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Agile Acquisition: History and Recommendations

EXECUTIVE SUMMARY AND REPORT
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PREFACE

Rapidly advancing threats and technologies have increased the need for the U.S. Department of Defense (DoD) to more quickly develop, field, and upgrade operational capabilities to ensure mission effectiveness and success. While Agile development along with DevSecOps (development, security, and operations) are being applied in the DoD for software development, there is an increasing need to address more rapid development of hardware and tightly integrated hardware/software systems.

This report discusses approaches (historical and current) by industry to address agile development for elements beyond software. It also discusses opportunities and cultural barriers to DoD implementation of Agile and DevSecOps for hardware and tightly coupled hardware/software systems.

This study was motivated, in part, by a section in the Joint Explanatory Statement of the Committee of Conference, accompanying the FY 2021 NDAA (House of Representatives, 2020, pp. 1761–1762). See Appendix B for details.

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Issues with Software-Only Use in the DoD. Systems are increasingly reliant on tightly integrated hardware/software systems. Changes in hardware will affect software—and vice versa. Software is often completed ahead of hardware, and system integration and testing require access to developed hardware. This causes delays, late and costly problem discovery, aging software, and disconnects in ownership and sustainment.

DoD Barriers to Address. There are cultural DoD barriers to implementing Agile and DevSecOps for hardware. For example, much DoD software is deployed on special-purpose hardware platforms, so there is a prevailing view that Agile does not apply or is too difficult to implement in weapon systems that are deployed in harm's way. There is also a gap in general knowledge of how to apply these techniques beyond software, little-to-no organizational support, and little explicit policy directing their use.

Recommendations. To fully leverage the potential of Agile and DevSecOps for both hardware and software, the DoD needs to address both functional applications and non-technical challenges to their application. Specific steps forward include the following:

- **Develop a Center of Enablement (COE) for Agile and DevSecOps** to provide practical advice to programs in applying these techniques to both hardware and software elements of acquired systems while facilitating workforce training and improvement in these areas.
- **Integrate Agile and DevSecOps initiatives with Digital Transformation** to improve management through the collection and sharing of program performance, share best practices and lessons learned, and improve workforce skills and insight.
- **Continue pursuing agility in contracting, requirements, and funding** to instill agility in the key inputs and support functions necessary to conduct system design, development, production, and deployment.
- **Address cultural and risk barriers through leadership and incentives** to support change, ensure proper employment of Agile and DevSecOps, and address workforce concerns.

SUMMARY

Rapidly advancing threats and technologies have increased the need for the U.S. Department of Defense (DoD) to more quickly develop, field, and upgrade operational capabilities to ensure mission effectiveness and success.

Agile and DevSecOps Defined

Agile development and the practice called DevSecOps *(development, security, and operations)* are two primary approaches to accelerate acquisition and improve relevance. Agile and DevSecOps do not skip steps or eliminate required work. Instead, they break down work and workflows into smaller activity sets to shorten cycle times and validate capabilities with more frequent user feedback. DevSecOps arose from the need to develop and operate incrementally to continuously deploy initial capabilities early while using operational data to inform subsequent improvements. Given the importance of security, it is explicitly prioritized throughout the DevSecOps cycle.

Issues with Software-Only Applications in the DoD

In the DoD, Agile and DevSecOps are often solely focused on the development of software in acquired systems. However, systems are increasingly reliant on tightly integrated hardware/software, wherein changes in hardware will affect software—and vice versa. Moreover, software is often completed ahead of hardware, yet system integration and testing typically requires access to hardware, too. This often results in waiting until the hardware is completed, causing late (and costly) discovery of problems, aging software, and disconnects in ownership of products and capabilities.

There are cultural DoD barriers to implementing Agile and DevSecOps for hardware. For example, much DoD software is deployed on special-purpose hardware platforms, so there is a prevailing view that Agile does not apply or is too difficult to implement in weapon systems that are deployed in harm's way. There is also a gap in general knowledge of how to apply these techniques beyond software, little-to-no organizational support, and little explicit policy directing their use.

Successful Applications to Hardware by Industry

In contrast, industry has applied the fundamentals behind Agile and DevSecOps not only for software but also for hardware and inter-reliant hardware/software systems. Over the past several decades, advances in introducing Agile and DevSecOps to the non-software environment have been realized. In some cases, the hardware development cycle time has been decreased. In other cases, simulated environments (e.g., NearOps [Near Operational] Environments) have been developed to allow software integration and testing prior to the availability of the actual hardware. Due to these linkages and dependencies, advances in Agile and DevSecOps processes continue to be applied to the hardware/non-software product lifecycle commercially.

For example, hardware-intensive commercial enterprises such as Saab Aircraft and Tesla have successfully completed full journeys to continuous innovation and deployment. These enterprises recognize that deploying new systems or capabilities cannot wait on the slowest components of the system. Instead, all components need to be deployed when ready, and both systems and organizations need to be structured to support modularity and flow. Here, Agile is an *enterprise mindset and approach* that must address and be applied to all aspects of the system. Saab Aircraft and Tesla (among others) demonstrate that agile practices can be adopted by hardware-intensive industries. The pathway is based on agile software and agile manufacturing principles, and then fully integrating hardware development into the flow of continuous innovation and deployment. Extensive use of digital engineering, modeling, and simulation are key enablers, along with strong product owners who can speak for the customer ahead of actual deployment.

Agile applied to hardware has been successfully implemented in industry through the Agile Manufacturing process. As defined by Tulip (2022), "Agile Manufacturing is an approach to manufacturing that leverages flexibility, bottom-up innovation and augmentation in order to adapt, through an iterative process, to changing conditions." Critical to Agile Manufacturing is addressing changing conditions (e.g., user demands, supply chain disruptions, technology evolutions, and regulatory environments) as rapidly as possible (Patel et al., 2014). Agile Manufacturing empowers workers to produce, in real-time, a product that meets customer needs in a timely matter—all within a competitive marketplace. In the case of the DoD Acquisition environment, the need for rapid product development and deployment that adjusts to changing customer needs is paramount given the competitive nature of adversaries. Agile Manufacturing incorporates Agile methods (flexibility, rapid product releases, focus on customer value, etc.), and also incorporates DevSecOps methods.

Opportunities for Implementing in the DoD

While the primary focus of DevSecOps is on software development in the DoD, it also can be applied to hardware and parallel hardware/software development when hardware can be incrementally developed, deployed, and improved. Agile and DevSecOps practices have been implemented with various degrees of success in many DoD acquisition programs. Successes have been seen especially in software-based acquisition programs, but extending these practices to hardware and hardware/software systems is an opportunity to improve acquisition agility and responsiveness to operational needs. In cases where hardware cannot be fully deployed at scale (e.g., an aircraft carrier's hull form), simulated environments such as NearOps allow software integration and testing.

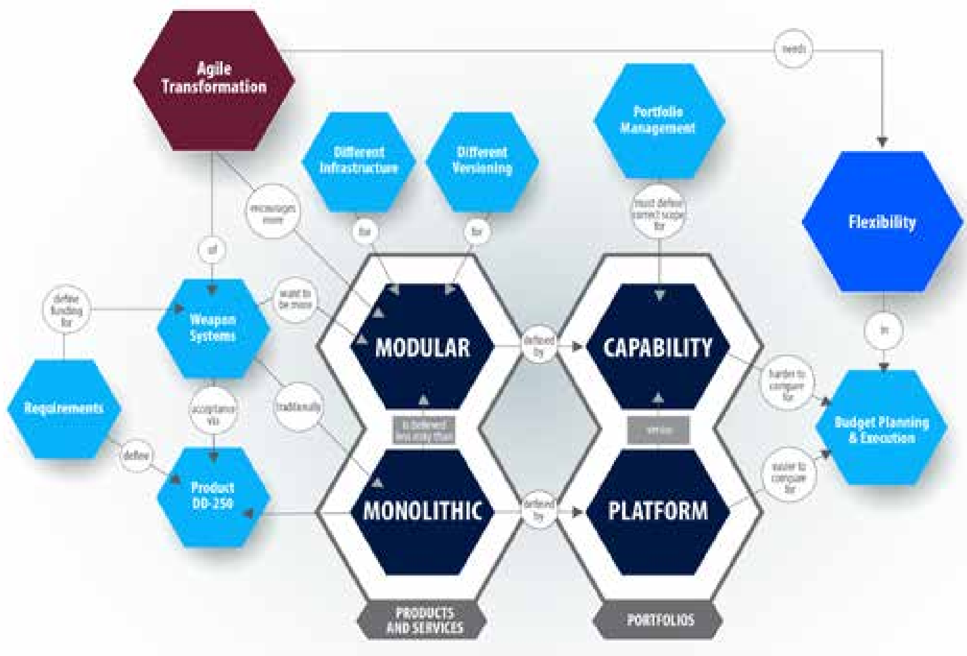

Figure S.1. Acquisition's cultural challenges to Agile transformation

To fully leverage the potential of Agile and DevSecOps (both for hardware and software), the DoD needs to address both functional applications and non-technical challenges to their application. Specific steps forward include the following recommendations.

- **Develop a Center of Enablement (COE) for Agile and DevSecOps** to provide practical advice to programs in applying these techniques to both hardware and software elements of acquired systems while facilitating workforce training and improvement in these areas.
- **Integrate Agile and DevSecOps initiatives with Digital Transformation** to improve management through the collection and sharing of program performance, share best practices and lessons learned, and improve workforce skills and insight.
- **Continue pursuing agility in contracting, requirements, and funding** to instill agility in the key inputs and support functions necessary to conduct system design, development, production, and deployment.

PURPOSE

During World War II (WWII), the U.S. Department of Defense (DoD) became a technological leader of the world, forcing innovation and improvement across a variety of technologies. This leadership persisted for several decades. Today, the imperative to remain on the forefront as a technological leader persists, but innovation and technological advancement is primarily driven by the commercial sector—creating new challenges for the Department's ability to quickly procure and integrate commercial solutions and lowering the barrier of entry for both our allies and adversaries.

