more so. We can improve our understanding, but we cannot make it perfect. I believe both sides of this duality, because I have learned much from the study of systems.[1]

Core to systems engineering is what George Hazelrigg calls the *fundamentals of decision-making*.[2] Systems engineers are not software developers, electrical engineers, or mechanical engineers. They assimilate the work of those specialists and many others to make decisions that lead to better designs, integrated systems, critical analyses, and cost-effective products. The use of models and simulations in preforming these tasks long predates the term *systems engineer*.[3] To do the job well, systems engineers must understand the risks and limitations of the models, contextualize the assumptions behind representations of designs, and never take the product of another engineer at face value without understanding the thinking behind it. Good systems engineering is hard, which brings us to digital engineering.

Digital engineering became policy with the 2018 Defense Department Digital Engineering Strategy, which built on the 2006 U.S. Department of Defense (DoD) policy for model-based systems engineering (MBSE).[4] Yet the term *digital engineering* reflects widely varying defini-

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[1] Donella H. Meadows, *Thinking in Systems: A Primer*, Chelsea Green Publishing, 2008, p. 87.

[2] George A. Hazelrigg, *Fundamentals of Decision Making for Engineering Design and Systems Engineering*, Neils Corp, 2012.

[3] Systems engineering as a practice and the use of models therein traces to ancient history, including the I Ching in China circa 1500 BCE and the great Pyramids of Giza circa 3000–2000 BCE. The term *systems engineering* evolved in the United States during development of television networks at the Radio Corporation of America (RCA) in the 1930s and 1940s and Bell Labs in the 1940s, and the concept of systems analysis was defined by the RAND Corporation in the late 1940s and early 1950s. See Arthur D. Hall, *A Methodology for Systems Engineering*, D. Van Nostrand Company, Inc., 1962; and Charles West Churchman, *The Systems Approach*, Delacorte Press, 1968.

[4] U.S. Department of Defense, *Department of Defense Digital Engineering Strategy*, Office of the Deputy Assistant Secretary of Defense for Systems Engineering, June 2018; Dwayne Hardy, “Model Based Systems Engineering and How It Aids DoD Acquisition & Systems Engineering,” *Proceedings of the 9th Annual Systems Engineering Conference, Focusing on Improving Performance of Defense Systems Programs*, October 2006. Appendix A of this report contains a brief history of digital engineering.

tions across the department and the defense industrial community. *Consistently inconsistent* best describes how understanding of digital engineering differs from one weapon system program to the next.[5] Stakeholders engaged in relevant work tend toward a Justice Potter Stewart perspective on digital engineering: They know it when they see it.[6] Others have labeled good engineering practices, including models and simulations that they were already leveraging, as digital engineering.

The loose constraints on definitions might foster innovation by not overly restricting practice and, thus, allow good ideas to rise to the top without government interference. However, they could also produce program activity and expenditure that meets DoD policy to the letter of the law, not necessarily the spirit of the law. Without consistency and measurable goals, some digital engineering activity seems to be motivated by a general sense of goodness. This motivation is facilitated by the ambiguity in the definitions and goals of the DoD digital engineering strategy, along with such arbitrary service directives as the doctrine of the acting Assistant Secretary of the Air Force for Acquisition, Technology and Logistics to achieve "a measure of authoritative virtualization that replaces, automates, or truncates formerly real-world activities."[7]

This doctrine omits a key aspect that engineers and program managers must understand: To what end? Virtualization itself is not a goal. The question of why should we expend resources to virtualize a weapon system must be answered in terms of system goals and mission goals, and it must be well understood for virtualization to have value. If virtualization is to replace real-world activities, then the approach is unlikely to succeed without the goals of those real-world activities clearly defined in advance. No models or simulations can substitute for real-world activity without additional risk.

Program executive offices, program managers, and lead systems engineers need decision support frameworks to leverage modern engineering tools to provide the warfighter with capability at the speed of war. We took two tacks to such decision support: (1) a standard DoD cost-benefit analysis (CBA) approach per well-established practice and (2) a systems engineering approach to understand modeling and simulation needs while gathering relevant data on digital engineering.

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[5] The nature of this analysis and the associated terminology have led us to choose the term *weapon system*. That term, for consistency, is used throughout this report. We wish to emphasize that the analysis and findings extend to systems that would not be described as weapons and to systems that are nonmilitary and non-DoD.

[6] Peter Lattman, "The Origins of Justice Stewart's 'I Know It When I See It,'" *Wall Street Journal*, September 27, 2007.

[7] Will Roper, *Bending the Spoon: Guidebook for Digital Engineering and e-Series*, Department of the Air Force, January 19, 2021, p. 2.

Objective and Approach

The Office of the Under Secretary of Defense for Research and Engineering (OUSD[R&E]) has identified a need for program managers and engineers to better understand the costs and benefits of implementing digital engineering over a system life cycle. This report is aimed at initially addressing that need for an audience of program managers, program executive officers, lead systems engineers, and other leaders in the acquisition community. With that audience in mind, this report documents a framework approach for collecting information from programs pursuing digital engineering to understand the size and timing of anticipated and realized costs and benefits of digital engineering.

Our study started with understanding the literature, background, current state of practice, and system boundaries of digital engineering in DoD and, to a lesser extent, industry. We also examined the practice of CBA across the department to derive a general framework for analyzing the costs and benefits attributable to digital engineering activities. Subsequently, we developed a normative systems engineering framework to optimally derive and analyze data on digital engineering activities in support of engineering decisions. Finally, we examined the risks, rigor, and associated leverage points of digital engineering for achieving improved outcomes.

This research benefited from insights and information gathered from subject-matter experts. We held semistructured discussions with 25 engineers, managers, and scholars with expertise in digital engineering applications and initiatives. Their professional affiliations included Office of the United States Assistant Secretary of the Army for Acquisition, Logistics, and Technology; Army Futures Command (including U.S. Army Combat Capabilities Development Command Aviation and Missile Center and U.S. Army Combat Capabilities Development Command Ground Vehicle Systems Center); Naval Air Systems Command (NAVAIR) (including Program Executive Office, Air, Anti-Submarine Warfare, Assault, and Special Mission Programs and Naval Air Warfare Center Aircraft Division); National Reconnaissance Office; a major automotive company; and six leading academic departments in engineering. These discussions covered activities associated with digital engineering, stressing insights about digital engineering costs and benefits. We also asked each participant to recommend documentation and data regarding the activities, costs, and benefits discussed. Their recommendations augmented the sources identified through our literature scan.[8]

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[8] This report also benefitted from past and concurrent RAND analyses of digital engineering for the Department of the Air Force through Project AIR FORCE, including discussions other research projects held with stakeholders.

Organization of This Report

Chapter 2 conveys the results of a literature review focused on publications that espouse quantifiable benefits from digital engineering and establishes working definitions using current practice to lend consistency to subsequent chapters. Chapter 3 provides a CBA framework applicable to digital engineering activities being implemented by weapon system programs. The approach builds on established DoD and service CBA guidance and practice. Chapter 4 develops a logic-model framework using systems engineering principles to support stakeholders in making informed digital engineering decisions from the ground up. Chapter 5 identifies leverage points in an analysis of rigor and risk in digital engineering where new policy might lead to net improvements in weapon system outcomes. Chapter 6 summarizes the work and discusses recommendations derived from our analysis.

CHAPTER 2

Overview of Digital Engineering and Its Use in the Department of Defense

Our study of the background of digital engineering reflected the complexity of the digital engineering environment and the multiple mental models involved in practice. We reviewed other RAND reports and thoroughly reviewed the history and technology preceding today's DoD guidance and state of practice. If digital engineering is proving advantageous for its pioneers, then it stands to question what the lesson from their activities means for DoD and the weapon system life cycle. Our examination of the literature and interviews with digital engineering experts and communities addresses the use of digital models, simulation, and software; difficulties that arise from varied definitions and terminology; and the benefits and costs of digital engineering activities and how they are identified and measured. We end the chapter with some working definitions using our analysis.

Digital Models, Simulation, Software, and the Department of Defense

DoD's record stands tall with a history of leveraging models and simulations in pursuit of advanced technologies and capabilities. Where once massive wind tunnels harnessed megawatts of energy to provide air flow data on aircraft, simulations now perform much of the work faster and cheaper.[1] Where waterways and transportation networks were once modeled physically at scale under vast hangers outside Vicksburg, Mississippi, supercomputers now do the calculations and support designs for the Army Corps of Engineers.[2] U.S. Air Force advanced simulations have supported design decisions at every step of the Sentinel program,

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[1] Edward M. Kraft, "The Air Force Digital Thread/Digital Twin-Life Cycle Integration and Use of Computational and Experimental Knowledge," *Proceedings of the 54th American Institute of Aeronautics and astronautics Aerospace Sciences Meeting*, 2016.

[2] S. Keith Martin, Morgan M. Johnston, Kiara I. Pazan, Mario J. Sanchez, Mary Claire Allison, and Gary Lynch, "Screening Channel Design Alternatives Using Ship Simulation," *Journal of Waterway, Port, Coastal, and Ocean Engineering*, Vol. 147, No. 5, 2021.

and the Advanced Framework for Simulation, Integration, and Modeling (AFSIM) software suite simulates warfighting domains from "sub-surface to space."[3]

These and other advanced simulation processes have evolved along with DoD technology, sometimes leading industry, sometimes trailing industry, but never far apart. There have been bumps in the digital road, which we will address later in Chapter 5, but the digital domain dominates DoD development and has done so for decades.

On the software side, DoD has had to deal with restrictive acquisition regulations and oversight that hinder rapid development and deployment. Recent advances from software factories and from leveraging minimal viable product (MVP) approaches are narrowing the gap with commercial practices and promise to bring cutting-edge capability to the warfighters within hours instead of months.

DoD is working to improve its digital engineering capabilities to support the weapon system life cycle. The propositions offered by adopting digital engineering are that it could improve decisionmaking, enhance communication, increase "understanding of and confidence in the system design," and boost efficiency.[4] The department remarks that pioneers in industry and research are "implementing digital engineering activities to great benefit."[5]

Digital engineering is a policy approach, based fundamentally on prescribing the broad use of MBSE (systems modeling language [SysML]) that follows in a very long line of such acquisition and development policies since the creation of DoD, from which many valuable lessons might be learned beyond the scope of this project.[6] An engineering approach in industry would necessarily originate bottom-up from engineers with a need for defining goals and solving a problem. This approach contrasts with the use of digital engineering and MBSE, which originated at the highest level and is being directed on the lower echelons of development and acquisition (i.e., policy).

A large bureaucracy such as DoD necessarily runs on policy. Policy motivations generally include better, faster, and cheaper operations; warfighter overmatch; technology at the speed of war; and capabilities that can compete with such near peers as China. In understanding the goals of this project, an early step was recognizing that the respective key stakeholders might have different motivations, different goals, and different approaches to policy. Where digital engineering practitioners confuse a policy approach with an approach to engineer-

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[3] Shaun Waterman, "How GBSD/Sentinel is Using Digital Twins," *Air Force Magazine*, Vol. 105, No. 5, 2022, p. 26; Wright-Patterson Air Force Base, "Advanced Framework for Simulation, Integration and Modeling Software," webpage, undated.

[4] U.S. Department of Defense, 2018, p. 3.

[5] U.S. Department of Defense, 2018, p. 25.

[6] Lessons might be learned from preceding DoD and congressional acquisition and development initiatives, many of which are outlined in J. Ronald Fox, *Defense Acquisition Reform, 1960–2009: An Elusive Goal*, Center of Military History, U.S. Army, 2012; and Christopher H. Hanks, Elliot L. Axelband, Shuna Lindsay, Rehan Malik, and Brett D. Steele, *Reexamining Military Acquisition Reform: Are We There Yet?* RAND Corporation, MG-291-A, 2005.

ing practice, there might be a need to step back and reexamine the goals behind each in an attempt to reduce the information asymmetry.[7]

In our research about who DoD digital engineering pioneers are and what they are implementing, the literature identifies a wide variety of activities that can be done and have been done with digital engineering. For example, the literature often associates MBSE with such activities as developing and managing requirements, managing and reusing designs, simulating performance, and communicating concepts and requirements. The literature also tends to identify digital twins and digital threads with advanced manufacturing and maintenance activities (e.g., automating parts fabrication with 3D models, reporting trouble codes inflight to maintainers). Together, MBSE, digital twins, and digital threads are used or proposed for a variety of activities across the entire system life cycle.[8]

Many of these activities have been conducted by government organizations or defense programs, and others have been conducted by contractors or defense industry. Some activities are prospective or aspirational, meaning that we did not identify documented experience using digital engineering for the activities, but literature suggests it could be used to carry them out. Appendix D contains a summary of the digital engineering activities identified in the literature.

Digital Engineering: A Multiplicity of Terms and Definitions

A difficulty in studying the published literature on digital engineering benefits and costs comes, in part, from the varying definitions of what digital engineering is and the equally varying perspective of those applying it. Often, such digital engineering terms as *authoritative source of truth (ASoT)*, *MBSE*, and *digital twins* mean different things to different groups of people. Comparing results using different definitions of digital engineering makes it difficult to generalize inferences about their benefits and costs. Attempts to create generalized definitions from the existing variety of classifications have been done but might result in overly broad descriptions that allow any activity to satisfy the conditions.

Digital engineering definitions allow for broad applications of the terms that allow all programs to dictate whether they are performing the process. If every program is implementing digital engineering, then it also might be the case that none of them are. Table 2.1 shows the dichotomy of concepts and terminology in the digital engineering literature and lists the

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[7] The dimensions of information asymmetry might include the weapon system supplier and government, the Systems Engineering and Technical Assistance (SETA) staff and government, government leadership and government engineers, or the end users and government leadership. For an example of the ramifications of information asymmetry in the quality of outcomes and products, see George A. Akerlof, "Quality Uncertainty and the Market Mechanism," *Quarterly Journal of Economics*, Vol. 84, No. 3, 1970. A key stakeholder referred to this as *pretending* during a conversation on this phenomenon.

[8] See Chapter 5 and Appendix D for more analysis of the digital twins concept in relation to rigor required for effective digital engineering.

counterpart perspective. The column on the right reflects a perception of the defense industrial complex pre–digital engineering that might not be accurate. In systems engineering terms, the authors do not present an objective, factual perspective of the ground state.

With different conceptions of the components of digital engineering, it is difficult to assess whether a program is applying digital engineering to its processes. If the highest conception of digital engineering is the standard, then no engineering team can declare that they are performing it. If the lowest conception of digital engineering is the standard, then any program can claim that it is engaged in digital engineering but could realistically be engaging in just engineering as it has been done for decades. The inconsistency of the application

TABLE 2.1

Basic Constituent Elements of Digital Engineering (at Face Value) Mapped to Non–Digital Engineering Counterparts

Digital Engineering Element	Non–Digital Engineering Counterpart
Computers complete tasks (automation)	Humans complete tasks
Computers make errors (automation)	Humans make errors
Digital data system centralizes information	Paper document data system centralizes information
Digital data system supports communication and analysis, stakeholder engagement, information retrieval and discovery, decisionmaking, and customization	Paper document data system supports communication and analysis, stakeholder engagement, information retrieval and discovery, decisionmaking, and customization
Digital data capture, management, and sharing	Paper document data capture, management, and sharing
Conduct verification and validation activities earlier	Conduct verification and validation activities later
Computer work environment supports making changes and simultaneous work	Physical work environment supports making changes and simultaneous work
More (digital) tools are available and used	Less (digital) tools are available and used
More (digital) tools require more stakeholder input	Less (digital) tools require less stakeholder input
Computers make predictions	Humans make predictions
Digital libraries support reuse	Paper libraries support reuse
Multiple viewpoints are available	A single viewpoint is available
Specific people are designated modelers	Specific people are not designated modelers
Structured information is unambiguous	Unstructured information is ambiguous

SOURCE: Adapted from “logical justifications for causal links in final [digital engineering causal] model” (Kaitlin Henderson, Tom McDermott, Eileen Van Aken, and Alejandro Salado, “Towards Developing Metrics to Evaluate Digital Engineering,” *Systems Engineering*, Vol. 26, No. 1, January 2023, pp. 27–31).

creates further issues when attempting to assess whether a new program should take the digital initiative when standards and comparison have these levels of heterogeneity in their implementation.

Authoritative Source of Truth

A central tenant of digital engineering is the ASoT, which, in theory, serves as a centralized haven for the authoritative model and its associated data.[9] If an engineering team needs to communicate or understand a portion of the model, then they refer to the ASoT. The difficulty arises in practice if the ASoT is characterized and realized in different levels. To some, it entails an engineering model that carries through the development process. To other groups, the ASoT serves as a data repository to which engineering teams can update variables in real time and across teams. Even when the concept of an ASoT is used as a mutual data repository, the data are not always centralized but rather accessed via a similar gateway to different data servers. The different levels that the ASoT can embody minimize the net value of the term in describing its function or structure.

Digital Twin

The term *digital twin* has a spectrum of definitions in digital engineering literature. At the simplest level of abstraction, a digital twin is the virtualized counterpart of a physical system. The concept of a digital twin encounters ambiguity when identifying the fidelity and use of that virtual model as it pertains to the engineering process.

There are different levels of conception of the digital twin paradigm. At its most ambitious, the digital twin informs the design of the system, supports upkeep during sustainment, and assists in real-time warfighting scenarios. In moderated terms, the digital twin can be built to inform the design process and relay information between its physical counterpart to provide updated information to engineering teams. In its realistic scenario, the digital twin is a model that helps engineering teams during the design and development process to inform choices, preemptively identify defects, and theoretically save costs that would be incurred during sustainment of the system.

Even at its simplest articulation, the consensus on the fidelity of the digital twin and the necessary number of digital twins is not clear among DoD users. Digital twins can be numerous snapshots of a model, multiple digital twins carried forward, or a singular all-encompassing model used through its intended contribution to the engineering process. The fidelity and design goals of the digital twin beg the purpose of its application and practicality.

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[9] The term itself demands clarification. If a model or data set are *authoritative*, then an authority is implied. We have not seen guidance to establish that authority in an office or in a person. Stating that data or a model are true requires verification, and verification requires an authority. True does not correlate to correct if the wrong question is being answered; that implies validation, something omitted altogether from documented descriptions of the ASoT.

An all-encompassing model that can address the questions of any inquiring engineer would prove costly and be restricted to the conceptions of its developers. If the digital twin serves focused engineering objectives, then it might be the case that it would fall into the category of a general engineering model. Thus, the term might be vacuous and indistinguishable from any previous iteration of an engineering model.

Digital Engineering Benefits

In surveying the literature, the complexity of quantifying the benefits of a DoD policy or engineering approach becomes apparent. When aiming for improvements, DoD aims for reduction in costs, expedience of schedule, and improvements in performance (also known as mission or capability). Cost and schedule can be measured in dollars spent on certain engineering tasks or processes and in time to completion. Warfighting performance might be abstract depending on the purpose of the weapon system in question and additional purposes perhaps not considered when a system was originally conceived. Across weapon systems, many programs have grown in cost and schedule, but might have also improved in performance.

If the goal is to maximize warfighting capabilities, then cost and schedule are constraints rather than optimization functions. If performance is the key indicator of success or the preferred metric, then the paradigm for CBA must shift with it. This poses a question on how to measure performance, which we will address in Chapter 4.

In the literature, the benefits of digital engineering activities are virtually always qualitative, often aspirational, widely applicable, and frequently designed, theoretically, to offset costs during the sustainment phase. If digital engineering initiatives are executed properly, then investments in design and development will generate payoffs through the end of the life cycle. Of total costs, the classic systems engineering benchmark has been that "concept, design and development phase[s] cumulatively account for 20% of the total life cycle cost [and the] remaining 80% of cost occurs in the production, testing, operations, support, maintenance, and disposal phases."[10] The issue with implementation is that, according to those practicing and writing about it, digital engineering benefits will materialize well after the life cycle decision point of whether to use it.

Anecdotal evidence from the literature points to better communication, increased traceability, improved consistency, and better management of complexity as top cited benefits of MBSE.[11] These benefits are generalizable to any program, and their payoffs are difficult, if

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[10] Azad M. Madni and Shatad Purohit, "Economic Analysis of Model-Based Systems Engineering," *Systems*, Vol. 7, No. 1, 2019, p. 7. See also Thomas Shaw, "The Critical Role of Systems Engineering in Effective Product Development," Space Programs and Technologies Conference and Exhibit, 1994; Michael Wetzer, "Integrating Systems Engineering with Enterprise Management," paper presented at the Space Programs and Technologies Conference, Huntsville, Alabama, March 24–27, 1992.

[11] Henderson et al., 2023.

not impossible, to tie back to MBSE or digital engineering activities. How, for example, would an analyst objectively study these benefits in the absence of the organizational, cultural, and political factors that also influence them? Such benefits as improved communication could reduce the schedule of tasks, but if that efficiency gain is redirected to increased complexity or performance, then the gains might become obscured in the process. All programs would benefit from improved communication and other qualitative improvements, but digital engineering being the sole or primary mode of achieving these benefits is questionable.

In Chapter 4, we will address the importance of absorptive capacity as it relates to understanding these benefits, digital engineering notwithstanding.[12]

Claimed Digital Engineering Benefits Tend to Lack Generalizability

Engineering endeavors for weapon systems have different goals and metrics for operational success. Digital engineering as a paradigm does not deviate from this reality. If a program is not designed with digital engineering in mind, then there will not exist an alternative where it is and vice versa (the counterfactual that we will address in Chapter 3). When the F-35 began development, the goal was not to redevelop the F-15 or F-22 with updated methodology, but rather to develop a new system with enhanced capabilities. Although the F-15, F-22, and F-35 programs fall into the broader category of military aircraft, a comparison among them introduces a degree of heterogeneity and blurs the robustness of a cost-benefit comparison. This generalizability process worsens as programs become increasingly dissimilar and increasingly complex.

Differences in maturity of digital engineering efforts make cross comparison and success stories difficult to extrapolate to other programs and services. For example, survey respondents disagreed about the existence of consistent metrics across the enterprise, consistent use of shared models, and whether models are the basis for technical process.[13] These factors add a layer of complexity to comparison. To make useful comparisons of benefits, programs would have to be similar in scope, purpose, and have relatively equal levels of digital engineering maturity. DoD weapon system programs are unique and scarce, and any generalizations about implementing digital engineering will carry uncertainty.

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[12] Paraphrasing the definition leveraged in Chapter 5 for use in this analysis, absorptive capacity measures the ability to evaluate and use outside knowledge and is largely a function of the level of prior related knowledge. At the most elemental level, this prior knowledge includes basic skills or even a shared language but might also include knowledge of the most recent scientific or technological developments in a given field. Thus, prior related knowledge confers an ability to recognize the value of new information, assimilate it, and apply it to weapon system goals.

[13] Thomas A. McDermott, Nicole Hutchison, Megan Clifford, Eileen Van Aken, Alejandro Salado, and Kaitlin Henderson, *Benchmarking the Benefits and Current Maturity of Model-Based Systems Engineering Across the Enterprise*, Systems Engineering Research Center, SERC-2020-SR-001, March 19, 2020.

Claimed Digital Engineering Benefits Are Rarely Empirically Supported

Of the literature we reviewed, only six papers documented empirical support for claims about the benefits of digital engineering. Most benefits are difficult to substantiate, perhaps speculative, and identified through the subjective perceptions of authors or survey respondents. This is not to say these claims are incorrect, only that they have rarely been justified by objective evidence. This section first discusses claimed benefits of digital engineering before proceeding to illustrate supporting evidence.

Drawing from a literature review of 847 papers concerning MBSE, Henderson and Salado (2020) identified 360 papers that cited MBSE benefits (whether empirically supported or not).[14] Concurrently, McDermott et al. (2020) classified the cited MBSE benefits into four overarching categories covering 48 specific benefits (reproduced in Table 2.2).[15]

Although McDermott et al. (2020)'s classification of reported benefits is comprehensive, the literature documenting empirical evidence of benefits is limited and accounts for only a subset of benefits identified by their work.[16] The literature data presented in McDermott et al. tend to project many digital engineering benefits to later stages in the life cycle, particularly the operations and sustainment phases. We revisit this in Chapter 4 by considering the metrics associated with the goals of weapon system sustainment.

Despite indications of flaws in their approach, Rogers and Mitchell (2021) reported that using MBSE reduced systems engineering labor hours per requirement by 18 percent and reduced the total number of defects discovered through testing by 9 percent while shifting 18 percent of defect discovery to before testing.[17] A decade earlier, Saunders (2011) presented that introducing MBSE to the Australian Air Warfare Destroyer Combat System program reduced specification defects by 68 percent.[18]

Carroll and Malins (2016) identified 21 case studies with quantifiable metrics on cost and schedule, concluding that the primary benefit of MBSE is reducing rework by preventing

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[14] Henderson et al. (2023, p. 4) stress that "The majority of the papers (240) were found to contain benefits that were only perceived or expected to occur by the authors. Only two of the papers had a defined measurement methodology, however, both of those had various methodological problems that might affect the validity of their findings."

[15] Thomas A. McDermott, Nicole Hutchison, Megan Clifford, Eileen Van Aken, Alejandro Salado, and Kaitlin Henderson, *Benchmarking the Benefits and Current Maturity of Model-Based Systems Engineering Across the Enterprise*, Systems Engineering Research Center, SERC-2020-SR-001, March 19, 2020.

[16] McDermott et al., 2020.

[17] Edward B. Rogers III and Steven W. Mitchell, "MBSE Delivers Significant Return on Investment in Evolutionary Development of Complex SoS," *Systems Engineering*, Vol. 24, No. 6, 2021, pp. 397 and 401.

This manuscript by Rogers and Mitchell is addressed in Chapter 5 as an example of deriving incorrect conclusions through lack of rigor and referencing prior work that does not relate to the subject at hand—in this case, the authors are building on an analysis of software defects from the 1970s.

[18] Steve Saunders, "Does a Model Based Systems Engineering Approach Provide Real Program Savings? Lessons Learnt," slides presented at the Informal Symposium on Model-Based Systems Engineering, Defence Science and Technology Organisation, Edinburg, South Australia, October 25, 2011, slide 13.

