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Key Points

Digital engineering represents an evolution of design, modeling, simulation, and systems engineering practices for existing and future military capabilities enabled by advances in computing power, data analytics, cloud storage and processing, and secure information sharing.

Digital engineering provides a seamless "digital thread" of continuously updated, authoritative artifacts that program stakeholders can access in real time, keeping everyone from program managers to sub-tier suppliers on the same page.

Digital engineering reduces acquisition program costs, design reworks, and bureaucratic overhead. It enables higher production quality with less waste and improved sustainment and modernization activities. These benefits have the potential to accelerate the acquisition, development, and fielding of new capabilities independent of purely policy-based acquisition reform.

Senior defense leaders must understand the costs, benefits, and limitations of digital engineering practices if they are to optimize their implementation across the range of DOD programs, from older legacy capabilities to next-generation new start systems.

Despite broad implementation of digital engineering across U.S. prime defense contractors, its use remains limited among sub-tier suppliers and the Department of Defense's acquisition workforce.

Digital Engineering: Accelerating the Defense Acquisition & Development Cycle in an Era of Strategic Competition

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Abstract

Today's Department of the Air Force (DAF) is in crisis and faces severe capability and capacity shortfalls across nearly every mission area. Despite the need to rapidly recapitalize and modernize the force, the Department of Defense's (DOD) legacy approaches to acquisition, development, and sustainment have proven too costly and inefficient to meet warfighter needs. They are also too slow to keep pace with the aggressive and ongoing modernization efforts of global adversaries like China. Moreover, perpetual efforts to reform U.S. acquisition policy have fallen short of the need to accelerate new capability development and fielding. Digital engineering has the potential to help develop and field new capabilities faster and at lower costs, independent of acquisition reform.

Digital engineering encompasses numerous advances in computing power, data analytics, cloud storage, and secure information sharing that are revolutionizing decades of incremental improvements in design, modeling, simulation, and systems engineering practices—areas where legacy approaches continue to create program challenges. With the right infrastructure and integration, digital engineering can connect the entire lifecycle of defense systems, from initial requirements definition through testing, manufacturing, operation, and sustainment. New-start defense acquisition programs can fully exploit these advantages and save time and resources, while the continued sustainment and modernization phases of legacy and hybrid weapon systems can benefit from digital engineering applications focused appropriately and pragmatically. However, older systems may require significant time and budget to reverse-engineer a digital engineering architecture, so decision-makers must be discerning about how and when to pursue these efforts.

Despite the advantages digital engineering offers, there are still barriers to its widespread adoption within DOD, including stand-up costs, interoperability issues, workforce training issues, cyber security considerations, model validation, and cultural resistance. U.S. defense leaders must become more literate in digital engineering to craft nuanced policy guidance that right-sizes its implementation across the scope of DOD programs and delivers on cost and speed goals. The DOD workforce must also be trained to use digital engineering in their workflows and processes in order to accelerate the development and delivery of capabilities that can restore America's military dominance.

Introduction

Technological superiority has long underpinned America's military dominance. However, decades of prioritizing counter-insurgency missions, deferring foundational recapitalization programs, and divesting force structure to cope with budget pressures have eroded that advantage. This is especially true for the Department of the Air Force. Today's Air Force flies the oldest, smallest aircraft inventory in its history, and the Space Force is pressed to overhaul most elements of its technical architecture to meet the rise in demand for space-based capabilities while mitigating the burgeoning threat environment on orbit.

Rapidly restoring and expanding American overmatch—especially in air and space—is now an urgent national security priority that requires fielding new technologies at scale. Yet, the DOD's legacy approaches to acquisition, development, and sustainment have proven too costly and inefficient to meet warfighter needs. New defense programs still require well over a decade to transition from requirements definition to initial operational capabilities. Likewise, modernization programs that insert new capabilities into existing weapon systems remain beset by cost overruns and schedule delays. This is proving *too slow* to keep pace with the aggressive and ongoing modernization efforts of global adversaries like China and cedes the innovation and agility initiative to these competitors.

Burgeoning global threats like China's military modernization and build-up demand rapid, responsive, and resilient capability development and fielding.[1] That is why digital transformation is integral for equipping America's military for dominance in the 21st-century battlespace. Digital engineering presents a set of tools and processes, like modern computing advances and model-based program management approaches, that can increase the speed, quality, affordability, and performance of DOD's capability development. This could transform and accelerate the Department of Defense's (DOD) legacy engineering, acquisition, and production processes, thereby speeding capability to the warfighter. Digital engineering technologies and techniques that already exist could remedy many acquisition ailments—lengthy timelines, cost overruns, performance shortfalls, and maintenance burdens, to name a few—if the DOD and the services fully embrace it.

A key reason why digital engineering holds such promise is that it can create a level of integration that facilitates unprecedented visibility and cross-team collaboration not found in legacy approaches. Digital models can serve as a program's authoritative source of truth—a definitive and robust master set of digital artifacts, including their work histories, encompassing all aspects of a program. As engineers make changes to a new weapon system design, a digital thread enabling access to the authoritative source of truth ensures all stakeholders will have the ability to see any and all changes instantly as they propagate across the project's entire ecosystem. That is not possible with older approaches. For example, engineers developing different subcomponents can check for whole-of-system consequences that a design change might incur. Program managers can also exercise real-time program oversight and drill down to specific details or anticipate potential issues. This level of collaboration can reduce incompatibility issues or design and manufacturing rework that can cause serious developmental delays. In other words, digital engineering empowers enterprise thinking, not just excellence within a stovepipe; great work, if produced in isolation, may yet prove incongruous when integrated later in the development process.

Understanding Digital Engineering

Digital engineering is the natural and transformational evolution of engineering practices that leverages exponential gains in computing power, data analytics, modeling and simulation software tools, and secure information transfer technologies. Together, these technologies have a synergistic effect that can empower all defense program stakeholders, who may be scattered across the globe, to collaborate from "authoritative artifacts" quickly and accurately—and in real time. An authoritative artifact is like the master version of a document but could be any of a number of products like 2D blueprints, program requirements documents, prototype testing models, and other digitized models. The complete collection of these artifacts for any one development project is called the "authoritative source of truth," and digital engineering tools open collaborative access to the authoritative source of truth across the development cycle to an unprecedented degree. Another way to understand this is that digital engineering combines longstanding digitized modeling and simulation tools with recent advancements in processing, networking, and systems engineering to create a real-time "digital thread," an architecture akin to the digital shared workspaces or sharing platforms becoming ubiquitous across private commercial workplaces. The increased integration that can be achieved across program teams improves the efficiency and quality of processes and products across the entire lifecycle of a system. It also safeguards the integrity of the authoritative source of truth. Moreover, the real-time integration and transparency of program activities can provide government officials, such as program managers and executive steering committees, full insight into and oversight of the program regardless of milestone dates. This can alert them to early issues or enable a flow of continuous certification and approval, thus streamlining program execution.

Digital Engineering Key Terms and Definitions

•**Artifact:** Product, model, document, or other technical or performance data related to a program's development, creation, operation, and sustainment.

•**Computer-aided design/computer-aided modeling (CAD/CAM):** Software programs and other tools to innovate digitally—instead of using paper-based designs or blueprints—and simulate physical models like aircraft in wind tunnels. CAD/CAM can supplement or, in some cases, fully replace paper design and simulation practices.

•**Digitized artifact:** The conversion of analog artifacts like paper blueprints and clay models into a digitized format like a Word document or CAD file.

•**Authoritative source of truth:** The central and definitive reference point for a program regarding requirements, design, and data in a digital engineering paradigm. When this source is digitized and cloud-based, changes propagate throughout the digital design model.

•**Digital thread:** The network infrastructure and software that connect and update digital models of programs and systems. Having a digital thread is what enables all stakeholders to have access to the authoritative source of truth in real time.

•**Digital engineering:** The combination of digitized engineering tools and practices like CAD/CAM and MBSE with cloud computing and big data analytics to enable program stakeholders to interact fluidly with an authoritative source of truth. Digital engineering supports a whole-of-enterprise lifecycle approach to systems requirement generation, design, manufacturing, sustainment, and operations.

Digital engineering benefits do not end with initial design. The technology is relevant for the entire lifecycle of a program. Stakeholders can refine a new weapon system's requirements early in its initial development through modeling and simulation tradeoff studies. Subsequently, during a capability's design phase, digital engineering tools like rapid virtual prototyping and testing could accelerate its maturation. As a design nears the creation, linking digital engineering models directly to a capability's production systems could enhance automation, improve quality control, and streamline the manufacturing of a new capability all the way from its smallest supplier to its prime contractor. These are just a few advantages of enabling all participants to better understand the totality of what they are producing as a cohesive whole while also allowing them to look at highly specific details.