As other countries accelerate the pace of their acquisitions, the U.S. is lagging behind. (Greenwalt and Patt 2021)

Figure 1. New Capability Delivery (Greenwalt and Patt 2021)

Today's Defense Acquisition System (DAS) was built on the "waterfall" or "v-model" methodology. These are largely sequential approaches to developing systems or capabilities – starting with high-level needs and requirements, developing systems, testing and validating them, and delivering them. This is a logical approach, but as currently implemented, is bureaucratic and slow. The average time for major acquisition systems development and initial fielding is 5–7 years. When including the advanced time to develop and approve requirements and obtain funding, initial development can take over a decade, resulting in systems being delivered that are technically and operationally obsolete. In comparison, commercial sector companies today could not survive at this pace.

One of the ways that these current approaches can be enhanced is through an organizational focus on continuous improvement, in which continuous improvement becomes part of the culture supported by methods, processes, and tools that encourage everyone to look for ways to advance operations. This includes suggesting ideas to improve efficiencies, evaluating current processes, and finding opportunities to eliminate unproductive work. There are two main mechanisms for continuous improvement that may be of great benefit to the DoD:

1. **Agile** – an approach that seeks to improve process flow, rapidly generate functions/capabilities incrementally, and rapidly react to changing customer needs (i.e., constantly deliver some value) and
2. **DevSecOps** – an approach that seeks to improve processes and reduce bottlenecks in systems and processes.

For several decades, Agile and DevSecOps techniques have helped to improve the speed of delivery and the quality of both hardware and software products. This report focuses primarily on applying Agile and DevSecOps defense approaches on both hardware and mixed hardware/software acquisition programs to address the diverse capabilities and challenges the Department faces in today's evolving, competitive technological and adversarial environment, in compliance with the directive from the 2021 National Defense Authorization Act.[1] Because current Agile practices incorporate many of the principles of Lean, Lean is discussed (when appropriate) in the context of Agile.

[1] See Appendix B, "Terms of Reference"

CONTINUOUS IMPROVEMENT AND DEPLOYMENT

The fiscal year (FY) 2018 National Defense Authorization Act (NDAA) (House Report [H.R.] 2810, Public Law 115-91) defines the term "Agile Acquisition" as "acquisition using agile or iterative development." **Agility is the ability to reliably and rapidly deliver customer value in the face of uncertainty and change.** While the term "Agile" is most commonly referred to in terms of software development, there is a wider application for Agile in the area of Agile project management. Broadly defined, Agile project management is an iterative process that focuses on customer value first, team interaction over tasks, and adapting to the current business reality rather than following a prescribed plan. The primary goal of Agile transformation, including within the military, is to iterate and adapt to achieve **continuous innovation and deployment of valuable capabilities** to the **end user** and **necessary support processes**. This is in response to competitive pressures of rapid innovation, technological advancement, and fast adoption of products and services across commercial industry and governments worldwide. Continuous innovation and deployment require continuous development of the workforce and organizational practices as well as of products and services. Olsson and Bosch presented the "Stairway to Heaven" model as an approach to help organizations that create complex systems, such as the DoD, transition from more traditional development approaches (their definition) towards continuous innovation and deployment practices. This is shown in Figure 2.

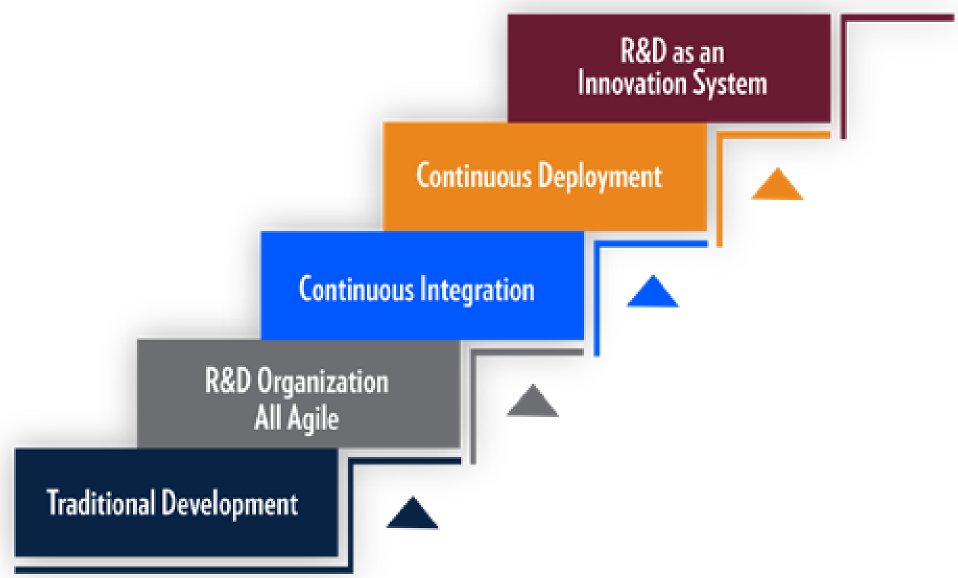

Figure 2. "Stairway to Heaven" Model (Olsson and Bosch 2014)

Olsson and Bosch characterize traditional development by "slow development cycles, sequential phases, and a rigorous planning phase where requirements are frozen up front" (2014). The authors summarize a series of evolutionary stages:

- **All agile:** deliberate introduction of agile practices, a shift to small development teams, and a focus on features over components (software) and capabilities over platforms (systems).
- **Continuous integration:** automated testing, a platform to which new capability is continually delivered, and a modularized architecture.
- **Continuous deployment:** internal and external stakeholders to be fully involved and a proactive customer with whom to explore new capabilities.
- **R&D as an innovation system:** management of the full development ecosystem (internal/external) in order to align internal business strategies with the dynamics of competition. Critical to each stage is the alignment of internal and external processes to take advantage of agility (Olsson and Bosch 2014).

The DoD has embarked on this journey primarily for software systems. However, **continuous innovation and deployment is a total system concern, and involves hardware components** in a system as well as software, process, and other human-oriented intangible components. In the DoD, much of the software is deployed into special-purpose hardware platforms, so currently there is a prevailing view that Agile does not apply to—or is too difficult to implement in—weapon systems that are deployed in harm's way.

Looking at industry examples, hardware-intensive enterprises such as Saab Aircraft and Tesla have successfully completed full journeys to continuous innovation and deployment. These enterprises recognize that deploying new systems or capabilities cannot wait on the slowest components of the system, but rather that all components need to be deployed when ready and that both systems and organizations need to be designed to support modularity and flow. Agile is an enterprise mindset and approach that must address and be applied to all aspects of the system.

SAAB

Saab Aircraft introduced Agile practices into the Gripen fighter program over 10 years ago and has scaled its use to implement agile practices in every discipline and at every organizational level in the Gripen E model development. Autonomy at the team level is the core practice, and teams are allowed to tailor practices in their workflows, drawing from both agile software practices and lean production practices. As it is difficult to gain rapid customer feedback cycles at the aircraft level, Saab uses internal product owners as a proxy for pilots and maintainers. Saab states that these agile methods are primarily beneficial in managing variability, which leads to consistency in cycle times and transparency in design variability that would unnecessarily impact routine processes and existing design stability. Saab also cites prioritization of work, improved strategic capability planning, continuous improvement, and reduced bureaucracy as important outcomes of their agile transition. Factors that enable this transition are modular design practices and test automation through virtual simulators. Virtual environments allow local integration such that development activities can be performed continuously and components integrated as they become available (Furuhjelm 2015).

TESLA

Since its inception, Tesla has applied concepts of Agile development to all of its design and manufacturing processes. Tesla entered the automotive market obsessed with innovation. From the start, its focus has been on continuous innovation by deploying improvements rapidly and evolving from customer feedback. Tesla's approach created a fast feedback cycle that enables the company to quickly address software bugs and to continually increase vehicle safety and reliability. As a result, Tesla has achieved a much more rapid path to affordable electric vehicles and customer satisfaction than traditional automakers, and consequently has achieved considerable disruption in the marketplace.

Tesla's Silicon Valley software culture easily embraced agile innovation teams with individual product owners to accelerate design, development, and innovation cycles. There is a multi-functional team behind every component of a Tesla vehicle, and each uses its autonomy to innovate on their individual components that are supported by a modular base structure in each of their model lines. Engineering and product teams are collocated at the manufacturing facility. In addition, Tesla built its manufacturing facilities to take advantage of agile development: robotics and adaptable factory processes and layouts allow hardware changes to be adapted into factory operations in days.

Of importance to note, Elon Musk stated that although Tesla was built with an agile culture and mindset from the start, it was full digital adoption that allowed continuous innovation and development. Models, simulations, and software-programmed processes were key enablers to fully agile vehicle development (Trotsenko 2022).

1.1 AGILE ACQUISITION

Principles of Agile in software date back to a seminal Win Royce paper in 1970 entitled "Managing the Development of Large Systems." In this paper, Royce introduced the waterfall model (inherent in today's DoD acquisitions) and highlighted the potential issues associated with that model:

> *I believe in this concept [waterfall model], but the implementation described above is risky and invites failure* (Royce 1970).

Royce noted the fundamental flaws in the waterfall model: 1) testing is at the end, therefore 2) flaws in the design are not identified until the end. Royce further stated, "One can expect up to a 100-percent overrun in schedule and/or costs." Royce promoted three strategies to overcome these flaws: 1) do the design more than once, update, and learn; 2) plan, control and monitor testing; and 3) continuously involve the customer. Alternatively, "To give the contractor free rein between requirement definition and operation is inviting trouble." These three strategies are fundamental in agile development today and address the potential issues of the waterfall model.

The waterfall model long used in DoD acquisition is inappropriate when any other workflow can be found that addresses Royce's three strategies cost effectively. For purely software systems, this entails a complete shift away from waterfall approaches. For more hardware-intensive functionality, which applies to most organizations, this entails a blend of Agile and more sequential approaches. Success at continuous innovation and deployment only occurs when the full enterprise achieves an agile mindset.