TABLE 2.2

Benefits of MBSE Identified by McDermott et al. (2020)

Category	Benefits
Quality	• Improved system quality • Increased rigor • Increased traceability • Reduced errors* • Reduced cost • Reduced risk • Improved risk analysis • Improved system design • Increased effectiveness • Improved deliverable quality • Better requirements generation • Increased accuracy of estimates • Improved predictive ability • Better analysis capability • Improved capability • More stakeholder involvement • Strengthened testing*
Velocity and agility	• Reduced time • Improved consistency • Increased capacity for reuse* • Easy-to-make changes • Reduced rework* • Reduced waste • Increased productivity* • Increased efficiency • Increased transparency • Increased confidence • Increased flexibility • Better requirements management • Ease of design customization • Higher level of support for integration • Increased uniformity • Increased precision • Early verification and validation • Reduced ambiguity
User experience	• Higher level support for automation • Reduced burden of systems engineering tasks* • Better manage complexity • Improved system understanding • Reduced effort* • Better data management/capture • Better decisionmaking
Knowledge transfer	• Better accessibility of information • Better knowledge management/capture • Improved architecture* • Multiple viewpoints of model • Better communication and information sharing • Improved collaboration

SOURCE: Adapted from McDermott et al., 2020.

NOTE: An asterisk indicates the benefit has been documented in the literature on MBSE.

defects early in the system life cycle.[19] However, none of the case studies directly compared MBSE with document-based systems engineering, and several of the case studies did not distinguish systems engineering from MBSE.[20] Furthermore, cost and schedule benefits associated with reduced rework were not directly measured but were inferred from the Defense Acquisition University's analysis of cumulative cost to correct defects over the life cycle.[21] Perhaps through similar inference, the National Defense Industrial Association explains that

> The cost to correct requirements errors increases exponentially with development phase. A requirement error introduced during the requirements development phase that is detected and corrected during system test is 25 to 90 times more costly to correct than if it was corrected during the phase in which was introduced.[22]

A commissioned report relating to an MBSE system architecture demonstration estimated a 20 percent reduction in labor effort as a result of reusable components and emphasis on architecture, while another performer estimated a 6 percent reduction in effort.

Through a study comparing document-based systems engineering with MBSE for robotic space system architecture modeling, simulation, and evaluation, Younse et al. (2022) reported that MBSE automated 49 percent of total knowledge processing (compared with 0 percent with document-based systems engineering), reducing the engineering team's cognitive burden.[23]

Although bold and not otherwise substantiated, West and Blackburn (2018) recounted that at an American Institute of Aeronautics and Astronautics conference

> One weapon developer indicated the "disruptive" effects of [digital twin] technologies include a 500 percent increase in product durability, a 30 percent reduction in cost, a 25 percent decrease in product weight, and a 21 percent reduction in parts count, all the while utilizing a more streamlined manufacturing process that involves 90 percent reduction in tooling and a 95 percent decrease in inventory.[24]

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[19] Edward Ralph Carroll and Robert Joseph Malins, *Systematic Literature Review: How Is Model-Based Systems Engineering Justified?* Sandia National Laboratory, March 1, 2016.

[20] Carroll and Malins (2016, p. 17) explain that they presume "that an MBSE approach is a refinement of an SE [systems engineering] approach and the justifications for an SE approach are inherited by an MBSE approach."

[21] Carroll and Malins, 2016, p. 22.

[22] National Defense Industrial Association, *Final Report of the Model Based Engineering (MBE) Subcommittee*, February 10, 2011, p. 20.

[23] Paulo Younse, Jessica Cameron, and Thomas H. Bradley, "Comparative Analysis of Model-Based and Traditional Systems Engineering Approaches for Simulating a Robotic Space System Architecture through Automatic Knowledge Processing," *Systems Engineering*, Vol. 25, No. 4, July 2022.

[24] Timothy D. West and Mark Blackburn, "Demonstrated Benefits of a Nascent Digital Twin," *Insight*, Vol. 21, No. 1, March 2018, p. 44.

Digital Maturity

If a stakeholder in the DoD digital engineering environment adheres to the policy that digital engineering in some capacity will benefit a weapon system program, a measurement of the respective program's ability to execute digital engineering activities could be a useful metric. This concept is known as *digital maturity* in the digital engineering literature.

Several assumptions, not least that capability equals ability and that the defined digital engineering capabilities will translate to program benefits if properly engaged, precede the validity of this approach. There might be some capabilities that have little or limited bearing on a program—hydrodynamics simulations have little bearing on simulating a tank cannon reloader, for example. So, generalizing digital maturity across multiple programs might not accurately or repeatably reflect the impact of digital engineering or any benefits therefrom.

There is also a cost and effect judgment that should be included but is not included in the maturity model approach (e.g., at what cost is a specific level of maturity beneficial to a program versus another level of maturity). Having a high level of capability might benefit a weapon system program—but would the same or similar benefit come from the next lower grade of maturity?

Maturity model measurement has historically been exclusively a software approach to organization management, derived from the protocols developed at Carnegie Mellon for the Capability Maturity Model Integration (CMMI).[25]

As an addition to discussion in this chapter, Appendix B contains an analysis of the Department of the Air Force (DAF) *Digital Maturity Guide*.[26] Although the risks of taking a maturity model approach to digital engineering are discussed in the appendix, the published maturity approach excludes any aligned measurement of costs associated with the respective maturity levels. History of the maturity approach has shown that without a clear delineation of the associated costs, weapon system programs generally opt for the highest level of maturity. Aligning detailed costs with risks and benefits in a maturity model approach might provide systems engineers with the necessary decision support, but the literature lacks this perspective.

Digital Engineering Costs

The literature tends to group investments specifically necessary for digital engineering into the following four general categories:[27]

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[25] Information Systems Audit and Control Association: Capability Maturity Model Integration Performance Solutions, homepage, undated.

[26] U.S. Air Force, Department of Digital Transformation Office, *DAF Digital Maturity Guide*, version 2, undated.

[27] Thomas Light, Obaid Younossi, Brittany Clayton, Peter Whitehead, Jonathan P. Wong, Spencer Pfeifer, and Bonnie L. Triezenberg, *A Preliminary Assessment of Digital Engineering Implications on Weapon System*

- information technology (IT) infrastructure
- data and architectures
- models and tools
- workforce

Necessary IT infrastructure includes computing hardware, storage, bandwidth, connectivity, and cloud-based services. Light et al. (2022) emphasized that, whether digital engineering leverages cloud services or government data centers, costs to store, maintain, and exploit data will continue to mount well beyond initial investment.[28] For example, the benefit of reusing data in future programs is predicated on maintaining those data even past current program retirement. Furthermore, software used to exploit these data could become obsolete well before the data's usefulness expires, necessitating added future software investments. Although perhaps tongue-in-cheek, West and Pyster (2015) and West and Blackburn (2017) discussed cost estimates of implementing digital twins and digital threads. Citing the Air Force Research Laboratory, West and Pyster (2015) found that a fully developed digital twin would require approximately 1 exaflop performance computer processing power.[29] For context, the world's fastest rated supercomputer, Oak Ridge National Laboratory's Frontier, currently clocks in at 1.1 exaflops.[30] Prior RAND work estimating data storage requirements reached similar conclusions.[31] Arguably, these estimated cost figures are a function of the inconsistent and vague definitions involved in the policy, marketing, and practice of digital engineering, though they also address the impracticality of the policy vision maintained by some leaders in the community.[32]

Digital engineering standards, data, and architecture include an acquisition reference model and government reference architecture, establishing model access and traceability criteria, configuration management, and negotiating data rights and intellectual property. The closest quantitative finding that we identified in the literature is from a DoD science

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Costs, RR-A586-1, 2022. These cost groups derive also from the five lines of effort discussed during the 2020 Air Force Digital Engineering Industry Day presentations sponsored by Air Force Materiel Command and the Air Force Research Laboratory. The category excluded is the cost of developing policy, and cost of standards is excluded from the second bin.

[28] Light et al. (2022) roughly estimated that, for maintenance model purposes alone, a single aircraft's sensors would generate tens to hundreds of terabytes of data per sortie.

[29] Timothy D. West and Art Pyster, "Untangling the Digital Thread: The Challenge and Promise of Model-Based Engineering in Defense Acquisition," *Insight*, Vol. 18, No. 2, August 2015; Timothy D. West and Mark Blackburn, "Is Digital Thread/Digital Twin Affordable? A Systemic Assessment of the Cost of DoD's Latest Manhattan Project," *Procedia Computer Science*, Vol. 114, 2017.

[30] Oak Ridge National Laboratory, "Frontier Supercomputer Debuts as World's Fastest, Breaking Exascale Barrier," press release, May 30, 2022.

[31] Light et al., 2022.

[32] We trace these policy visions partially and informally to our perception of the need for improved absorptive capacity in DoD.

and technology effort reflecting a $50.4 million cost share ($26.1 million by government and $24.3 million by industry) to execute an MBSE system architecture demonstration.[33]

The category of models and tools includes software (e.g., product life cycle management, computer-aided design, analysis, simulation, MBSE packages) and software license fees. It also includes the cost of delivering models that would be digital engineering–specific as opposed to standard engineering decision models. However, ambiguity exists in this and the previous category in the literature because the terms *model* and *architecture* are respectively poorly defined in digital engineering and MBSE practice. A SysML model, for example, is classified as a software design architecture. Describing a transition to MBSE, Cole et al. (2019) discussed how developing models and migrating data are labor-intensive and prone to error, requiring substantial data validation efforts.[34] Exemplifying a source of error, they noted that migration depended on a manually updated spreadsheet with over 100 columns capturing many-to-many relationships. Furthermore, they found that "a single modeler must track the efforts of approximately 10 other engineers," and that the engineers often complained when asked for clarification or information.[35]

Workforce investments include planning, training and education, staffing, and labor (e.g., to develop and tailor digital models and tools to weapon system). Graham et al. (2022) conducted a comprehensive study of 24 different but complementary proposals to develop DoD's digital engineering workforce.[36] The most ambitious proposal, establishing and running a Digital Service Academy, would cost approximately $800 million up-front and $250,000 per student year thereafter. All other proposals combined amount to an estimated $500 million per year in ongoing costs.

Graham et al. also estimated that increasing DoD's digital engineering workforce (military and civilian) by 5 percent would cost approximately $500 million annually. In their estimated investment needed to develop and operate high-fidelity digital twins and digital threads, West and Blackburn (2017) concluded that DoD could need about 40,000 new graduates in related disciplines (about 25 percent of current annual U.S. university throughput).[37] Implementing digital engineering will also necessitate training current personnel. Despite other shortcomings

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[33] William Jacobs, Alex Boydston, Pierre Ba, Kevin Rhamy, James Davis, Marcell Padilla, Hannah Roberson, Scott Dennis, Tim Kinch, and Beverly Yost, *Joint Multi-Role Mission System Architecture Demonstration—Capstone Demonstration, Government Final Report*, DEVCOM Aviation and Missile Center Technology Development Directorate and DEVCOM Aviation and Missile Center Software, Simulation, Systems Engineering and Integration Directorate, May 2021, Not available to the general public.

[34] Bjorn Cole, Vikram Mittal, Stephen Gillespie, Nguyen La, Richard Wise, and Alex MacCalman, "Model-Based Systems Engineering: Application and Lessons from a Technology Maturation Project," *Procedia Computer Science*, Vol. 153, 2019.

[35] Cole et al., 2019, p. 208.

[36] David R. Graham, Gregory A. Davis, Cheryl D. Green, Peter K. Levine, Maggie X. Li, and David M. Tate, *An Assessment of Options for Strengthening DOD's Digital Engineering Workforce*, Institute for Defense Analyses, IDA Paper P-21560, February 2022.

[37] West and Blackburn, 2017.

in their approach,[38] Rogers and Mitchell (2021) reported that it took about 600 hours to train engineers on MBSE tools and processes for the Submarine Warfare Federated Tactical Systems (SWFTS) program.[39] Additionally, Rogers and Mitchell shared that

> We do not factor out the training in this analysis because it is a recurring expense as small numbers of engineers routinely rotate on and off large programs like SWFTS. Labor to design, implement and populate the DOORS® [Dynamic Object-Oriented Requirements System] database and the MBSE model and process do not factor into this case study.[40]

This finding runs contrary to our findings, as appropriate skills represented a key factor when discussing digital engineering with respective weapon system offices. Virtually all addressed the digital engineering requirement from their leadership by rapidly engaging additional SETA staff versed in SysML.

Estimates of total cost can reach staggering proportions. Employing the Constructive Cost Model II cost estimation model, West and Blackburn (2017) found that a high-fidelity digital twin and digital thread collection for DoD efforts would cost between $1 trillion and $2 trillion for a digital twin and between $80 billion and $180 billion for digital thread.[41] They explained that even at this level of investment, it would take a team of developers one-third the size of Microsoft's about 250 years to complete.

Conclusions and Definitions

Although the research literature paints a picture of extensive effort dedicated to the analysis of digital engineering, the picture is far from complete. There are many reasons why the literature on digital engineering remains relatively immature:

- Absent a consensus about what constitutes digital engineering, scholars and practitioners lack a common foundation on which to conduct analysis of costs and benefits.
- The literature reflects, at many levels, the disconnects between DoD policy, DoD engineering practice, commercial engineering practice, software development practice, systems engineering, and, at times, science and science fiction. This reiterates a need for concise and agreed on definitions in this field; the careful, consistent use of terminology; and the definitive establishment of measurable goals and objectives for the practice of digital engineering. Published efforts to establish ontologies and taxonomies of this field have, to date, fallen short.

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[38] See Chapter 5 for an analysis of the rigor of Rogers and Mitchell (2021).

[39] Rogers and Mitchell, 2021.

[40] Rogers and Mitchell, 2021.

[41] West and Blackburn, 2017.

- Tracking digital engineering investments and distinguishing them from other costs (e.g., systems engineering, multipurpose IT investments) does not appear to be a standard practice, along with stating the alternative to digital engineering.
- There is a tendency in digital engineering and MBSE literature to conflate computer science and systems engineering. In computer science, architectural models as represented in unified modeling language (UML) and SysML interchange and function as deterministic black boxes that could be readily combined.[42] Systems engineering includes the understanding that the respective architectures, models, and simulations include different engineering goals behind their design, different assumptions that were made to accommodate modeling limitations, and different sources of program risk.[43]
- A common premise in the literature is that digital engineering benefits will materialize well after the life cycle decision point of whether to use it. This supports a need for empirical data on digital engineering contributions to program goals and corresponding decision support frameworks.
- Some publications blur the lines between digital engineering costs and enterprise investments that support digital engineering. Rogers and Mitchell (2021), for example, excluded training costs in digital engineering as those would be, according to their narrative, incurred by the enterprise anyway.
- The proprietary nature of industry cost structures inhibits disclosure of digital engineering costs.
- It is plausible that, given digital engineering's novelty to the respective published authors, much effort has been devoted to making the case for digital engineering by projecting its possible benefits without at the same time evaluating its costs.
- Some authors—and some services—are looking to a digital engineering maturity model as a path to improving outcomes without any cost, causal, or risk analysis to support that conclusion.

As stated at the outset of this chapter, the term *digital engineering* evokes a litany of definitions, interpretations, and ambiguity across the literature and the DoD community. To measure the process and respective benefits in terms of progress along the path to success, we recommend a common goal across the DoD community that is facilitated by a succinct, achievable, measurable common definition. To pursue our project objectives, we posit a baseline definition of digital engineering on which to motivate and align the frameworks that follow in subsequent chapters.

We found that the definitions in DoD's Digital Engineering Strategy are not sufficiently concise or measurable to satisfy our needs for this analysis. The strategy defines digital engi-

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[42] Because of their common association, we will use the shorthand of SysML for either SysML or UML.

[43] Decades ago, computer science used the metric of *defects* to measure software quality. That metric has long been superseded by the metric of *waste*, yet MBSE and digital engineering practitioners continue to use defects, reflecting a basis of MBSE in 1970s waterfall software development.

neering as "an integrated digital approach that uses authoritative sources of system data and models as a continuum across disciplines to support life cycle activities from concept through disposal," and an approach to "modernize how the Department designs, develops, delivers, operates, and sustains systems."[44] It can be further parsed into the following five benefit areas as described in the strategy:

1. Formalize the development, integration, and use of models to inform enterprise and program decisionmaking.
    a. Formalize the planning for models to support engineering activities and decisionmaking across the life cycle.
    b. Formally develop, integrate, and curate models.
    c. Use models to support engineering activities and decisionmaking across the life cycle.
2. Provide an enduring ASoT.
    a. Define the ASoT.
    b. Govern the ASoT.
    c. Use the ASoT across the life cycle.
3. Incorporate technological innovation to improve the engineering practice.
    a. Establish an end-to-end digital engineering enterprise.
    b. Use technological innovations to improve the digital engineering practice.
4. Establish a supporting infrastructure and environments to perform activities, collaborate, and communicate across stakeholders.
    a. Develop, mature, and use digital engineering IT infrastructures.
    b. Develop, mature, and use digital engineering methodologies.
    c. Secure IT infrastructure and protect intellectual property.
5. Transform the culture and workforce to adopt and support digital engineering across the life cycle.
    a. Improve the digital engineering knowledge base.
    b. Lead and support digital engineering transformation efforts.
    c. Build and prepare the workforce.[45]

These goals for digital engineering in this Office of the Secretary of Defense definition tend to be general versus concise and nebulous versus readily measurable and achievable. As mentioned earlier in this chapter, these goals do not delineate from the counterfactual; that is, how is digital engineering different from not executing digital engineering? What would not incorporating technological innovation to improve engineering practice look like?

Furthermore, the concept of *authoritative sources of systems data* is difficult to align with a weapon system program. This part of the strategy leaves ambiguous the respective authorities and how those authorities would integrate those data in a digital approach. The concept

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[44] U.S. Department of Defense, 2018, p. 3.

[45] U.S. Department of Defense, 2018, pp. 5–23.

of *models as a continuum across disciplines to support life cycle activities* represents an aspirational perspective that does not align with current or foreseeable engineering practice, in which models and simulations have very specific goals for defined engineering decisions—thus providing benefits readily traceable to the program goals and the expense of the models themselves.

For our analysis, we require a more concise and achievable definition of digital engineering goals.

We consider—from our informal, nonattributional observations and in the most general possible terms—that the respective military services are taking distinct approaches to digital engineering in their respective acquisitions and organizational structures. One service is very enthusiastically approaching digital engineering, though maintaining a mostly software-centric mental model of systems that we see in much of the literature from the International Council on Systems Engineering (INCOSE) and others. Another service is taking a more systems engineering perspective to digital engineering, building on extensive, in-house engineering experience. Another service is taking a slightly more cautious, conservative tack to digital engineering. The respective services differ in their approaches to enterprise investments that might support digital engineering in the long term and where costs for digital engineering are borne by the respective weapon system program. These respective mental model differences naturally would factor into how the respective services might approach any sort of cost-benefit concept for decision support. We strive to accommodate them all in Chapters 3 and 4.

The U.S. Navy has published a concise definition of digital engineering. The framing of the Navy definition in systems engineering terms and using the specifications of the Office of the Secretary of Defense definition makes it readily leverageable for our analysis needs of concise and achievable, aligns with the DoD Digital Engineering Strategy, and adopts (by inference) the measurable weapon system program goals underlying respective life cycle activities. With the addition of weapon system program goals for clarity, and removing the ambiguous reference to authoritative sources of system data, it becomes our working definition of digital engineering (shown in Box 2.1).

To constrain the definition to what MBSE actually looks like in practice and operations using our research, we offer that the following brief and concise description (Box 2.2) in the

BOX 2.1

Digital Engineering—Working Definition for This Analysis

An integrated, computation-based approach that uses system data and models across disciplines to support weapon system program goals and the corresponding life cycle activities from concept through disposal.

SOURCE: Developed using Naval-LIFT, “Naval Digital Engineering Body of Knowledge - Naval DEBoK - Naval-LIFT Wiki,” 2023, Not available to the general public; author analysis.

form of a definition might help to clarify DoD practice and improve weapon system program outcomes—a leverage point. This limited-scope definition aligns well with what we have determined current DoD practice of MBSE to be *sub lucem*, as well as a limited survey of commercial practice.[46] MBSE practice is dominated by the software development architecture aspects of the subject systems, to perhaps include data interface architectures.

This definition reflects our observation that some activities reflect government and contractor policy in a top-down direction versus bottom-up engineering need in their activities under the heading of MBSE.

Where the causality and benefits related to weapon system program goals might be difficult to ascertain, some key stakeholders have called this practice *pretending* to do MBSE.[47]

This definition is limited to the what of MBSE and omits the why. These definitions are presented as a part of the scope of this analysis and their importance to the subsequent chapters. Other definitions related to digital engineering, as mentioned earlier in this chapter (e.g., *authoritative source of truth* and *digital twin*) would benefit from clarification.

BOX 2.2

MBSE

The use of standardized tools, predominantly SysML or UML, to map architectures, system interfaces, requirements, and descriptive models.

SOURCE: Discussions with stakeholders have reflected the availability of, use of, and at least cursory knowledge of other tools, not least of which include Simulink, Unified Architecture Framework®, Architecture Analysis and Design Language, Integrated Definition Methods, Comprehensive Systems Design Language and Life cycle Modeling Language, UNICOM System Architect, and SysML v. 2. Our informal and limited survey of active weapon system programs only observed the use of a packaged versions of SysML or UML open-source code (e.g., NoMagic MagicDraw, IBM Rational Rhapsody) as being actively used in DoD programs for MBSE. When queried, this was described by stakeholders as the designated (by their enterprise) tool. Some stakeholders surveyed for another RAND effort mentioned issues with SysML interoperability, teachability, and transferability.

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[46] Our very limited survey of commercial industry for this project found one verified example where SysML had been used to improve performance, a case where retroactive application of the tool in deployed automobile software found design and coding errors, or defects. When those errors were corrected, it reduced warranty costs for the car manufacturer. That measurable return on investment led to support for SysML and MBSE in the organization.

[47] The nonattributional nature of our analysis precludes direct quotation.

CHAPTER 3

Cost-Benefit Analysis Framework

Having established the ground state of DoD digital engineering practice and a working definition of digital engineering, both using our observations and analysis in the preceding chapter, the next step is to codify the established DoD cost-benefit approaches and develop a framework for leveraging them in supporting weapon system program decisions on digital engineering.

To date, there has been virtually no formal analysis linking DoD digital engineering efforts to quantifiable impacts on program cost, schedule, and performance outcomes. This is, in part, because there are very few examples of mature DoD digital engineering efforts since the 2018 implementation of the policy. Many of the investments to support digital engineering are being made by programs now, and the benefits of those investments are not likely to be fully realized for many years.[1]

In this chapter, we present a framework for evaluating the costs and benefits of digital engineering activities being pursued by DoD programs. The framework is intended to highlight and organize evidence that might be used to inform decisionmakers on the relative magnitude and types of costs and benefits that are associated with digital engineering efforts. It also strives to identify logical connections between digital engineering activities and their influence on program outcomes.

We begin by reviewing guidance on how to conduct CBA, particularly within a DoD context. We then describe a step-by-step framework for conducting a CBA that is tailored to digital engineering activities being pursued by weapon system programs.

Standard Cost-Benefit Analysis Practices

The literature on CBA is extensive. At its core, CBA provides an approach for evaluating the merits of different decisions, particularly those related to resource allocation. It seeks to systematically identify and compare the costs and benefits that will occur over time under

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[1] Some authors use the term *return on investment* or *ROI* in discussing benefits of DoD digital engineering paradigms. Our perspective is that ROI is a finance concept that involves other such finance concepts as net present value, with minimal bearing on defense, and therefore is inappropriate. CBA is the preferred concept, but we nonetheless examined the work of those using such terminology as ROI for empirical evidence.

alternative paths that might be pursued. The costs and benefits might be monetary and nonmonetary in nature. Although CBA is an inherently quantitative approach, when data on certain costs and benefits are either highly uncertain or unavailable, it can still provide a useful framework for drawing out logical connections between actions and their potential impacts.

Applications of CBA can be found in many public policy domains. In the context of defense, Melese, Richter, and Soloman (2018) note that "CBA can be applied: i) to guide defense policy (i.e. [sic] the allocation of resources between major missions or military goals) and ii) to guide defense investments (i.e. [sic] choices between alternative projects or programs to achieve a given mission/goal)." They also note, however, that a "significant challenge in applying CBA to defense decisions is the complex and often controversial task of measuring benefits."[2] This challenge is certainly the case with digital engineering, because the impacts of digital engineering activities being pursued by defense programs are likely to be varied and potentially influence cost, schedule, and weapon system performance or effectiveness in numerous uncertain ways.[3]

Guidance on how to conduct a CBA and related assessments have been developed by several DoD organizations and stakeholders. Examples include the following:

- Department of Defense Instruction (DoDI) 7041.03, *Economic Analysis for Decision-Making*, Director, Cost Assessment and Program Evaluation, September 9, 2015, change 1, October 2, 2017
- Air Force Instruction 65-501, *Economic Analysis*, Department of the Air Force, October 29, 2018
- Office of the Deputy Assistant Secretary of the Army (Cost and Economics), *U.S. Army Cost Benefit Analysis Guide*, February 23, 2018
- Department of the Navy, *Economic Analysis Guide*, 2013
- David W. Perkins and Maeve P. Carey, *Cost-Benefit Analysis and Financial Regulator Rulemaking*, Congressional Research Service, R44813, May 11, 2017
- U.S. Department of Defense, *Defense Acquisition Guidebook*, September 16, 2013.

We draw heavily from this guidance in the development of our approach.

The U.S. Army's *Cost Benefit Analysis Guide* is a particularly useful reference. It lays out eight primary steps involved in the CBA process, as shown in Figure 3.1. The objective and steps pursued in a CBA approach largely parallel those that would be taken in a systems engineering trade study.[4] As noted in the figure, CBA seeks to understand both the quantifiable

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[2] Francois Melese, Anke Richter, Binyam Solomon, *Military Cost-Benefit Analysis: Theory and Practice,* Routledge Studies in Defence and Peace Economics, June 8, 2018, p. 4.

[3] As of the beginning of 2024, few empirical evaluations of digital engineering or such related concepts as MBSE have been conducted. Most benefits of digital engineering that have been discussed in the literature are difficult to verify and measure.

[4] AcqNotes, "Trade Study," webpage, July 29, 2023.

FIGURE 3.1

Eight Steps in U.S. Army's CBA Process

SOURCE: Redrawn from Office of the Deputy Assistant Secretary of the Army (Cost and Economics), 2018, p. 12.

and nonquantifiable costs and benefits over time. Costs and benefits should be viewed from the perspective of the service as an enterprise rather than from an individual program perspective.[5] However, it might be appropriate to consider an even broader perspective if some costs and benefits spill over and affect the other military services and U.S. taxpayers.[6]

The context in which a CBA is being conducted is important and can affect what information is available to conduct a CBA and how the CBA will be used. A CBA can be conducted

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[5] For example, if some investments to pursue digital engineering by a program are being funded outside the weapon system program pursuing digital engineering, those costs should still be accounted for in the CBA.