Because new start programs can be conceived digitally from the outset, they are better candidates to realize the full potential of digital engineering across their lifecycle. Legacy defense platforms can also benefit from the prudent application of digital upgrades, but U.S. defense leaders must weigh the budget and time required to retrofit a digital architecture against the platform's remaining service life and operational value. Hybrid or legacy weapon systems that may have older or even no digital artifacts often require the reconstruction of those artifacts through reverse engineering. As this can be hugely time-consuming and costly, senior leaders and program managers should tightly focus and scope these efforts only when they make sense.

Despite the tremendous potential that digital engineering presents, significant barriers to its adoption remain. For example, subcomponent suppliers often do not have access to the requisite software tools, their software may be incompatible with their prime contractors' software, or it may not interface with their production line manufacturing tools. Working these modernization efforts may prove cost-prohibitive for certain firms, especially if they need multiple types of technology to connect a broad range of upstream companies. DOD and the primes may need to help fund these efforts if the benefit is deemed sufficiently consequential.

Additional concerns involve disparate workforces that may not be fully trained in the use of relatively new digital engineering tools. Physical and cyber security is also a major concern because every member of a program, from the smallest supplier to the program manager, at highly dispersed locations, must have access to the digital thread.

What Are Legacy and Hybrid Weapons?

Legacy weapon systems: Legacy weapon systems were originally designed well before the advent of software design programs or other digital computer tools. Examples of these types of weapon systems include the B-52 and Minuteman III. Some of these weapon systems may have undergone modernization or service life extension programs that have some element of digitization, but their core artifacts fundamentally predate CAD/CAM and cannot facilitate digital engineering without extensive reverse engineering efforts and associated expenses.

Hybrid weapon systems: Hybrid systems were designed with some degree of CAD/CAM and systems engineering or a digital thread, but they were not originally conceived in a wholly integrated digital engineering ecosystem. Hybrid systems such as the F-22 and F-35 have a preexisting codebase, CAD/CAM models, and other digital artifacts.

Another reality is that digital engineering results must still be validated through physical testing before simulation is accepted as a substitute because the technology is still in a pioneering phase. Modeling and simulation can benefit many programs by abbreviating test requirements, but there remain regimes where simulation cannot fully replace the complexities of the physical world or the unknowns of truly radical designs. As quickly as these methods are advancing and maturing, "trust, but verify" remains a prudent course for the foreseeable future.

Perhaps most critically, digital engineering faces cultural and bureaucratic resistance from many within the DOD. Workers often do not have the training, infrastructures, or incentives to take advantage of the new processes that digital engineering offers. For example, they may not be comfortable conducting ongoing or spot reviews of program activities through the digital thread, or they may not fully understand how to translate traditional milestone reviews into a continuous oversight model. Yet, if acquisition leaders do not adapt their processes to take on digital engineering practices, government program managers may remain constrained to the old inadequate process that are failing to fulfill institutional expectations. This organizational inertia could threaten our nation's ability to develop and deliver new military capabilities at the speed warfighters need.

It is important to recognize that while digital engineering holds much promise, it is not a panacea that will fix all aspects of a troubled program. Competent strategy, well-defined requirements, not pushing too far into unproven bleeding-edge technology, competent program leadership, and ample and consistent funding remain fundamental elements to any program's success, whether digital engineering is involved or not. Digital engineering is a tool that, when used effectively, can confer benefits in all areas of the acquisition cycle. It cannot make up for the foundational challenges of a troubled program.

Despite these cautionary observations, the opportunities afforded by digital engineering far outweigh any disadvantages—especially given the magnitude of the challenges facing the services. The Air Force and Space Force top this list, given the sheer amount of modernization and recapitalization it requires to meet the demands of the National Defense Strategy. DAF leadership must implement digital engineering practices and technologies. This involves the DAF requiring U.S. defense leaders to mandate the use of digital engineering for all its new start programs and provide incentives for prime contractors to push digital engineering deep into their supplier base. The DAF can streamline this effort by providing common software tools to companies and promoting open standards. Moreover, DAF leaders should provide guidance to program managers for legacy and hybrid weapon systems on how to optimize the implementation of digital engineering to mitigate costs and maximize benefits. Additionally, the DAF must ensure cybersecurity is paramount in any software tool, digital artifact, and digital thread across all its digital engineering efforts.

Crucially, the DAF must overcome its own bureaucratic inertia and cultural resistance to digital engineering. Training its acquisition workforce in digital engineering processes, providing incentives for the employment of digital engineering, and rewarding performance are steps toward this end. These efforts are imperative to keep pace with the demands of the increasingly challenging global security environment. Anyone doubting this sense of urgency should consider the Secretary of the Air Force's warning when he explained at the 2024 Air and Space Force Association's Warfare Symposium, "We are out of time. We are out of time. We are out of time. . . . For at least two decades, China has been building a military that is . . . purpose-built to deter and defeat the United States if we intervene in the Western

Pacific."[2] It is time to build the capabilities and capacity America needs to succeed in the modern threat environment. Digital engineering is a key factor in realizing that goal.

DOD's Acquisition Process Cannot Keep Pace, Much Less Out-pace China

DOD's legacy approaches to defense acquisition, development, and sustainment are too costly, too inefficient, and *too slow* to keep pace in an ever-more-dangerous world. While the United States deferred and canceled key recapitalization programs and divested capability and capacity over the past 30 years, China has methodically developed the capabilities required to assert itself as a hegemonic power in the Pacific and eventually beyond. Today, the forces the United States can bring to bear to defend its interests in this portion of the globe are insufficient to deter, much less defeat, Chinese aggression.[3] Department of the Air Force Secretary Kendall has repeatedly stressed the need to accelerate the development and delivery of advanced capabilities to the Department of the Air Force: "I have been sounding alarms about China's military modernization program. There is no time to lose in responding to this challenge."[4] The pace of Chinese military technological development is accelerating; China's continued rate of military innovation and modernization risks the U.S. military falling even further behind.

China is not the only threat. The U.S. faces concurrent challenges, given Russia's aggression in Europe, continued instability in the Middle East, and stark realities tied to a nuclear-ambitious Iran and North Korea. Combined, these factors are stressing the U.S. national security enterprise in ways not seen since the Cold War and represent immense risks to U.S. and allied interests. These include existential threats to the homeland. Addressing the full breadth and depth of these challenges demands a modern set of capabilities fielded in sufficient capacity.

While the threat environment is growing and evolving, America's arsenal is not. U.S. capabilities and capacity are badly out of alignment with demand, and force modernization continues to lag. The U.S. defense acquisition enterprise is struggling to keep up, and examples of its shortfalls abound.[5] Program challenges are often measured by schedule and cost, and U.S. defense programs are taking longer and are more costly to develop and field—and time *is* money. Schedule delays can result from design discoveries, engineering rework, and material and supplier issues. Increasing costs can lead to program restructuring, diminished production quantities and rates, or even program termination.

These outcomes ultimately disadvantage U.S. warfighters, who require the delivery of capabilities in quantities and on timelines relevant to high-end warfighting operations they must conduct during a conflict with a sophisticated near-peer aggressor. "Relevant timeline" does not mean *just before* conflict erupts—warfighters need capabilities well in advance if they are to develop the tactics, techniques, procedures, and other methods of using them that will provide an edge over adversaries.[6]

A GAO analysis found that the most significant cause of cost overruns is engineering and design issues.[7] The RAND Corporation similarly found that some critical interrelated drivers for recent notable program cost overruns include:

- Siloed requirements generation and cost-performance tradeoff analysis processes that do not engage a program's broad stakeholder communities;
- Optimistic evaluations of technology readiness and development that result in poor cost estimations;
- Insufficient data about component costs;
- Unanticipated difficulties integrating subsystems creating program delays;

- Unanticipated issues testing technologies and subsystems that create program delays; and
- Ineffective oversight and program management resulting in supply chain bottlenecks, schedule slips, and cost overruns.[8]

U.S. defense leaders recognize that these problems have become pervasive within defense acquisition programs. Yet attempts to remedy these issues have failed to address them fully. In a 2017 assessment of defense acquisition reforms, then-Under Secretary of Defense for Acquisition, Technology and Logistics Frank Kendall wrote:

> *The Congress almost continuously makes legislative changes that affect defense acquisition, often under the rubric of "acquisition reform." These efforts wax and wane, but they recur with higher intensity every few years, often as a result of dissatisfaction with the performance of the "acquisition system." Some of these efforts have produced very positive results.... Others have had mixed results or worse.*[9]

In fact, DOD's budget for 14 of its major programs grew by $37 billion over the last fiscal year alone due to increased technology modernization costs, production inefficiencies, and supply chain disruptions.[10] This is a clear indicator that its acquisition challenges continue to grow despite multiple attempts at reform.