As a software movement, Agile evolved through a series of software process models such as the spiral model and today's processes such as Scrum. The Agile software movement also evolved in parallel with hardware manufacturing initiatives such as the Toyota Production System (which originally implemented core aspects of the Agile mindset) and Lean Manufacturing (which formalized concepts of continuous improvement and elimination of waste). Figure 3 highlights this evolution.

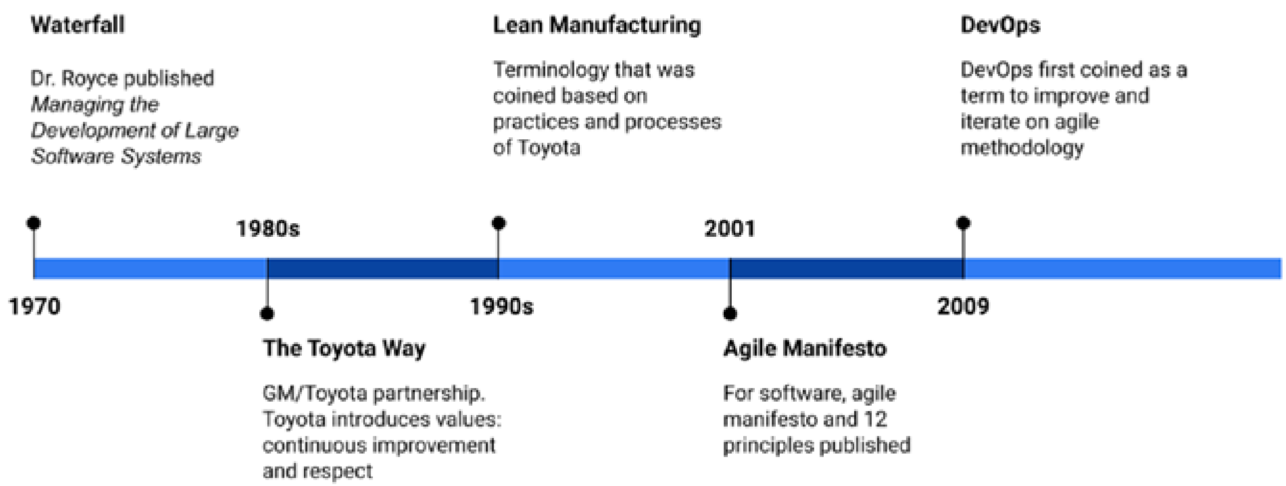

Figure 3. Timeline of Continuous Development Concepts (Digital DNA 2022)

In the 1990s, the Agile software movement reacted to the prevailing software processes that were mired in bureaucracy and demoralized software developers. Consultants such as Alistair Cockburn, who studied developers' productivity, observed that the people responsible for producing the software product had the least control over it. A variety of techniques such as eXtreme Programming, Crystal, and SCRUM were introduced that gave developers control of the product and quickly gained developer acceptance. They summarized the change from rigorous external control to developer control in the *Agile Manifesto* in 2001:

> *Based on their combined experience of developing software and helping others do that, the seventeen signatories to the Manifesto proclaimed that they value:*
>
> - *individuals and interactions over processes and tools*
> - *working software over comprehensive documentation*
> - *customer collaboration over contract negotiation*
> - *responding to change over following a plan*
>
> *That is to say, while both sides have value and the items on the right should be considered, the authors of the manifesto chose to tip the balance in favor of the items on the left.* (Beck et al., 2001)

The core principle behind the Agile Manifesto is "flow," i.e., the flow of work should continue consistently across cycles of product development and support. The goal is not to eliminate work, but to achieve balance. Agile attempts to balance four goals:

1. the creation of product/service capabilities;
2. the utility of those capabilities to stakeholders;
3. translation of the design across disciplines; and
4. management of team size to overcome cognitive limitations of the individual versus complexity of the team.

Two core principles of Agile are "balanced teams" and "thin-slicing" workflows. The cyclic nature of Agile encourages thin vertical slices of workflow across disciplines to deliver thin slices of value (capabilities) more rapidly and consistently as opposed to large horizontal slices of workflow that are subject to planning bottlenecks and constraints. Thin slicing gives the enterprise the ability to innovate, change, and deploy rapidly in response to emerging needs and opportunities.

In, systems, Agile favors principles of *modularity, flexibility, and accountability*. *Modularity* supports management of system size and complexity by partitioning and isolating system capabilities from each other. *Flexibility* supports learning as developers and customers are able to use capability slices earlier and pivot away from inadequate capabilities to more valuable capabilities. *Accountability* supports speed, as decisions are pushed down to the lowest levels of developer and user.

Agile is generally implemented in sprints: short periods of planned work where some clear capability is developed, as illustrated in Figure 4. One of the benefits of the sprint approach is that each sprint creates a functional part of the final product. These short periods are usually weeks or at most a few months, which is dramatically different than the longer time periods often used in traditional acquisition. Another major benefit of this approach is that experimentation is encouraged, a dramatic difference from the current acquisition approach. Because sprints are relatively short, higher risk/reward approaches can be tried; if they do not succeed, then the learning will go immediately into the next sprint.

The DoD, like many organizations and companies that have previously institutionalized the waterfall approach, has struggled to make the shift to Agile. Over years of employing more sequential approaches, the Department, like other organizations, has created siloed organizations responsible for one part of the process with movement to a different stage (silo) triggered by full completion of the activity, coupled with large testing events at the end of development. As Royce states, this approach invites risk. There are more factors that contribute to the slow adoption of Agile that will be discussed later.

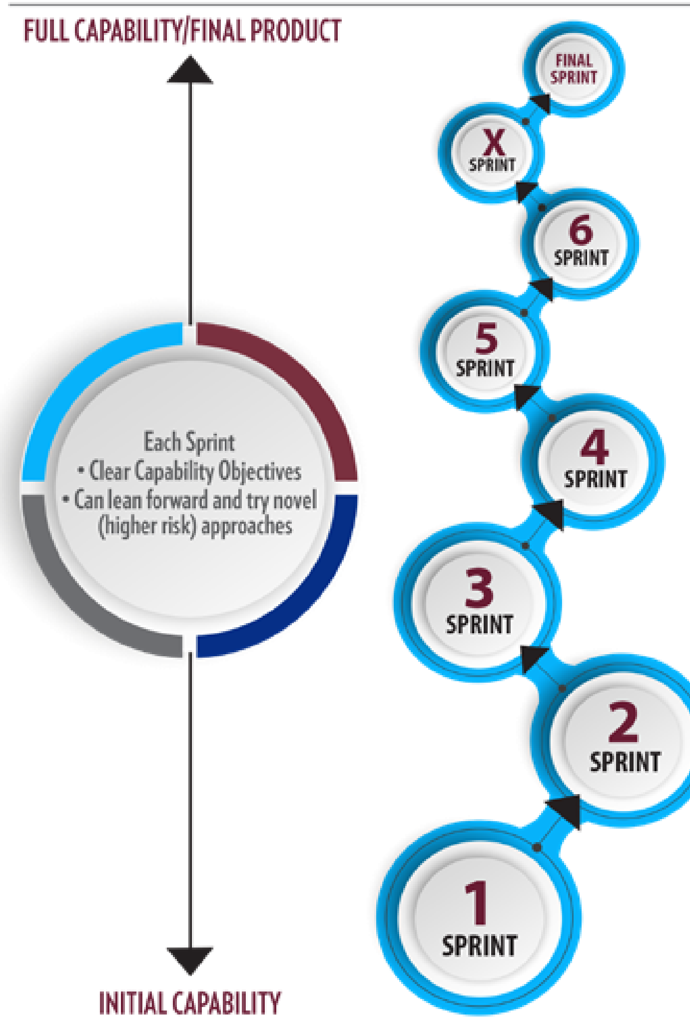

Figure 4. Agile Sprint Development Concept

1.1.1 AGILE HISTORY: AGILE IN HARDWARE AND SOFTWARE SYSTEMS

The case studies of Saab Aircraft and Tesla demonstrate that agile practices can be adopted by hardware-intensive industries. The pathway is based on agile software and agile manufacturing principles, then fully integrating hardware development into the flow of continuous innovation and deployment. As illustrated by the Tesla example, extensive use of digital engineering, modeling, and simulation is a key enabler, along with strong product owners who can speak for the customer ahead of actual deployment.

Although Agile and DevSecOps are typically associated with software system acquisition, most DoD acquisition programs involve both hardware (i.e., non-software) and software elements. In many cases, dependencies exist between these elements and their product lifecycles are linked. Changes to one element will impact the other element. In many cases, the software is completed ahead of the hardware, yet system integration and testing typically requires access to the hardware. This often requires waiting until the hardware is completed, but this can result in discovering problems late in the development cycle, aging software (i.e., software that is put on the shelf), and driving disconnects in ownership of product and capability. Over the past decade, advances in introducing Agile and, later, DevSecOps to the non-software environment have been realized. In some cases, the hardware development cycle time has been decreased. In other cases, simulated environments (e.g., NearOps [Near Operational] Environments) have been developed to allow software integration and testing prior to the availability of the actual hardware. Due to these linkages and dependencies, advances in Agile and DevSecOps processes continue to be applied to the hardware/non-software product lifecycle.

As defined in (Peterson 2021), both software and non-software manufacturing sectors exhibit similar product lifecycles (i.e., product definition, design, prototyping, development/testing, operations, maintenance, and sustainment). The difference is primarily the duration of each lifecycle phase and the domain of work: deterministic vs. emergent. "[Software] product development, unique change (e.g., logic flow complexities, etc.), is emergent, not deterministic. The work is filled with unknown-unknowns and acting in the space changes the space. Conversely, a worker making wheels all day long on an assembly line knows when the wheel is built and when it is not." (Peterson 2021). In the Agile/DevSecOps software domain, the work is always emergent and the durations of each phase can be minutes, days, weeks, or months, whereas in the non-software domains, the work is generally deterministic and measured in months and, in some cases years. The goal in both software-intensive and hardware-intensive work is the same: reduce phase durations and quickly react to changing end-user demands.