[6] See, for example, Meleseet, Richter, and Solomon, 2018.

either *ex ante* or *ex post*. An *ex ante* CBA will occur in advance of implementing a policy, program change, or investment and will often seek to inform whether a change is likely to be justified using the anticipated costs and benefits. Alternatively, an *ex post* CBA will seek to estimate the costs and benefits associated with a change to a policy, program, or investment after the change has been made and the impacts have been realized. To conduct an *ex ante* CBA, one would hope to draw on findings from *ex post* assessments conducted for related activities. The CBA guidance developed by the U.S. Army focuses on *ex ante* assessments.[7]

Subject-matter experts we spoke with noted that there are almost no formal *ex post* or *ex ante* assessments of digital engineering or MBSE implemented to date for DoD. Furthermore, even though several DoD acquisition programs have been pursuing digital engineering for many years, it is premature to conduct an *ex post* assessment because many of the benefits are not expected to be experienced until sustainment (many years from now). In practice, we envision value in evaluating via CBA methods ongoing efforts to implement digital engineering. In this case, a decision to pursue (or not pursue) digital engineering might have already been made by a program, but information is learned to inform other programs that might pursue related digital engineering efforts.

In the next section, we describe general guidance on the type of issues and steps that should be considered when conducting a CBA for ongoing digital engineering efforts in defense programs. As DoD program efforts mature and the impacts of digital engineering are more fully understood, assessments should be updated to reflect observed outcomes. These observations can inform future efforts to design and direct investments to DoD digital engineering efforts.

Framework for Evaluating the Costs and Benefits of Digital Engineering Activities

The assessment of digital engineering activities should be undertaken in an independent and objective way to avoid biasing the findings toward any perspective or set of activities. As a result, it might be advantageous for the assessment to be undertaken by a third party with experience conducting CBAs, analyses of alternatives, cost-effectiveness analyses, or trade studies. Because of the technical nature of digital engineering applications, we also emphasize the need for input from program managers and system engineers familiar with the weapon system under study. As noted by the U.S. Army (2018, p. 13), CBA analysis "[m]ust be tailored to fit the problem, because finding the optimal solution is the focus of the CBA." Digital engineering approaches are evolving and are in no way standardized at this point; as a result, deviations for the approach presented in this chapter to address the unique aspects of digital engineering applied to defense programs should be considered and explored. The approach described here draws heavily from the U.S. Army's CBA approach presented in Figure 3.1. The primary steps are summarized in Table 3.1.

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[7] Office of the Deputy Assistant Secretary of the Army (Cost and Economics), 2018.

TABLE 3.1

Prototype Approach for Assessing the Costs and Benefits of Program Digital Engineering Efforts

Step	Description
1	Understand the weapon system goals over its life cycle and determine what type of analysis is needed.
2	Identify and select specific digital engineering activities for analysis (e.g., development and use of digital models for acquisition activities) and what would be done if digital engineering were not pursued.
3	For each digital engineering activity, characterize what up-front investments are required (investments in workforce, data rights, IT infrastructure, models/tools, etc.).
4	For each digital engineering activity (or for a set of digital engineering activities), characterize how they are expected to affect program cost, schedule, and performance or mission effectiveness over the weapon system's life cycle and any associated risk.
5	Compare alternatives and document results.

Step 1: Weapon System Goals

To understand and assess the costs and benefits of leveraging digital engineering approaches in a program, the team conducting the assessment should start with an understanding of the program and the digital engineering approaches that are being pursued or proposed.[8] The team should also clarify how the CBA will be used. Is it intended to inform a program digital engineering decision or is it being conducted to collect information on DoD digital engineering efforts to inform other programs that might pursue similar activities in the future? Given the lack of formal assessments of digital engineering activities and their impacts, any team conducting a CBA of DoD digital engineering activities should anticipate that other programs will potentially use its findings in some way in the future. As a result, we emphasize the need to document the data, methodology, and findings (Step 5) in a way that is accessible to appropriate personnel affiliated with the program and the broader DoD community.

In this first step, the team should also consider whether a CBA is appropriate and at what point in time it might best be implemented. For example, if a program is encouraged (or obligated) to implement digital engineering activities but the program is not well enough defined to specify specific digital engineering activities that might be reasonably implemented, other such exploratory activities as reviewing digital engineering activities being pursued by other

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[8] We assume that a CBA assessment of digital engineering activities is most likely to be conducted for programs that have stated they are pursuing digital engineering. In principle, however, a program that opts for a more traditional engineering approach that falls outside the digital engineering concept could be evaluated. In this instance, observations of program costs and benefits would be evaluated against the counterfactual of whether the program took steps to pursue digital engineering concepts (e.g., used models more extensively for requirements developments, to develop sophisticated models to support test and evaluation activities, or to develop computing or IT environments to support the flow and sharing of information across relevant development, production, operational, and sustainment communities).

programs might be more beneficial. Similarly, if such weapon system performance measures as *measures of effectiveness* (which measure how well an alternative can meet mission requirements) and *measures of suitability* (which specify how well an alternative can be supported in the operational environment) have not been defined, it might be premature to conduct a CBA. Finally, if a program is directed through policy or other channels to implement digital engineering, the CBA might best be timed to coincide with digital engineering planning efforts to inform what specific digital engineering activities should be pursued. The timing of the CBA should reflect the decisions it seeks to inform and be coordinated with internal program planning efforts.

Assuming that a CBA is appropriate, the team should collect and understand information on the program implementing digital engineering, such as its planned cost and schedule by life cycle phase, key performance parameters, and other programmatic details documented in the initial capabilities document (ICD), capability development document (CDD), and capability production document. Given the focus on digital engineering, the team conducting the digital engineering CBA should also understand the program's system engineering plan (if one has been developed). Discussion with a program's program manager and chief systems engineer should occur to understand the program digital engineering plans and options.

Step 2: Digital Engineering Activities

DoDI 7041.03 makes several points that are worth emphasizing. For example, a "sound economic analysis recognizes that there are alternative ways to meet a given objective and that each alternative requires certain resources and produces certain results."[9] To assess the costs and benefits of digital engineering, it is critical to be explicit about what activities are being pursued under the umbrella of digital engineering. This step seeks to accomplish this by forcing the analysts to define in clear terms what digital engineering activities are being conducted by a program (and will be assessed), how they will be implemented, by whom (e.g., by the government program office, the prime contractor, or suppliers), and their timing.

Just as important for an analysis of digital engineering's costs and benefits is defining what would be done if those digital engineering activities were not conducted. For framing purposes, it will often be useful to establish a non–digital engineering status quo or baseline alternative that digital engineering activities can be compared against. This might reflect the use of more traditional engineering approaches that fall outside the digital engineering paradigm. To the extent there are no alternatives to a digital engineering activity, those activities should be excluded from the CBA.

We have found that programs pursuing digital engineering activities are often doing so in meaningfully different ways and with different objectives in mind. It is important to emphasize many digital engineering activities are not standardized. One program's set of

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[9] DoDI 7041.03, 2017, p. 6.

digital engineering activities might look significantly different than the activities in another program.

To help define a reasonable set of counterfactual activities to evaluate against, an analyst might want to consult such measures of digital maturity as the DAF's *Digital Maturity Guide*, which puts digital engineering activities in context with other approaches for accomplishing related weapon system activities.[10] For example, if a model is going to be developed and used to support test and evaluation activities, it would likely be advantageous to specify how test and evaluation activities would likely be conducted in the absence of that model. It might, for example, require a greater number of physical prototypes to be developed and additional physical testing.

To illustrate what specific activities might be included in a CBA of digital engineering for a real program, we reviewed documentation and spoke with subject-matter experts familiar with the U.S. Air Force's Sentinel Program.[11] Each of the activities listed in Table 3.2 is likely to require targeted additional resources to accomplish over more traditional activities conducted during the technology maturation and risk reduction and engineering and manufacturing development phases.

Although all the references agree that the key to CBA is to consider multiple, distinct alternatives and to compare them using their relative costs and benefits, the DoD paradigm of digital engineering poses specific barriers to making such comparisons.

TABLE 3.2

Examples of Digital Engineering Activities Pursued as Part of the Air Force's Sentinel Program

Life Cycle Phase	Examples of Digital Engineering Activities
Technology maturation and risk reduction	• Connect engineering and cost models for cost versus capability analysis. • Use modeling more intensely to define and refine requirements and acquisition strategy (thousands of iterations). • Establish Sentinel's SysML-based architecture model (e.g., government reference architecture model). • Develop advanced visualization techniques.
Engineering and manufacturing development	• Define data and model requirements that prime contractor or suppliers must share with government (through government reference architecture). • Digitally connect previously siloed sources of information. • Transfer ownership of the technical baseline to the government. • Use models more intensely for test and evaluation activities. • Develop data and model validation and verification steps.

SOURCE: Draws on Jason Bartolomei, "Digital Engineering Exemplars: Ground Based Strategic Deterrent," Air Force Digital Campaign Industry Exchange Day presentation, video, September 21, 2020; and discussions with subject-matter experts.

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[10] Digital Technology Office, "Welcome to the Department of the Air Force Digital Guide," webpage, Department of the Air Force, undated. See also, for example, Steven Turek, "Assessing Digital Maturity," briefing presented to authors, undated.

[11] Prior to April 2022, Sentinel was known as the Ground-Based Strategic Deterrent, ergo the use of that term for the same program (Table 3.2) in the title of Brig Gen Bartolomei's referenced presentation.

First, we found that programs pursuing digital engineering often have not formally characterized what they would do in the absence of digital engineering activities. For comparison approaches, the analyst conducting the CBA must carefully consider what activities are being assessed as digital engineering and define what alternatives are appropriate to compare those activities against. If no alternatives to a digital engineering activity can be reasonably identified, assessing the costs and benefits of that activity lacks context and comparability. In this instance, there is no decision to be informed by a CBA and no comparison of costs and benefits to be made.

Second, virtually all activities classified by DoD as digital engineering existed before the 2018 publication of the DoD digital engineering strategy. Systems engineers used variable reference databases across subsystems for decades before anyone thought to call it an ASoT. SysML and the Department of Defense Architecture Framework (DoDAF) date from the 1990s. Electronic sharing of engineering designs and simulations was a key to scores of weapon system programs since the 1970s, not least of which the original F-16 program, in which manufacturing was shared by the United States and five North Atlantic Treaty Organization countries: Belgium, Denmark, the Netherlands, Norway, and, later, Turkey.[12] Simulations, computer-aided design, and models to compare design alternatives have all been around for a very long time, making the label of digital engineering or non–digital engineering one of perspective. As a result, it might be useful to characterize digital engineering as occurring along a continuum, with different levels of digital engineering maturity and implementation rather than as the result of a policy shift.

Step 3: Up-Front Investments

In this step, the analyst must identify and estimate what investments are required to conduct the digital engineering activities and their alternative. In many cases, it will be sufficient to quantify what additional resources are necessary to conduct the digital engineering activities over the identified alternatives. The services and the literature tend to group investments required to support digital engineering activities into the following four areas:

- IT Infrastructure
  - computing hardware
  - bandwidth and connectivity
  - cloud-based services
  - physical infrastructure
- Data
  - acquisition reference model, government reference architecture, ASoT
  - simulation, models, and data
  - configuration management of models and data

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[12] U.S. Air Force, "F-16 Fighting Falcon," webpage, September 2021.

  - data rights, intellectual property
- Tools
  - digital engineering tools
  - workflow tools
  - engineering tools
  - translators, add-ons, graphics emulators
- Workforce
  - systems engineering knowledge
  - labor required to develop and tailor digital models and tools to weapon system
  - workforce training on applicable software
  - workforce development plan.

The identification of investments required to support digital engineering can apply to a portfolio of digital engineering activities or be linked back to specific activities. When thinking about these enabling investments, it is useful to further consider which investments are likely to be one time and which are likely to drive recurring costs for a program.

Security costs factor into all four of these categories of expenditure. IT infrastructure requires digital engineering–specific security activities that can include multi-level security infrastructure. Data will have security aspects that might overlap with and possibly complicate proprietary protections. Tools will have to function in sensitive and secure environments and might be difficult to approve for classified processing because of open-source code considerations. Workforce precludes the other three categories because without cleared personnel well versed in classified, multi-level engineering and acquisition, the program cannot function.

This step in the process is likely to be challenged by a variety of factors. In particular, we note the following:

- Programs do not define what they would do if they did not implement digital engineering, making it challenging to isolate digital engineering costs.
- Discussions with cost analysts and program office staff suggest digital engineering costs do not map neatly to specific work breakdown structure elements, making them difficult to quantify.
- Enterprise efforts to support digital engineering are limited—each program is implementing digital engineering in its own way, with its own resources.
- Program resources available to support digital engineering might be inadequate in some instances.

Analysis in this step should be conducted in consultation with program management, financial management, and cost analysts working on the program.

Step 4: Impact on Program Cost, Schedule, and Performance and Mission Effectiveness and Any Associated Risk

Service policies imply that digital engineering activities are inherently beneficial. For example, Air Force Instruction 63-101/20-101 states "[t]he PM uses Digital Engineering . . . to the maximum extent practicable."[13] Given the implementation guidance, many weapon system programs might not have formally considered the costs and benefits of digital engineering approaches they are pursuing, at least at the level needed to support a formal CBA.[14] This step in the CBA process seeks to logically connect digital engineering activities with their impact on weapon system cost, schedule, and performance.[15]

Estimates of digital engineering costs and benefits should use empirical evidence when possible. If empirical evidence of the magnitude of costs and benefits is limited, that must be acknowledged, and a variety of possible outcomes reflecting an appropriate degree of uncertainty should be explored. When projecting future outcomes, key assumptions should be made explicit. Additionally, "[w]hen quantification is not possible, the analyst should still attempt to document significant (qualitative) costs and benefits. Minimally, qualitative costs or benefits should be discussed in narrative format."[16]

To assess impacts on weapon system performance from digital engineering activities, it might be useful to consider whether those activities will affect any key performance parameters (KPPs) or key system attributes (KSAs).[17] Conceptually, these are derived from user-reviewed scenarios, use cases, and vignettes that describe the majority of the mission-derived goals for a given weapon system. They can include a menu of goals and performance parameters that might be interrelated, but each can be mapped to the needs of the service and DoD. To the extent digital engineering might influence any KPPs or KSAs, there might be mean-

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[13] Air Force Instruction 63-101/20-101, *Integrated Life Cycle Management*, Secretary of the Air Force, June 30, 2020, change 1, November 23, 2021, p. 68.

[14] CBA guidance also notes that "[t]he statement of the objective should clearly define and quantify (to the extent possible) the function to be accomplished. The statement of the objective should not assume a specific means of achieving the desired result." This is particularly relevant for digital engineering; digital engineering should not be a goal in and of itself, but instead a means to a desired program cost, schedule, and performance end state. See DoDI 7041.03, 2017, p. 6.

[15] We emphasize here that the impacts of digital engineering need to be mapped to impacts on weapon system cost, schedule, and performance rather than such lower-level benefits as improved collaboration among team members.

[16] DoDI 7041.03, 2017, p. 6.

[17] Defense Acquisition University, "DAU Glossary: Key Performance Parameter," webpage, undated. These parameters are usually delineated initially in the ICD, the CDD for the development acquisition. The Joint Capabilities Integration and Development System (JCIDS) operational requirements process mandates certain statutory KPPs for all acquisitions: energy, system survivability (kinetic, cyber, and electromagnetic spectrum), force protection, sustainment, and net-ready performance attribute (the last is no longer mandatory).

ingful performance impacts that should be explored and documented. We consider this in more depth in Chapter 4.

Even when a digital engineering and non–digital engineering alternative activity can be reasonably defined, programs can only pursue one path. As a result, the outcomes that would likely occur under the path not taken need to be estimated rather than observed.[18] In this instance, formal modeling might be required using historical data for programs that fall along the spectrum from traditional to digital engineering. Alternatively, case studies of similar programs that pursued different engineering approaches and paths might be warranted. At a minimum, a logical narrative should be developed that links digital engineering activities to any anticipated cost, schedule, and performance impacts.

The following are common examples of digital engineering benefits claimed anecdotally for DoD programs identified during our research:

- Physical prototyping: Digital models may reduce the need for costly physical prototypes.
- Test and evaluation: Digital testing might reduce the iterations of physical testing needed or refine the testing and evaluation plan more precisely, resulting in less spending on testing and evaluation.
- Manufacturing: Digital engineering efforts might allow greater optimization of manufacturing designs during production.
- System complexity: Digital engineering facilitates the engineering of more highly complex systems, leading to greater weapon system performance.
- Government collection of weapon system intellectual property: Digital engineering will facilitate the transfer of intellectual property to the government (e.g., government ownership of the technical baseline), allowing government and contractors to compete to a greater extent for sustainment activities.[19]
- Weapon system maintenance and modifications: The systematic collection of weapon system data might aid in future maintenance and modification efforts.
- Weapon system reliability: Digital engineering approaches can help identify defects earlier in the design process.

During our research, however, we found no direct empirical evidence that would help inform analysts on the magnitude or likelihood of these impacts and their relationship with weapon system costs, schedules, and performance.[20] Regardless of whether the benefits of

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[18] In *ex ante* analysis, both actual and counterfactual outcomes would necessarily be estimations.

[19] The ownership of intellectual property and weapon system data are contractually defined per the Defense Federal Acquisition Regulation Supplement. Because these data and intellectual property come at a cost, the program leadership faces a net life cycle CBA decision balanced through negotiation with the provider.

[20] This is consistent with Henderson and Salado's (2020) report, which reviewed 847 papers dealing with the implementation of MBSE generally and found that nearly all reported benefits were perceived and lacked empirical evidence (Kaitlin Henderson and Alejandro Salado, "Value and Benefits of Model-Based

digital engineering can be quantified in terms of direct impacts on program outcomes, logical and complete narratives describing the process by which digital engineering activities are likely to generate cost, schedule, and performance are useful to develop in support of decisionmaking.

In addition to identifying and quantifying (when possible) impacts of digital engineering on program costs, schedules, and performance, the risks and uncertainty associated with digital engineering activities should also be considered. Risks can take a variety of forms. An assessment of risks could take the form of identifying factors that have the potential to reduce the benefits of digital engineering or potentially lead to negative outcomes. Some examples that have been raised by subject-matter experts and in the literature in the context of DoD digital engineering efforts include issues obtaining training, education, and personnel resources required to support government digital engineering efforts; system integration challenges across unclassified and classified networks; and approval challenges for the use of products and software within a program's digital engineering environment.

Step 5: Compare Alternatives and Document Results

The findings from the CBA should be documented to support current and future decisionmaking. In the case of an *ex ante* assessment, the findings might inform a decision on whether and to what extent to implement digital engineering. In the case of an *ex post* assessment, the findings might be used to inform whether other programs should pursue certain digital engineering approaches in the future. Sensitivities that were identified during steps 1–4 that might affect the magnitude or likelihood of certain impacts should also be documented.

Because a digital engineering CBA is likely to identify a mix of quantifiable and nonquantifiable costs and benefits, we recommend the results be organized as such. We also recommend that the identified impacts be grouped into those that relate to weapon system life cycle costs (by life cycle phase), schedules, and weapon system performance. Although methods for combining or weighting quantifiable impacts across areas exist, we found that presenting the unweighted impacts by category to be useful because different decisionmakers and users of the CBA are likely to value (and weigh) cost, schedule, and performance impacts differently.

CBA Framework Summary

Established DoD and service regulations provide a consistent approach to CBA. Tried and true over generations of cost analysts, CBA is accepted practice in DoD as a decision support tool—affected by the fidelity of the analysis, the complexity of the weapon system, and the associated technical risk. We took this established tool and leveraged it for digital engineer-

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Systems Engineering [MBSE]: Evidence from the Literature," *Systems Engineering*, Vol. 24, No. 1, December 31, 2020).

ing specifically, resulting in the Cost-Benefit Analysis for Digital Engineering framework, the first of two approaches that can be leveraged by a program for assessing digital engineering.

CHAPTER 4

Systems Engineering Evaluative Framework

The preceding chapters have established the overview of digital engineering, the standard DoD approach to CBA, and a framework for applying that approach to digital engineering activity. The goal of this chapter is to leverage classic systems engineering principles in the context of the project objective: provide cost and benefit-based decision support to weapon system programs in determining the optimal use of digital engineering activities.

The preceding chapters use history and the ground state. They depict the descriptive scenario, what the world looks like today and how we might, in today's world within the constraints of current processes, conduct a CBA of digital engineering activities useful to DoD.

Systems engineering deals with the normative. We look at optimal approaches to achieve defined system goals—approaches not constrained by current processes. Starting with the weapon system goals, how might we analyze optimal digital engineering approaches to achieve those goals? Optimal would necessarily be a consideration of costs, schedule, and performance, so we develop a decision support framework accordingly in the determination of digital engineering activities in a weapon system program.

For this analysis, we start with the systems approach from classic systems engineering practice. We then use a logic-model construct published by the University of Kansas, to establish context and system boundaries for digital engineering.[1] The logic model helped us establish the process flow framework of determining which digital engineering activities to optimally leverage and why—that is, support for digital engineering program decisions. To better understand the framework, we also consider a case study of generic practice that leverages digital engineering in the sustainment goals of a weapon system. First a bit of background to establish the systems approach as the foundation of the framework.

The Systems Approach

> In the systems approach, concentration is on the analysis and design of the whole, as distinct from . . . the components or parts. . . . The systems approach relates the technology to the need, the social to the technological aspects; it starts by insisting on a clear under-

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[1] Community Tool Box, "Section 1. Developing a Logic Model or Theory of Change," webpage, Center for Community Health and Development at the University of Kansas, undated.

> standing of exactly what the problem is and the goal that should dominate [the] solution and lead to the criteria for evaluating alternative avenues. . . . It makes possible the consideration of vast amounts of data, requirements and (often conflicting) considerations that usually constitute the heart of a complex, real-life problem. It recognizes the need for carefully worked-out compromises, for trade-offs among the competing factors. It provides for simulation and modeling so as to make possible predicting the performance before the entire system is brought into being. And it makes feasible the selection of the best approach from the many alternatives.[2]

This is a common, accepted definition for an engineered system (shown in Box 4.1), with the operative term being *goal*.[3] The systems engineering process of defining those goals gives the program focus and the means on which to measure success—as well as measure the benefits of digital engineering, as we shall demonstrate.[4] The complexity of developing modern, complex systems that have human dependencies and multiple, sometimes independent goals has given rise to the modern practice of systems engineering. It is therefore paramount that the systems engineers and the practitioners of digital engineering carefully and thoroughly define the system goals of the new or existing weapon system in a methodical and hierarchical manner so that all stakeholders understand and that program managers ensure that the goals remain the focus of the program effort, to include any digital engineering activity.[5]

The DoD approach to defining system goals is codified in the acquisition process of DoDI 5000.02 and verified in acquisition decision gates; in such artifacts as the ICD, CDD, KPPs,

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[2] Simon Ramo, *Cure for Chaos: Fresh Solutions to Social Problems Through the Systems Approach*, David McKay Company, Inc., 1969, pp. 11–12.

[3] John E. Gibson, William T. Scherer, William F. Gibson, and Michael C. Smith, *How to Do Systems Analysis: Primer and Casebook*, John Wiley & Sons, 2016, p. 4. There are systems without definable goals (the Solar System comes to mind), but they are also not engineered systems and fall outside the scope of our analysis.

[4] This premise diverges from the Institute of Electrical and Electronics Engineers (IEEE) Computer Society perspective as depicted in *Systems and Software Engineering System Life-Cycle Processes, IEEE/International Organization for Standardization (ISO) 15288-2023* in important ways that distinguish software processes from systems processes. Systems processes are more comprehensive and more relevant to the field of cyber-physical engineering as practiced in commercial industry and weapon system development in the defense industrial complex. The IEEE/ISO 15288-2023, in an approach that clearly diverges from systems engineering principles, focuses on "the ultimate goal of achieving customer satisfaction" (International Organization for Standardization, International Electrotechnical Commission, and Institute of Electrical and Electronics Engineers Computer, *International Standard—Systems and Software Engineering, System Life Cycle Processes*, 2023, p. 1).

[5] An apocryphal anecdote about systems thinking at the National Aeronautics and Space Administration (NASA) recounts President John F. Kennedy visiting Cape Canaveral in 1962. The NASA staff were all lined up to greet the President, and he approached a custodial worker in the crowd and asked, "What do you do?" The custodian replied, "I am working to put a man on the moon." Some due diligence on the part of the authors found no record of a reference for this story, but the NASA anecdote shares a marked similarity to a tale told of Sir Christopher Wren speaking with stonemasons during the 17th century construction of St. Paul's Cathedral in London.

BOX 4.1

An Engineered System

A set of components so interconnected as to accomplish a defined goal.

and KSAs; and in the concept of operations process. In broader perspective, acquisition goals derive from operational goals as a part of the JCIDS process.[6] We are not suggesting duplication of any of these or their replacement, merely that they be done well, in accordance with good systems engineering practice. Those tasked with conducting independent, third-party CBA should be well versed in the goal development process that was used both to define the program and to decide on digital engineering activities to help achieve those weapon system goals. (Appendix C discusses the goal-development process in further detail.)

The literature overflows with good systems approaches, including systemic thinking, design thinking, and Russell Ackoff's seminal *On Purposeful Systems*.[7] The underlying principle sums up as follows: The better the descriptive scenario or ground state is understood, the better the normative scenario or goal is defined and understood, the more informed the engineering decisions will be. We offer in Appendix C a few critical characteristics of system goal definition that have direct implications for digital engineering and the Systems Engineering Evaluation Framework (SEEF).[8]

A Systems Engineering Framework

We developed a SEEF of digital engineering, depicted in Figure 4.1. The underlying hypothesis is to leverage the systems approach in logically assessing how we could improve a weapon system development process via the activities and tools of digital engineering. Once we establish how we can use digital engineering to conduct or improve weapon system development, a weapon system program will be able to leverage the SEEF to understand quantitatively the relationship between the associated costs and the delineated benefits to the weapon system program.