More recently, defense leaders have established an ever-growing number of "innovation" offices and boutique acquisition approaches in an effort to circumvent the quagmire of traditional acquisition offices and processes. While the Air Force's Rapid Capabilities Office and Space Force's Space Development Agency have proven capable of cutting through "bureaucratic constraints to accelerate even the most complicated major acquisitions," these workarounds have limited impact because they do not execute the vast majority of defense acquisition programs.[11] Under the 2020 Adaptive Acquisition Framework, these offices were accompanied by a patchwork of defense acquisition approaches ranging from Middle Tier of Acquisition (MTA) to Small Business Innovation Research (SBIR) grants. These approaches to supplementing the traditional Major Defense Acquisition Programs (MDAP) acquisition and development processes have proven marginally effective, at best. In fact, a 2023 GAO report concluded that "schedule delays and lack of progress in maturing technologies raise questions about MTA programs' overall ability to deliver capabilities more quickly."[12]

Even if these boutique defense acquisition pathways functioned flawlessly, their limited scope would fail to address existing challenges at the scale needed, given the vast size of the conventional defense acquisition portfolio. In the last two years alone, the GAO found that the average cycle time for a U.S. defense program increased by 7 percent, even as China's rate of capability development continues to accelerate.[13] Darlene Costello, the Principal Deputy Assistant Secretary of the Air Force, noted that while it took 30 years for China to develop a counterpart to the F-15, "It only took 10 [years] to match the F-22 with the stealthy J-20."[14] While the J-20 is not the equal of the F-22, China has demonstrated its ability to counter U.S. capabilities rapidly and in quantity. On average, the PRC develops and delivers major weapon systems in 7 years, less than half the U.S. average of 16 years. [15] This pace of capability development, production, and fielding confers a key operational advantage to China—the ability to outpace and out-

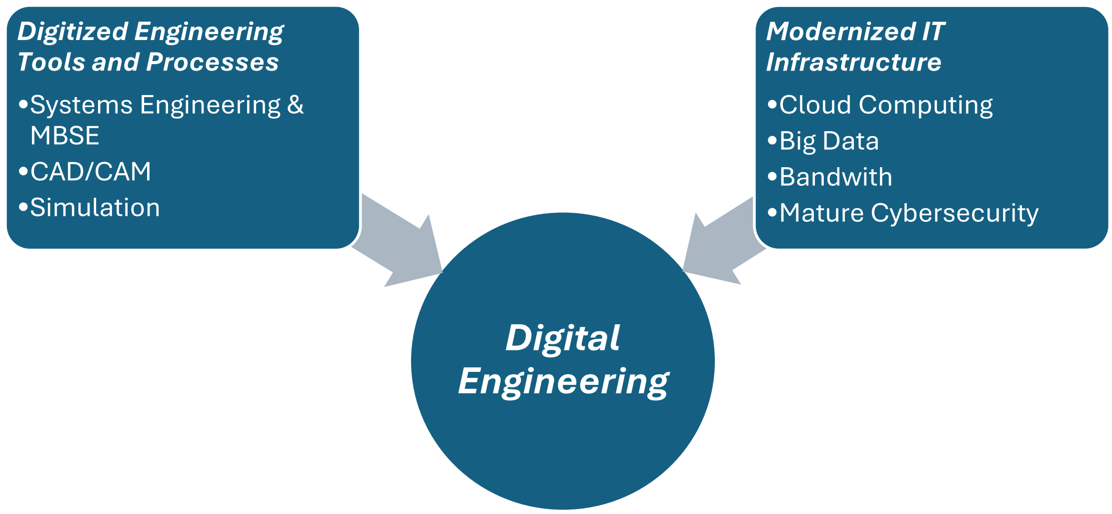


Figure 1: Digital Engineering is the marriage of legacy processes and IT innovations, begetting evolved processes and improved digital toolsets.
Source: Mitchell Institute

adapt U.S. forces. Looking ahead, China is on track to complete military modernization by 2027 and become a "world-class" military by 2049.[16] As Costello noted, "The case for change has never been more acute."[17]

Pivoting to a digital architecture and digital acquisition approach has the potential to accelerate U.S. defense acquisition to keep pace with China without the need for major policy reforms. Because it improves collaboration, coordination, and design insights across all program stakeholders, digital engineering can mitigate or even resolve many of the problems GAO and RAND identified as chief causes for DOD's chronic acquisition delays. Digital engineering can help make developing and interacting with requirements easier, design and testing faster, and program management and collaboration smoother. Digital engineering is not a silver bullet. It cannot compensate for poor strategy, bad management, or a brittle industrial base. However, digital engineering does have the potential to meaningfully improve the collaboration and information-sharing that defense acquisition stakeholders need to meet the pacing threat.

Transforming Analog to Digital Engineering

In a way similar to modern workers collaboratively managing projects and files over Microsoft Teams or Google Docs, today's large-scale, complex acquisition projects require the kind of collaboration that is only possible when all of a program's stakeholders have access to the same authoritative documentation, models, and other program information. High bandwidth networks and advances in processing, cloud computing, and big data are facilitating a revolution that is changing long-entrenched engineering practices and bureaucratic processes into a combined practice known as digital engineering. Prior to these information technology (IT) advancements, geographically distributed teams of engineers and acquisition professionals had to rely on physical documentation that required time-consuming deconfliction and coordination of plans and designs. Digital engineering makes these tasks as frictionless as possible by allowing acquisition project stakeholders to work from the same digital model that is continuously updated in real time.

Early systems engineering development

Creating better models to meet the complexity and demands of defense acquisitions is not a new trend. As early as the 1950s and through the 1970s, U.S. defense leaders began applying systems engineering practices to address challenges created by the increasing complexity of DOD's acquisition programs.[18] Systems engineering is a design and management approach that seeks to treat a program for a new defense capability as an integrated whole across its lifecycle rather than as a collection of isolated and disconnected parts. This was a crucial development for addressing the risk of part incompatibilities or schedule mismatches created by the growing intricacies of DOD's weapon systems. Systems engineering sought to resolve these problems by improving the collaboration and coordination of engineering and management across a program's lifecycle.[19] Still, legacy systems engineering relied on paper documents and physical models. Because these documents had to be physically shared, multiple disparate teams responsible for a defense program could easily become desynchronized, and resolving competing or divergent interests or reaching consensus on program specifications required a great deal of time. Moreover, paper program documents like operational and design requirements, technological specifications, and manufacturing reports could be inaccessible, challenging to engage with, and difficult to assess holistically. For instance, engineers would need to sift through reams of useless data to find the information they needed to complete any given task, such as the specifications for an aircraft's wing to attain specific inflight range requirements. Even when teams found the needed data, it would not necessarily contain all of the engineering specifications, tolerances, and interdependencies related to an aircraft as a complete system, like how the wing affected the aircraft's stealth profile or weapon loadout.

Early 1970s computation and software models enabled acquisition program engineers and managers to do their jobs better, but it wasn't until the 1980s and 1990s when improved computing power, software, and modeling allowed them to use tools like computer-aided design (CAD) and computer-aided modeling (CAM) to accomplish their tasks more quickly and accurately.[20] Major defense contractors adopted these computer-aided design tools to tackle ever-more complex problems ranging from designing stealthy curves to integrating subsystems. The B-2

Analog to Digital Engineering Terms

- **Systems engineering:** A function-based approach to program management that looks at programs in phases and allows for the collaboration and coordination of numerous stakeholders in different engineering and management fields across the lifecycle of an engineered system from design to manufacture, use, and retirement.

- **Model-based systems engineering (MBSE):** An evolution in systems engineering practices from analog tools to more digitized engineering tools. In MBSE, digital models replace paper and digital documents as the "authoritative source of truth." Like systems engineering, MBSE supports the program lifecycle from the development of requirements through design, manufacturing, and sustainment.

- **Digitized engineering:** The translation of analog engineering practices to computerized forms. CAD/CAM is one example, but it may also include measures as simple as scanning physical documents and uploading them to a computer instead of xeroxing copies for physical storage or sharing.

program, for example, used advanced digitized design and simulation tools to achieve significant cost and time savings compared to traditional aircraft design methods. One B-2 engineer noted that using CAD/CAM software resulted in a "significant reduction in paperwork…and time" needed to complete the aircraft's design and prototyping phase of development.[21] Other related tools, like the NASA Structural Analysis (NASTRAN) program, proved "indispensable" for analyzing the structural integrity of potential designs and reducing costly redesign work.[22] Technologists and production managers then fed these digitized models into automated machine tools, which facilitated the rapid and accurate transition from design to prototyping.[23] However, the basic engineering processes—and limitations—remained unchanged.

By the early 2000s, model-based systems engineering (MBSE) began replacing paper and analog design artifacts like 2D blueprints, program requirements documents, prototype testing, and manufacturing data with these CAD/CAM digitized models. MBSE represented a step change in program management by creating more accessible and interactive authoritative documents and artifacts. Engineers and other stakeholders could now not only quickly reference program-relevant data but also use models directly in combination with other tools.[24] In addition, improved 3D visualization of intricate systems allowed engineers to use digitized simulation and testing techniques to reduce the time needed to create and then test potential designs. MBSE proved remarkably powerful and was quickly adopted across the defense aerospace industry. However, while electronically sharing these artifacts and models was more efficient, version control could still be a challenge, and early applications of MBSE still relied on siloed system models that could not integrate functions and decisions across all acquisition program stakeholders.