As noted previously and described in the Tesla and Saab case studies, Agile applied to hardware has been successfully implemented in industry through the Agile Manufacturing (AM) process. As defined in (Tulip 2022), "Agile Manufacturing is an approach to manufacturing that leverages **flexibility, bottom-up innovation** and **augmentation** in order to adapt, through an **iterative process**, to changing conditions." Critical to AM is addressing changing conditions (e.g., user demand, supply chain disruptions, technology evolution, and regulatory environment) as rapidly as possible (Patel et al., 2014). AM empowers workers to innovate (e.g., modify production methods, enhance product features) in real-time and produce a product that meets customer needs in a timely matter—all within a competitive marketplace. In the case of the DoD Acquisition environment, the need for rapid product development and deployment that adjusts to changing customer needs is paramount given the competitive nature of adversaries.

IIoT- Industrial Internet of Things

"The use of certain internet of thing technologies - certain kinds of smart objects within cyber-physical systems - in an industrial setting, for the promotion of goals distinctive to industry." (Boyes et al 2018)
This can include interconnected sensors, instruments, and other devices networked together with computers industrial applications, including manufacturing and energy management.

AM incorporates Agile methods (flexibility, rapid product releases, focus on customer value, etc.), and also incorporates DevSecOps methods. The increased availability of the Industrial Internet of Things (IIoT; see callout box) enables the realization of real-time production (supply chain, technical advances, available labor) and operational data (customer use, maintenance and sustainment data), as well as real-time (automated) adjustments to various stages of the production lifecycle.

Factors driving the continued need for AM in the non-software environment include:

- **Rapidly changing environments:** Technology and customer demands are rapidly changing. Customization, rapid delivery, and cheaper production are helping to drive agility into the non-software manufacturing sector.
- **Evolving technology:** Manufacturing is rapidly transitioning into the digital age. Examples include digital command and control, additive manufacturing (both 3D and 4D printing), distributed operations, and digital engineering (e.g., MBSE, etc.). In addition, increases in the availability of "boutique" manufacturers who specialize in low production runs of customized parts and advances in the availability of specialized materials used in the production of components – especially in adaptive manufacturing (Shahrubudin, et al., 2019) – are helping to drive the need for AM in the non-software environment.
- **Modular/Commodity manufacturing:** Industry is increasingly moving into modular and/or commoditized manufacturing (Azoulay, et al., 2021). Standards and the use of open platform architectures increasingly add flexibility and an evolutionary product pathway to the manufacturing pipeline.
- **Data driven manufacturing:** The ability to collect and analyze information in real time from both the production line and in operations allows quick forecasting, predictive maintenance, rapid supply-chain adjustments, real-time quality control, and real-time feedback on how the product is used or not being used – which often leads to product improvements bringing more value to the end-user.

1.2 DevSecOps IN HARDWARE AND SOFTWARE SYSTEMS

Within the DoD, DevSecOps (Development, Security, and Operations) is the preferred term to reference and approach to implement the concept of DevOps, the background of which illustrates the role DevSecOps plays within the Department. The term DevOps was coined in 2009 by Patrick Debois at the first DevOpsDays conference (also organized by Debois) in Ghent, Belgium. The term resulted from the converging of existing trends in software development (Lean, Agile, Warehouse Scale Computing[2], and massive International IT applications, i.e., Google, Netflix, Twitter, etc.) and the rise of horizontal scaling of applications in the enterprise (due to the rise of massive user bases and therefore increased transactions). This was supported by an established standard for information technology operations from Great Britain, IT Infrastructure Library (ITIL) (OGC 2022), that further structured the movement. Figure 5 illustrates the typical DevOps cycle, highlighting the relationship between the development steps of coding, building, and testing and the learning from the operational environment.

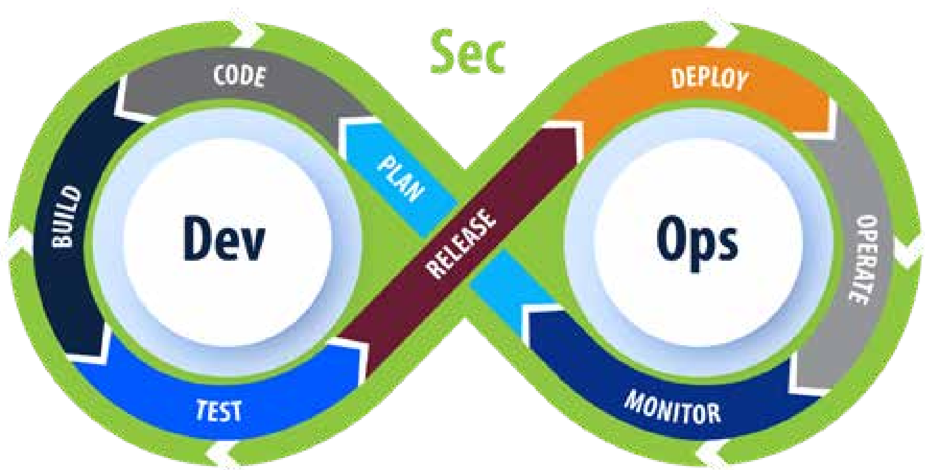

Figure 5. Typical DevOps Cycle

This rise of horizontal computing (increasing capacity by adding more servers, in contrast to vertical scaling, increasing the computing power of a single machine) and massive, consumer-focused applications led to an increasing need for more responsive development and operations. Long lead-time development strategies—such as the waterfall model—could not provide the short-time intervals necessary to support and enhance these systems. The rise of DevSecOps provided a more responsive solution, but it required significant organizational change in people (behaviors), processes, and tools. As mentioned previously, DevSecOps is an evolution of Lean and Agile enabled by emerging technology.

Four core principles of DevOps are:

1. **Value placed on team:** everyone values each other's time and contribution to the flow.
2. **Automation:** the automation of predictable, routine, and well understood tasks.
3. **Horizontal integration:** all functions in the product pipeline from capability definition through deployment and support should participate in the flow of value.
4. **Measurement and continuous improvement:** the primary measure is consistency of cycle time through feedback loops of implementation to use. This is not just speed; it is the ability to establish a cadence.

DevOps represents an evolution from the current Defense acquisition approaches presented earlier in this report, which rely heavily on the "waterfall" or "V" lifecycle models. These models are generally linear and sequential, where requirements are formalized and locked before proceeding further. A key challenge with these established approaches is that the learning that happens as development progresses may necessitate changes to artifacts created earlier in the lifecycle, which is difficult if not impossible. While these principles are easiest to learn and improve upon in workflows and products that are malleable – such as software, manufacturing process, and human organizations – they certainly have the power to transform large-scale acquisition. Capabilities dependent on technologies with low maturity and high risk are less amenable to Agile and DevSecOps practices because the technical uncertainty limits the ability to achieve consistent cycle times. However, this does not mean the components of an acquisition program that can be automated and horizontally integrated must ignore cycle-time consistency; in fact, block-cycle management and its focus on cycle-time consistency has been a core practice of military sustainment for many years.

[2] Barroso, L.A. & Holze, U. The datacenter as a computer: An introduction to the design of warehouse-scale machines. Morgan & Claypool, 2009.

Within the DoD, DevSecOps (Development, Security, and Operations) is the preferred term to reference and approach to implement the concept of DevOps. The Department's use of the term reflects the need to ensure that software and information technology deployments are adequately tested for security, and that issues with security post-deployment are addressed within an appropriate cycle time. The emphasis on DevSecOps also responds to current broad need for improved cybersecurity.

DevOps and DevSecOps should not be thought of as separate entities, encompassing only two or three roles. Instead, DevSecOps is part of DevOps that emphasizes the importance of security; it does not eliminate other roles and functions that enable DevOps (DevSecOps). The Department's emphasis on the importance of security in our capabilities is now being adopted by industry partners. The takeaway is these are not separate activities, and much of industry continues to use the terms "DevOps" or "Dev*Ops" (pronounced "Dev-star-Ops"), with the "*" representing any type of system attribute that is emphasized. The term "DevSecOps" is used from this point forward but the above history and principles extend to any system attribute, not only security.

DevSecOps arose from the need to make sure that software and information technology deployments are adequately tested for security and that issues with security post-deployment are addressed within an appropriate cycle time. In the DoD, the emphasis on DevSecOps responds to the mission criticality of the products and services and a current broad need for improved cybersecurity.

Challenges in Acquisition Practice

Current Defense acquisition approaches rely heavily on the "waterfall" or "V" lifecycle models. These models are generally linear and sequential, where requirements are formalized and locked before proceeding further. A key challenge with these approaches is that the learning that happens as development progresses may necessitate changes to artifacts created earlier in the lifecycle, which is difficult if not impossible.

One very simple example is that of requirements; these are "locked" early as part of the Joint Capability Integration and Design System (JCIDS) process. As a program develops, if it is discovered that a requirement must change – perhaps because technology has advanced or because the needs of the warfighter have changed – this is quite difficult. Often either the requirements remain static or a stop work order is required. This halts progress for 6 or 12 months or longer while the requirements issues are resolved. The inherent brittleness in this process reduces programs' ability to be responsive.

1.3 RELATIONSHIPS BETWEEN AGILE AND DevSecOps

Figure 6 depicts how DevSecOps practices augment the Agile workflow. Note that while the security/compliance considerations are unique to DevSecOps, the other principles are common to all DevOps approaches.

Figure 6. Relationship and overlaps between Agile and DevSecOps

It is worth noting that Agile and DevSecOps practices are rooted in documented processes that follow rigorous plan-build-test-release flows inherent in DoD acquisition. Agile and DevSecOps do not skip steps or eliminate required work. Instead, they break down work and workflows into smaller activity sets to shorten cycle times and validate capabilities with more frequent user feedback.

1.4 MEASURING PROGRESS

As noted throughout this report, Agile and DevSecOps practices have been implemented with various degrees of success in many DoD acquisition programs, especially in software-based acquisition programs. For example, as reported in (Orosz et al. 2021; Orosz et al. 2022), researchers are involved in a series of case studies focused on the introduction of Agile and DevSecOps practices into space-based software-only acquisition environments. These studies are targeted at identifying best practices and to date have produced a useful set of lessons learned. While the initial baseline DoDI 5000.02 project was entirely waterfall based, subsequent projects have introduced Agile and DevSecOps in progressively increasing levels with the second project consisting of roughly a 50/50 hybrid Agile/waterfall mix and the third and current project consisting of a roughly 70/30 hybrid Agile/waterfall mix effort.