Logically following that premise within the system boundaries as defined in Figure 4.1, we consider how the multiple options for leveraging digital engineering can be compared in terms of digital engineering costs and weapon system program benefits to support rational decisions on the part of program managers and systems engineers.

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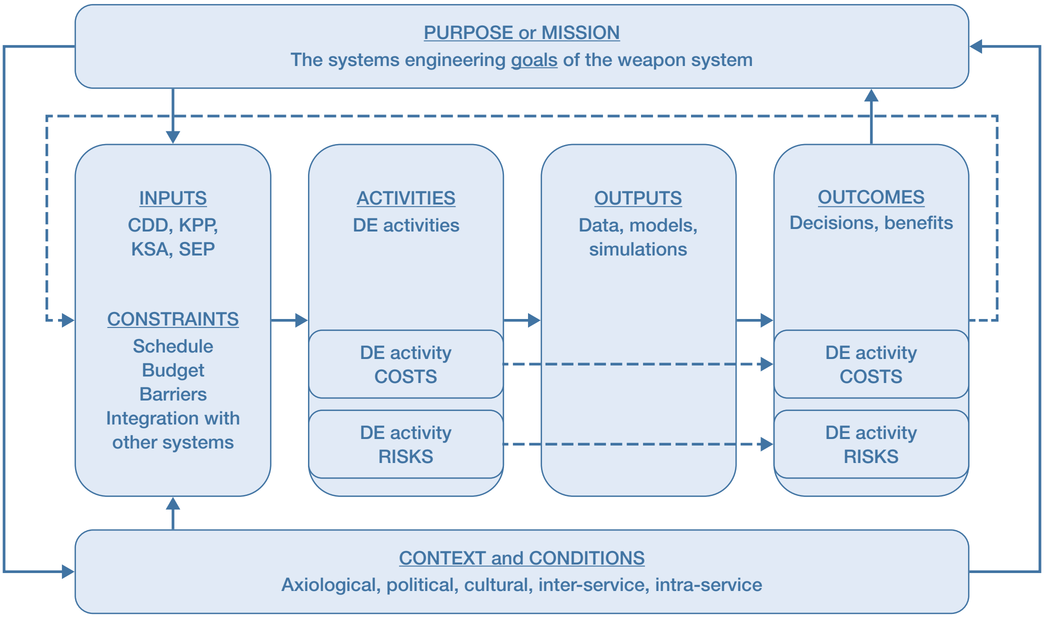
[6] J-8 Joint Requirements Oversight Council, *Manual for the Operation of the Joint Capabilities Integration and Development System*, August 31, 2018.

[7] Russell L. Ackoff and Fred E. Emery, *On Purposeful Systems: An Interdisciplinary Analysis of Individual and Social Behavior as a System of Purposeful Events*, Transaction Publishers, 2005.

[8] Gibson et al., 2016.

FIGURE 4.1

Process Flow for Digital Engineering Decision Support: SEEF



SOURCE: Author adaptation of logic-model material from Community Tool Box, undated.
NOTE: DE = digital engineering; SEP = systems engineering plan.

In Figure 4.1, the outcomes on the right feed back into the inputs on the left and back up to the weapon system goals. Looking at why we execute digital engineering practice, the intent is to improve and refine our designs and the design processes through modeling and simulation. That would be manifested by iterative changes to the design and the requirements that codify the design, ergo the feedback loop with the goal of improving the weapon system—reflected in the arrow from outcomes up to purpose or mission. This objective for digital engineering aligns with a recent U.S. Government Accountability Office report, which states the following:

> Leading companies use iterative processes to design, validate, and deliver complex cyber-physical products with speed. Activities in these iterative cycles often overlap as the design undergoes continuous user engagement and testing. Knowledge about the product's design is progressively refined and stored in a digital thread—a common source of information that helps stakeholders make decisions, like determining product requirements, throughout the product's life. As they proceed, product teams refine the design to achieve a minimum viable product (MVP)—one with the initial set of capabilities needed

> for customers to recognize value. They use modern manufacturing tools and processes to produce and deliver the product in time to meet their customers' needs.[9]

Tying the advantages offered by digital engineering activities to the program mission through a logical and quantifiable process such as SEEF will reduce dependence on the kind of difficult-to-substantiate projections of digital engineering benefits that we found in our study of the literature. For example,

> One weapon developer indicated the "disruptive" effects of [digital twin] technologies include a 500 percent increase in product durability, a 30 percent reduction in cost, a 25 percent decrease in product weight, and a 21 percent reduction in parts count, all the while utilizing a more streamlined manufacturing process that involves 90 percent reduction in tooling and a 95 percent decrease in inventory.[10]

Outcomes in the SEEF approach have units of measure associated with digital engineering activity costs (dollars), risks (dollars, time, performance), and units associated with the weapon system benefits (more on units for benefits later in this chapter). The net approach provides measurable, comparable data to support decisions on digital engineering in the program.

We posit that the SEEF approach will provide evidence-based assessments of digital engineering benefits consistent with good systems engineering practice. The approach will greatly facilitate tracing the digital engineering costs through the weapon system life cycle and map them readily to program benefits, thus providing the necessary evidence for informed program decisions. It is also our hope that the SEEF approach will not add measurably to the burdens already on program leadership while facilitating their decision process during the established early program systems engineering activities. We further posit that the approach can be used at any phase of the weapon system life cycle from before the system goals are codified to retirement of the system. SEEF will not provide a DoD standard CBA as does the framework in Chapter 3.

Purpose or Mission, Context and Conditions

The framework begins with the weapon system purpose or mission, which in systems engineering terms is the goals of the weapon system. To ensure that all readers understand the systems engineering principles underlying the goal definition process at a common level, we provide some fundamentals that apply directly to the SEEF framework in Appendix C. Although we posit that most readers are aware of the systems engineering goal definition approach,

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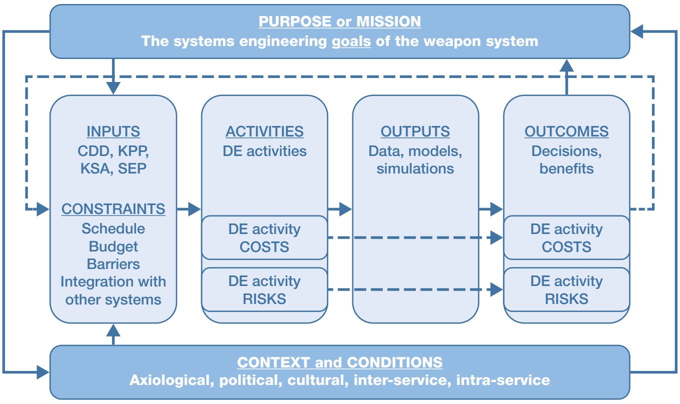
[9] U.S. Government Accountability Office, *Report to Congressional Committees: Leading Practices: Iterative Cycles Enable Rapid Delivery of Complex, Innovative Products,* GAO-23-106222, July 2023. The MVP approach is outside the scope of this analysis but will be addressed, in part, in a forthcoming RAND report.

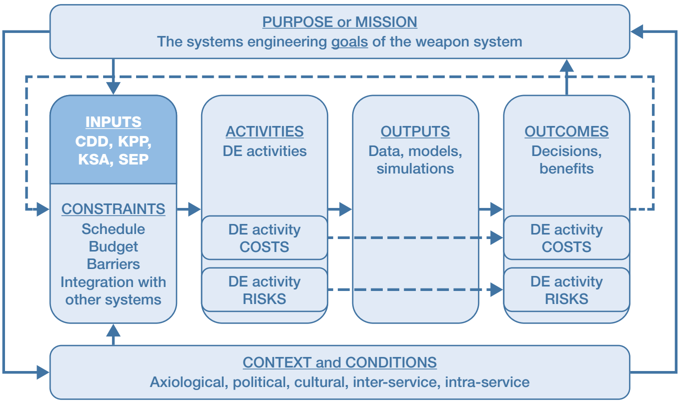
[10] West and Blackburn, 2018, p. 44.



we endeavor to align the reader's understanding of systems engineering taxonomy, lexicon, and concepts with our approach to the systems engineering goals of the weapon system. The U.S. Government Accountability Office and others have emphasized how the goal definition process is both critically important and a hurdle DoD is working to fully master.[11]

Inputs

Once developed, the engineering goals are codified in the acquisition documents. Every weapon system has KPPs or KSAs, usually delineated initially in the IDD for the development acquisition, and an SEP that will describe the systems engineering development plan to include all digital engineering activities associated with the acquisition.



DoD acquisition direction mandates certain statutory KPPs for all acquisitions: energy, system survivability (kinetic, cyber, and electromagnetic spectrum), force protection, sustainment, and net-ready performance attribute, (the net-ready KPP is no longer mandatory).[12] Conceptually, these are all derived from user-reviewed scenarios, use cases, and vignettes that describe most of the goals for a given weapon system. They can include a menu of goals and performance parameters that might be

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[11] U.S. Government Accountability Office, *Weapon System Requirements: Detailed Systems Engineering Prior to Product Development Positions Programs for Success*, GAP-17-77, November 2016; Michael Wetzer, 1992, p. 1543; and Shaw, 1994, p. 4527.

[12] Bill Kobren, "New JCIDS Policy and Guidance," *Defense Acquisition University* blog, September 12, 2018.

interrelated but each can be mapped to the needs of the service and DoD. Typically, they can be quantified in empirical metrics via indexes of performance (IoPs) (e.g., delivery schedule, lifetime, mean time between failure, mean time between maintenance, mean time to repair, mean downtime, unrefueled variety, data rate, payload, speed) and the aspects that might make the system unique (e.g., blast resistance or accuracy on target under specific conditions). Such DoD-wide technical considerations as modular open-system architecture (MOSA) would be codified for a system in the KSAs (and the lower-level requirements) and should be testable in requirements verification tests, though the mechanics of MOSA might influence such KPPs as sustainment and be manifested in maintenance and human factors simulations.

Ideally, such a technical factor as MOSA should be traceable through the systems engineering of a weapon system and digital engineering activities should facilitate determining the cost, benefits, and performance of that technical factor, including the cost of the digital engineering itself and trade-offs when the inevitable design changes are necessary.

Nonetheless, the obligation to do so in a weapon system program is codified in policy and the results documented in the ICD, the CDD, the KPPs and KSAs, concepts of operation, and, most recently, in the iterative MVP process.[13] Simply reading the weapon system KPPs does not provide adequate depth for a cost analyst to understand the alignment of digital engineering activities to weapon system program goals—though it certainly is a good start.

In addition to weapon system–specific KPPs, DoD has established mandatory KPPs that align with the highest-level goals of the department and that each contain aspects of cost, schedule, and performance. Our interest in the KPPs reflects that they are both system goals and that they can be quantified through such readily calculable IoPs as dollars, days, percent, miles, and others. Aligning digital engineering activities to those KPPs is certainly a good start toward quantitatively measuring the respective activity impacts and, also, a medium for both reusability and categorization of certain digital engineering activities. The KPPs unique to a development weapon system, however, are likely where the best measurable benefit from for new cutting-edge digital engineering activities lies and therefore should be the ones under the most scrutiny for costs and benefits.[14]

Relating Digital Engineering Goals to Program Goals

Simply put, every expenditure in a weapon system program should align with program goals. The object of every program cost starting at conception should affect the program output in some way. Ergo, every digital engineering activity in a program should align with specific program goals to determine the corresponding costs and benefits in terms of the weapon

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[13] DoDI 5000.88, *Engineering of Defense Systems*, Office of the Under Secretary of Defense for Research and Engineering, November 18, 2020.

[14] In some perspectives, all digital engineering activities are new.

system program.[15] That might sound overly simple and even trite to some in government, but those who espouse the leveraging of industrial practices in DoD as a justification of MBSE and digital engineering must consider that commercial industry follows a very similar practice in justifying investment in digital tools.[16] That premise forms the basis for the SEEF approach and the logic flow in Figure 4.1.

For example, as digital engineering benefit is often projected for the sustainment phase, we consider the program goals laid out in the material availability (commonly abbreviated, A_M) KPP—a system goal directly related to sustainment.[17] Although the IoP for A_M is a percentage, it reflects cost, schedule, and performance. The A_M percentage reflects performance—100 percent of the weapon systems being available on average would reflect an optimum performance using total weapon system capability. It also reflects a cost using performance, as any percentage less than 100 percent means DoD must own and maintain a fraction of the total number of a weapon system in the inventory that it cannot use at a given time and at a net additional cost.

If less than 100 percent of the weapon systems are available, the balance is unavailable, ergo inoperable at a given time. This might indicate that those weapon systems are being repaired or upgraded. Repairs and upgrades require resources (costs) and affect operational schedules (time) while commanders wait for resources to become available. That delay might reflect supply chain scheduling, parts manufacture scheduling, or even personnel scheduling. One scheduling perspective might be that more weapon system units would need to be manufactured to provide a net operational warfighting capability, thus affecting the date the fleet becomes fully operational.

In the context of A_M, we might hypothetically consider some of the following examples of digital engineering activities:

- physical modeling, dynamic modeling, and simulations using materials analysis of the system that reveal wear, sensitivity analysis, and time to failure so that designs and materials can be improved; analytics that can be used to predict maintenance; and hardware upgrades designed while in-service
- discrete event simulation of logistics and the spare parts supply chain to help monitor real-time supply chain data, adapt the supply chain to contingencies, consider Bayesian impacts, and study the sensitivity analysis of the supply chain

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[15] Enterprise-level expenditures that do not align with a single weapon system program would necessarily align with the service or DoD goals collectively and be measurable against those goals.

[16] A factor confirmed in our nonattributional discussions with industry and academia representatives.

[17] We will explore material availability more later in the analysis, but for now, the DoD definition is "the percentage of the total inventory of a system operationally capable (ready for tasking) of performing an assigned mission at a given time, based on materiel condition" (Office of the Assistant Secretary of Defense for Sustainment, undated).

- training simulator modeling to enhance the skillset of the humans that must maintain the weapon systems (establishing a field-user feedback loop here improves overall performance by incorporating corrections to the model and innovations from the field)
- operator training simulator modeling to ensure the operators do not use the system incorrectly and render it inoperable
- data links from physical sensors in production weapon systems during prototype and operational phases to provide real-time data to these and other digital engineering applications and algorithms.

These example digital engineering activities can all be planned for in the SEP and accounted for with appropriate metrics, including line-item costs, work breakdown structure, the digital engineering cost groups described in Chapter 3, and their respective IoP toward the weapon system goals measured. Reuse, repurposing, or multipurposing of these activities can also be planned in the SEP, documented, accounted for accordingly (including assumptions), and measured against the benefits to the weapon system goals. The SEEF framework can facilitate these decisions.

DoD Digital Engineering Strategy and Systems Engineering Research Center/ INCOSE

This goal alignment approach is different than that specified in the 2018 DoD Digital Engineering Strategy. Those five policy goals do not map succinctly to program engineering goals and therefore remain difficult to quantify in a cost-benefit approach. Such goals as better communication tend to obfuscate impact and justify expenditure on what might be superfluous architecture models and model-based acquisition approaches without understanding of the assumptions and limitations thereof.[18]

The approach to deriving weapon system goals in a CBA is also different from the approach espoused by the Practical Software and Systems Management (PSM) Digital Engineering Measurement Framework.[19] That approach alludes vaguely to what we want to achieve to satisfy our business goals and objectives. The process described, however, generalizes on all information as a function or product of digital engineering without aligning the data (or describing an approach to aligning those data) with the weapon system goals (or in determining those digital engineering activity goals and metrics up-front in the SEP). In other words, digital engineering as an end to a means.

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[18] U.S. Department of Defense, 2018. We note repeatedly in our study of the digital engineering community that the practiced concept of better communication almost universally reflects better communication in SysML specifically. Fluency in SysML is not only required but assumed across developers, users, and acquisition professionals.

[19] PSM, National Defense Industrial Association (NDIA), INCOSE, Systems Engineering Research Center (SERC), Aerospace Industries Association, and Department of Defense Research and Engineering, “Practical Software and Systems Measurement (PSM) Digital Engineering Measurement Framework,” version 1.1, PSM-2022-05-001, June 21, 2022, p. 3.

Although some of the metrics described in the PSM framework as "Primary Benefits and Applicable Measurement Specifications from the Causal Analysis" might indeed be aligned with some weapon system goals, others are so ambiguous as to reflect aspirational concepts rather than concrete benefits.[20] None of the PSM, SERC, and INCOSE goals can be readily quantified with IoPs; therefore, digital engineering success in their perspective lacks objective metrics, much less IoPs. The PSM measurement framework starts with the somewhat nebulous "Information Need" without any association of that need to goals other than "information needed by stakeholders."[21]

Constraints

Constraints for digital engineering are dictated by the boundaries of the weapon system program—for example, schedule, budget, human factors, and integration with the DoD

BOX 4.2

A Concise Summary of Key DoD Acquisition Policy on Digital Engineering

Digital engineering activities, their respective program goals, and all associated constraints are to be documented in detail in the SEP and tracked over the life cycle by the appropriate indexes of performance, including cost.

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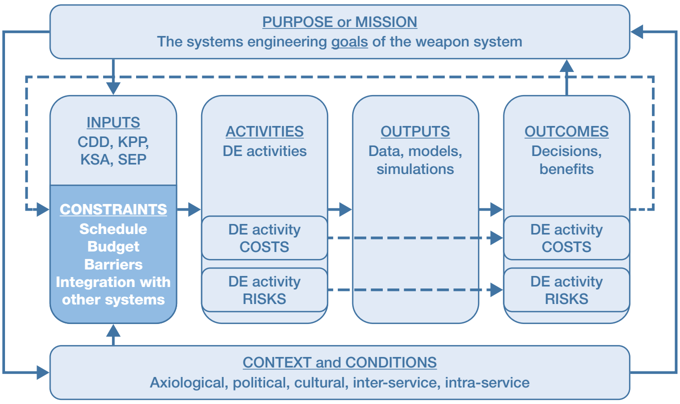
[20] PSM et al., 2022. The digital engineering benefits per PSM (version 1.2), SERC, and INCOSE were higher-level support for automation, early verification and validation (V&V), reusability, increased traceability, strengthened testing, better ASoT, higher level of support for integration, multiple model viewpoints (PSM et al., 2022). We saw referenced a different set of eight metrics that have replaced the version 1.1 set in an as-yet unreleased edition of PSM version 2. Taking those new metrics under consideration as this report was finalized, we stood by our original assessment that the metrics described in the PSM are difficult if not impossible to tie quantitatively or empirically to weapon system goals (PSM authors discussion with authors, October 25, 2023).

[21] PSM et al., 2022, pp. 18–20. We postulate that the digital engineering approach espoused in the referenced document will lead to (1) unnecessary costs in terms of support, tools, SETA, and models that might have very limited if any program utility and (2) early architectural models that unnecessarily constrict preliminary designs and therefore lead to inferior weapon systems. Despite many references in the literature on digital engineering postulating improved quality of information, improved information needs, and improved communications, no empirical application or even suggestion of information and communication theory per Claude Shannon or metrics of entropy could be found in DoD-sponsored work. This begs such research questions as how much information can be transmitted by the SysML architecture model of a system? How does that compare with other media? There are empirical metrics that could be brought to bear for comparison of benefits across options (Claude E. Shannon, "A Mathematical Theory of Communication," *Bell System Technical Journal*, Vol. 27, No. 3, 1948). The perspective held in these measurement approaches seems to be principally from the IEEE/ISO 15288. When discussed with the authors of the PSM, they replied that the IEEE/ISO 15288 is a software and systems management standard and therefore should not be considered in that light—although our observation reflects that it is considered in that light, suggesting space for follow-on research.

enterprise. These constraints will be codified through documentation and recorded in the SEP and other actions and artifacts of the DoD weapon system program life cycle development flow including the acquisition strategy (Box 4.2) and the program protection plan.



This life cycle process starts at the material development decision/ICD phase, which include the initial analysis of alternatives, requests for information, the alternative systems review, and the acquisition strategy development. All decisions and direction regarding the determination of which digital engineering activities are leveraged will be thoroughly and concisely documented in the SEP along with the appropriate metrics for assessing cost, schedule, and performance impacts of the respective digital engineering activities. The constraints will include the budget and schedule aspects of the digital engineering activity, security in all domains (cyber, physical, personnel, etc.), how the digital engineering activities interface and integrate across the system, relevant regulations and directions, and other crucial details for management of digital engineering functions and resources over the life cycle. This does not represent new analysis, but a simple, concise summary statement of existing DoD policy.

This statement is supported throughout the current acquisition literature but not stated as succinctly. See, for example, instructions in the SEP outline, Table 2.5-1, Digital Ecosystem row:

> Describe how the program uses the digital ecosystem in the system's design of life cycle activities to establish system performance validation capability through models, simulations, or digital twin instantiations. Describe how the digital ecosystem will be maintained through the sustainment phase of the system to facilitate enhancements, updates, and changes.
>
> Describe how the digital ecosystem or parts of it will be required to stay updated and maintained in order to support quick software updates and fast delivery to the field. Identify design considerations that (i) leverage the digital engineering implementation and digital representations of design products (e.g., digital threads, digital twin) and (ii) the

> program plans to use to support development activities, manufacturing activities, operations, and sustainment activities.[22]

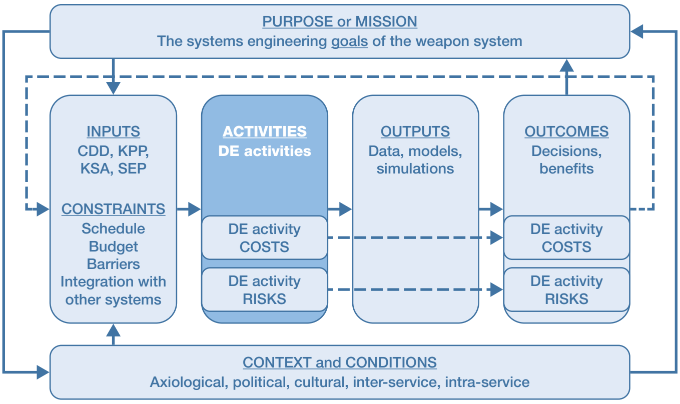
From that passage in the SEP template, we derive some assumptions for digital engineering and the associated costs. For example, "describe how the digital ecosystem will be maintained" implies but does not explicitly state that metrics will be derived to determine the state of and costs of maintenance of the digital ecosystem—otherwise there will be no empirical evidence to reflect if it is adequately maintained and why or why not. The assumption is that the systems engineer replying will provide information as to how it will be maintained as well as how well it will be maintained.[23] It implies also that there will be workforce tasked with said maintenance. It also implies that costs of maintaining the digital ecosystem will be accounted for as a part of the program budget and work breakdown structure—that would seem to be included in the *how*.

Making these characteristics a part of the next revision of the SEP template would greatly facilitate the measurement and understanding of digital engineering activities going forward.

In the SEP context, the SEEF approach will help the weapon system program to identify design considerations that (1) leverage the digital engineering implementation and digital representations of design products (e.g., digital threads, digital twin) and (2) the program plans to use to support development activities, manufacturing activities, operations, and sustainment activities.[24]

Activities

In determining the preferred digital engineering activity using the SEEF paradigm, three factors play principal roles: (1) How does the digital engineering activity support engineering decisions in terms of the respective weapon system KPP (or *benefits*)? (2) What will be the pro-



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[22] Office of the Under Secretary of Defense for Research and Engineering, *Department of Defense Systems Engineering Plan (SEP) Outline*, Version 4.0, September 2021, pp. 14–15.

[23] IEEE/ISO 15288-2023 delineates such software-centric parameters as the *how*. Good systems engineering would necessarily derive indexes of performance related to the goals associated to reflect the *how well*. Also consider the precepts of quality management practice where improvement comes from, knowing where you are and where you want to be.

[24] Office of the Under Secretary of Defense for Research and Engineering, 2021, p. 15.

jected *costs* of the digital engineering activity? (3) What will be the projected risks of the digital engineering activity (or *probabilistic costs*)?

Selecting Digital Engineering Activities to Support Engineering Decisions

Though we listed a few general examples of digital engineering activities in the A_M example earlier in this chapter, it is outside our scope to provide a catalog of digital engineering activities and approaches.[25] OUSD R&E, SERC, and INCOSE have already done so in such references as their respective Digital Engineering Bodies of Knowledge (DEBoKs).[26] The Navy has an excellent set of resources at their Navy Digital Engineering Body of Knowledge (NDEBoK).[27]

One source that we have not seen referenced but consider worth noting on the part of weapon system programs as an invaluable source for analytics activities related to digital engineering is the *INFORMS Analytics Body of Knowledge*.[28] We posit that a lead or chief systems engineer and a program manager would study these references, along with any service-specific resources, appropriate supporting materials (such as General Services Administration schedules for software licenses), and contractor awardee-proprietary modeling and simulation tools when planning a program. We also recommend the decisionmakers be well versed in systems engineering principles.

Given the diversity of DoD program types that will leverage digital engineering, providing detailed guidance on the selection of specific digital engineering activities beyond the few examples included in this report would be of limited utility. Multiple options might exist to support respective engineering decisions, and the program will be best suited to determine which are better, with support from the SEEF framework.

In the SEEF paradigm, early digital engineering activity decisions would be made starting before Milestone A as a part of developing the initial program SEP, likely continuing through the contract award in conjunction with the primary provider. For example, an early leveraging of digital engineering could be the development of system simulations based on the initial requirements to be used for validation by stakeholders and requirement refinement—a key facet of MVP development. The SEP should plan for this in a way where costs and benefits can be projected. In many programs, the request for proposal might specify digital engineering activities, possibly including digital contract data requirements lists, which will become

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[25] With advances in simulation methods, systems engineering approaches are constantly improving. Examples include such critical human factor aspects as understanding the nausea induced by staring at a display screen in a moving vehicle or the impact on the human body of an undercarriage explosion. These all came from lessons learned the hard way in combat. No model that is not specifically designed for an expressed purpose will reflect such advanced system issues. These models tend to be bespoke and expensive, and economies from reuse need to be very carefully considered as there are accompanying risks.

[26] SERC, "The Digital Engineering Body of Knowledge: An Interactive Environment," webpage, January 25, 2023; DeBOK, homepage, undated; USD(R&E), "Digital Engineering," webpage, undated.

[27] Naval-LIFT, 2023.