Digital engineering has the potential to remove this friction and create programmatic synergies by combining MBSE and established software tools with cloud storage and processing, big data analytics, and high-speed, high-bandwidth networks. Ideally, the implementation of digital engineering in a program could break down stovepipes at every one of its lifecycle phases, synchronize and integrate all program activities, facilitate better and more accurate technical and design choices, improve the speed and quality of a capability's production, and radically enhance government oversight throughout. Speaking at the Air and Space Forces Association's Air Space Cyber Conference in 2022, Dr. Naveed Hussain, Vice President and Chief Engineer for Boeing Defense Space and Security, explained:

> *We have been [using]…physics based digital models for decades. That is how we've optimized our designs… test, and…lifecycle… What's accelerating now…is how all these models interconnect and how we think about not just the platform, but the production system and the sustainment systems altogether.*[25]

Digital engineering in the 2020s

Advanced processing, big data analytics, and cloud computing and storage have dramatically enhanced the utility of digital models created by tools like CAD/CAM. Because these models can now be stored in and shared through secure, high-bandwidth networks linked to cloud technologies, any stakeholder, from supplier to engineer to program manager, can access a program's digital artifacts at any time. This infrastructure enables a digital thread of models that serve as a program's "authoritative sources of truth." As engineers make changes to the design, these

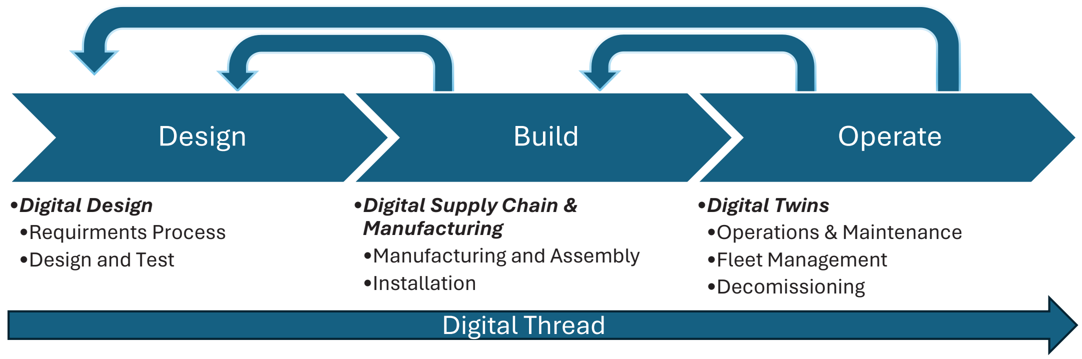


Figure 2: Digital engineering can improve processes across all stages of development, production, and operation of capabilities.
Source: Mitchell Insitute

changes are instantly updated and propagated throughout the digital thread, ensuring that all stakeholders instantly see any and all changes. This level of integration facilitates unprecedented system visibility and cross-team collaboration, and this can also enable engineers to design more sophisticated systems without the potential hazards that previous design teams faced.

In the past, even a slight change in a weapon system design could inadvertently introduce engineering consequences that would ripple throughout the design's other components and design features. For example, a change in the location of a fuel pump's in-flow and out-flow valves might not mate properly with an aircraft's fuel tank lines or its engine. Today, through digital engineering, requirements officers and engineers can iterate on tradeoff studies; engineers on different subsystems can check for whole-system consequences of subsystem design changes; and government program managers have real-time program oversight and can drill down to specific details or anticipate potential issues. This can reduce a program's development and production costs and speed new capabilities to America's warfighters. Importantly, the value of digital engineering does not end with weapon system production; it can confer advantages across a weapon system's lifecycle.[26]

The benefits of digital engineering extend across a capability's entire lifecycle

Through maintaining an authoritative source of truth and creating digital twins, digital engineering can improve the quality, cost, and speed of development across a weapon system's entire lifecycle, from sustainment and modernization upgrades to major part improvement programs and service life extensions. Moreover, the nature of a system's digital thread and the access it provides to its authoritative source of truth gives government managers total insight into their programs. This is especially true for new start programs since their stakeholders can begin from a metaphorical "blank sheet of paper" to implement digital engineering practices from the very first stage and realize digital engineering's full range of benefits.

Harnessing digital engineering during a program's design phase

Digital engineering can save time and money beginning with the start of a new program's design phase by improving trade-off analyses that inform requirements development and the testing and evaluation of design choices. A program's digital thread allows government managers to continuously monitor and assess their program's performance to catch issues earlier in a development cycle. Digital engineering's advanced simulation tools can also accelerate the testing of design alternatives and reduce the number of required test points. All this means that program issues can be caught and rectified earlier in their development cycle with less bureaucratic friction—and this saves time and money.

Digital engineering can better inform requirements generation. The relative ease of generating digital models and simulations today allows program requirements managers to make early rough-cut decisions on how certain requirements may impact a potential system's desired capabilities and mission outcomes.[27] Once requirements are created, these digital artifacts allow program teams to interact with specifications more directly and intuitively. For instance, requirements can be presented to managers as digital models instead of traditional 500-page slideshows or documents. As a result, the requirements can be distributed across a program's ecosystem so they can be read and understood by all stakeholders and inform engineering tasks. Amanda Brown, Pratt & Whitney's 6th Generation Fighter Digital Strategy Director, noted that this approach allowed her company to cut an estimated 48-month preliminary design review process to 28 months.[28] She added that successes like this can only help change a company's legacy culture and help speed digital engineering training and integration.

Digital models can facilitate design tradeoff analyses. Several DOD new start programs have already benefited from digital engineering's high-fidelity modeling, simulation, and analysis. Digital models can enable stakeholders to better understand how different design choices may impact factors such as the cost, survivability, producibility, range, and payload of a new weapon system. Engineers working on the B-21, the Ground Based Strategic Deterrent (GBSD), and the Hypersonic and Ballistic Tracking Space Sensor (HBTSS) have all used digital models and advanced simulation capabilities to rapidly evaluate, iterate, and optimize system designs. Kathy Warden, the President and CEO of Northrop Grumman, shared that the B-21 program explored thousands of designs in a digital environment before choosing a design.[29] Likewise, Northrop Grumman's GBSD Sentinel ICBM engineers also took full advantage of digital tools to scan and assess six billion potential designs to optimize cost and capability.[30]

Digital artifacts can decrease government oversight burdens to accelerate timelines for developing new platforms. Digital engineering can accelerate timelines for completing design milestones for new platforms and delivering prototypes or production-representative vehicles for testing. This is because the transparency that digital engineering provides to all stakeholders enables continuous government oversight of and insight into the program. Instead of waiting for large milestone reviews, government officials can catch issues as they emerge. This continuous oversight averts miring the development in major and lengthy engineering rework and redesign and, instead, helps to continue progress. Officials can also provide approvals for specific areas to proceed even if others do need longer attention to avoid putting all progress on hold until an arbitrary review date.

As an example, DOD's Missile Defense Agency selected L3Harris to design and launch four space vehicles as part of its HBTSS Program in January 2021. L3RHarris completed the program's critical design review for an HBTSS prototype in less than a year and credits its use of digital engineering to assess multiple designs against threats virtually, test designs through simulation, perform other assessments concurrently, and then make rapid improvements.[31] Major aircraft programs are experiencing similar successes. The Air Force leaders noted that the B-21 bomber design went from contract award to first flight in 2023

Generative Design's Early Promise

Rather than relying solely on human ingenuity, automated and generative design processes use computational tools like artificial intelligence/machine learning (AI/ML) to explore a design space more thoroughly and arrive at optimized designs faster. Pairing improved simulation and modeling capabilities with these capabilities could further increase design iteration speeds. Organizations like NASA have already used the technique to design and produce components that are stronger and more cost-effective in less time.

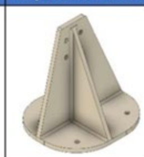
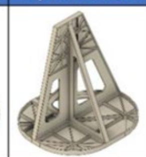
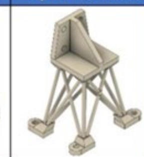
Designer	Expert Humans	Expert Humans	Expert Humans	Expert Humans	AI	AI
Design						
Iterations	1	2	3	4	31	31
Mass (kg)	0.59	0.18	0.27	0.18	0.2	0.2
1st Mode (Hz)	137	37	65	108	147	177
Max Stress (MPa)	26.3	189	103	60.7	14.8	11.2
Manufacturing	CNC $1700, 3 weeks	CNC No quotes	CNC No quotes	CNC/AM No quotes	CNC $1000, 3 days	AM $2000, 3 weeks

Figure 3: Generative Design and Digital Manufacturing: Using AI and robots to build lightweight instruments. In this example, a fastener was designed by three human teams, while AI was used to design the same function. All designs were quantitatively evaluated for measures such as mass, maximum stress, and time and cost to produce. The AI design was highly unconventional yet competitive with the human designs. Source: NASA.

within eight years.[32] Such an astonishingly fast pace for a modern, highly sophisticated aircraft program would not have been possible without digital engineering.