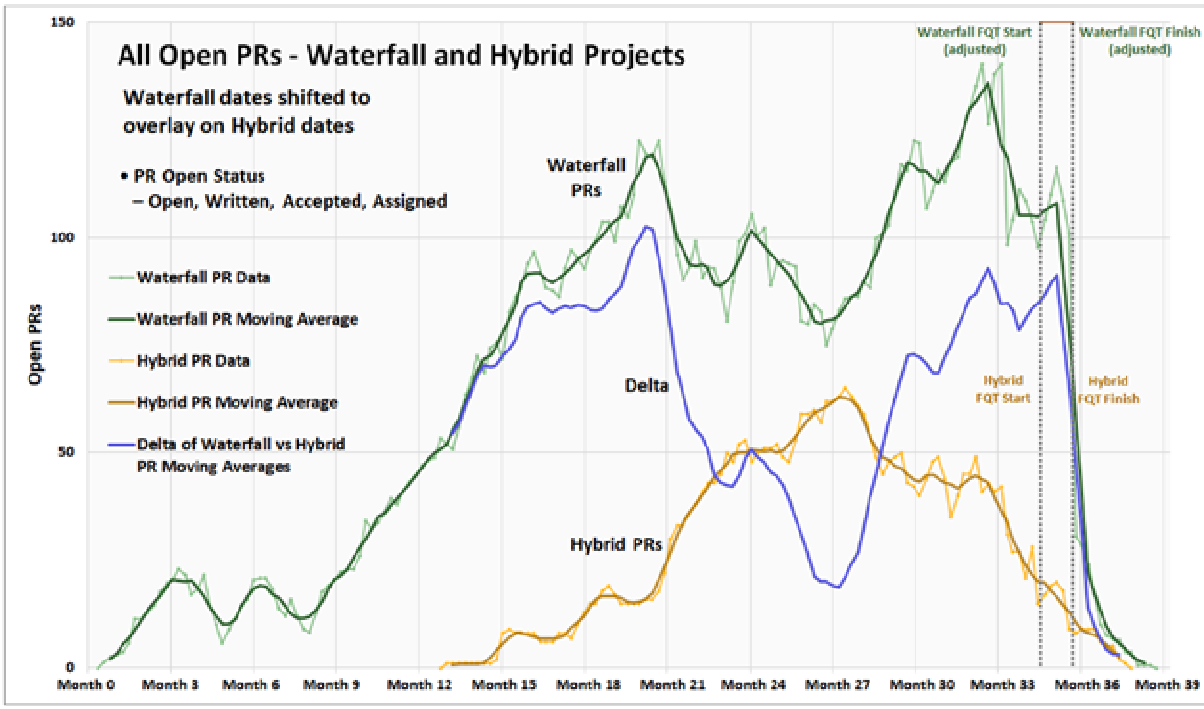

Figure 7. Upper trace are PRs for Project A. Lower trace are PRs for Project B. The two peaks in the upper trace reflect the "bow-wave" of PRs (Orosz et al. 2021)

As summarized in the preceding Figure 7 the hybrid 50/50 waterfall and Agile mix project (Project B) produced approximately 85.4% fewer open problem reports (PRs) than the traditional waterfall project (Project A). Further, an analysis of the performance of the waterfall portion of the 50/50 hybrid project as compared to the Agile portion revealed that the Agile effort produced approximately 95.7% fewer open problem reports as compared to the waterfall portion of the effort (illustrated in the following Figure 8).

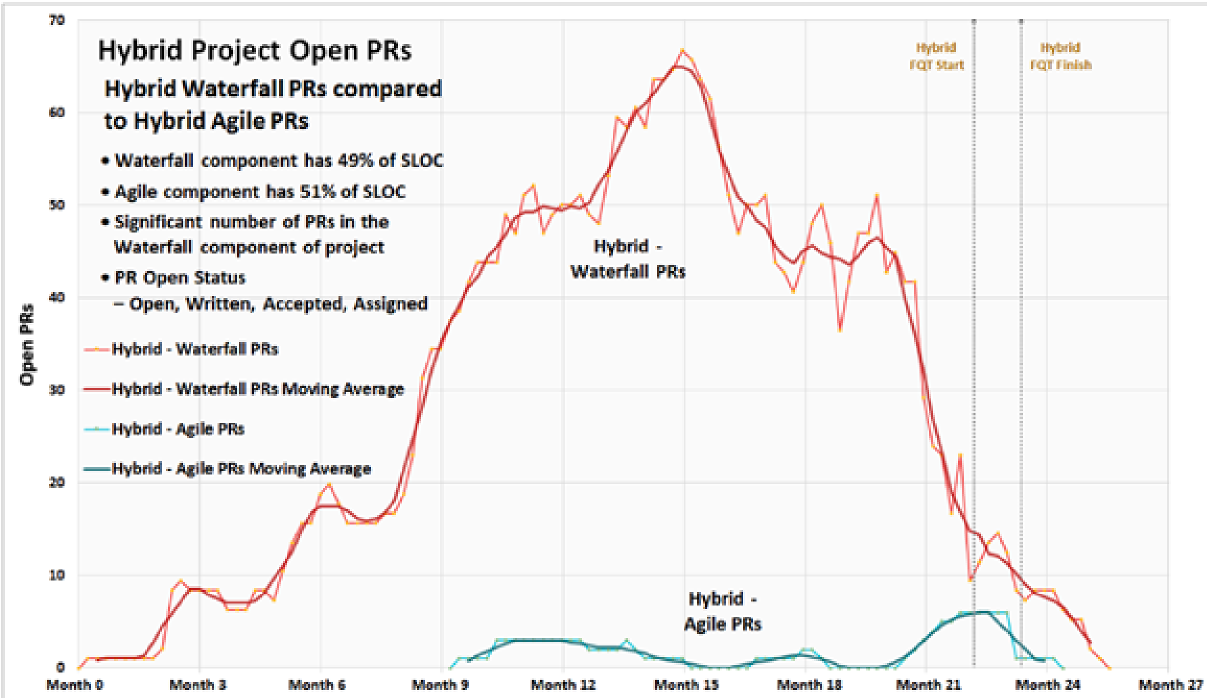

Figure 8. Upper trace shows recorded PRs for the waterfall portion of Project B. Lower trace shows recorded PRs for the Agile portion of Project B (Orosz et al. 2021)

Over time, the DoD will develop standard methods of collecting and evaluating the benefits of applying Agile and DevSecOps practices over traditional (prior) DoDI 5000.02 waterfall methods and incorporate that into program measurement data. The DoD and the U.S. Army have jointly sponsored a long-term effort to support measurement experience on DoD programs, targeting Government Program Managers with objective measurement guidance for program cost, schedule, and technical objectives. The guidance can be found on the Practical Software and Systems Measurement (PSM) website (psmsc.com). The PSM Support Center (PSMSC) first released their Practical Software Measurement guide in 2001. In 2021, PSMSC, the National Defense Industrial Association (NDIA), and the International Council on Systems Engineering (INCOSE) jointly released a specification for measurement of continuous iterative development (CID) targeted at defense programs that are employing Agile and DevOps methodologies. In CID, primary outcome metrics are associated with successful deployments: capabilities committed versus completed, cycle time/lead time, release frequency, mean time to restore (a failed release), and product value. These metrics apply to any release, whether internal to test or external to the customer. In 2022, PSM, NDIA, INCOSE, and the Aerospace Industries Association (AIA) jointly created and released a specification for Digital Engineering (DE) measurement, building from the previous software and CID work. The DE measurement specification recognizes the critical aspects of software and CID measurement as applied to the modeling and test activities in more hardware intensive developments. At this point, the software and CID measures are mature, but DE measures are early in their evolution. As measurement is a core aspect of digital and agile transformation, all DoD programs should use these guides to help quantify their development process performance.

CHALLENGES TO DoD IMPLEMENTATION

There are several challenges to implementing Agile and DevSecOps within the DoD and each fall under the umbrella of "**disconnects**." It is not possible to optimize the technical and engineering acquisition processes for one of these techniques and not make major changes in other areas. This section outlines core issues, illustrated through examples and other work.

Figure 9 below describes the core acquisition cultural mindset that impedes Agile or DevSecOps transformation.

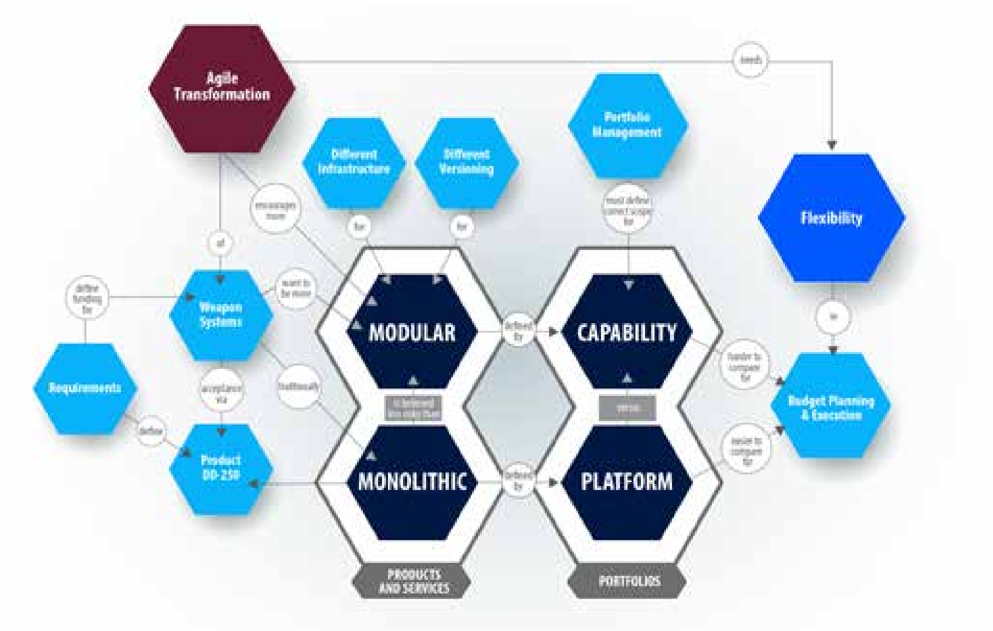

Figure 9. Acquisition's cultural challenges to Agile transformation

Within the Department, major capabilities are still budgeted for and executed as "monolithic" systems defining platforms rather than modular systems that focus on agile capabilities. Weapon systems in particular still undergo a rigorous requirements development process with formal requirements-based assessment of the product. This process is well-ingrained into the traditional acquisition of large monolithic weapon system platforms. In the software acquisition pathway, capability needs are favored over rigid requirements. This is good for pure software systems but for software embedded into weapon systems, approaches to define capabilities into more modular packages with iterative releases is needed. This is a change in mindset as well as the related development and test infrastructures. It is becoming clear that digital transformation and related digital engineering initiatives will improve this situation in the development processes. Adaptability in the budgeting process is also crucial. However, it is harder to plan for and control Agile capabilities that change on a timescale shorter than the two-plus year budgeting process (McGarry, 2021). The evolution will affect both the DAS and the Planning, Programming, Budgeting, and Execution (PPBE) processes.