[28] *INFORMS Analytics Body of Knowledge*, John Wiley & Sons, 2018.

a part of the contract. Proposals will contain specific, proposed digital engineering activities (often proprietary) and their correlation with weapon system program benefits. Ideally, the DoD program manager and lead systems engineer would lead a series of digital engineering decision meetings of all the critical stakeholders for the program and the program's life cycle. Source selection committees would be tasked with grading the digital engineering responsiveness, innovation, measurability, and clear ties to weapon system program benefits in respective proposals. During the response period, the source selection committee could drill down on issues related to digital engineering approaches, possibly leveraging the SEEF framework.

Such gathering of the stakeholder minds over the early life cycle will facilitate sharing of digital engineering resources over the weapon system life cycle and support brainstorming digital engineering innovation in a program. If the program has already started and is at some midpoint in the life cycle, the SEEF process builds on the decisions made earlier in the life cycle and documented in the SEP.

Digital Engineering Activity Costs

In Chapter 3, we describe four categories of digital engineering–related costs: IT infrastructure, data, workforce, and tools. These four cost categories are hierarchical and interdependent. IT, data, and tools require the correlating workforce expertise and capability, or expenditures in those areas will not show the proper benefit. Likewise, tools require data, and data and tools require IT infrastructure as a foundation. Systems engineers and program managers require understanding of the interdependence of these factors to establish the digital engineering aspects of the program effectively, as do the cost analysts.[29]

For SEEF, we break down each of these four cost categories into four cost bins. Not all 16 bins will apply for all programs, but all digital engineering costs, even if zero for a bin, should be accounted.

BOX 4.3

Digital Engineering Modeling Risks

Understanding of the modeling risks is half the battle, the other half is ensuring that these risks are understood wherever and whenever the model is used, especially if the model is incorporated into a larger analytic mechanism.

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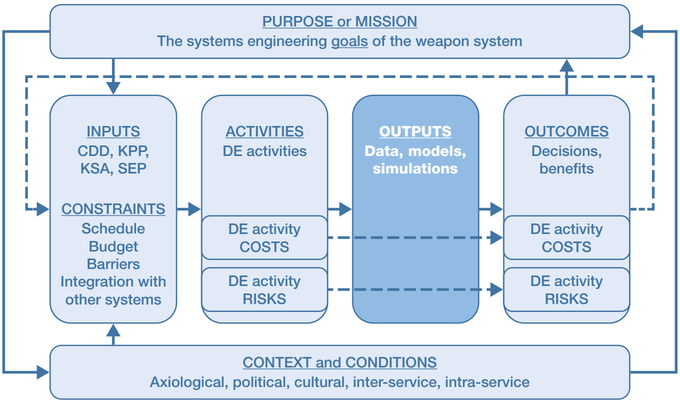
[29] This is more thoroughly explained by the case study to follow and Figure 4.4.

Digital Engineering Activity Risks

All digital engineering activities have risks, require assumptions, and deviate from reality in important ways that must be documented and understood (which we discuss further in Chapter 5).[30] Understanding these risks requires deep understanding of the respective algorithm, model, or simulation. This phase of the SEEF requires understanding that modeling risks (Box 4.3) are probabilistic costs—and we cannot emphasize this enough.[31] Elsewhere in this report, we list a few of the programs where those risks were not fully understood or were possibly lost in transfer or in translation.

Just as we do not catalog the respective digital engineering activities, we do not catalog their respective risks. All sources of digital engineering activities should include careful examination of those risks, and all leveraging of digital engineering activities must include understanding of those risks across the program wherever that algorithm, model, or simulation has bearing on the design, manufacture, or operation of the weapon system. This understanding of the risks of any model will be paramount to program success. Where the respective digital engineering risk understanding does not exist in the program is a manifestation of absorptive capacity need and is itself a program risk.



Outputs

To the right of the digital engineering activities are the outputs they produce. These can be presented in raw form, processed form, visual form, or graphically realized form. One acquisition category (ACAT) I weapon system program with which we held discussions emphasized

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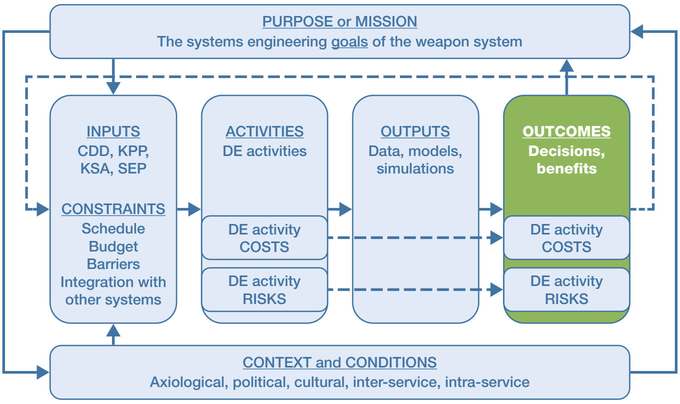
[30] To assume otherwise is to assume that all systems behave like software code.

[31] Consider the following example: There are many published analyses of the Boeing 737MAX design issues that led to the deaths of 346 people and caused Boeing to incur corporate costs associated directly and indirectly with those design issues that are still being accounted. Several analyses point to failure of the maneuvering characteristics augmentation system. Several of those analyses trace that system failure back to the software development modeling approach that Boeing used, in which design assumptions of the maneuvering characteristics augmentation system (or *modeling risks*) were kept from test pilots and even operational pilot instructions. For an example of those analyses, see Murillo de Oliveira Dias, André Teles, and Raphael de Oliveira Albergarias Lopes, "Could Boeing 737 Max Crashes Be Avoided? Factors That Undermined Project Safety," *Global Scientific Journals*, Vol. 8, No. 4, April 2020.



that their digital engineering activity simulation approach allowed them to consider millions of design options. Those millions of simulations and the associated data are the outputs.

The distinct outputs of each digital engineering activity will provide the raw material from which the stakeholders will form their engineering decisions.

Outcomes

In terms of impact on the weapon system program, the outcomes are the benefits tied to each respective digital engineering activity. In the ACAT 1 example mentioned in the previous section, the outcome of the millions of simulations includes the selection of the best engineering design options using those simulations. This final phase of SEEF provides decisionmakers with the listing of all digital engineering activities associated with a program life cycle along with the mapped costs and risks for those digital engineering activities.

This mapping will be complex. Multiple digital engineering activities support decisions related to multiple goals and KPPs. The respective costs will need to be parsed over the goals and KPPs—possibly broken down by subcontractors and along the supply chains, depending on the level of analysis required. Accounting for digital engineering activity risks needs to be complete and continuously maintained, never disassociated from the digital engineering activity.

Finally, the iterative nature of systems engineering and SEEF dovetails well with the improvements and changes to the system goals over the life cycle and the possible addition of digital engineering activities along the way. The outcomes feed back into the goals accordingly.

SEEF Case Study: Mandatory Key Performance Parameters for Sustainment

In a development acquisition, the list of weapon system KPPs would be long and detailed, as discussed in the previous sections. For simplicity and generic understanding, we consider just the KPP of *sustainment* and the next-tier system goals for an abstract, illustrative example that is technology agnostic and shows the SEEF framework.[32] Sustainment makes a useful example, as we showed in Chapter 2. It stands out as a frequently cited area of digital engineering future program benefit in the literature, so it makes for an ideal case study.

The sustainment KPP consists of two mandatory key factors (lower-tier goals): material availability and operational availability.[33] It also consists of three mandatory supporting KSAs: reliability, maintainability, and total ownership cost for all ACAT I programs. For the sake of this case study, we will illustrate a SEEF flow for the two key factors of the KPP goal and include in the outcomes the KSA correlation via the IoPs reliability, maintainability, and total ownership cost.

As in any good systems engineering approach, the goals defined by the KPPs are clearly measurable, as delineated in Table 4.1. By providing IoPs, we can judge and compare quantitatively the benefits of using digital engineering activities—or even of not using digital engineering activities, the baseline. The IoPs do not necessarily need to be defined as the KSAs as in this example, but they should relate to the KSAs, and the KSAs should be definable in terms of IoPs. For example, reliability could be defined with established engineering IoPs, such as mean time to failure or mean time to repair.

DoD defines A_M as the percentage (the IoP) of the total inventory of a system operationally capable (ready for tasking) of performing an assigned mission at a given time, using materiel condition.[34] DoD defines *operational availability* (A_O) as the reflection of reliability, maintainability, and supportability in real-world support environments, including the reliability and maintainability achieved through engineering design, the manufacturing fidelity, actual

TABLE 4.1

Measurement of Digital Engineering Benefits in Terms of Key Performance Parameters

Key Performance Parameters	Metric	Index of Performance
Material availability	Material availability	Percentage (0 to 100)
Operational availability	Reliability	Probability (0.0 to 1.0)
Operational availability	Maintainability	Time
Operational availability	Total ownership cost	Dollars

SOURCES: AcqNotes, 2021; Reliability Analysis Center, undated.

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[32] Sustainment, in terms of improved performance and reduced operations and support costs, is often cited as a point of potential cost-benefit for digital engineering. As of early 2024, no verifiable data have been found that reflect evidence corroborating this postulation in DoD acquisitions.

[33] AcqNotes, "Materiel Availability," webpage, August 3, 2021; Reliability Analysis Center, *Operational Availability Handbook, Section 1: Introduction to Operational Availability (A_O)*, undated.

[34] AcqNotes, 2021.

maintenance policies, in-theater assets, and all post-delivery weapon system supply chain considerations.[35]

Using the approach presented here in conjunction with the SEP outline instructions for reliability and maintainability could also support empirical evidence of digital engineering cost-benefits associated with the mandatory KPPs.[36] The narrative in this chapter in no way seeks to replace the procedure of the SEP outline or DoDI 5000.88.

Case Study Assumptions

In this case study, we simplify the illustration by considering only four digital engineering activities for each of two goals, A_M and A_O, where there would likely be more for each. We obliquely emphasize digital engineering activity similarities across the respective lower-tier goals for illustrative purposes, to demonstrate where respective digital engineering activities might support multiple weapon system goals. We abbreviate the lists of respective digital engineering activity risks for simplicity. For space and clarity considerations, we map digital engineering costs for the six digital engineering activities using the four cost categories in Chapter 3; the implication is that all 16 cost bins apply to each activity.

The SEEF illustration contained in this chapter reflects the cost bins of the first pass draft estimations and is subject to iteration when the framework is evaluated on actual weapon system case studies.

Understand the Weapon System and Its Life Cycle

In understanding the two goals that we consider here, A_M and A_O, we need to understand the weapon system and the engineering factors that come into play. We are using the most generic possible assumptions for this case study, ignorant of the specific weapon system technology and so as general as possible. We do not know whether the case study system flies, floats, or fires, so we make a few assumptions. Discounting combat-related damage, the non-combat-related reasons why a system might be unavailable could be as result of faulty software, worn mechanical parts, mechanical failure, electrical failure, maintenance training, supply chain issues, or others.

Next, we peruse our catalog of digital engineering approaches for modeling tools that will provide the data we need in support of understanding these availability factors.[37] Such a

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[35] Mathematically, Defense Acquisition University denotes A_O as MTBM/(MTBM+MDT), where MTBM is mean time between maintenance and MDT is mean downtime in actual conditions, including such factors as delays getting parts or personnel, number of spares on hand, and others. See Reliability Analysis Center, undated.

[36] DoDI 5000.88, 2020, pp. 39–42.

[37] This resource might include any and all DEBoKs mentioned earlier, the proprietary tools and approaches used by the awardee or system supplier, a catalog of operations research approaches, and any other engineering tools that might be relevant.

selection will involve a classic systems engineering trade study (for example, a combinatorial optimization-type heuristic exercise perhaps) bounded by the constraints mentioned earlier in this chapter with the objective function ultimately tied to specific engineering design questions that are themselves tied to weapon system program goals. The key to doing this well lies as firmly in the expertise of the decisionmakers as in the techniques for selecting tools.

In this case study, we arbitrarily surmise six distinct digital engineering approaches for understanding and engineering the A_M and A_O of a weapon system:

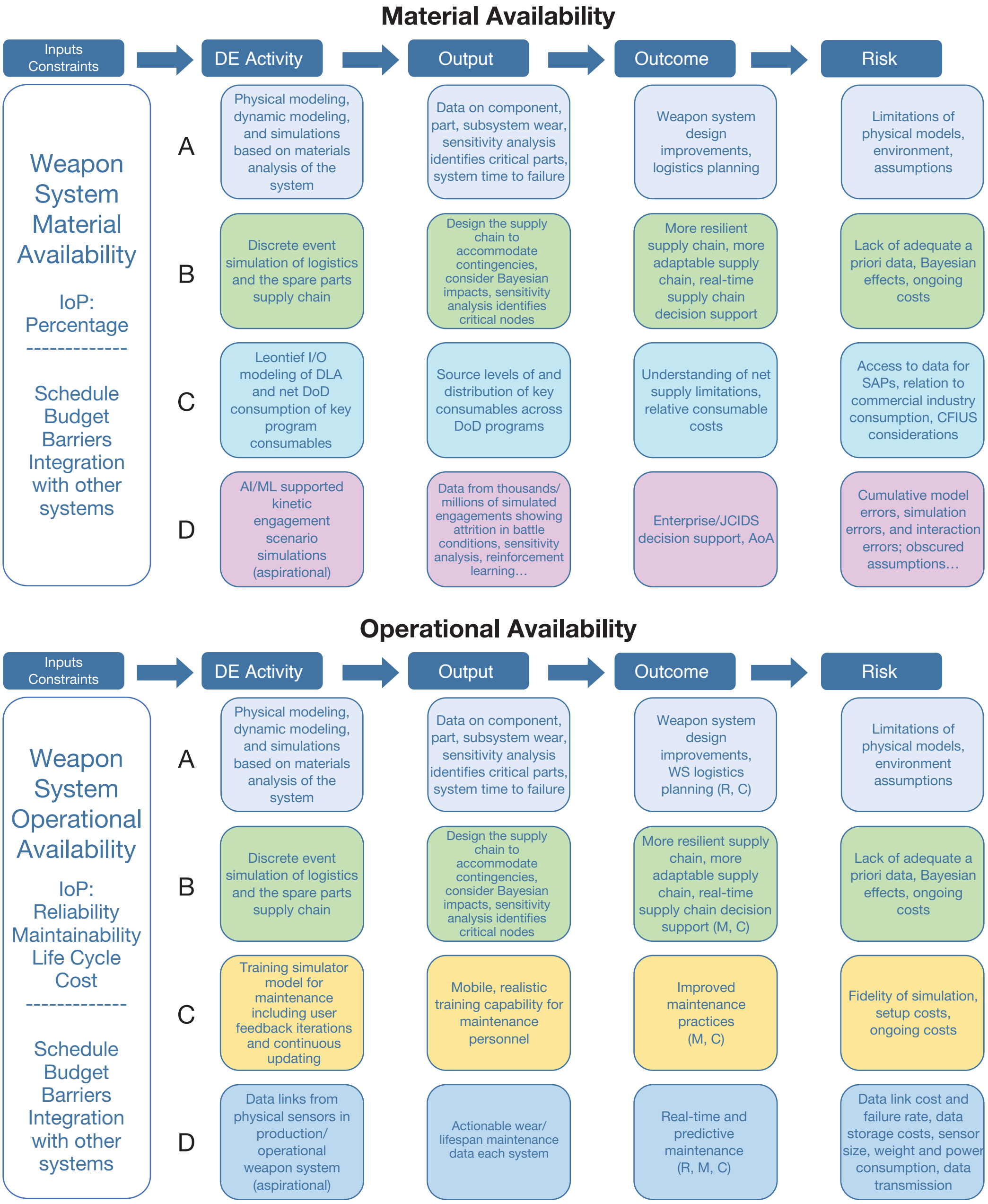
1. physical models using mechanics and materials science to determine system wear and failures
2. discrete event simulation of supply chains to understand parts availability during manufacture and spare parts while in operation
3. Leontief input-output models to reflect such system material consumption as rare earth materials and raw materials
4. artificial intelligence– and machine learning–supported engagement simulations (aspirational—such as advanced framework for simulation, integration, and modeling [AFSIM]) to see how well the system design performs in warfare conditions
5. training simulations for improving weapon system maintenance practice
6. a networked system of physical sensors that would provide operational weapon system functionality data for depot and deployment maintenance and predictive analytics (aspirational).

This list of possible digital engineering activities in our narrow-focus example of A_M and A_O availability is neither complete nor comprehensive—it merely offers some relevant but arbitrary examples to demonstrate the SEEF. The top and bottom panels of Figure 4.2 illustrate the flow of this part of the SEEF process.

These six possible digital engineering activities—A through F, shown in Figure 4.2—would, via SEEF, be mapped to their respective outcomes in terms of the corresponding KPP IoPs we established—reliability, maintainability, total ownership cost—and the A_M percentage. These outcomes are engineering decisions that would be supported by the respective digital engineering activity as the program works to achieve the KPPs. They answer questions for the engineers, such as how can we reduce wear in system components? How can we reduce maintenance times? How can we improve the availability of replacement parts? All these questions support the engineering goals of the sustainment KPP. Therefore, they logically support the respective weapon system goal and therefore correlate to quantifiable benefits in the weapon system program. Each digital engineering activity also bears specific risks that need to be correlated with that activity. We align examples of those risks in the right column of Figure 4.2, and they need to be considered and weighed against decisions to employ the respective activity. Figure 4.2 represents the blue highlighted areas of the SEEF framework in Figure 4.3.

FIGURE 4.2

Logic Model of Digital Engineering Activities as a Function of Weapon System Goals



Material Availability

Inputs Constraints		DE Activity	Output	Outcome	Risk
Weapon System Material Availability IoP: Percentage ------------- Schedule Budget Barriers Integration with other systems	A	Physical modeling, dynamic modeling, and simulations based on materials analysis of the system	Data on component, part, subsystem wear, sensitivity analysis identifies critical parts, system time to failure	Weapon system design improvements, logistics planning	Limitations of physical models, environment, assumptions
	B	Discrete event simulation of logistics and the spare parts supply chain	Design the supply chain to accommodate contingencies, consider Bayesian impacts, sensitivity analysis identifies critical nodes	More resilient supply chain, more adaptable supply chain, real-time supply chain decision support	Lack of adequate a priori data, Bayesian effects, ongoing costs
	C	Leontief I/O modeling of DLA and net DoD consumption of key program consumables	Source levels of and distribution of key consumables across DoD programs	Understanding of net supply limitations, relative consumable costs	Access to data for SAPs, relation to commercial industry consumption, CFIUS considerations
	D	AI/ML supported kinetic engagement scenario simulations (aspirational)	Data from thousands/ millions of simulated engagements showing attrition in battle conditions, sensitivity analysis, reinforcement learning…	Enterprise/JCIDS decision support, AoA	Cumulative model errors, simulation errors, and interaction errors; obscured assumptions…

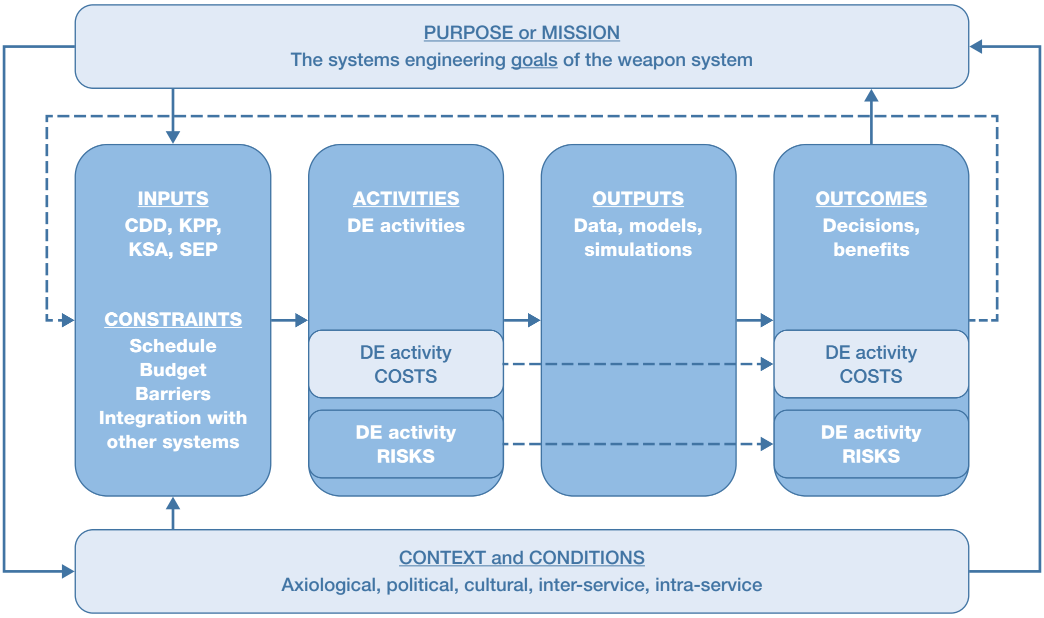
Operational Availability

Inputs Constraints		DE Activity	Output	Outcome	Risk
Weapon System Operational Availability IoP: Reliability Maintainability Life Cycle Cost ------------- Schedule Budget Barriers Integration with other systems	A	Physical modeling, dynamic modeling, and simulations based on materials analysis of the system	Data on component, part, subsystem wear, sensitivity analysis identifies critical parts, system time to failure	Weapon system design improvements, WS logistics planning (R, C)	Limitations of physical models, environment assumptions
	B	Discrete event simulation of logistics and the spare parts supply chain	Design the supply chain to accommodate contingencies, consider Bayesian impacts, sensitivity analysis identifies critical nodes	More resilient supply chain, more adaptable supply chain, real-time supply chain decision support (M, C)	Lack of adequate a priori data, Bayesian effects, ongoing costs
	C	Training simulator model for maintenance including user feedback iterations and continuous updating	Mobile, realistic training capability for maintenance personnel	Improved maintenance practices (M, C)	Fidelity of simulation, setup costs, ongoing costs
	D	Data links from physical sensors in production/ operational weapon system (aspirational)	Actionable wear/ lifespan maintenance data each system	Real-time and predictive maintenance (R, M, C)	Data link cost and failure rate, data storage costs, sensor size, weight and power consumption, data transmission

NOTE: The logic model includes example risks associated with each digital engineering activity. C = total ownership cost, CFIUS = Committee on Foreign Investment in the United States, DE = digital engineering, DLA = Defense Logistics Agency, M = maintainability, R = reliability, SAPS = Special Access Programs, and WS = weapon system.

FIGURE 4.3

SEEF Framework of Inputs, Constraints, Digital Engineering Activities, Outputs, Outcomes, Risks



NOTE: DE = digital engineering. This is the same framework shown in Figure 4.1 as applied to the case study.

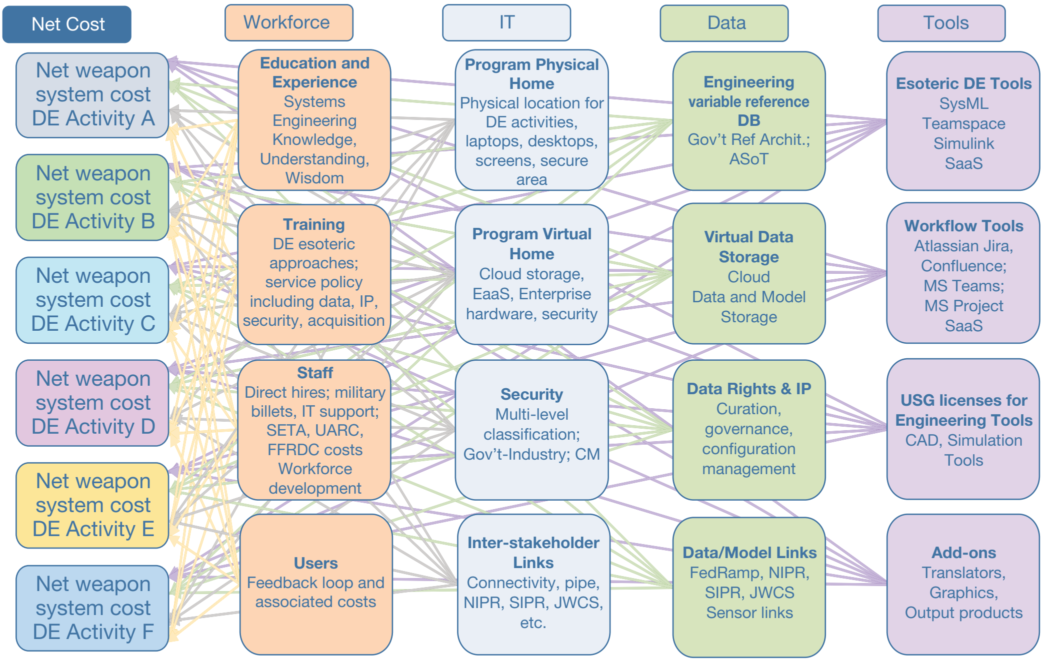
The replication of two of the digital engineering activities in both goal maps in Figure 4.2—A_M and A_O—reflects how digital engineering activities could benefit multiple weapon system program goals. This will require expert parsing by the program of digital engineering activity costs across multiple KPPs in an analysis.

For each of the digital engineering activities, we map in Figure 4.4 16 digital engineering activity cost bins among the four categories—workforce, IT, data, and tools—as described earlier in the section entitled "Digital Engineering Activity Costs." This figure reflects a relationship that is interdependent and hierarchical between the respective costs going from the left (higher) to the right (lower). Security and classified operations considerations are ubiquitous across the bins, affecting all costs, as are the enterprise (service branch, program executive office) investments in digital engineering capability that come to bear on the specific program. These enterprise investments require expert cost parsing from the perspectives of both the weapon system program and from the enterprise.

The workforce investments in digital engineering form the foundation of the activity, a factor to which we will allude later in Chapter 5 as a critical aspect of absorptive capacity. Just below that are the foundational investments in IT capacity, both program and enterprise. Data fall next in importance because without data the tools cannot function. Lastly, the tools; important but dependent on the systems engineering approach and the data collection pro-

FIGURE 4.4

An Illustrative Mapping of the Six Sample Digital Engineering Activities to 16 Digital Engineering Cost Groups



SOURCE: Mapping derived from Step 3 in Chapter 3 (Figure 3.2).

NOTE: From right to left, the figure depicts a hierarchical ascendency of costs and interdependency. CAD = computer-aided design, JWCS = Joint Worldwide Intelligence Communication System, NIPR = non-classified Internet Protocol router, SETA = systems engineering and technical assistance, SIPR = secret Internet Protocol Router, UARC = university affiliated research center.