Digital engineering can accelerate real-world test and evaluation programs. The use of high-fidelity digital modeling to rapidly test and iterate designs can eliminate real-world test points while executing thousands more virtual tests, thereby improving performance at little cost while also shrinking program development timelines. Program managers can streamline flight test programs because the veracity of the modeling and simulation is robust enough that mundane test points, such as speed and performance data that are "in the heart of the flight envelope," are not needed. This can free test programs to focus on exploring edge cases where the digital model may not be as reliable or data may be missing. For example, flight test programs would focus on extremely slow and fast flight test points, high-altitude test points, or other examples of extreme performance areas. During his tenure as Air Force Chief of Staff, General CQ Brown acknowledged this approach might anger traditionalists in the test and evaluation community, but he poignantly argued that such techniques are exactly what will "change the way we do things… in the future."[33] This is one way to "reform" acquisition procedurally.

Digital engineering can reduce schedules and costs. Since time is money, reducing design man-hours, the need to rework designs to fix issues, and design test points can yield substantial cost savings. Of course, this requires fixes to be identified early, but that is part of the promise of digital engineering. Secretary Kendall estimated that new digital approaches may produce an overall 20 percent savings in the time and cost to develop new capabilities.[34] This is a significant figure given the growing cost of certain major weapon programs. L3Harris estimates its digital design approach realized 90 percent cost savings on HBTSS.[35] In all the examples above and others, digital engineering has shown early promise in delivering new start warfighting capabilities faster, cheaper, and better.

Digital engineering can improve production quality & timelines

Producing sophisticated systems and components of defense capabilities has always been a labor-intensive process with plenty of room for error. Digital engineering can improve manufacturing efficiencies and enhance the producibility and quality of new systems by using IT infrastructure to facilitate supply chain management, machining, parts creation, and other steps that are part of transitioning a new capability from its prototyping to manufacturing stages.

Digital models can enhance the producibility of new systems from the beginning. In past programs, seemingly innocuous decisions made during the design phase could create manufacturing challenges that would drive up costs, increase production timelines, or even send designs back to the drawing board. With digital engineering, planning for production does not need to wait until the design is finalized. The digital thread enables production teams to begin interacting with models early, even engaging with design engineers to enhance producibility. Because more data can be freely shared and the transition from design to manufacturing is more seamless and transparent, these manufacturing challenges may be minimized or even averted.[36] Speaking about this concept at the 2022 Air, Space & Cyber Conference, Naveed Hussein, Vice President and Chief Engineer of Defense, Space and Security at Boeing, explained that an engineer linked via the digital thread to the authoritative source of truth can "think about the trades that she's making in the work that she's doing…and how that decision affects the entire lifecycle and the trades that unlock between performance and producibility."[37]

The first B-21 aircraft unveiled in December 2022 was a production model rather than a bespoke prototype and was built using regular factory processes with "regular factory technicians, not engineers."[38] This first-build B-21 included all the mission systems and low-observable stealth coatings that production bombers will have.[39] This is a major leap for the Air Force, as all of its first aircraft to date have been prototypes or production representative *test* vehicles—meaning that they will undergo further design iteration and testing before a production model is finalized.

Digital models of the factory floor can allow manufacturers to simulate and optimize the manufacturing process. Optimizing for production goes beyond the design of a system itself. Manufacturing facilities can also be digitized with models that inform production planners and managers to optimize production lines. Issues with manufacturing supply chains, part tolerances, assembly sequences, tooling needs, quality control, and inspection were previously discoverable primarily through costly trial and error. With digital models, all of these considerations can be identified and addressed earlier in the manufacturing process, preventing costly rework and delays. Tom Jones, corporate vice president and president of Northrop Grumman's Aeronautics Systems sector, noted that the company has taken the B-21 digital engineering model "all the way down into shop floor instructions" and combined it with augmented reality to improve efficiencies performance across the board.[40]

Digital twins of factories can also improve overall manufacturing and assembly speeds. Lockheed Martin has created such a digital twin for its F-35 "smart factory" at Fort Worth.[41] This virtual model connects real-world manufacturing operations to planning systems to optimize assembly line workflow. Digital manufacturing has reduced total assembly time by 75 percent by allowing automated drilling and improved transfer of components between workstations.[42] Digital twins of the factory paired with digital models of aircraft have the potential to create substantial improvements in manufacturing efficiencies and production rates.[43]

Digital manufacturing techniques can improve manufacturing efficiency and quality. Digital models can enhance the entire defense production ecosystem, from facility planning to tooling and digital instructions for sub-tier suppliers. A GAO report on the Air Force's new T-7 trainer found that the use of digital engineering-enabled construction techniques "eliminate[d] the need for manual drilling for tens of thousands of fasteners on each aircraft, saving significant resources and reducing drilling mistakes and nonconformities by approximately 98 percent as estimated by the contractor." This resulted in not only significant time savings but also increased production quality by an estimated 50 percent.[44]

The same benefits can be realized by extending the use of digital models through a program's subcontractors and suppliers. When suppliers are part of the digital ecosystem and proficient in advanced manufacturing techniques, they can improve supply chain flexibility and resilience. A Boeing spokesperson noted that digital engineering and 3D modeling of the F-15EX allows for "flexibility in the supply chain as long as our supply base is equally enabled."[45]

Digital engineering in operations, sustainment, & modernization

Digital engineering and digital twins are transforming how defense organizations operate and maintain complex systems like aircraft, ships, and even production factories. Digital models and twins can be used to factor sustainment and operations more easily into the designs of these complex systems to minimize their operational costs and optimize their performance. Digital engineering and digital twins can also enable higher fidelity training and operational planning for new systems before they are fielded.

Virtualization of systems can improve operations and training. Digital models and twins, paired with augmented and virtual reality (AR/VR), can allow operators and maintainers to conduct higher fidelity training, operational planning, and system management than might be feasible otherwise due to limited numbers of new systems or operational constraints like limited test ranges. Digital models of new aircraft that are in development or in limited production allow their operators and maintainers to gain familiarity with the aircraft and buy down time to create tactics, techniques, and procedures for their maintenance and sustainment before they are even fielded.

Before the B-21's first flight, experienced USAF pilots were brought onto the factory floor into the ground test center for just this purpose.[46] Simulated models of legacy aircraft like the B-52 similarly allow pilots and maintainers to become familiar with planned fleet-wide retrofits before full implementation. The B-52's digital engineering-enabled Virtual Training System "has already started to deliver," according to the Air Force.[47] Using virtual reality and a B-52 simulation that has been retrofitted with new engines, airmen can develop tech manuals and training curricula today rather than waiting four more years for the first flight—the usual workflow. Col Ruscetta says this improved training capacity is "a key enabler and game-changer."[48]

Data analytics and models can inform predictive maintenance. Instructions and models stored in the authoritative source of truth of a system, alongside individual digital twin data, AR/VR, or other digital tools, can help maintainers conduct maintenance on systems with greater speed and accuracy. Improving analysis of a capability's part failure rates is another way that digital twins and big data analytics can inform future maintenance choices. Predictive maintenance can reduce unnecessary inspections and improve spare inventory planning. For instance, legacy approaches for manually inspecting for fuel debris in aircraft engines can be highly subjective and result in overcautious decisions to replace engines when not required—or worse, a decision to not replace engines when actually needed. Better digital tools can not only speed analysis results to maintainers but eliminate guesswork and thereby minimize unplanned system downtimes by ensuring that maintenance is necessary and performed before problems are allowed to escalate.

Digital models can accelerate the development and fielding of planned capability upgrades. Digital models and digital twins capture invaluable data about how systems perform over time, which could be used to inform future programs and even their upgrades. In an increasingly software-defined operational world, being able to provide actual performance data promptly back to software engineers could provide immediate and measurable gains in warfighting effectiveness. Pratt & Whitney, for example, captured terabytes of data regarding its F119 engine during real-world flights of the F-22 stealth fighter.[49] This data was used to create a high-fidelity digital model, which enabled the company to determine that certain sections of the engine were more robust than expected. Pratt & Whitney used this information to update the F119's software to improve engine performance. As new start systems increasingly shift to open architectures designed to enable easier tech refresh, their performance data could prove similarly useful to inform future upgrade planning for new and existing systems.

Digital models can enable continuous cyber security and vulnerability assessments. Digital twins can provide cyber specialists the opportunity to "hack" models to investigate their vulnerabilities and test fixes. The Air Force is already doing this, testing digital models of its GPS imaging infrared satellite system without putting actual satellites at risk. The Air Force launched these satellites between 1997–2009 before many modern-day cyber threats had emerged. By creating digital twins of these satellites, the Air Force was able to conduct cyber penetration testing, vulnerability scans, and mock cyberattacks in a simulated environment to identify potential weaknesses before they affect real-world operations.[50]

Digital models and twins can improve service life extension programs. Data collected over the years or decades-long service lives of systems can be aggregated into digital models and then used to track their performance degradation and plan major maintenance events. By creating a virtual replica of a system, operators can assess the remaining service lives of its major components or systems as a whole and the need to upgrade or replace them. Should the need arise, this data can also help inform the structural modifications for comprehensive Service Life Extension Programs (SLEP). This predictive capability allows better data-driven SLEP planning and forecasting for optimal timing of upgrades and rebuilds versus replacements. Digital thread data gives visibility into as-operated conditions, enabling correlational analysis between usage and component lifespan. These insights can optimize SLEP requirements and tailor them to each system's real-world wear and tear rather than its initially projected operation and employment.