DIGITAL ENGINEERING

In the context of the DAS, an initiative that must be considered is Digital Transformation (DoD 2018). An objective of the continuous improvement approaches discussed is shortening the duration required for each phase of the product lifecycle (e.g., product definition, design, etc.). Digital engineering – specifically model based systems engineering (MBSE), digital twins, and digital threads – are used to reduce the duration and staffing required to design, prototype, test, and react to changes in customer needs and requirements. The key driver here is to digitize and virtualize as much of the lifecycle as possible. MBSE is used to digitally represent the product design to help with visualization, testing, and evaluation before any "metal is cut." Further, MBSE is preferred to traditional paper approaches to design as these modeling systems can also be used to implement non-physical aspects (e.g., the physics) of a product. For example, when modeling the suspension of an automobile, the physics behind the compression and expansion of system components can be captured within the model. Further, interfaces between systems are automatically maintained and tested as the model is designed or modified. Examples of MBSE tools currently in use include Cameo, Genesys, and OpenMBEE[3,4,5]

3 Cameo: https://www.3ds.com/products-services/catia/products/no-magic/magicdraw/

4 Genesys: https://www.vitechcorp.com/genesys_software/

5 OpenMBEE: https://www.openmbee.org/

Digital twins (an exact virtual model of an operating product) are a key component of implementing DevSecOps in the non-software manufacturing sector. With the continued growth of IIoT and the availability of real-time (performance) data collection and analysis, digital twins are useful for predicting future maintenance needs, determining how the product is currently used, and allowing "what-if" analysis to determine impacts to the product due to changes implemented in the design.

Finally, as noted in *Appendix B: Agile Manufacturing History and Additional Information*, digital engineering, when combined with Agile, DevSecOps, and IIoT, is essentially an OODA loop [28] for product manufacturing. Real-time production and operations usage is collected (Observed), analyzed (Orient), decisions are made (Decide), and courses of action are undertaken (Act). This OODA process is repeated with various stages of the product lifecycle (e.g., design, development, production, deployment, etc.) and undergoes continuous modification to meet a changing development and operational environment.

1.5 CULTURE

The DoD acquisition culture has run counter to many reform and innovation attempts for years. In 2013, Air Force Lt. Col. Daniel Ward published "Changing Acquisition Culture: What and How" through the Center for National Policy. Though nearly a decade old, it addresses many of the challenges still seen today. Lt. Col. Ward proposed the FIST framework – Fast, Inexpensive, Simple, Tiny – to deliver affordable systems that are available when needed and effective when used, and away from the all-too-common delays and overruns associated with unnecessarily complex procedures and technologies (2013). Ward highlighted a then-recent Acquisition Review Journal that expressed the zeitgeist this way: "In general, a product delivered quickly, cheaply and simply will not perform as well as one with more time, money, and arguably more complexity…" and expressed concern that "most readers simply accepted this sentiment as self-evident, because they are part of an acquisition culture that has a high regard for expensive, large, complex systems and expect a project's performance to be directly proportional to its cost, schedule and complexity. In this culture, more always means better."

In 2020, former Defense Secretary Mark Esper stated at a Center for Strategic and International Studies event that "… the thing we've got to really get at – and it takes time, and it's probably the most difficult part and the hardest to change – is the culture" (Everstine, 2020). One aspect Esper noted is the risk-aversion in the existing DAS culture. (See "Risk" section below.)

The way in which policy flows down poses a challenge to the broad DoD acquisition culture. Frustration in Congress, the DoD, and the defense industry with the long times to deliver weapons due to too much bureaucracy sparked a set of reforms in the 2016 NDAA. Each subsequent NDAA has included acquisition reforms such as digital transformation, inclusion of industry standard approaches like agile, etc. Policy-level changes, however, have not addressed the fundamental culture of the DoD acquisition system and the challenges that this "business as usual" approach creates in trying to make change and spark innovation.

DoD policy must be reflected in new and revised Service policies, and each Service may choose to interpret these policies in slightly different ways. Then the acquisition workforce within each Service must interpret and embrace these policies. This adoption takes time, but also means that while there are cultural challenges that are true across the Department, no one-size-fits all solutions will work in each micro-culture within the different Services, Program Offices, etc.

1.5.1 FRAMEWORKS FOR UNDERSTANDING ORGANIZATIONS

Cultural change is a difficult undertaking and it is helpful to have a framework for understanding the culture and cultural change. The Government Accountability Office (GAO) released a *Framework for Assessing the Acquisition Function at Federal Agencies* in 2005. The Framework states that:

> *Federal agencies have responsibility for a vast array of missions…. To achieve these various missions, federal agencies use a variety of approaches and tools, including contracts to acquire goods and services needed to fulfill or support the agencies' missions. Federal agencies award contracts worth over $300 billion annually. Acquiring these goods and services in an efficient, effective, and accountable manner is therefore essential. However, our work—as well as the work conducted by the inspectors general, other accountability organizations, and the agencies themselves—continues to identify systemic weaknesses in key areas, which often result in cost, schedule, and performance problems on individual procurements.*

The GAO framework consists of 4 cornerstones:

- **Cornerstone 1:** Organizational Alignment and Leadership
- **Cornerstone 2:** Policies and Processes
- **Cornerstone 3:** Human Capital
- **Cornerstone 4:** Knowledge and Information Management

While this framework is focused on acquisition, it is clear that the cornerstones highlight culture. While policies and process outline the formalized or expected culture, organizational alignment and leadership are focused on how these policies and processes appear in practice. Likewise, while human capital tends to focus on the development of necessary skills, there are underlying cultural values that illustrate which skills are most emphasized and which, though important to acquisition, may be deemphasized in the organization. While knowledge and information management seem to be more process-oriented, the value placed on these activities and the level to which they are embraced by the workforce are also core indicators of culture. This makes the GAO framework a useful tool for examining not only the overall acquisition approach of an organization, but one which can give core insights into the organizational culture and who well or poorly it aligns with that approach.

Culture, Automation, Lean, Measurement, and Sharing (CALMS) is a framework that assesses a company's ability to adopt Agile and DevSecOps processes, as well as a way of measuring success during a DevSecOps transformation (Forsgren and Humble 2015; Humble and Molesky 2011). In practice, these mirror the principles illustrated in the Saab case study: build shared accountability, automate as many tasks as possible, use lean principles to eliminate waste and optimize workflow, measure rigorously and continually improve, and create openness and transparency across teams. These are fundamental practices that can be applied to any organization or culture, making the CALMS framework a useful tool for identifying areas where culture is not supportive of Agile or DevSecOps practices.

1.6 LEADERSHIP

Studies have shown that the *single most important element* in determining success in changing an organization's culture is the interest, support, and even passion displayed by its leader (Heskett, 2021). The quality of leadership is strongly linked to the level of employee engagement, and employee engagement that is based in large part on trust is a critical factor in achieving any kind of change. Though cultural change can take time, there are examples of leaders who are able to drive concentrated efforts on addressing critical challenges in culture quickly. One example is Satya Nadella, who was able to transform Microsoft's inflexible, hierarchical and overly-accountability-focused culture in months rather than years or decades by shifting and guiding the company's focus toward growth, delivery for the customer, and working as one integrated entity. (Wadhwa et al. 2021)

DoD Acquisition leaders must not only embrace and incentivize needed changes but model and reward them. One of the ways this can be done is to overcome the knee-jerk reaction to issues or changes in programs. Often, when a program suggests or requires changes, messaging from DoD leadership indicates that this is seen as a lack of planning or evidence of incompetence. The budgeting and accounting approaches in acquisition reinforce this. (See "Metrics" below.) In Agile, the phrase "fail fast" is common. In the DoD, the idea of "failure" is seen as negative, but particularly in complex systems development, some level of failure is inevitable. Approaches and designs will be tried that ultimately will not work. The DoD must fundamentally shift away from the idea that this constitutes "failure" and move towards the view that these are opportunities to learn and improve rapidly.

This approach is counter to the current culture and processes, but the Department will benefit from understanding how current approaches can be adjusted to fit into a more incremental approach. For example, DD-250s are used as formal documentation that a program has met its requirements. It is a confirmation of capability assessment and part of a definitive process for accepting products. Agile approaches are clear about the goals and requirements for each sprint with a built-in assessment process. The DD-250 approach applied incrementally to each sprint, rather than at the end of a program, could utilize the existing process while also improve flexibility.

It is critical that leadership within the Department embrace such mechanisms for flexibility. One of the common misconceptions about agile approaches is that they make failure acceptable. This is inaccurate. These approaches instead redefine failure. Today, failure is usually having a single, pre-defined solution failt to work as expected. In an Agile organization, which encourages experimentation, having a single solution note work is an opportunity to learn. In this sort of organization, true failure is the failure to learn and adapt an approach when we do not meet user needs. The real failure is not addressing the mission need or capability gap; any specific solution should be viewed as temporary and should shift based on new technological advances. In order to enable continuous improvement changes in the Department, leadership must embrace this revised view of failure versus learning.