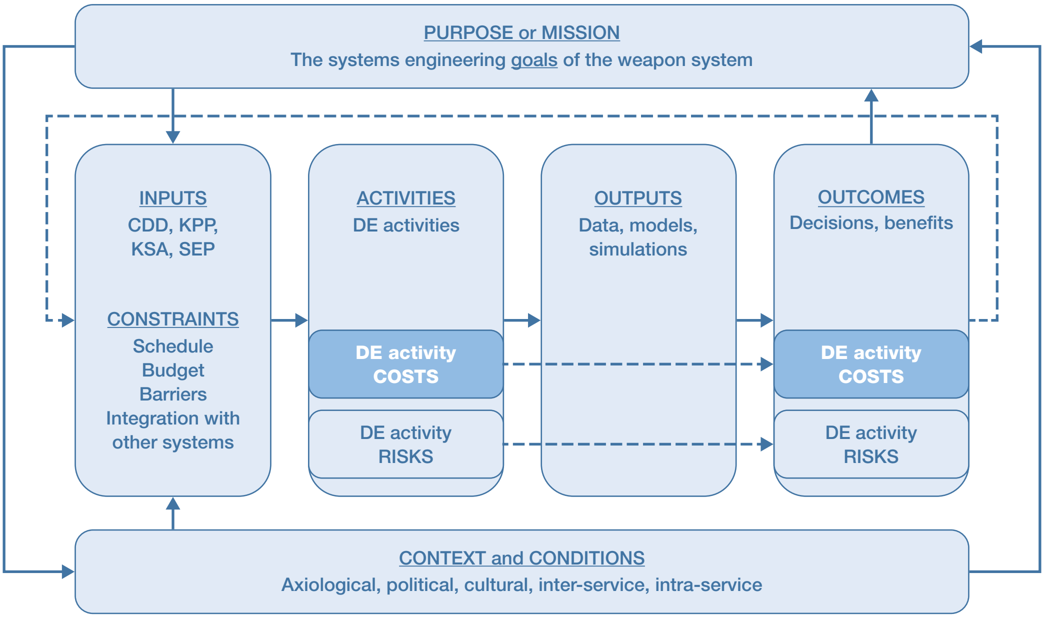
cess, therefore, never a first consideration. A goal-based engineering approach should always be tool-agnostic.

The mapping accounts for the cost aspects of Figure 4.1., as depicted in the blue highlighted areas of Figure 4.5.

We can now logically map the SEEF summary of the cost, risk, and outcome for each proposed digital engineering activity, as well as associate it directly with the corresponding goal in terms of one or more KPP. In Figure 4.6, from left to right, digital engineering Activities A and B map to both KPP A_M and A_O and have measurable benefits in terms of Am (percentage) and A_O (reliability [probability], maintainability [time], and total life cycle cost [dollars]).

Note that the IoPs associated with the respective digital engineering activities map per Figure 4.6. For example, activities A and B will have IoPs of percentage, probability, time, and dollars according to both KPPs A_M and A_O. As digital engineering activities B and C correspond only to KPP A_M, the IoP is just percentage. Likewise, the IoPs for digital engineering activities E and F will be the IoPs corresponding just to A_O: probability, time, and dollars.

FIGURE 4.5
Digital Engineering Activity Costs in SEEF



NOTE: DE = digital engineering.

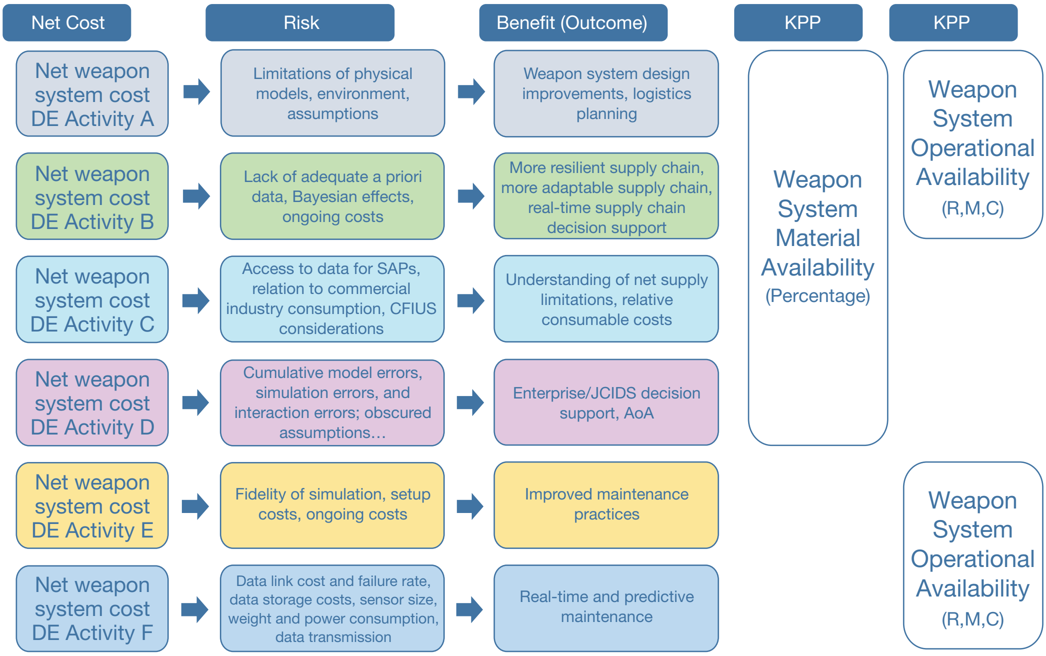
Deep Dive Vignette: Simulation-Based Maintenance Training as Part of Operational Availability

As a deep dive example, for digital engineering Activity E from the list in Figure 4.6, the net analysis under SEEF would take the following flow for a new weapon system program, considered here in isolation from other digital engineering activities for clarity. The ground state (current or prior practice) is assumed to be paper maintenance manuals for the weapon system distributed periodically to the field where operational maintenance takes place. For that traditional method, it is possible to predict reliability, maintainability, and total life cycle cost using prior, similar program data. If we leverage digital engineering tools to simulate a fully virtual system for field maintenance training, repair information, and updating, we then use those tools to develop empirical forecasts for what the change would be in reliability, maintainability, and total life cycle cost in the operational weapon system. This deep dive reflects again the principles of a systems engineering trade study comparing the fully virtual system option with the do-nothing, business as usual ground state by using simulations to compare the two.

We might predict faster repairs because of better repair efficiency and less time to search for information. Life cycle costs might be lower because of better repair problem diagnosis from better training. Better trained maintainers might have important feedback for the program engineers, resulting in weapon system design improvements. Presumably, we would

FIGURE 4.6

Summary of Cost, Risk, and Outcome for Each Proposed Digital Engineering Activity



NOTE: R = reliability, M = maintainability, and C = total ownership cost.

predict that all the relevant IoPs would improve—reliability and maintainability would go up as the quality and speed of operational maintenance improves, and total life cycle cost would go down as the cost of having weapon systems in repair declines. If we pull on the maintainer feedback loop thread, other program IoPs could also improve over the life cycle. Total life cycle cost would not include the cost of the virtual maintenance training digital engineering activity—yet.

Then, we delineate the risks to the weapon system and the mission that might be presented by a virtual maintenance training system. Those could include cyber compromise of the maintenance system leading to system failures; safety consideration assumptions made by the training designers; system fidelity assumptions made by the system modelers; costs for maintaining the maintenance system that were not correctly calculated; or dependence on communications links, say 5G, that are not reliable or available.

Next, we calculate all the costs for the 16 bins in Figure 4.4. for the life cycle of the virtual maintenance training system. These values become the basis for the program decision of developing a virtual maintenance training function for the weapon system: (1) a baseline on which to make a do-nothing judgment, (2) a life cycle cost and risk assessment of adding the system (the cost will be in addition to the reduced baseline total life cycle cost that we predicted for adding the virtual maintenance training capability), and (3) measurable benefits in the KPP IoP terms for adding the capability of virtual maintenance training.

It might be, for example, that the additional cost of adding the capability is more than the improvement to total life cycle cost from the original values. However, we might decide that the improvements to reliability and maintainability over the paper-based ground state are well worth the additional cost. In other words, better sustainment might be worth more life cycle cost; a Pareto frontier decision.

Finally, the process provides metrics that can be empirically recorded over the life cycle and reflected back on the simulated forecasts, providing correlation between cost and benefit, some reasonable assumption of causality in light of all other factors (e.g., culture, politics) and information for this and other weapon system programs. If the SEEF is considered in an existing weapon system that currently uses paper-based maintenance training or one that has already adopted a digital training simulation approach, then the analysis would start from a different point in the life cycle. The starting point of the framework would be to obtain concrete, historical weapon system data for reliability, maintainability, and total life cycle cost. Then, improvements to those values from the new application of virtual maintenance training would be forecasted, along with the risks to the weapon system and to the mission. The digital engineering activity cost is then calculated for the balance of the weapon system life cycle. This process results in data on which to decide the net value-added to the program of the additional digital engineering activity.

SEEF Framework Summary

The SEEF of digital engineering approaches in a program provides the following:

- An approach for establishing decision support at any phase in a weapon system program for which digital engineering activities might be employed. It provides a medium through which the program leadership can compare digital engineering activity alternatives and a correlation to how their respective use will benefit the program and what the respective program risks might be.
- A rubric for measuring and mapping the individual and cumulative costs of the respective digital engineering activities in a weapon system program to the beneficial impact on program goals, including program KPPs.
- SEEF could be manifested in an Excel spreadsheet format for a complex weapon system program. Using a spreadsheet would facilitate executing the SEEF process while not adding an additional tool or training to a program.

CHAPTER 5

Rigor and Risks

In our study of digital engineering in DoD and the practice thereof, we observed and recorded certain key leverage points associated with addressing rigor and risk that might help practitioners improve their outcomes. This chapter is a compilation of those leverage points and, therefore, might not follow a logical narrative flow but could serve as reference of distinct findings from our analysis. Although outside the scope of our original project description, we identify these leverage points in the hope they will benefit DoD by guiding policy and process improvements that could improve weapon system outcomes.[1] These leverage points should also assist practitioners employing SEEF in selecting appropriate digital engineering activities and establishing the risks for the respective activities.

Rigor

DoD's goal above all else is to protect the nation. In the interest of achieving that goal, the department innovates, designs, and manufactures systems, many with lethal capability. At the same time, those systems must reflect the very best possible levels of precision, safety, and dependability. U.S. lives and allied lives depend on it. In other words, engineers (Box 5.1) who are engaged in DoD development must leverage the key aspect of scientific principles from the definition: rigor.

BOX 5.1

Engineer

An engineer is a person whose job is to design or build machines, engines, or electrical equipment, or things such as roads, railways, or bridges, using scientific principles.

SOURCE: Quoted from Cambridge Dictionary, "engineer," webpage, undated.

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[1] For more depth on leverage points in systems, see Meadows, 2008, Chapter 6.

Rigor, the use of empirical methods that are evidence-based, reviewable, and reproduceable in making engineering decisions, should be a key leverage point in the DoD application of digital engineering. Rigor, wherever and whenever possible, should not be optional. To state or imply that something is better than something else, or that an approach is an improvement over established practice is important information for the stakeholder, be they warfighter, policymaker, or taxpayer—if that statement is backed rigorously.

The conclusion of the 2018 Department of Defense Digital Engineering Strategy clearly states "sectors of private industry and engineering centers in the DoD have embraced this transition, implementing digital engineering activities to great benefit."[2] This statement in a policy document implies rigor: discernable cause and measurable effect.

Axiologically, many factors might engage to contradict the use of rigor. In DoD, cultural avoidance of risk might mean not empirically documenting a risk taken to obfuscate any accounting. The DoD acquisition process depends on risk management, so offerors might deal with risk in a nebulous fashion rather than rigorously to improve their perceived position, also known as marketing. Authors might suppress rigor to improve the impact of their published work, implying success without empirical evidence. We report extensive absence of rigor in the published digital engineering and MBSE literature relating to DoD efforts—even in papers that presented empirical outcomes from the use of digital engineering and MBSE—see Chapter 2 and Appendix D.

Rigor in Publications—An Example

As a leading example, referenced by many in the digital engineering community with whom we spoke in 2023, consider the article published in the INCOSE journal *Systems Engineering* in 2020 by Edward B. Rogers III and Steven W. Mitchell of Lockheed Martin entitled "MBSE Delivers Significant Return on Investment in Evolutionary Development of Complex SoS."[3] This paper relies on, through three tiers of references (that is, publications referencing the results of other publications that reference the results of still other publications), manuscripts describing rigorous work on software defect costs by Barry Boehm in the 1970s and published in the 1980s. We note the following: (1) The practice of software development has evolved significantly since the 1970s, making the premises of the originally cited work no longer valid, ergo some of the conclusions of the subsequently cited work are equally invalid. (2) The assumptions of the original model by Boehm are lost in the temporal layers of cumulating citations, reflecting both a lack of rigor and a risk emblematic of reusing models. (3) Software defect costs, although once a measurable metric for software performance, are no longer considered useful metrics for software development and not useful metrics for the cost or benefits of a systems engineering process.[4] (4) The conclusion we derive from the promi-

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[2] DoD, 2018, p. 25.

[3] Rogers and Mitchell, 2021.

[4] Waste is a current metric for software development. See, for example, Whitehead et al., forthcoming.

nence of this manuscript in the digital engineering community is a need for greater knowledge of systems engineering practice among stakeholders (i.e., absorptive capacity in DoD).

Absorptive Capacity

Deriving from the need for rigor in digital engineering is the factor of absorptive capacity (Box 5.2). The benefit of the models, access, data, and intellectual property over the life cycle is a function of the government's absorptive capacity. The government's ability to include direct-hire (and uniformed), decision-level understanding and wisdom in a program and through the top of the command chain is, according to academic research, closely related to program risk.[5]

A key aspect of the DoD Digital Engineering Strategy (and how some services are approaching digital engineering) is the full, unhindered government access to all data, models, and simulations via a Government Reference Architecture or ASoT. Although this concept theoretically reduces the information asymmetry between government and contractors in the development process, the actual benefit of this access during the weapon system design phase would necessarily be a function of the government's absorptive capacity. In the most general terms, making constructive use of the most-detailed scientific and engineering data and models of a weapon system development requires a level of understanding and wisdom commensurate with the critical technology. The costs of providing the government with that access would necessarily need to be weighed against the government's ability to understand and wisely act thereon. For the government to actively engage in and benefit

BOX 5.2

Absorptive Capacity

The ability to exploit external knowledge is thus a critical component of innovative capabilities. We argue that the ability to evaluate and utilize outside knowledge is largely a function of the level of prior related knowledge. At the most elemental level, this prior knowledge includes basic skills or even a shared language but might also include knowledge of the most recent scientific or technological developments in a given field. Thus, prior related knowledge confers an ability to recognize the value of new information, assimilate it, and apply it to commercial ends. These abilities collectively constitute what we call a firm's 'absorptive capacity.'

SOURCE: Quoted from Cohen and Levinthal, 1990.

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[5] Wesley M. Cohen and Daniel A. Levinthal, "Absorptive Capacity: A New Perspective on Learning and Innovation," *Administrative Science Quarterly*, 1990, pp. 128–152.

from that level of information and knowledge transfer, a significant level of program-relevant understanding and wisdom on the part of the government is required.[6]

Our study of DoD literature and the digital engineering materials of the respective services has revealed no consideration of absorptive capacity or the concept behind absorptive capacity in weapon system development, acquisition, digital engineering, or MBSE. There are, as yet, unstudied cost, schedule, and performance risks associated with insufficient levels of government absorptive capacity. Consider, for example, a digital, continuous design review-type environment in which every change of government stakeholder leads to changes, however minor, in design or philosophy, resulting in an environment of perpetual scope creep. An unbounded digital transformation culture without adequate absorptive capacity could lead to less-than-optimal decisions facilitated by the access and tools of digital transformation.

Using Russ Ackoff's data, information, knowledge, understanding, and wisdom hierarchy, we provide a notional mapping of digital engineering and absorptive capacity in Figure 5.1. Arguably, the delineation between digital engineering and absorptive capacity is not quite as distinct as portrayed in Figure 5.1., but artificial intelligence and machine learning have not replaced human judgment quite yet—at least not in the digital engineering paradigm. The digital engineering tools can only answer the how-to questions that the humans have designed them to answer.

It is very important to conflate absorptive capacity neither with training nor with maturity. In the most general terms, resolving absorptive capacity issues might be a form of workforce development, but the goals must be long-term, strategic, and extend up the chain of command to include educated, informed, and experienced leadership. In other words, improved absorptive capacity requires institutional changes that likely include less outsourcing of knowledge and a shift in culture. It is also very important to not conflate systems engineering with computer science. As stated earlier, in computer science, models interchange and function as deterministic black boxes that can be readily interchanged or combined. Systems engineering includes the understanding that respective engineering models include different goals behind their respective design, varied assumptions that were made to accommodate modeling limitations, different sources of and impacts from risk, and an understanding of the importance of stakeholder organization absorptive capacity.

Figure 5.1. also helps convey the importance of the people in digital engineering. As before in the KPP case study, the government workforce is both the apex and the foundation of achieving the underlying digital engineering goals of better development, engineering, acquisition, and sustainment.

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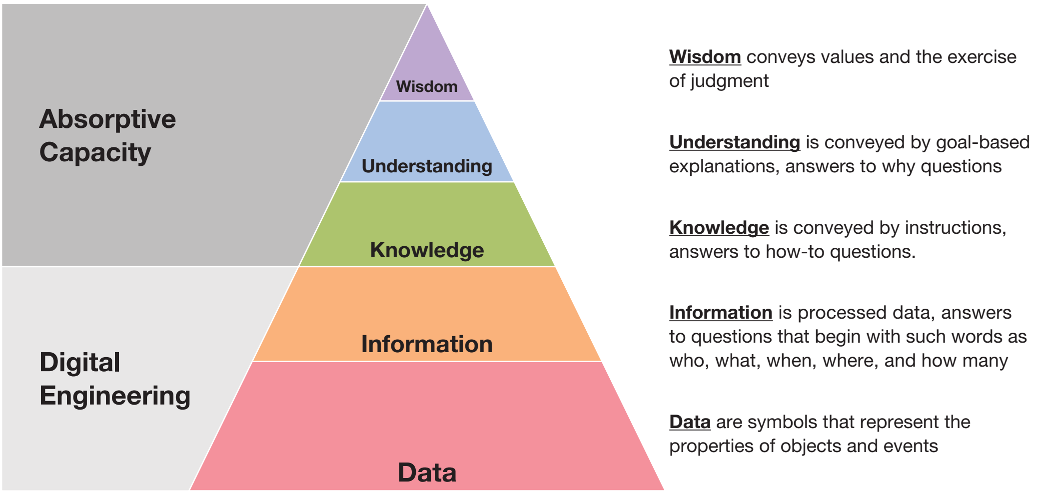
[6] Excluding FFRDCs and SETA support. Those add an additional layer of information asymmetry. Yu-Shan Chen, Ming-Ji James Lin, and Ching-Hsun Chang, "The Positive Effects of Relationship Learning and Absorptive Capacity on Innovation Performance and Competitive Advantage in Industrial Markets," *Industrial Marketing Management*, Vol. 38, No. 2, February 2009; Anker Lund Vinding, "Absorptive Capacity and Innovative Performance: A Human Capital Approach," *Economics of Innovation and New Technology*, Vol. 15, No. 4–5, 2006.

FIGURE 5.1
Absorptive Capacity in DoD Digital Engineering



SOURCE: Adapted from Russell L. Ackoff, "From Data to Wisdom," *Journal of Applied Systems Analysis*, Vol. 16, No. 1, 1989.

The Digital Twin Concept and Terminology

In the above discussion on absorptive capacity, we reference Cohen and Levinthal, 1990, who emphasize the requirement for a common language among stakeholders. In many ways, the digital twin concept offers an example of a departure from a common language—and therefore risk of nonrigorous engagement. The lack of a concise ontology for digital engineering allows for multiple interpretations of the term *digital twin*, ranging from an engineering model to a digital representation of a physical system that is accurate at a *twin* level of fidelity—however that might be defined. It might lead to confusion, or it might lead to flexing the definition to suit the stakeholder. In essence, digital twins as a nebulous concept are a departure from rigor.[7]

As discussed at length in the analysis of Chapter 2, practitioners lump a myriad of concepts into the category of digital twin. Some digital practitioners espouse the ability of the perfect model to tell stakeholders all that there is to know about a weapon system, the concept of the digital twin of a physical system. Building such a model will show the designers and engineers aspects of a system that they had not known before.[8] The aspirational perspec-

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[7] A reviewer of this report stated: "It is not just that the concept is vague and ill-defined, it is also that we are using new-found jargon for otherwise well-understood terms."

[8] As an aside, this concept circles back to the origin story of UML as a model-based approach to building software. As described elsewhere in this report, it turned out that the work to make the UML models sufficiently accurate was greater than the line-by-line coding approach to building software. We might posit that the same might be true about building arbitrary digital twins versus classical engineering models.

tive reflected in the use of this digital twin concept lacks the rigor that DoD needs to effectively execute its vital mission. In critical ways, the concept ignores a legacy of scientific and engineering discourse and practice dating back millennia. As referenced in Chapter 2, if a near-perfect simulation of a single example of a weapon system could be built, the amount of processing power and data storage would make that model prohibitively expensive to own and operate.

If the term *digital twin* serves merely as a synonym for engineering model, which is what we observed in the literature describing actual practice, we suggest not adding confusion or hype to the weapon system program with new terminology for established concepts. *Engineering model* is a term that is understood, consistent, and has stood the test of time. It conforms with the need for rigor in digital engineering.

As stated in the introduction of this report and elaborated on in Chapter 4, virtualization benefits a program only if virtualization is associated with program goals and designed to support a decision process. For example, the virtualization of an aircraft that is suitable to present a new concept to an audience, what filmmakers might call visual effects or VFX, has minimal characteristics that make that simulation useful in any other context, such as engineering design, training, or operations.

Models cost money.[9] Good engineering dictates that any model be rigorously designed with specific goals in mind—generally to compare engineering alternatives, to assess potential designs, and to validate engineering concepts. In that context, as shown in the SEEF process, decisions can be made that include the cost of the model and the benefits to the weapon system. In the broader DoD context, some technical factors derive from policy directives and, therefore, might require additional traceability or demonstration.

Modular Open Systems Approach

As an example of rigor in digital engineering practice, a policy-driven technical factor in a weapon system program, such as MOSA, should be traceable throughout the program artifacts and readily accessible. How might that look in the digital engineering world—or as a digital twin?

MOSA involves, at a minimum, the following potential engineering applications of modeling and simulation activities if we are to fully simulate the function as in a digital twin:

1. network architecture
2. data link physics
3. circuit design
4. mechanical design
5. physical and material properties of links

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[9] "No bucks, no Buck Rogers" (Tom Wolfe, *The Right Stuff*, Farrar, Straus, and Giroux, 1979). The risk from a model is a probabilistic cost, never zero as no model is perfect, as discussed in Chapter 4.

6. connectors
7. interfaces
8. manufacturing simulation
9. supply chain analytics
10. human factors of manufacture
11. installation
12. maintenance.[10]

There are therefore at least 12 possible models and simulations to describe MOSA in all or part of a weapon system—plus the cross-integration thereof, including the engineering variables database and the balance of an authoritative source of truth.[11] Naturally, each of these comes at an additional cost to the program. We infer that the concept of a near-digital twin of just the MOSA characteristics of a weapon system would be extremely complex, expensive, time-consuming, and of indeterminate value to weapon system goals as an exercise by itself.

Implying that any model, simulation, or compilation thereof is so comprehensive as to be able to support all design, acquisition, engineering, production, training, operation, and maintenance of a weapon system would be misleading and even naïve.

Lack of Metrics

In an Agile software development–themed environment, lack of rigor is the rule, as is a lack of most metrics that are not Agile-related (e.g., backlog). That software developer mental model has dominated much of the digital engineering and MBSE practice and manifested in the lack of metrics. In our interactions with digital engineering practitioners, we often heard accounts of Agile tasking and workflow in weapon system programs and the execution of MBSE and digital engineering.[12] We have attempted to resolve the need for empirical quality measurement in our work, as documented in Chapter 4, but that work requires testing and refinement in practice to become truly rigorous, useful, and lead potentially to better outcomes.

Rigor and the Underlying Goals for Digital Engineering

In terms of strategic goals, the literature and directives avoid rigorously aligning digital engineering goals with DoD acquisition, sustainment, research, or engineering goals in whole or in part. Much of the material alludes to or clearly states that digital engineering will help the

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[10] Cardinal not ordinal numbered.

[11] This statement omits the different aspects of *describes*—e.g., design alternatives, operational functionality, thermal properties, power consumption, ad nauseum.

[12] We note the paradox from the MBSE foundational concepts being a waterfall software development, predating Agile.

United States be better prepared to confront China and other timely strategic points of policy reference.[13]

For example, the OUSD(R&E) National Defense Science and Technology strategy states that:

> National Defense Science and Technology strategy for the Department of Defense (DoD), [to be] informed by the 2022 National Defense Strategy (NDS) and structured around three strategic pillars: mission focus, foundation building, and succeeding through teamwork. This technology strategy will chart a course for the United States' military to strengthen its technological superiority amidst a global race for technological advantage.
>
> The OUSD(R&E) will develop critical technologies, rapidly prototype them, and conduct continuous campaigns of joint experimentation to improve on those technologies and deliver capabilities. More swiftly transitioning technology from invention to successful fielding will require changes across the Department. The OUSD(R&E) will support reforms to the Department's resource allocation processes and will pursue novel mechanisms and alternative pathways to rapidly field technologies. The OUSD(R&E) will engage a community of stakeholders to work to develop appropriate pathways to field relevant technologies supporting required joint warfighting capabilities.[14]

We concur with these National Defense Strategy goals and their actionability where digital engineering and other advanced acquisition activities are pursued via the practice of good systems engineering through scientific and mathematical rigor and weapon system goal-focused means.

In the pursuit of that rigor, DoD should establish a clear goal hierarchy for achieving it. For example, among the hierarchical goals of digital engineering are the replacement of paper communication with electronic communication, be it via electronic documents, databases, or models and simulations. DoD needs to delineate (perhaps through the DoD 5000 series or through repeatable contractual means) exactly how digital contract data requirements lists (CDRLs) are to be transmitted and delivered at respective classification levels.[15] Spelling this out clearly now will permit inclusion in future weapon system contracts and reduce the possibility of data vacuums as the Joint Program Office is experiencing with the F-35.[16] The U.S. Government Accountability Office also specifies the need for a succinct plan (hierarchical

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[13] Kyle J. Hurst, Steven A. Turek, Chadwick M. Stelpp, and Duke Z. Richardson, *An Accelerated Future State*, Air Force Materiel Command, undated.