Digital engineering paired with digital twins enhances complex system performance across the entire lifecycle. Operators can optimize performance based on real-time data; maintenance is proactive and efficient; upgrades are better informed and thus planned more prudently; and institutional knowledge persists over generations. The data and insights provided by digital engineering, digital models, and digital twins are key enablers for cost-effective operation and sustainment.

Digital Engineering Can Dramatically Improve Sustainment & Modernization of Legacy and Hybrid Weapon Systems

While digital engineering dramatically improves new start programs across their entire lifecycles, it can also result in substantial benefits if applied to the modernization and sustainment of existing and hybrid weapon systems that lack full digital threads and artifacts. However, there are important criteria to apply regarding when the investment to digitize a component of a legacy system is worth the return.

Most of the DAF's force structure was designed and built before the widespread use of CAD/CAM digital modeling tools. Digital artifacts for these legacy weapon systems often do not exist or are incompatible with current software and technologies. Even "new" types like the C-17 airlifter declared initial operating capability thirty years ago—about the same time the World Wide Web was fielded. Instead of replicating an entire weapon system in a digital ecosystem, program managers should scope work to target specific modernization and sustainment areas to ensure the benefits exceed the costs. Digital models will have to be reverse-engineered and purpose-built for these legacy systems when a business case supports the investment.

B-52s, which have been the backbone of the Air Force's bomber fleet since they were first fielded in the 1950s, are a prime example. Digital artifacts do not exist to support the re-engining of this fleet, and engineers will have to create digital models if they want to leverage the benefits of digital tools for new and upgraded B-52 engines and pylons. Even so, right-sizing the application of digital engineering to modernization and sustainment activities can reap outsized gains for the service, as they have been doing with the B-52's Virtual Training System.[51] Air Force senior leaders will need to decide how to implement digital engineering to its current legacy and hybrid weapon systems, what resources are required to do so, and what the desired benefits to managing their remaining lifecycles would be.

Digital Engineering can address diminishing manufacturing sources, improve parts strategies, and improve part upgrades. Legacy aircraft often suffer from diminishing manufacturing sources (DMS) when suppliers either stop making the parts they need or the suppliers go out of business. In the past, the Air Force has generally had to make a bulk purchase of spares before the end of a platform's production run with the hope that the spares inventory would last for the duration of the platform's service life. Alternatively, DMS might force maintainers to upgrade a system with a more modern part, which can create form, fit, and function issues. Digital models allow new components to be prototyped and manufactured to reduce compatibility issues. One B-1B program manager observed that, by using a digital model of the aircraft, "We will be able to design a part and fit test it in the digital world before we manufacture the real thing. The ability to do a virtual fit check could be very beneficial."[52] The creation of high-fidelity digital models can be focused on a specific new component and integration area to create replacement parts without testing their fit in the real world. This can reduce the time and cost of system repairs.

Digital engineering can improve and expand the supplier base. Digital models of legacy systems can help reduce vendor lock for existing components and reduce the barriers to entry for manufacturing legacy components. If a supplier can interface with the digital thread, they can build to part specifications and achieve certification more easily. Joe Stupic, head of the B-1 division at the Air Force Life Cycle Management Center, notes that "anyone can bid on the darn part" because they do not need to first reverse-engineer designs based on 1980s paper documents.[53] Modern manufacturing processes can then rapidly reproduce the needed parts.

Digital engineering can improve capability insertion programs for legacy and hybrid platforms. Digital engineering facilitates the rapid prototyping and subcomponent selection during the modernization of hybrid and legacy systems. A logical insertion point is through modernization work that may not require a significant backlog of reverse engineering. The Low Drag Tank developed to support F-22 modernization, for example, incorporates 3D modeling, which allows for the tightly controlled tolerances necessary to maintain its stealthy signature while greatly reducing the assembly time of the subcomponents and assembly rework. As the F-35 continues to advance with new capability insertions, its program managers are embracing its MBSE foundation through digital engineering applications to gain benefits like "better understanding of impacts of design changes…digitized sharing of requirements, verification, design and development data and real-time access to digital artifacts" to improve efficiency and final build quality.[54] Transitioning from MBSE to full digital engineering could yield even greater benefits. This would require training the F-35 Joint Program Office (JPO) workforce in digital engineering techniques and transitioning paper-based and outdated CAD/CAM products to a centrally accessible and model-centric approach.[55] Similar work will be needed for any hybrid program migrating from a digitized to a digital engineering framework.

A generalized digital model can support service life extension and major component replacements. Digital engineering can accelerate the design process for major retrofits to existing systems, although a major caveat is that more extensive validation is required compared to new designs that are fresh off the production line. The inherent wear and tear caused by thousands of flight hours creates substantial differences between an airframe's original factory specifications and its actual condition. As a result, these airframes are less likely to conform to digital models created from their original blueprints.

On the one hand, virtual digital aircraft can simulate years of structural loads and usage to reveal locations prone to fatigue or failure earlier.[56] This predictive capability can help transition aircraft maintenance to proactive operations where maintainers anticipate issues before they occur rather than discovering them after a failure.[57] On the other hand, creating validated digital models of the Air Force's existing aircraft will not be cost-free, especially since many of its aircraft have very different configurations and flight histories. This means digital aircraft may need to be tailored for each aircraft in a particular fleet if service officials require a certain level of specificity on a per-tail basis, given the scale, scope, and complexity of desired initiatives. To digitally recreate a B-1B to support future sustainment and parts manufacturing, the Air Force awarded Wichita State $100 million to fully disassemble and scan a retired B-1B airframe. Applying a similar process to each individual airframe in the Air Force's fighter and bomber forces would simply not be feasible from both a budgetary and schedule perspective. What that effort revealed was a macro digital representation of a B-1 and micro details of a specific tail. The former is useful for many applications, and the latter is necessary for certain sustainment efforts. Executing a business case assessment is essential to understand how and where digital engineering may provide value in relation to the effort and resources expended to execute the digitization.

To this end, the cost and difficulty of implementing a digital engineering solution for legacy systems can be mitigated by creating high-fidelity models that are limited to relevant systems and integration areas during periods of intensive and invasive upgrade work. The integration of the B-52's new engines during the Commercial Engine Replacement Program (CERP) serves as proof of this concept.[58] Prior to finally selecting Rolls Royce for CERP, the Air Force and Boeing required engine developers to provide virtual "engine agnostic" lower fidelity models of their engines to test how well each would integrate into the B-52.[59] After the Air Force selected Rolls Royce's F130-200 engine for CERP, it was then possible to create "a much more mature virtual prototype" with additional features that were not included in the engine's original digital model.[60] Virtual testing using the more advanced engine model that Boeing and Rolls Royce eventually created helped identify integration issues earlier than physical trials would have allowed, which prevented costly schedule slippage.[61]

Barriers to Implementing Digital Engineering Must Be Understood to Facilitate Its Widespread Adoption

Despite digital engineering's many advantages, barriers continue to persist that hinder its widespread adoption by the Department of the Air Force. For legacy and hybrid capabilities, the burden of reverse-engineering digital models, building their digital library, and other requirements can impose time and cost burdens on already stressed programs. Also problematic is the absence of well-understood, accepted business case analyses that substantiate the need to transition to digital engineering. Digitizing every element of legacy designs is incredibly time-intensive and costly and may yield data that is not germane to much of the sustainment enterprise. Instead, efforts should be focused on areas where intensive work is expected, systems are experiencing distinct challenges, or potential risks to longevity exist. Effectively planning, programming, and resourcing for legacy digitization requires senior Air Force leaders to better understand the business case considerations behind this effort. Presently, they do not have the financial justification for investing in wholly transitioning legacy and hybrid capabilities to digital models, nor do they fully understand the opportunities lost by not employing digital engineering to its fullest potential in new start acquisition programs.

It is also important to recognize that digital information must be safeguarded. The potential for cyberattacks on digital threads is another challenge that can hinder the transition to digital engineering practices. However, the most significant barrier to implementation may be cultural in nature. Without robust training and clear, compulsory guidance on how to use digital engineering in ways that will improve the entire acquisition oversight process, well-intentioned acquisition professionals may remain resistant to digital transformation.