1.7 RISK TOLERANCE WITH RESPECT TO CONTINUOUS DEVELOPMENT

Former Defense Secretary Mark Esper stated in 2020 that "[s]ervice efforts such as the Air Force's pitch days for rapid contract awards are just the beginning of the Pentagon's effort to move faster in its acquisition process, *but much more work remains to make the five-sided building change its overall risk-averse culture."* Esper's remarks again highlight risk aversion as an obstacle to change and innovation (Everstine, 2020).

The "big bang" acquisition approach wherein a vendor is asked to deliver, manage all subcontractors, and often have little interaction with the customer has repeatedly failed to deliver capability, let alone on time and within budget. The DoD acquisition community generally views agile approaches as increasing risk, but as illustrated previously, agile approaches can reduce and mitigate risks **if properly applied**. The agile approach delivers capability incrementally and provides regular insights into progress and opportunities to address challenges. This is a fundamental shift in the idea of how risk is assessed in the Department and also a shift in its risk tolerance, with the expectation that risks early in a program or sprint are acceptable and the overall risks decrease as programs learn with each increment. This concept is illustrated in Figure 10.

Changes to Contracting

Current contractual approaches put primary risk ownership on the vendor. This means the primary risk on the government side is whether the contract is written perfectly, forcing contracting officers to take a strongly risk-averse posture and creating pressure to develop monolithic systems with large contracts. Recent data by the GAO states that in FY 2019, the DoD obligated $190 billion on service acquisitions, stating that the "DoD relies on contractors to provide a wide array of services, including support for management, information technology, and weapon systems" (2020). DoD Contract Management for Service Acquisitions has been listed as a high-risk area for the Department since 2001, and findings from the GAO highlight issues with contracting that create risks for the Department. For the discussion of utilization of Agile or DevOps and contract risk, there were two highlights of particular relevance:

- DoD's service requirements reviews were narrowly focused on individual contracts rather than entire capability portfolios; and
- DoD's efforts to use its inventory of contracted services to inform management decisions were hindered by data collection issues (GAO 2021).

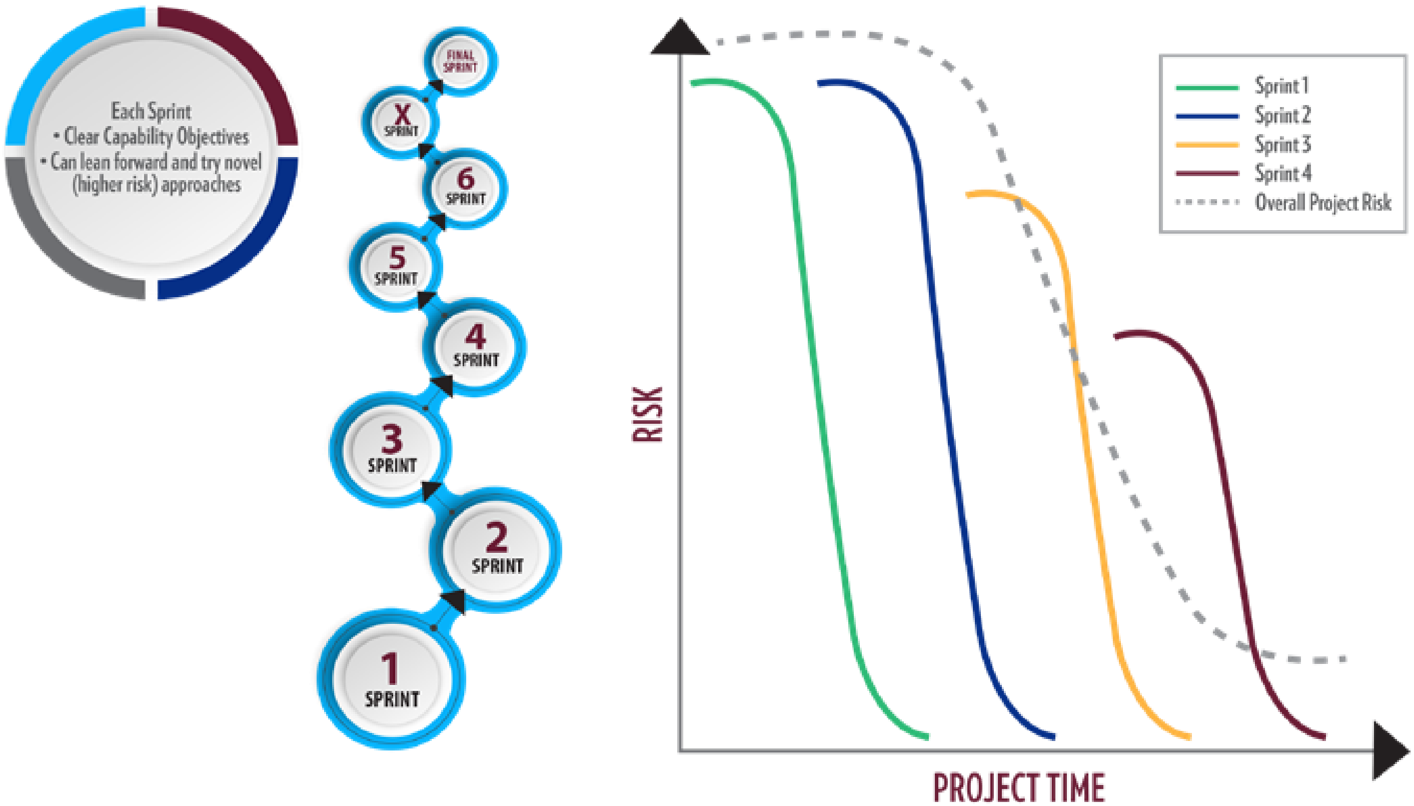

Figure 10. Notional model of project risk reduction using an Agile approach

Agile approaches enable flexibility in the requirements for implementation, while keeping the end-goal capability in mind. DevSecOps improves data collection particularly from fielded systems, which can be a critical input to future decisions. So these techniques can in part help to address these risks.

A common criticism of the current acquisition approach in the Department is that it simply takes too long to field capabilities. A contract may be for 5, 7, 10, or more years. And though learning occurs during these programs, often by the time a capability is "completed", it is either no longer as technologically relevant or the environment has changed. One option that has been used in the Department on a small scale is modular contracting – a process which allows the government to explore multiple options and appropriately scope and validate as a program progresses. Devine (2018) provides a simple overview of what this can look like in practice (Figure 11). Modular contracting can support more agile or DevSecOps approaches that will enable learning and earlier capability deployment but requires a change in the contracting approach.

Figure 11. Notional Example of Modular Contracting in a Space Context (Devine 2018)

This modular approach can improve the flexibility the government has in pursuing options that work and weeding out those that do not. The current acquisition system allows for this approach, but it is counter to common practice. Modular contracting is often perceived by the workforce as higher risk than traditional contracts. But with mounting evidence that the large, monolithic contracts of the past are less likely to result in the capabilities needed in the time delivered, this mindset must change. The phrase "fail fast" is often used to describe agile, and this raises a red flag for the risk conscious. However, "failure" in this sense is not a failure as the current DoD acquisition systems defines it: large-scale failures such as Future Combat Systems (FCS), which after going several years and billions of dollars over budget, never delivered the promised capability. The true meaning of "failure" in an Agile sense is "small failures at the sprint level that allow teams and programs to learn quickly." From this perspective, Agile techniques reduce overall risk by increasing the speed at which programs quickly learn what works and what does not. In otherwise, agile does not "fail fast" but allows an organization to "learn fast".

Modular contracting is an essential part of this approach, but not without challenges. The largest challenge may be that managing multiple small contracts and shifting approach to a portfolio of related contracts may be difficult for the current contracting workforce. However, it is necessary if the Department is to implement Agile or DevSecOps successfully. This represents a fundamental shift in how the majority of the acquisition workforce has been trained. Efforts such as DAU's updates to support training the Adaptive Acquisition Framework have begun the work on this path, but the Department will have to provide clear focus and support for the workforce in making this transition.

1.8 METRICS

Cornerstone 1 of the GAO's Framework for Assessing the Acquisition Function at Federal Agencies (2005, see "Culture") addresses the challenges of appropriately aligning acquisition functions with an agency's missions and needs and emphasizes the critical role of leadership commitment. According to the framework, there are several indicators that the acquisition process is either immature or failing to appropriately evolve, including:

- a lack of clear metrics that continuously measure and assess how effectively acquisition supports the agency missions and acquisition goals; and
- performance measures are in place but not consistently utilized or communicated.

While metrics are critical in determining the effectiveness of acquisition, the Department invests in missions with no clear indicators of success—the top level is that a year culminated without war or other significant aggressive action from an adversary. While Congress demands tactile plans and outcomes, metrics around process, process change, and/or progress are not clear and do not have clear outcomes. Many capabilities receive investment but are not used, and there is no clear indicator on these. Portfolio management across different missions will be difficult (e.g., nuclear versus aircraft refueling).

Metrics in an operational context, while important, present particular difficulties and generally seem different than what DoD does. The Ops part of DevOps is more difficult in a weapons system (as compared to its use in other systems). An example is seen in the attempt to change the F-35 from 2-year to 6-month update cycles. The user community refused, stating the change was "too hard, too much training, too disruptive," and a 1-year update cycle was settled upon.

The Department faces a difficult challenge: defining metrics of success. This is an area the Department differs from industry. The Department cannot use profit as an indicator and often number of users is not valuable. For example, the number of users for classified programs tends to be small but that does not equate to their value. Many capabilities are not only based on current state but a projected adversarial landscape—i.e., 2030 and beyond. Further complicated by the fact that deterrence is a huge component of our strategy, that is to never use a capability may be a success but that does not preclude the need to develop.