[14] Heidi Shyu, "USD(R&E) Technology Vision for an Era of Competition," memorandum, Under Secretary of Defense for Research and Engineering, February 1, 2022.

[15] Things change quickly and this might be dated, but an examination of the criteria for CDRL delivery as of late 2023 reflect physical delivery via registered mail to a physical address spelled out in the contract.

[16] Steve Trimble, "The Weekly Debrief: No Easy Fix For F-35 Sustainment Cost Problems, GAO Says," *Aviation Week and Space Technology*, September 25, 2023c.

goals) for data and intellectual property related to sustainment in the F-35 program.[17] This need extends across all weapon system development. As a critical part of the digital engineering paradigm, DoD needs to develop an operational framework for establishing these hierarchical goals for data and intellectual property at the earliest possible stages of a weapon system development and acquisition.

The Risks of MBSE and Digital Engineering in DoD Practice

> On s'engage et puis on voit![18]
>
> You Can't Wait for ROI to Justify Model-Based Design and Analysis for Cyber Physical Systems' Embedded Computing Resources.[19]

In English, Bonaparte's quote translates to "let's attack first and then decide what to do next." This has been a *modus operandi* of many software developers for almost as long as there has been recorded code. Let us start coding and see what happens next. This approach has proven itself time and again to lead to problems, costs, and rework—yet it transmutes directly into the concept of building a model first in an engineering approach, as exemplified by Schenker and Hugues. They argue that much more needs to be done in advancing the model-first paradigm—but admit that the decision to do so rests on "a leap of faith."[20] Their prescription to ignore the cost-benefit perspective runs orthogonal to all industry practice that we observed, in which justifying investment requires some proof in the form of evidence that the investment will return benefits.[21]

Studies reflecting the benefits of systemic planning before doing in systems engineering form the core of modern practice and proven success.[22] The goal definition process described in Appendix C (including stakeholder scenarios and a study of alternatives) at the very least need to precede any modeling and then inform decisions about the alternatives.

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[17] U.S. Government Accountability Office, *F-35 Aircraft: DOD and the Military Services Need to Reassess the Future Sustainment Strategy*, GAO-23-105341, September 21, 2023b.

[18] Napoleon Bonaparte, 1815, as quoted in Alessandro Barbero, *The Battle: A New History of Waterloo*, Bloomsbury Publishing USA, 2009, p. 11.

[19] Alfred Schenker and Jerome Hugues, "You Can't Wait for ROI to Justify Model-Based Design and Analysis for Cyber Physical Systems' Embedded Computing Resources," Carnegie Mellon University, Acquisition Research Program, June 1, 2023.

[20] Schenker and Hugues, 2023, p. 213.

[21] The concept of return on investment (ROI) is contextually a financial industry expression of profit returned from investment. As DoD and the respective services do not have profit as a goal, the perspective of cost-benefit that we have leveraged is more accurate in this context.

[22] Shaw, 1994.

MBSE policy derives from a software development tool, UML, that was created to replace line-by-line coding with object-oriented architecture development. UML was a labor-saving device for coders whereby objects—effectively blocks of reusable code—would facilitate coders' efforts by reducing the necessary typing. (A leap of faith was required to assume that a coding tool could become an architectural foundation for systems engineering; we might assume that some confusion of software engineering with systems engineering might have taken place.)

We note here and analyze in some depth in Appendix A that when the dialect of UML known as SysML was adopted by DoD and INCOSE as the *de facto* system architecting standard over the DoDAF/System Architect that was the *de facto* prior standard, many shortcomings of the UML approach that had been documented at that time were overlooked and have continued to be overlooked as MBSE has evolved into digital engineering within DoD.[23] (The future release of SysML v.2 might address some of these shortcomings.)

We have mentioned many of these shortcomings earlier in the report, but, in general, they are included in the differences between a software architecture and a systems engineering modeling and simulation approach. For example, the interoperability of software architecture models is taken for granted, but that is not the case in systems engineering. Other examples would include consistency of metrics and units and the conceptual delineation of an architecture versus a system simulation model.

Architecture As Distinct from Modeling in Systems Engineering

In systems engineering, all models follow from engineering goals and questions. Whereas architects, be they designing a house or a cloud computing center, use architectural syntax and nomenclature that includes, by inference, the physical properties of the components in the system they are designing. Architects do not include in their architectural models a submodel or linked models of the physical stress on each and every 2 x 4 stud and 2 x 8 rafter, or of the hydrodynamics through every water pipe and valve. Cloud service architects do not include simulation models of the photons or optical transmission modes in every strand of data-carrying optical fiber. The respective properties are implied in the syntax, nomenclature, and shorthand of the respective architectural design. The physical and functional properties of the respective system components are established (and standardized) elsewhere—not in the work of the architect.

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[23] Alex E. Bell, "Death by UML Fever: Self-Diagnosis and Early Treatment Are Crucial in the Fight Against UML Fever," *Queue*, Vol. 2, No. 1, 2004; R. K. Pandey, "Architectural Description Languages (ADLs) vs UML: A Review," *Association for Computing Machinery Special Interest Group Software Engineering Notes*, Vol. 35, No. 3, May 2010; Christiane Stutz, Johannes Siedersleben, Dörthe Kretschmer, and Wolfgang Krug, "Analysis Beyond UML," paper presented at the 10th Anniversary Institute of Electrical and Electronics Engineers Joint International Conference on Requirements Engineering (RE 2002), Essen, Germany, September 9–13, 2002, pp. 215–218.

In MBSE (and digital engineering) policy, all of a system's associated models, simulations, data, and supporting analysis can be and might be linked via a single architecture model.[24] In addition, the DoD policy projects that this mega-and-meta model will be inherently useful because using it will reduce written documents, improve communication, improve the design process, and facilitate the operations and maintenance of the system. This last benefit will arrive because operators will, at some time later in the life cycle, be able to leverage predictive analytics, the basis for which originated near the conception phase of the life cycle in this mega-and-meta model.[25]

DoD practitioners and DoD-related MBSE documents emphasize this later-in-the-life-cycle predicted utility of models.[26] On the other hand, the limited evidence that we found in commercial (non-DoD) industry of MBSE-type practices required immediate evidence of the value (ROI) of the modeling activity before it could be authorized.[27]

Risks of Model Assumptions, Model Availability Heuristic, and Model Aggregation

Research shows that starting a development program with a descriptive architecture will create, albeit unintentionally, constraints on the scope of the system and therefore limits on the design.[28] Although these limits were unintended, they nonetheless will affect system performance and mission, especially in the complex, multi-stakeholder, multi-goal environments of the defense industrial base. As models are transferred from entity to entity, contractor to government, or contractor to supplier, for example, assumptions will be made that the transmitting entity understood something better, and, therefore, the model is to be trusted—when that assumption might not be correct.

A foundational concept of the science of behavioral economics, the *availability heuristic*, plays a role in MBSE where stakeholders and engineers focus on the most current or available

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[24] U.S. Department of Defense, 2018. In some DoD and military service digital engineering dialects, terms might include *authoritative source of truth* or the *government reference architecture* to refer to policy-driven structures for aligning data and model.

[25] U.S. Department of Defense, 2018; Roper, 2021.

[26] Hardy, 2006.

[27] Robert Cloutier, Brian Sauser, Mary Bone, and Andrew Taylor, "Transitioning Systems Thinking to Model-Based Systems Engineering: Systemigrams to SysML Models," *Institute of Electrical and Electronics Engineers Transactions on Systems, Man, and Cybernetics: Systems*, Vol. 45, No. 4, April 2015; Rogers and Mitchell, 2021; Alex Boydston, Peter Feiler, Steve Vestal, and Bruce Lewis, "Architecture Centric Virtual Integration Process (ACVIP): A Key Component of the DoD Digital Engineering Strategy," *Proceedings of 22nd Annual Systems and Mission Engineering Conference*, September 1, 2019.

[28] Sijia Meng, "Availability Heuristic Will Affect Decision-Making and Result in Bias," paper presented at the 3rd International Conference on Management Science and Innovative Education, November 2017.

aspects of the model before them, to the ignorance of all else.[29] Thus, the model itself becomes a very real limit to both innovation and to meeting the needs of the warfighter.

It is important to consider the real-world conditions, in which most teams working on the architectural models will be very busy and will willingly assume that someone else did the homework, made the required calculations and decisions, validated the model and the model assumptions, and validated them correctly. DoD practitioners with whom we spoke to inquire about steps taken to mitigate these concerns, including the cadre of people studying and practicing model-based acquisition, deny that these and other aspects of constraining the model are risk factors or important considerations.

Knowledge Gap in Model Aggregation for Digital Engineering

This analysis found a gap in the study of risks from model aggregation as they derive from the practice of digital engineering. Assembling multiple models or simulations into a greater whole has not only been studied in detail but has led to a few Nobel Prizes.[30] There might be very important lessons to be learned from the esoteric details of such topics as Arrow's Impossibility Theorem and rank reversal in decision support derived from combined and aggregated models. It is possible that risk from model aggregation might include scenarios in which the least optimal outcome for a system design dominates. We do not make that conclusion, merely highlight the possibility using prior work and a corresponding need for new study.

Evidence of Risks

Causality can be difficult to show when it comes to design and engineering methodologies, and many logical reasons dominate the decision by management to not explore whether a methodology contributed to a failure but rather to dedicate resources to fixing the engineered system. However, in the spirit of engineering where failure is neglecting to learn from mistakes, many historical engineering failures involved digital engineering principles of modeling and architecture at some level and might offer opportunities to learn and improve the community of practice. These examples include the C-17 development program, the F-35 development and production program, the 737MAX development and production program, the T-7A development and production program, the Starliner reusable spacecraft program, the trans-service hypersonics programs, the KC-46A refueling vision system development and production program, and the E7A development program.

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[29] Daniel Kahneman, *Thinking, Fast and Slow*, Farrar, Straus and Giroux, 2011.

[30] Hazelrigg, 2012, p. 227. Tip of the purple RAND hat to Kenneth Arrow and his legion of former graduate students.

Most recently, at the time of this draft (June 2023), a 737 manufacturing glitch was attributed to flawed digital design communication between Boeing and Spirit AeroSystems.[31] (Boeing and Spirit's digital engineering approaches were cited as exemplary in the Air Force Materiel Command document *An Accelerated Future State* one month after the May 10, 2023, *Aviation Week* article on the digital engineering and manufacturing failures.[32]) Such an example is relevant because the airframe is used in military applications and the digital engineering processes behind the issue might be tied to the probabilistic costs resulting from the problem. In the DoD weapon system program environment, a program manager and a systems engineer should understand whether there is relevant risk to be considered from this information—and any relationship to digital engineering practice.

We do not conclude that digital engineering led to these issues. We surmise that good systems engineering practice includes learning through analysis what contributed to system failures, be it engineering, management, communications, or something else, and adding that knowledge to the cumulative, community practice of risk mitigation. Logically, that community practice of systems engineering should then be leveraged directly into the practice of digital engineering policy to reduce risks.

Assumptions that digital engineering will inherently reduce risk have been presented without substantiation. As an example, the conference paper "Insights from Large Scale Model Based Systems Engineering at Boeing," which features a bow-tie plot indicating that more MBSE is better, is shown in Figure 5.2. No data, no rigor, just better.[33] The implication by inference is that MBSE reduces risk, resulting in fewer problems. We caution that such conclusions themselves add system risk because they influence decisionmaking without empirical evidence.

SysML Associated Risks

Problematically, MBSE does not use methodologies that are themselves inherently rigorous. First and foremost is the choice of SysML v.1 (to distinguish from SysML v.2 in this section) as

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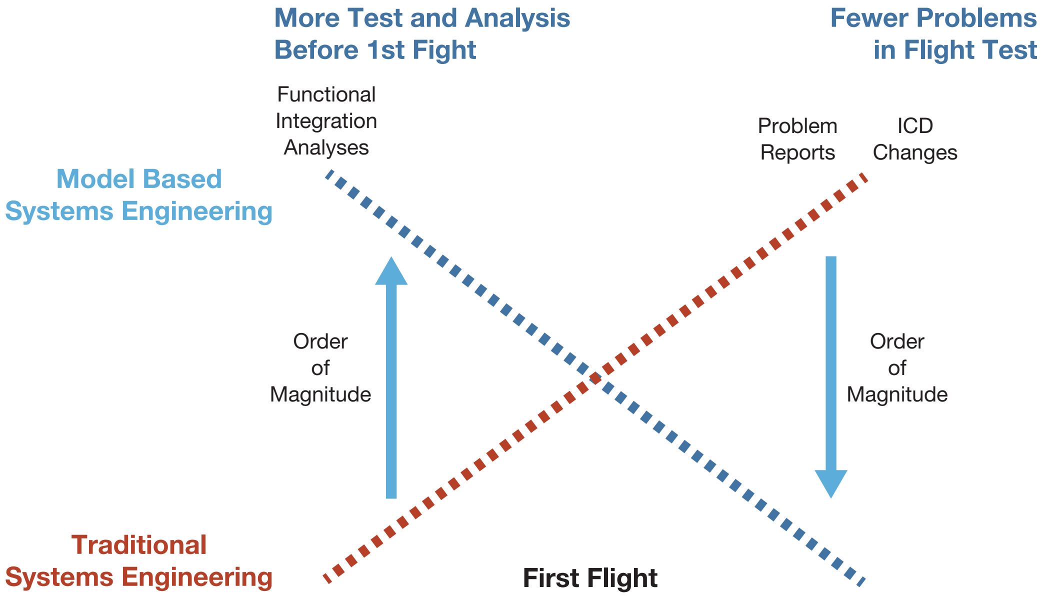
[31] Hazelrigg, 2012, p. 227; Jeremiah Gertler, *F-35 Joint Strike Fighter (JSF) Program*, Congressional Research Service, RL30563, February 16, 2012; De Oliveira Dias and De Oliveira Albergarias Lopes, 2020; Steve Trimble, "Fast-Tracked U.S. Air Force T-7A Slowed by Ejection Seat Issues," *Aviation Week*, May 3, 2023a; Kenneth Chang, "Boeing Starliner Flight's Flaws Show 'Fundamental Problem,' NASA Says," *New York Times*, February 7, 2020; Steve Trimble, "U.S. Hypersonic Push Exposes Deep Industry, Testing Gaps," *Aviation Week*, May 17, 2023b; Valerie Insinna, "Boeing to Take Charges on KC-46 Tanker over Quality Issue —Finance Chief," Reuters, March 22, 2023; Brian Everstine, "How Soon Can U.S. Air Force's E-7A Rapid Prototype Be Ready?" *Aviation Week*, May 16, 2023; Sean Broderick and Michael Bruno, "Spirit AeroSystems Outlines Latest Boeing 737 Disruption," *Aviation Week*, May 10, 2023.

[32] Hurst et al., undated.

[33] Robert Malone, Brittany Friedland, John Herrold, and Daniel Fogarty, "Insights from Large Scale Model Based Systems Engineering at Boeing," paper presented at the 26th Annual International Council on Systems Engineering International Symposium (IS 2016), Edinburgh, Scotland, United Kingdom, July 18–21, 2016.

FIGURE 5.2

Avoiding Test Errors Through Early System Architecture Modeling



SOURCE: Reproduced from Malone et al., 2016, Figure 4.

the tool used most often for architectural and descriptive modeling.[34] SysML v.1 is a 27-plus-year-old approach to object-oriented software design.[35] The architecture structure of SysML v.1 and the corresponding licensed tools do not require interconnected variables, values, equations, or engineered integration balancing—unlike most established systems modeling approaches, such as Simulink, Stan, iThink, Stella, and what we have heard about as-yet-unreleased SysML v.2. This lack of rigor leaves the interconnection of the system components to the discretion of the modeler and allows for errors that might propagate throughout the system model and the design.

SysML v.1 has no inherent probabilistic, Bayesian, stochastic, time series, or event series capability, a critical set of dimensions in systems modeling for systems engineering. It also is not inherently secure. As an open-source product that has been around a very long time, a lot of developers have touched it, including those in countries the United States considers adver-

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[34] This work is being done without access to SysML v.2, which might rectify any or all the issues we raise in this section.

[35] When asked why they use SysML, several stakeholders responded that it was the tool they were told to use or that—for the designated purpose of system architecture modeling—it was the best available tool. When the shortcomings of SysML were pointed out, the stakeholders were unaware of better modeling approaches.

saries.[36] Our analysis has not revealed any thorough cybersecurity analysis or mechanism to certify or maintain certification of SysML v.1 among any of the users or services—though it might exist and be classified beyond the scope of our work.

SysML v.1 does not lend itself to multi-level classification (MLC) or the distribution of MLC over a working supply chain network. On a certain ACAT I program, the MLC factor has required multiple distinct classified systems for SysML v.1 be constructed at different physical locations at program cost. Such costs might be bearable for very large programs, less so for smaller ones, though they might have similar security requirements.

Note that we are unaware of any studies on the long-term maintenance over time and the declassification protocols for MLC data capabilities. What, for example, happens to the data when the format and relevant tools are outdated and unavailable?

As mentioned previously, a discussion with an engineer at a major car manufacturer that uses SysML v.1 for architectural design analysis revealed that this commercial use is for software mapping. In that scope, SysML v.1 had saved the company money during the maintenance phase by revealing previously hidden vehicle software defects in sold vehicles. To reiterate, a software development approach was leveraged to find software defects that saved the corporation on warranty repair costs.

We see systemic risks resulting from overconfidence in the utility of specific MBSE and digital engineering tools, including SysML, along with a thriving ecosystem in the defense community to promote the continued use of those tools.

Fortunately, we also see efforts in the digital engineering community and DoD to rectify parts of this scenario, such as SysML v.2, and we support all constructive work in that direction.

Summary

Digital engineering, practiced as part of a larger systems engineering approach, requires maintaining a state of appropriate rigor to deliver data to the decisionmakers that will be useful in executing development and delivery of a weapon system. All the risks throughout the complicated array of models and simulations in the digital engineering activities affect the net system cost and must be considered in those decisions. The obligation to consider rigor and risks in digital engineering includes such systemic factors as absorptive capacity and information asymmetry across the program. Good systems engineering is hard.

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[36] Chinese publications on MBSE and digital engineering are among the higher-quality manuscripts on those subjects, generally leveraging scientific rigor, replicable case studies, and very practical applications, such as manufacturing processes.

CHAPTER 6

Conclusions and Recommendations

> Natura abhorret vacuum.
>
> Nature abhors a vacuum.[1]

The tools of simulation and modeling evolved over millennia to provide engineers and scientists with capabilities of which the prior generations could only dream. Leveraging those capabilities in weapon system development, manufacture, operations, and sustainment is not only a very good thing, but also the logical progression of engineering practice. By establishing a policy of using MBSE and digital engineering to that end, while leaving definitions and practice to the respective stakeholders, many stakeholders with diverging goals have rushed to fill that vacuum, resulting in what a key DoD stakeholder referred to as people who pretend to do digital engineering. Ergo, a need exists for clear approaches to decisionmaking in the practice of the DoD digital engineering policy. DoD needs to eliminate the vacuum. Reiterating a footnote from the introduction to this report, the nature of this analysis and the associated terminology have led us to choose the term *weapon system* for consistency. The authors wish to emphasize that the analysis and findings extend to systems that would not be described as weapons and to systems that are nonmilitary and non-DoD.

Findings

This analysis has taken a first step toward establishing clear approaches to decisionmaking in the practice of the DoD digital engineering policy. We very carefully and objectively scrutinized the current state of practice and the literature from all sources looking for clues and lessons learned. We then analyzed what we found and derived cost analysis and systems engineering-based approaches to support program decisions.

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[1] “François Rabelais Quotes, 6 Science Quotes, Dictionary of Science Quotations and Scientist Quotes,” webpage, 2024.

Literature and Interviews

Although the research literature paints a picture of extensive effort dedicated to the analysis of digital engineering, the picture is far from complete. There are several reasons why the published research and analysis on digital engineering and the associated costs and benefits remains relatively immature:

- Absent a consensus about what constitutes digital engineering, scholars and practitioners lack a common foundation on which to conduct analysis of costs and benefits.
- Tracking digital engineering investments and distinguishing them from other costs (e.g., systems engineering, multipurpose IT investments) does not appear to be a standard practice.
- The proprietary nature of industry cost structures inhibits disclosure of digital engineering costs.
- Much effort has been devoted to making the case for digital engineering by projecting possible benefits without, at the same time, evaluating costs.
- Some authors—and some services—are looking to a digital engineering maturity model as a path to improving outcomes without any cost, causal, or risk analysis to support that conclusion.

Recommendations

The following general recommendations for DoD policy result from our analysis of digital engineering practice in the DoD ecosystem leading up to the development of the frameworks:

- Develop consistency and goal-focused consensus in what digital engineering is (and is not).
- Establish clear digital engineering program goals and system boundaries to eliminate pretending.
- Collect program goal-derived data (IoPs) to support assessment of digital engineering costs and benefits.
- Eliminate aspirational and general guidance (top-down direction) for implementing digital engineering in such terms as *to the maximum extent practical*.
- Promote an environment in which digital engineering is a useful tool among many others to be used in good systems engineering practice and weapon system project management.
- Objectively analyze enterprise digital engineering tools in their operational context—e.g., how practical is expecting universal fluency in SysML (or SysML v.2) across all program stakeholders in support of project goals? If fluency is a policy goal, what are the costs?

- Promote digital engineering practice and culture where learning from mistakes is as important as achieving success. The list of DoD programs that have fallen short is long and no program is perfect. Failure is not learning from those mistakes.
- Establish policy whereby understanding and mitigating risks is a key facet of digital engineering and MBSE practice.
- Establish a roadmap for identifying and achieving absorptive capacity needs across DoD and the respective services in conjunction with the respective digital transformations. Promote understanding among stakeholders that transformation before the absorptive capacity is adequate increases program risks.
- Amend the boilerplate for the SEP to include, succinctly, text to the effect that digital engineering activities and their respective program goals are to be defined and documented in the SEP and tracked over the life cycle by the appropriate IoPs, including cost.
- Develop a framework for establishing the hierarchical goals for leveraging data and intellectual property in a weapon system program, establish criteria for standard data media across DoD for the delivery of digital CDRLs, and codify the process in regulations or data standards in conjunction perhaps with the National Institute of Standards and Technology.
- Establish DoD weapon system program life cycle decision and milestone gate criteria that include (1) the digital engineering activities engaged, (2) the decision process, such as SEEF, that was leveraged to select the respective activities, including the respective goals and KPPs affected and IoPs, (3) the risks of the respective activities, including modeling assumptions, (4) rigor in the digital engineering activity, including third party analysis of costs and benefits, and (5) the constraints that affect the respective digital engineering activities (e.g., program budget, such human factors as personnel, schedule, regulations).
- Objectively study and develop recommendations for the long-term life cycles of MLC systems, data, and infrastructures as required by many if not most digital engineering programs. Consider the long-term maintenance over time and the declassification protocols for MLC data capabilities. Establish protocols for the data when the format and relevant tools are outdated and unavailable. Establish protocols for when classified or sensitive digital engineering data are spilled, including into machine learning training data bases—e.g., plan for classified digital engineering data to show up in a Retrieval Augmented Generation system.

Future Work

Good research leads to more research. For every idea and theory, there are many more waiting in the associated research to emerge and advance the state of the art. We hope that in our open and critical approach, we have started a conversation of improving the use of DoD resources in digital engineering. The work in this report is intended to be used, and the actionability cannot be determined or refined in a vacuum. The next phase of the frameworks effort should be to try our approaches on case study DoD weapon system programs and refine them.

There is a need for aligning program cost analysis with digital engineering practice. We have heard from some stakeholders that this could be a useful way to improve cost estimation, analysis, forecasting, and other program decision support tools. There are many concepts of interest here including modeling work breakdown structures and cost estimation directly into design architectures, modeling supply chains and predicting disruption costs, studying the levels of investment required to adequately understand supply chains and supply chain risks through digital engineering activities, and, as we detailed in this report, modeling weapon system sustainment and the associated costs.

Many new analyses would be useful for DoD policy, including focused analysis of how digital engineering does the following:

- operationally applies in the Industry 4.0 paradigm across sustainment functions in the respective services
- supports and improves developmental test, evaluation, and assessments
- supports and improves training and operations
- supports and improves logistics, manufacturing, and all levels of supply chains
- addresses the leverage points (rigor and risks) described in Chapter 5
- supports decisions for acquiring data and intellectual property over the program life cycle.

There is a need for critical analysis of model-based acquisition. The risks of some of the approaches are significant and are being broadly ignored. Analysis of and publication of these risks can only improve practice. There is a need to analyze and codify lessons from past digital engineering–like practices in DoD and aviation, starting perhaps with the C-17 development and acquisition. There is a need to reconcile digital engineering with advanced development practices, such as minimally viable products. Digital engineering is founded on waterfall principles. Do we modify digital engineering approaches to better accommodate the adaptive acquisition framework?

Absorptive capacity presents a critical area ripe for analysis and policy. DoD is a highly process-oriented agency, relying on repeatability where workforce considerations are difficult to pin down. Can highly complex technology weapon systems be effectively managed through a life cycle that way, or should other approaches to absorptive capacity come to bear? As we mention in Chapter 5, absorptive capacity levels in a program and program risk go hand in hand—though we do not offer a bow-tie graph.

Research and analysis leading to a framework for establishing the hierarchical goals for data and intellectual property in a weapon system program would seem to fill an important gap in the current state of practice. This might include criteria for standard media across DoD for the delivery of digital CDRLs and for continuous exchange of data. Failure to establish even the most general data guidelines might lead to a plethora of formats and additional costs.

APPENDIX A

A Brief History of Digital Engineering

The origins of the DoD digital engineering paradigm trace their lineage to the structured software architectures of the 1970s pioneered by such developers as Tom DeMarco and Edward Yourdon. These approaches spawned the concept of computer-aided software engineering tools.[1] In parallel, the paradigm of object-oriented software development evolved to where, in 1995, Grady Booch, Ivar Jacobson, and James Rumbaugh integrated multiple conventions of software engineering and architecture into UML. Their goal was to construct an object-based programming tool whereby lines of code are replaced with objects, thereby simplifying and expediting the coding process. As it turned out, UML required an extreme level of detail and effort that paradoxically made line-by-line coding more efficient, and so it failed to be adopted for its intended purpose.[2] The front-end structured approach to software development was also overshadowed by the Agile approach at the dawn of the new millennium, making architectural frameworks a tool for later documentation but not useful for the new approaches to development.