Constructing a relevant digital authoritative source of truth for current capabilities that do not have any useful digital artifacts would require significant engineering efforts. Senior leaders must be shrewd when choosing how to scope digital efforts for legacy systems and determine when creating these digital foundations provides genuine value. Digital threads, artifacts, models, and twins are foundational resources for digital engineering, but they simply do not exist for legacy weapon systems. Instead, weapon systems that were entirely designed by analog processes require ground-up digitization. Reverse-engineering a legacy system to build digital artifacts means interpreting analog design specifications and conducting exhaustive real-world measurements of the physical system itself. Reconstructing a thread of digital artifacts for an entire weapon system would cost significant time and budget. Yet, using legacy paper and analog systems may not be a viable option either. Modern engineering is fundamentally digital, and in some cases it would be impractical to perpetuate obsolete processes, artifacts, or software for systems that the Air Force must sustain for years or even decades.

Hybrid systems that have a mix of analog and digital artifacts may have a significant amount of outdated or obsolete technology that must be overcome to interface with modern digital software tools. Decisions to invest in building or updating digital modeling tools and ecosystems for current weapon systems should be informed by larger force structure considerations and a clear understanding of the efficiencies and advantages that could be realized. Hybrid systems were designed with some degree of CAD/CAM and systems engineering or have a digital thread, but they were not originally conceived in a wholly integrated digital engineering ecosystem. These hybrid systems, such as the F-22 and F-35, have a preexisting codebase, CAD/CAM models, and other digital artifacts. Yet these tools and software languages may not be compatible with current digital engineering programs and could drive substantial workloads when migrating these artifacts to a modern digital foundation.

The costs of digitizing legacy and hybrid weapon systems will not always outweigh the benefits. What makes sense for an aircraft like the B-52, which is intended to remain in the bomber force for decades and is undergoing extensive modification, may not make sense for aircraft that will be retired in the near future. Moreover, there may be real-world factors that affect the performance of legacy systems resulting from their age, operational stresses they have experienced, and numerous service life extensions and modernization upgrades that simply cannot be captured by a reverse-engineered digital model.

While it may not be feasible to reconstruct full digital twins of hybrid or legacy programs, digital models or even limited-scope models can improve the sustainment issues that are often unique to older systems like the B-52, A-10, and B-1B in some cases. While it remains true that the historied service life of each legacy system or airframe introduces far greater variance between whatever master digital model is created and the true state of each individual aircraft, the Air Force's reduced readiness rates and soaring costs of weapon system sustainment for aging aircraft means the service must look at doing things differently to address these shortfalls.

Fully implementing digital engineering could impose substantial and even prohibitive costs. Digital engineering's advanced modeling and simulation software and supporting IT infrastructure require major up-front and sustained investment. For example, to develop the Integrated Digital Shipbuilding program in support of the Ford-class carrier, the Navy's Research, Development, Test, and Evaluation (RDT&E) and Newport News Shipbuilding invested $631 million.[62] Industry must also invest to push the envelope of digital engineering, manufacturing, and sustainment. For example, Lockheed Martin has invested $6B over a decade in a holistic digital transformation to change the way they develop, produce, and sustain solutions, all with the goal of enhancing speed and agility.

Investments in training are also needed to empower employees to fully access and harness the information provided by the authoritative source of truth. Factories and their workforces need, at a minimum, a basic IT infrastructure in place like high-speed internet. In addition, employees require terminals like laptops or augmented reality glasses to interact with and view the digital models, manufacturing tutorials, and instructions stored within the authoritative source of truth. These investments may not always be feasible for some manufacturers.[63] The up-front investment requirements can be especially challenging for smaller companies that lack the financial resources of a prime contractor, even when potential long-term benefits outweigh the cost.

To lower barriers, the government should encourage the adoption of open architecture standards and factor the up-front adoption cost of digital engineering tools into acquisition awards whenever digital engineering is mandated. DOD should also support the transition to digital engineering throughout the supply base as part of its industrial base strategy and explore using small business programs as a means to support workforce training.

A lack of digital standards, incompatible tools, and tool immaturity can also hinder adoption. U.S. Government leaders should avoid strict architecture and design mandates for the digital engineering ecosystem, focusing instead on the creation of an open and interoperable system architecture. DOD should likewise consider maintaining digital tools and making them available to the supply chain and defense industrial base. Along with the prime defense contractors, DOD should continue to explore how to create enhanced interoperability across diverse sets of digital tools.

There are many different digital tools and models available to companies, and not all are compatible. The entire digital thread for a weapon system must be coherent and compatible and allow data and other crucial programmatic information to flow across its entire ecosystem to yield a net benefit across its lifecycle. This could be particularly problematic for vendors in the supplier base that service multiple prime defense contractors. If different primes each have their own proprietary or preferred digital tool—which is largely the case today—each supply vendor could be compelled to maintain a large, expensive, and redundant library of digital tools. In addition, user-friendly tools that can migrate and integrate data across proprietary software and models are still in their infancy.

Large swaths of the Air Force acquisition workforce remain culturally resistant to digital engineering processes. Leaders must encourage experimentation and provide opportunities not only for engineers but also other stakeholders like program managers to learn how to integrate digital engineering into their daily workflows. Finally, when feasible, program requirements and contract awards should mandate the creation of digital artifacts instead of or alongside analog artifacts.

Organizational resistance to change often stems from a lack of familiarity with new processes or technology and comfort with the status quo. Acquisition professionals may hesitate to fully embrace new review and approval processes because they lack training, do not understand how to use digital tools, or because they fear regulatory or legal liability. Realizing the value of digital engineering requires buy-in and adoption not just from engineers but all other defense acquisition stakeholders—from warfighters to program managers. As one industry survey found, engineers who lack modeling experience may find digital engineering tools "cumbersome, confusing, hard to learn, and hard to use."[64] The cross-disciplinary nature of digital engineering can create a steep learning curve. Simply providing tools and limited training is insufficient.

Misaligned bureaucratic requirements are complicit in perpetuating this resistance, causing some of the most pressing intangible barriers to digital engineering adoption. Contract requirements often continue to mandate traditional artifacts over digital deliverables, and program managers insist on traditional paper review processes and milestone meetings even when the program is fully digital. DOD leaders should work to overcome organizational resistance and cultivate workforce expertise by emphasizing the importance of digital engineering to improve speed and collaboration. Demonstrating the value of digital engineering to all stakeholders by pushing organizational involvement in digital engineering pilot projects can encourage grassroots buy-in. Program managers should also use the experience gained from early applications to provide clear and personal "use cases" for how digital engineering will make individual engineers, operators, and maintainers' jobs easier in order to encourage wider adoption.[65]

The unknown or unpublicized financial benefits of digital engineering can inhibit needed changes. DOD's leadership should demand rigorous data collection and analyses within their organizations to determine the impact of digital engineering practices across an acquisition project cycle. Proposals should mandate the disclosure of the costs and benefits of digital engineering as a means of informing DOD and Congressional decision-making.

DOD's acquisition professionals may resist including digital engineering and its associated changes in contract requirements until they are able to quantify and understand digital engineering's cost benefits. A lack of understanding incentivizes the status quo use of existing engineering, management, and production activities that are low-cost and technically acceptable. It will remain challenging for DOD's leadership, acquisition workforce, and related professionals to fully invest in digital engineering until it develops methodologies to capture its financial benefits. Duplicating programs with and without digital engineering to prove the value of digital engineering, however, is infeasible.

Defense prime contractors are leading the way here, conducting internal cost estimation, workflow, and quality assurance studies to begin to understand and validate the business case for digital engineering. For example, Lockheed Martin internally invested in Project Star Drive to measure, track, and better understand digital engineering from a cost, schedule, and quality perspective. This work spans existing, new start, and sustainment programs and incorporates suppliers and DOD partners to drive realism and ensure repeatability. Comparing representative case studies can also demonstrate the value of investing in digital engineering across various program types and sizes.

The dependence of digital engineering on digital threads creates cyber security and accessibility risks. Robust cybersecurity measures must be built into any weapon system, along with physical or analog backups for its mission-critical components. Changes made within the digital thread to the authoritative source of truth must be traceable and consistent to ensure reliable validation and authentication. These cybersecurity imperatives will remain important through implementation and must evolve with new threats throughout a program's lifecycle.

The very nature of digital engineering can make it extremely vulnerable to cyber-attacks. Every element of digital engineering is dependent on the integrity of its cyber security and accessibility, from the authoritative source of truth, digital models, and digital twins to the stakeholders' digital thread access. If, for example, the cloud computing centers that store digital artifacts are forced offline by a cyberattack, or if the networks the information rides on are denied, the digital ecosystem risks collapsing. Connecting assets to a wider network of any kind comes with unavoidable cyber security risks, and not simply from denial of service. Adversaries could seek to collect information regarding U.S. capabilities by infiltrating the digital thread and accessing the authoritative sources of truth, or they might seek to paralyze U.S. operations by attacking sustainment and supporting logistics databases.

The further that digital knowledge is permeated in the operational world or throughout the production and sustainment supply chain, the increased likelihood of a breach. This threat is especially serious for U.S. operators at the tip of the spear; the potential that a fighter, bomber, or ship could be disabled or destroyed due to software tampering must be taken seriously. The same holds true for vendors who lack the means or culture to properly secure data. Robust access controls and rigorously enforced norms are imperative to secure the digital thread while ensuring stakeholder access. Competing demands of security and accessibility must be balanced.

Other Key Points Department of the Air Force Leaders Should Understand

DAF leadership must be cautious regarding its appetite to "sensor up" its major weapon systems. The desire to optimize digital twins may drive efforts to install greater numbers of system and structural monitoring sensors. More sensors updating the digital twin can improve its veracity. For example, Formula One race cars with sensors installed provide instantaneous and continuous measurements that can be used to assess the performance of specific components and functions. However, incorporating numerous sensors on systems like aircraft or satellites may add unacceptable weight, space, power, or processing requirements to the system, and perhaps even at the cost of mission capabilities. These sensors may also drive up development, procurement, and operational costs, offsetting resources for other desired benefits. The incorporation of sensors that improve digital engineering performance must thus be balanced against more conventional operational performance tradeoffs.

Digital modeling and simulation cannot fully replace real-world testing, especially for novel technologies and complex integration programs. The Air Force must maintain sufficient real-world test and evaluation requirements in the acquisition process to validate digital models, and program managers must retain the capabilities to execute those requirements in a timely fashion. Test assets and programs are even more crucial for novel technologies and platforms. In these cases, additional levels of real-world testing should be required to prove operational functionality, especially when new capabilities are coming together for simultaneous integration.[66] Digital engineering, modeling, and simulation are most effective for systems and subcomponents with a high level of technological maturity where unknown unknowns are minimized.[67] DAF leaders should continue to require integration of live testing at key milestones and make data from digital twins accessible to industry partners to enable continued improvements in simulation and model performance.

Classification barriers are likely to limit digital engineering's application for classified programs. Classified data and designs often cannot be fully modeled or shared digitally. When they can, they may be confined to a more limited suite of software tools or file types. Yet excluding digital engineering applications outright on sensitive or classified projects risks foregoing significant benefits. Organizations should implement appropriate access controls rather than avoid digital engineering entirely. Creating compartmentalized and tiered access models with varying degrees of model and data fidelity and visibility dependent on user permissions can enable broader digital engineering adoption while maintaining information protection for classified programs. Programs like B-21 and the GBSD Sentinel that have successfully addressed the challenges that classification can pose to digital engineering should share their lessons learned and best practices with others.

Recommendations and Conclusion

The DOD's traditional acquisition approaches are ill-suited to deliver the increasingly complex modern weapon systems that are needed to ensure America's warfighters prevail against China's rapidly modernizing military on relevant timelines. Lengthy development cycles, cost overruns, and sustainment burdens continue to stymie major acquisition programs for these crucial capabilities. While digital engineering can address these issues across the military services, the Department of the Air Force is in a unique position to take advantage of digital engineering.

After decades of deferring or terminating the recapitalization of core mission areas, the DAF is now facing the need to modernize nearly its whole inventory. It is the oldest, smallest, and least mission-ready in its history, and, therefore, it has numerous opportunities for digital engineering integration across a variety of modernization and new start programs. Whereas the service must rapidly develop and field a new generation of capabilities to meet its expanding global operational commitments, the scale and scope of this demand are daunting, and a lethargic and outdated acquisition system is likely incapable of delivering. Digital engineering, in the sense of both tools and approaches, has the potential to accelerate the development and fielding of much-needed new major weapon systems at a lower cost while simultaneously improving the sustainment and modernization of the DAF's legacy fleet.

Recommendations

DAF leadership should pursue several concerted and targeted efforts—prudently based on specific program characteristics and requirements—to maximize their return on investment in digital engineering integration:

- DAF leadership should consider and incentivize the use of comprehensive digital engineering for new start acquisition programs. Require digital engineering for new start acquisition programs to maximize design and testing efficiencies and enable long-term affordable sustainment. Ensure contractors and subcontractors feed their digital engineering artifacts into the authoritative source of truth as part of their contract deliverables.
- DAF acquisition leaders should assess the feasibility of digital engineering solutions for legacy and hybrid weapon systems. The digital engineering use case for hybrid and legacy platforms is less clear-cut than for new starts. Acquisition leaders should evaluate where targeted digital upgrades can offer significant advantages before mandating the use of digital engineering for hybrid and legacy platform retrofits or sustainment actions. Wholesale digitization of a platform may provide minimal value compared to the implementation costs, especially for systems nearing retirement—like the A-10. Digital engineering could still provide substantial integration and virtual testing benefits for legacy weapon systems with ample in-service time remaining and significant planned modernization.
- DAF leadership must train its acquisition workforce to use digital tools and processes. Developing federal and service workforce expertise and buy-in for using digital engineering is foundational to fully access its benefits and mitigate its costs. The DAF should establish, maintain, and promote a uniform set of definitions related to digital engineering terms to avoid confusion and misaligned efforts.[68] While digital design tools like CAD/CAM are now widespread, fully embracing cloud-enabled model-based systems engineering requires

changing the culture of acquisition and engineering workforces. Pilot projects can help build workforce proficiency in digital engineering, but widespread adoption will require mandated education and training. This training should start with the acquisition and engineering workforce and then propagate out through the rest of the DAF's ecosystem as the platforms used by its operators and maintainers become increasingly integrated into the digital ecosystem.

- DAF acquisition leaders must promote open standards for digital engineering tools. Some companies have developed their own proprietary digital engineering software tools that are incompatible with the tools developed by other companies or even commercially available software. While companies may derive unique benefits from developing their own tools, they should not act as an ancillary profit center by imposing licensing fees or other special accommodations on suppliers or the DAF. Instead, DAF leaders should mandate the use of open standards or interfaces that ensure a variety of vendor tools, software, and formats are interoperable.[69] As they do so, they should avoid hard mandates that lock the defense and industrial enterprise to a single standard indefinitely.
- The DAF should maintain a library of digital engineering tools accessible to small businesses, sub-tier suppliers, or other non-traditional companies. The cost of procuring, licensing, and installing digital engineering software may pose a barrier to some small companies or suppliers. This would effectively bar them from entering the digital engineering ecosystem. This problem risks compounding if small companies, including non-traditional defense industrial base partners, must maintain multiple types of digital engineering tools to satisfy different prime contractors. While open standards can lower this hurdle, the DAF should create a library of approved software tools and then provide them to small businesses and suppliers. This could help these smaller entities to standardize their digital products and activities, improve the quality of their product, and ultimately expand the digital ecosystem.[70]
- The DAF and its prime contractors, partners, and suppliers must ensure their IT infrastructures are modernized and secure. Every participant in DAF programs—from the acquisition team to the prime contractor and down to the sub-tier suppliers—must ensure they have an IT infrastructure with sufficient capacity, speed, and security to function effectively in the digital ecosystem. Digital models do not matter if they cannot be accessed quickly and securely.[71]

Conclusion

Digital engineering can be a key element in addressing the Department of the Air Force's capability crisis. Implementing a digital engineering approach to new weapon system programs could help the service field these capabilities more rapidly and more affordably than continuing with traditional acquisition approaches. Digital approaches to sustainment may also help control costs associated with readiness, increase mission capability rates, and support more rapid modernization and capability insertion. For the legacy or hybrid weapon systems that make up the bulk of the Air Force's force structure, digital engineering can deliver many sustainment benefits. These efforts will incur some up-front costs to digitally reconstruct many of the artifacts to support those activities; they are not easy nor cheap but may be worth the resulting longer-term efficiencies and cost savings. Senior DAF leaders should be sufficiently "digitally literate" to identify applications in which digital engineering offers great potential and high payoffs across the DAF's entire portfolio, and they must be shrewd in matching program objectives to their goals for implementing digital engineering.

DOD and DAF leaders should look to the U.S. defense industry to provide quantitative and qualitative data regarding the value of digital engineering. Industry is comparing their legacy processes and tools, timelines, production methodologies, and other assessments to understand exactly where they derive value from digital engineering, though many of these software tools and processes are proprietary because they provide companies with a competitive advantage. From industry, defense leaders can also gain a better understanding of what metrics and outputs they should track to ascertain how to use digital engineering to accelerate schedules, lower costs, and increase readiness. Such insights can also inform DOD and DAF senior leaders how to better evaluate industry performance and spread best practices across the defense industrial base and deep into the supply chain.

The rapid pace of technological change and the emergence of 21st-century near-peer and asymmetric threats demand DOD to develop and field new, disruptive capabilities more responsively, flexibly, and cost-effectively. Digital engineering offers part of the answer to this challenge. By leveraging advances in model-based systems engineering, cloud computing, data analytics, bandwidth, and cyber security, digital engineering can help the United States regain and maintain its technological military advantage. A digital transformation is integral to equipping warfighters with superior systems and outpacing global challengers. A failure to exploit digital engineering risks a failure to succeed and remain operationally relevant, falling further behind an increasingly aggressive China that seeks to build a military that can dominate the Western Pacific. Allowing this to occur could result in existential, enduring, and difficult-to-reverse consequences. ✪

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