MODAF and DoDAF

Meanwhile in the UK, engineers in the Ministry of Defence developed a graphical approach to describing complex systems called Ministry of Defence Architectural Framework. By the year 2000, this had become the U.S. standard known as DoDAF, and the software tool System Architect was adopted as the industry standard for creating the multi-layered weapon system program perspectives of DoDAF.[3]

In the early-mid 2000s, a group of software architects, seeing the similarity between DoDAF and the graphical products of UML, created a dialect of UML that they called Systems Modeling Language, thus creating an open-source alternative to System Architect.[4]

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[1] Gerard O'Regan, "Ed Yourdon," in *Giants of Computing: A Compendium of Select, Pivotal Pioneers*, Springer, 2013.

[2] Bell, 2004; Pandey, 2010.

[3] U.S. Department of Defense Chief Information Officer, "The DODAF Architecture Framework Version 2.02," webpage, 2021.

[4] SysML.org, "SysML Open Source Project: What is SysML? Who created it?" webpage, undated.

SysML was adopted by a software-centric engineering organization, INCOSE, which coined the term *MBSE* to describe the use of SysML.[5] In 2006, the Office of the Under Secretary of Defense for Acquisition and Technology, MITRE, Lockheed Martin, Boeing, and others collectively aligned on the MBSE initiative as proposed by INCOSE for system architecture applications in weapon system programs.[6]

Model-Based

The term *model-based systems engineering* might catch some experienced systems engineers off-guard as all systems engineering through thousands of years of practice has been model based, making the term itself sound redundant.[7] Egyptians built scale models of pyramids to study the related mathematics, engineer their construction, and plan the required logistics.[8] Galileo developed mathematical models of the parabolic trajectory of cannon shells that proved to be highly accurate in practice.[9] Bell Labs practiced what Arthur D. Hall called *systems engineering* and defined it as "organized creative technology and its functions."[10] NASA

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[5] MBSE is "the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases" (INCOSE, *Systems Engineering Vision 2020*, September 2007, p. 15). See, also, SysML.org, undated.

[6] Hardy, 2006. Hardy writes:

> MBSE enhances the ability to capture, analyze, share, and manage the information associated with the complete specification of a product, resulting in the following benefits:
>
> - Improved communications among the development stakeholders (e.g. the customer, program management, systems engineers, hardware and software developers, testers, and specialty engineering disciplines).
> - Increased ability to manage system complexity by enabling a system model to be viewed from multiple perspectives, and to analyze the impact of changes.
> - Improved product quality by providing an unambiguous and precise model of the system that can be evaluated for consistency, correctness, and completeness.
> - Enhanced knowledge capture and reuse of the information by capturing information in more standardized ways and leveraging built in abstraction mechanisms inherent in model driven approaches. This inturn [sic] can result in reduced cycle time and lower maintenance costs to modify the design.

[7] Arthur D. Hall describes the origins of the concept that became labeled *systems engineering* at Bell labs in describing the 1940 development of the TD-2 radio relay system, "the name was new, but the functions were not." He traces *systems analysis*, which includes what we will call system goal definition later in this report, to a philosophy developed in the 1940s by the RAND Corporation. Hall adds the terms *systems thinking* and *systems approach* to the list of supporting concepts. These concepts had existed and evolved over millennia, so, although the authors use the term *systems engineering* here, it is used in a general sense to include the supporting concepts and the history of systems engineering predating 1940 (Hall, 1962, pp. 7, 26).

[8] Corinna Rossi, *Architecture and Mathematics in Ancient Egypt*, Cambridge University Press, 2004.

[9] Ronald H. Naylor, "Galileo: The Search for the Parabolic Trajectory," *Annals of Science*, Vol. 33, No. 2, 1976.

[10] Hall, 1962, p. 3.

and military engineers and program managers leveraged thousands of models in successfully putting men on the moon, giving rise to the current perceived value of good systems engineering practice in a complex program. [11]

We know from our study of the state of practice in DoD (Chapter 2 and Appendix D) that the term *MBSE* describes the leveraging of object-oriented architecture modeling, specifically SysML, as derived from waterfall, object-oriented software development practice of the late 1990s.[12] We have observed SysML used for architecture, system interface, and organizational modeling predominantly, with teams leveraging the tools for other applications as they see fit. We also know that stakeholders across DoD and the defense industrial base define the details and scope of MBSE differently.

Studies conducted by a DoD-sponsored university affiliated research center, SERC, in the 2010s worked to leverage MBSE as defined in SysML onto metamodel optimization concepts originated by such researchers as Markish and Kühne.[13] This work led ultimately to the concept of digital engineering as espoused in the 2018 policy document *DoD Digital Engineering Strategy*.[14]

Complexity

Prior RAND research has elucidated that a benefit of digital engineering policy is an improved ability to work in and with complex environments and systems. We agree with that observation. We also add, however, that working with increased complexities is a core tenet of all systems engineering practice and the evolution thereof since ancient times. The distinction between the increased application of improved modeling and simulation techniques as espoused by digital engineering and what would have been correct systems engineering practice without digital engineering policy remains nebulous and a problem when assessing the benefits of the DoD digital engineering approach. The prior RAND work also reflects where certain DoD programs that were already practicing correct systems engineering, including decision-support modeling, merely relabeled it as digital engineering to show compliance.

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[11] R. F. Miles Jr., *A Contemporary View of Systems Engineering*, Jet Propulsion Laboratory, January 15, 1974.

[12] Hardy, 2006.

[13] Jacob Markish and Karen Willcox, "Value-Based Multidisciplinary Techniques for Commercial Aircraft System Design," *American Institute of Aeronautics and Astronautics Journal*, Vol. 41, No. 10, October 2003; Thomas Kühne, "Matters of (Meta-) Modeling," *Software and Systems Modeling*, Vol. 5, No. 4, 2006.

[14] Mary A. Bone, Mark R. Blackburn, Donna H. Rhodes, David N. Cohen, and Jaime A. Guerrero, "Transforming Systems Engineering Through Digital Engineering," *Journal of Defense Modeling and Simulation: Applications, Methodology, Technology*, Vol. 16, No. 4, October 2019.

APPENDIX B

Analysis of Digital Maturity

We discussed the utility of using the metrics in the DAF Digital Maturity Guide v.2 as possible classes or categories for studying digital engineering or measuring costs or benefits. In essence, because that approach does not use systems engineering principles, we concluded that it would not be an efficient or effective approach to assessing costs or benefits in a weapon system program.

The Air Force digital maturity approach offers an organization-based set of criteria for executing the Air Force definition of digital engineering—that is, MBSE. The documentation seems to address digital engineering and MBSE interchangeably. According to the documentation, the principal question to be answered is: What are my organizational transformational objectives?[1] The maturity approach is much broader than a weapon system–specific approach but is designed to be tailored for a weapon system program through a workshop-type structure developed by Aerospace Corporation.[2]

The metrics themselves are mostly subjective and nonquantitative, using the original Office of the Secretary of Defense Digital Engineering Strategy (Table B.1). They are to be graded on a five-level Likert scale, weighed, and tallied to produce a net score using a provided Excel spreadsheet. Presumably, though it is not clearly expressed in the documentation, an organization would then work to improve that net score. Reiterating, this is not at all a systems engineering approach. The DAF Digital Maturity Guide v.2 establishes the categories of metrics and components for digital engineering listed in Table B.1.

Table B.1 depicts the maturity criteria for the digital maturity assessment as follows:

> The Digital Maturity Assessment focuses on quantifying digital engineering and management capabilities. The DAF has leveraged the International Council on Systems Engineering (INCOSE) model-based systems engineering (MBSE) Capability Matrix, which has been used and vetted in industry.[3]

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[1] Al Hoheb and Joe Hale, "Leading the Transformation of Model-Based Engineering: The Model-Based Capability Matrix," presentation slides, Aerospace Corporation, 2020, slide 2.

[2] Hoheb and Hale, 2020.

[3] U.S. Air Force, undated. The reference to industry practice is unverified, though government organizations that have leveraged the approach are listed on Hoheb and Hale (2020), slide 11. It is also unclear

The goal is an assessment tool used to characterize an organization's current and desired model-based capabilities:

> In its simplest form, a capability statement is a statement about your organization and its capabilities and skills that defines what its able to do by employing model-based effort.[4]

For the MBSE maturity matrix, the enterprise transformation goals are the following:

- Define the needed enterprise, extend, sustain, and capabilities (current and future).
- Plan to acquire capabilities across programs and systems.
- Integrate and plan their evolution.
- Perform acquisition and engineering development within resource constraints.[5]

An organization executing the assessment process systematically completes a checklist maturity matrix using Table B.1 in a half-day organizational workshop, producing a score sheet.

Context

Systems engineering and all the precursor concepts teach us that an anthropogenic system exists in context. It has a goal. Among the shortcomings manifested by other maturity model approaches, specifically capability maturity model integration and cybersecurity maturity model certification, is that they ignore system goals. Their intent is to analyze an organization, but that analysis will fall short without a correlation to the goals of the weapon system or systems.

The maturity score sheet directly reflects the DoD policy. Utility for the sheet might be deduced in that context. However, no correlation should be assumed between this maturity process or the score sheet and systems engineering, quality results in terms of any program goals, or any CBA. This is a top-down assessment of a policy, which, as we explained over the course of this report, will not necessarily be reflected in weapon system program benefits or outcomes. Our estimation is that the exercise of performing the MBSE maturity model assessment would not be a justifiable expense if the intent is to improve practice or outcomes. It represents MBSE for MBSE's sake and the presumption that MBSE is good.

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whether the entire organization referenced has leveraged the maturity approach or which entities within the organization.

[4] Hoheb and Hale, 2020, slide 6.

[5] Hoheb and Hale, 2020.

TABLE B.1

Table of Categories, Metrics, and Components

Category	Metric	Component
Infrastructure	Model environment	Tool access and governance
		Interoperability
	Collaboration	Capability
		Security
Modeling/analysis	Quality	Authoritative sources of truth
		Metrics
		Model-based verification and validation
Process/policy	Model management	Digital management strategy
		Model-based systems engineering
		Configuration management
		Process verification and validation
	Data management	Innovative technical processes
		Technical management processes
		Analysis, user interface, and visualization
Workforce/culture	Workforce	Digital user skills
		Common digital understanding
	Adoption	Digital artifact use
		Reference architecture implementation
		Milestone, program, and technical reviews; audits

APPENDIX C

Systems Engineering Goal Development

At the heart of the systems approach discussed in Chapter 4 is setting clear program goals so that all stakeholders are working toward the same end point. This appendix details the steps in to defining system goals.

Generalize the Question

Ask the most general possible question: What is required for mission success in the most general possible terms? Avoid problem statements; they focus on shortcomings in existing approaches. Translate them into goal achievement failure perspectives. If a problem statement is presented, generalize it. If the problem is that the landline phone on the desk does not work as desired, a technician replaces the desk phone. A systems engineer considers what the generalized goal is: to communicate in support of the mission. The descriptive scenario includes Microsoft Teams, Zoom, FaceTime, instant messaging, and mobile devices. The systems engineer then develops a normative scenario in which no desk phone at all is necessary, thus eliminating a complexity and an expense—a good systems approach.

Develop the Descriptive Scenario

In DoD systems, the ground state is highly complex but must be well understood to design actionable solutions. This early stage is where many DoD systems engineers will start by following waterfall software practice and begin architecting models. It is also where architecture models, by their nature, fall short of good systems analysis prerogatives because they omit many critical factors in the DoD domain and therefore unnecessarily constrain the development process.[1] Human factors, culture, command hierarchy, politics, extreme nonlinearities, Bayesian factors, information economics, behavioral economics, the axiological, observer effects, and many more critical aspects of the ground state system do not lend them-

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[1] This is a key element in the difference between systems engineering and software engineering. Architecture models can reflect software with high accuracy and are highly useful in many ways. By their nature, they omit key systems factors and therefore create working assumptions that are ignored in the design and create system risks by omission.

selves to documentation in SysML.[2] Modeling early also cognitively restricts design thinking to build on or take away from that baseline construct, where often the optimal solution might not use the baseline model at all—as in the phone example.[3] This restricting mechanism of artificial boundaries on the design through early modeling reflects the tenets of behavioral economics including the availability heuristic.[4] None of the DoD stakeholders with whom we spoke acknowledged the existence of this risk, and model-based acquisition representatives denied that it exists, yet all of the academic and commercial industry stakeholders with whom we spoke recognized it as significant.

Develop the Normative Scenario

DoD has gotten very good at engaging stakeholders in normative scenario development in recent decades. Many current complex systems programs have started with sets of user stories, vignettes, or mission scenarios during the concept phase. This scenario or user engagement approach is key to a blank sheet, innovative approach to achieving complex missions while understanding the hierarchy of the system goals. This approach needs to be separate and isolated from the descriptive scenario if a model was built because the behavioral economics of changing that model to fit the new scenario will constrict the set of solutions.

The completion of the normative scenario is the point at which system architecting should start. (All the critical systems analysis work toward goal definition has taken place temporally to the left of this point.) Architecting before the full establishment of the normative scenario constricts the design and leads to errors of omission, availability heuristics, and other undesirable effects. Models become a key tool in some aspects of the normative scenario phase and should be omitted in others for the following reasons.

Outscoping. The seminal example of outscoping in the normative scenario phase is documented in the Ackoff Navy lecture.[5] In a single meeting in 1951, by starting with goals and virtually ignoring the baseline technology, Bell Labs created the hierarchical goal structure that would define the future of telecommunications for over half a century.[6] This reflects the

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[2] The MBSE paradigm omits the importance to the system of these factors. There also is a human factors assumption in MBSE that everyone speaks fluent SysML. Our research showed that not only is that not the case, but virtually all the program organizations creating SysML had to hire outside SETA help to do so.

[3] The premise of cognitive restrictions from a baseline model is based on the engineers devoting so much time and effort to building the model that they want to see it used and become a part of the solution.

[4] Kahneman, 2011.

[5] Russell Ackoff, "Idealized Design, Systems Thinking, and a Model for Outlier Innovation," video, undated.

[6] The premise is simple, the entire phone system of the United States ceased to exist this morning—vaporized without a trace. Everything else is intact. Design a replacement. The Ackoff Navy Lectures are highly recommended for all systems engineers.

level of innovation that will be required for DoD to stay ahead of the United States' adversaries, but it also conflicts sharply with the use of SysML and the inherent limits of modeling.

Demonstrate alternative solutions to the key stakeholders. Long before a prototype is built, a digital simulation provides an economical means to get stakeholder feedback. This might be a minimally viable product of a software capability that can be readily shown on a screen, a detailed virtual reality simulation of a complex system, or anything in between depending on the solution. This is to give the user the opportunity to out scope the system further with such statements as, "did you think of X," or "what if the colonel needs Y?" Note that a SysML model might be appropriate here, but the key stakeholder very likely will not understand SysML. At this stage, SysML might be putting the cart before the horse if the objective is to provide a graphic or virtual reality demonstration early in the design process to communicate the design with the user.

Compare and contrast multiple engineering solutions to refine the design. This traces to the historical origins of systems engineering. When building a new house, one does not build multiple houses to see which one suits the buyer better; one starts with drawings and models and adapts according to design considerations and feedback. For this application, physical and mathematical models will be more useful than SysML because they readily provide the engineers with the data they need, are rigorous, and are readily comparable across different designs. SysML adds a layer of work here that might or might not be a useful allocation of resources. If the need is to reflect the integration of multiple software subsystems or objects in a complex weapon system, an architecture tool such as SysML might be exactly what is needed. If the engineering goals are physical—such as refining an aerodynamic structure, heat structure, or fuel viscosity—Simulink or another modeling tool might be more efficient and more beneficial.

Understanding system scope and life cycle. Normative scenario goals might include putting fires on targets within *X* distance, 90 percent operational weapon system availability, and conducting humanitarian evacuations with limited local logistics, but hierarchical systems goals need to include all the aspects that make the normative scenarios happen through the life cycle. Physics, hydraulics, personnel, training, human factors, electromagnetics, logistics, supply chains, environment, and a litany of other factors play roles in the design and comparison of alternatives in systems analysis. They all require their respective approaches and modeling capabilities.

APPENDIX D

Digital Engineering Activities Identified in the Literature

This appendix contains a series of tables that summarize digital engineering activities identified in the literature. Each table lists activities for which digital engineering has been used or proposed, the associated reference, and, if applicable, the organization or program that carried out the activity. In some cases, we group activities by similarity (e.g., requirements development and requirements management), but most activities are listed as identified by the source. Table D.1 focuses on MBSE, Table D.2 focuses on digital twins, Table D.3 focuses on digital threads, and Table D.4 focuses on the combination of MBSE, digital twins, and digital threads.

TABLE D.1

Activities Implemented Using MBSE

Activity	Reference(s) (Organization/Program)
Concept exploration, definition, analysis, and maturation	Carrol and Malins, 2016 (industry/multiple); Hale et al., 2017 (Department of Homeland Security (DHS)/U.S. Customs and Border Patrol, NASA Europa Mission, NASA Asteroid Redirect Robotic Mission)
Requirements development and management (including tracing requirements)	Carroll and Malins, 2016 (industry/multiple); Hale et al., 2017 (DHS/U.S. Customs and Border Patrol, Federal Aviation Administration); Cole et al., 2019 (Tactical Assault Light Operator Suit); Zimmerman et al., 2019 (Sentinel, Modular Active Protection System); Rogers and Mitchell, 2021 (Submarine Warfare Federated Tactical Systems [SWFTS]); Bayer et al., 2021 (Jet Propulsion Laboratory/Europa Clipper Project)
System integration and validation	Hale et al., 2017 (Federal Aviation Administration)
Design management and reuse	Carroll and Malins, 2016 (industry/multiple); Cole et al., 2019 (Tactical Assault Light Operator Suit); Zimmerman et al., 2019 (A-10 wing replacement); Rogers and Mitchell, 2021 (SWFTS)
Develop test and evaluation framework	Cole et al., 2019 (Tactical Assault Light Operator Suit)
Support test and integration/qualification	Carroll and Malins, 2016 (industry/multiple); Cole et al., 2019 (Tactical Assault Light Operator Suit)
Verification and validation	Carroll and Malins, 2016 (industry/multiple)

Table D.1—Continued

Activity	Reference(s) (Organization/Program)
Using MBSE to furnish government information and capture industry response	Schenker et al., 2022 (Army Joint Multi-Role Mission System Architecture Demonstration)
Architecture development and management	Zimmerman et al., 2019 (Modular Active Protection System); Bayer et al., 2021 (Jet Propulsion Laboratory/Europa Clipper Project); Rogers and Mitchell, 2021 (SWFTS)
Architecture modeling, simulation, and evaluation	Soegaard, 2016 (Joint Strike Missile); Younse and Bradley, 2022 (Mars Sample Return)
Simulations to verify performance, optimize configurations, characterize component interactions, and perform other assessments and evaluations of system components and sub-components	Maurandy et al., 2012 (Atomic Clock Ensemble in Space); Cole et al., 2019 (Tactical Assault Light Operator Suit); Zimmerman et al., 2019 (A-10 wing replacement); Bayer et al., 2021 (Jet Propulsion Laboratory /Europa Clipper Project); Younse and Bradley, 2022 (Mars Sample Return)
Support integration of hardware and software	Cole et al., 2019 (Tactical Assault Light Operator Suit)
Interface definition, management, and verification and validation	Hale et al., 2017 (NASA Engineering and Safety Center); Zimmerman et al., 2019 (SWFTS, Modular Active Protection System)
Analysis management	Rogers and Mitchell, 2021 (SWFTS)
Automate generation, reuse, and management of systems engineering documentation	Mitchell, 2014 (SWFTS)
Web-based reporting	Bayer et al., 2021 (Jet Propulsion Laboratory/Europa Clipper Project)
Provide a shared repository for capturing technical history, decisions, knowledge, etc.	Mitchell, 2014 (SWFTS)
Integrate systems engineering processes and products	Bayer et al., 2021 (Jet Propulsion Laboratory/Europa Clipper Project)
Automate systems engineering tasks	Mitchell, 2014 (SWFTS)
Systems engineering technical review management	Hale et al., 2017 (NAVAIR)
Modeling “everything” to demonstrate the art of the possible	Blackburn et al., 2022 (NAVAIR Systems Engineering Transformation)
Margins analysis	Carroll and Malins, 2016 (industry/multiple)

Table D.1—Continued

Activity	Reference(s) (Organization/Program)
Proposed Activities	
Using models to support solicitation, for system specification, and to communicate concepts and requirements	Boydston et al., 2019 (Army Joint Multi-Role Mission System Architecture Demonstration)

TABLE D.2

Activities Implemented or Proposed Using Digital Twins

Activity	Reference(s) (Organization/Program)
3D models to automate fabrication and assist labor, laser scan parts for reference, monitor inflight data to inform maintainers	West and Blackburn, 2018 (Lockheed Martin)
Laser scan parts to identify nonconformity, report trouble codes inflight to maintainers	West and Blackburn, 2018 (Boeing)
Demonstrations to understand the level of uncertainty in a given performance parameter and targeting testing where it was most effective at reducing that uncertainty	West and Blackburn, 2018 (Air Force Test Center)
Proposed Activities	
System conceptualization	Madni et al., 2019 (n/a)
Model verification	Madni et al., 2019 (n/a)
Testing (system validation)	Madni et al., 2019 (n/a)
Condition-based maintenance	Madni et al., 2019 (n/a)
Smart manufacturing	Madni et al., 2019 (n/a)

TABLE D.3

Activities Implemented or Proposed Using Digital Threads

Activity	Reference(s) (Organization/Program)
Support the manufacturing process for both the computer numerically controlled (CNC) machining of metal parts and the composite programming system approach to fiber placement in composite parts	West and Pyster, 2015 (Lockheed Martin)
Proposed Activities	
Exploration of system trade space	West and Pyster, 2015 (n/a)
Model-based analysis of alternatives	West and Pyster, 2015 (n/a)
System performance predictions	West and Pyster, 2015 (n/a)
Sensitivity analysis of performance results	West and Pyster, 2015 (n/a)

Table D.3—Continued

Activity	Reference(s) (Organization/Program)
Direct computer aided design-to-CNC and 3D printer prototyping	West and Pyster, 2015 (n/a)
System documentation development	West and Pyster, 2015 (n/a)
Digital interoperability assessments	West and Pyster, 2015 (n/a)
System/component life estimation	West and Pyster, 2015 (n/a)

TABLE D.4

Activities Implemented or Proposed Using a Combination of MBSE, Digital Twins, and Digital Thread

Activity	Reference(s) (Organization/Program)
Provide an Authoritative Source of Truth for managing information across the entire life cycle	Zimmerman et al., 2019 (Army Product Data Management, Future Vertical Lift, Sentinel, SWFTS)
Directly drive Computer-aided Machines with 3D models	Zimmerman et al., 2019 (Army depots)
Quickly update training or repair manuals	Zimmerman et al., 2019 (Army depots)
Ensure the acquisition of correctly configured parts	Zimmerman et al., 2019 (Defense Logistics Agency)
Planning and deconfliction of wire harnesses, cable runs, heating, ventilation, and air conditioning ducting, piping, and other elements	Cole et al., 2019 (Tactical Assault Light Operator Suit); Zimmerman et al., 2019 (Navy CVN-78)
Proposed Activities	
Conducting high-fidelity wargames	West and Pyster, 2015 (n/a)
Use virtual prototypes in simulation	Madni et al., 2019 (n/a)
Track performance and maintenance history of each physical twin over time	Madni et al., 2019 (n/a)
Detect and report anomalous behavior	Madni et al., 2019 (n/a)
Recommend and schedule maintenance	Madni et al., 2019 (n/a)

Abbreviations

ACAT	Acquisition Category
A_M	material availability
A_O	operational availability
ASoT	authoritative source of truth
CBA	cost-benefit analysis
CDD	capabilities development document
CDRL	contract data requirements list
CMMI	Capability Maturity Model Integration
DAF	Department of the Air Force
DEBoK	Digital Engineering Body of Knowledge
DoD	U.S. Department of Defense
DoDAF	Department of Defense Architecture Framework
DoDI	Department of Defense Instruction
FFRDC	federally funded research and development center
ICD	initial capabilities document
INCOSE	International Council on Systems Engineering
IoP	index of performance
IT	information technology
JCIDS	Joint Capabilities Integration and Development System
KPP	key performance parameter
KSA	key system attribute
MBSE	model-based systems engineering
MLC	multi-level classification
MOSA	modular open-system architecture
MVP	minimal viable product
NASA	National Aeronautics and Space Administration
NAVAIR	Naval Air Systems Command
NDEBoK	Navy Digital Engineering Body of Knowledge
OUSD(R&E)	Office of the Under Secretary of Defense for Research and Engineering
PSM	Practical Software and Systems Measurement
ROI	return on investment
SEEF	Systems Engineering Evaluation Framework

SEP	systems engineering plan
SERC	Systems Engineering Research Center
SETA	Systems Engineering and Technical Assistance
SWFTS	Submarine Warfare Federated Tactical Systems
SysML	Systems Modeling Language
UML	Unified Modeling Language

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RAND NATIONAL SECURITY RESEARCH DIVISION

RAND researchers worked to understand the costs and benefits of digital engineering in the U.S. Department of Defense (DoD) and develop a decision support framework for digital engineering activities in weapon system programs. To prepare, the authors reviewed the literature and interviewed stakeholders to understand the current state of digital engineering practice and prior efforts to assess the costs and benefits of digital engineering and model-based systems engineering. They then developed decision support frameworks incorporating (1) established DoD cost-benefit analysis approaches and (2) established systems engineering decision methodologies. Along the way, the authors noted critical issues with rigor and risks in the practice of DoD digital engineering and added that aspect to the study.

This research suggests that cost-benefit decision support for digital engineering is possible at any stage of a weapon system program life cycle if program data have been collected accordingly or if goal-based systems engineering principles are leveraged. Calculating definitive costs and benefits of digital engineering is imperfect because no analyst will have access to an identical weapon system program developed without digital engineering—the counterfactual scenario.

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