One area of particular difficulty is the use of metrics in an operational context. Particularly in view of DevSecOps, the metrics for this are important and generally seem to diverge from the metrics typically in use on DoD programs. The metrics for the "Ops" part of DevSecOps is perceived as difficult to measure in a weapons system. For example, the F-35 program tried to go from a two-year to a six-month update cycle. The user/operator community refused, believing that this change would be too hard, require too much training and ultimately be too disruptive. With negotiations, the program and user community eventually compromised on a one-year cycle. Culturally, the issue of deploying "continuous improvements" to a weapons system is difficult.

The key metrics in DevSecOps, established by Google's DevOps Research and Assessment (DORA) team are:

- Deployment Frequency
- Lead time for changes – how soon do changes get into operation?
- Change failure rate – quality of the changes, how many are bounced back?
- MTTR – Mean time to restore service – how quickly do you recover?

Not unsurprisingly, these metrics are focused on flow and how it affects operations.

The majority of programs in the Department are existing programs, i.e., legacy programs as opposed to new starts and therefore they already have established and approved acquisition strategies. The updated DoD Instruction (DoD-I) 5000.02, *Operation of the Adaptive Acquisition Framework* (2020), did *not* require all existing programs to re-establish their acquisition strategies. So, while there has been adoption of the new pathways by new programs, programs that were already in existence were not required to make these changes. The fact that some existing programs have gone through the effort to re-establish their acquisition strategies is a testament to the perceived benefits of this modernized approach.

1.9 BUDGETS AND FINANCIAL ACCOUNTING

As with any acquisition, budgetary resources are essential enablers. The U.S. Congress and DoD seek to sufficiently fund critical national security missions, however, predicting, budgeting, authorizing, and appropriating the type and amount of needed funding can be challenging. This is especially true when threats and technologies are changing faster than PPBE process timelines. The PPBE process spans two years and is further lengthened given that the DoD starts planning 19 months before the first stage, programming and budgeting begins. Threats and needs can change even after budgets are authorized and appropriated by Congress, and reprogramming of those funds is limited.

Agile acquisition—with timelines on the order of weeks or months, not years—is intended to respond to rapid changes in threats and technologies. However, unless the budgetary resources are available in the types and quantities needed, Agile can be halted until the PPBE process timelines catch up. Along with an overarching set of requirements that scope the operational capabilities to be acquired, Agile should have an overall budget within which the acquisition should operate. This includes not only the development costs but also the long-term lifecycle costs for maintaining, sustaining, and upgrading the capabilities.

Therefore, Agile development (hardware and software) requires either: sufficient contingency planning across funding types (budget activities) and reprogramming abilities to provide a sufficient overall budget; or it requires new budgetary approaches, such as the current Budget Activity (BA) 8 Pilot now experimenting with a single appropriation to seamlessly fund across Research, Development, Test, and Evaluation (RDT&E), procurement, operation, and sustainment of software programs. (DAU 2020, DoD 2021, Public Law 116-260)

Along with budgeting, it is important to have sufficient financial accounting of how the resources are spent to allow transparency into the acquisition and any associated issues (e.g., execution or poor performance of government or contractors). Even with a single appropriation approach (such as BA-8), it may be prudent and useful to track how those more responsive appropriations are expended to provide transparency for DoD and Congressional stakeholders as well as public taxpayers. Combining financial accounting with Agile performance metrics can improve this transparency.

1.10 WORKFORCE SHIFTS

Each of the challenges outlined above requires an evolution of the acquisition workforce, a fundamental shift in the core competencies to enable critical thinking and flexibility within the parameters of legislation and policy. The acquisition community is over 187,000 strong and while this means there is a wellspring of potential, it also means that the task of helping such a huge group successfully evolve together is daunting. (HCI 2022)

There are several aspects of the current acquisition workforce that further challenge major acquisition changes:

- Knowledge Management – Turn-over on teams and programs is a common phenomenon. Digital transformation initiatives should improve knowledge capture – both the decisions made and the rationale for those decisions and serve as a key enabler for Agile or DevSecOps. However, the workforce challenges for digital transformation are also strong (e.g., DoD 2018).
- Acquisition community (over 187,000 individuals) – Currently, the community does not share documentation or learn from each other in any sort of consistent or reliable way.
- Workforce enablers are critical – This aspect is necessary to transformation success and must be prioritized consistently at every level.

VISION

The following outlines the vision for a DoD acquisition system that enables Agile and DevSecOps for hardware, software, and combined cyber-physical systems.

1.11 DIGITAL TRANSFORMATION IN THE DoD: AN ENABLER FOR AGILE/DevSecOps

Digital transformation is fundamentally changing the way acquisition and engineering are performed across a wide range of government agencies, industries, and academia. It is characterized by the integration of digital technology into all areas of a business, changing fundamental operations and how results are delivered in terms of new value to customers. Digital transformation includes cultural change centered on alignment across leadership, strategy, customers, operators, developers, and designers.

In the DoD, evidence across the Services and industry has affirmed digital transformation is critical for successful acquisition in an environment of increasing global challenges, dynamic threats, rapidly evolving technologies, and increasing life expectancy of both our hardware and software systems currently in operation. Digital transformation requires the update of both acquisition and systems engineering practices to take full advantage of the digital power of computation, visualization, and communication throughout the lifecycle. The DoD must continue to practice systems engineering efficiently and effectively to provide the best advantage for successful acquisitions and sustainment.

In order to meet the challenges and realize the benefits of digital transformation, the acquisition workforce must itself undergo significant transformation (DoD Digital Engineering Strategy 2018, Goal 5). In particular, as systems engineering and acquisition evolve, every individual who works within a digital acquisition environment needs digital literacy, i.e., the foundations required to interact with digital systems, as this is no longer the realm of "engineers only." Anyone who works in acquisition will have to navigate models, find information critical to their roles in models, and make decisions based on this information. This need stems from the growing use of digital engineering to represent complex systems throughout their lifecycle. Engineers, and perhaps in particular systems engineers, must be able to create, evaluate, and use digital engineering methods to specify, evaluate, and manage systems during throughout DoD acquisition process.

To meet the challenges of and realize the benefits of digital transformation, the workforce will need new processes, methods, and approaches and to build new skills. In addition, a major cultural shift, including in leadership, budgeting, and accounting, will need to take place.

One area where digital transition will particularly support agile approaches is the concept of digital sign-off. This approach is more flexible and less dependent on monolithic documents, such as a "locked" requirements document. Instead, digital sign-offs inherently enable Agile approaches and will be critical to enabling this as well as true digital acquisition.

Digital transformation requires the DoD to address many of the same challenges as Agile/DevSecOps. In this context, some of the work should be done, but it is crucial for the changes to enable DE to be thought and developed in a way that also furthers Agile/DevSecOps and other methodologies. In short, as the Department works through digital transition, considerations for Agile, DevSecOps, and other relevant approaches should inform decisions. Otherwise, siloed efforts will continue to require large amount of time and money, but none of these initiatives will provide the expected and needed benefits.

RECOMMENDATIONS

A key finding of current work through the Systems Engineering Research Center (SERC) is that existing policies around Agile, DevSecOps, and even digital transformation are heavily siloed (McDermott et al., 2022). These policies do not reference one another or generally acknowledge the relationships among these initiatives. The findings from this research task informed the development of the following recommendations.

Recommendation: Develop a Center of Enablement (COE) for Agile/DevSecOps

A Center of Enablement (COE) is defined as a premier organization providing exceptional products and services in an assigned area of expertise with unique requirements and capabilities. COE's are established to provide the Department with the ability to speed the advancement of scientific knowledge and evidence-based practices. The Joint Ballistic Missile Defense Education and Training Center established in 2018 was the first Joint Center of Enablement for the Department (Saffen). A new Agile/DevSecOps COE would need to follow a similar model, combining insights from across the Services.

Recommendation: Integrate Agile and DevSecOps Initiatives with Digital Transformation

Digital transformation is a critical enabler for establishing Agile and DevSecOps acquisition approaches within the Department. Digital transformation is the process of changing overall practices to align with the changing landscape, i.e., digital disruption or adversarial threats in the context of the DoD. Digital disruption occurs when an emerging technology is integrated into a business or market. For incumbents, this will place increasing pressure to adopt or adapt to remain relevant; this can happen in industry or impact federal agencies and the nation's defense posture. Agile is more than a modern software practice; it can be applied overall as an important strategy for dealing with digital disruption.

Digital transformation requires a top-down culture change through education that promotes and supports digital engineering, modular contracting, and agile multi-functional teams. As part of the digital transformation, all records and practices regarding projects should be digital and universally available as much as practical.

In order to realize the digital transformation, we recommend that it be part of the COE in DoD that supports the digital and Agile transformation. The COE would serve as the nexus for the digital and Agile transformation and would:

- recommend best practices in digital and Agile transformation;
- serve as a repository for case studies and pace of agile innovation for DoD;
- interact with DoD industrial partners on Agile and Digital Engineering practices; and
- provide rotational assignments in the COE to seed best practices in the DoD organization.

Recommendation: Continue Pursuing Agility in Contracting, Requirements, and Funding

In addition to the engineering approaches discussed above, agile and responsive acquisition with continuous improvement will have only limited effectiveness without agility in the two inputs—requirements and funding—that are key to acquisition as well as in acquisition functions such as contracting. Agile is a team sport, therefore, the DoD must pursue improvements in these areas if it is to achieve fully the promise of agile acquisition. Thus, DoD should continue efforts in these other areas to:

- employ more adaptive contracting approaches available within the FAR, such as modular and incremental (rather than monolithic) contracting strategies;
- align requirements with Agile to quickly set the broader requirements context and rely on user feedback and upgrade needs for detailed and adaptive requirements, and
- continue pursuing PPBE reforms—both internal to DoD and to obtain more adaptive constructs in appropriations from Congress.

CONCLUDING REMARKS

Given the challenges DoD faces in the present and the future, it is important that Agile methodology is used throughout the Department to facilitate continuous improvement in personnel, practices, and products. Digital transformation provides the basis for this evolution, and the lessons in commercial industry have shown that Agile can be applied successfully not only narrowly to the software elements of defense systems but more broadly to the hardware and interrelated hardware/software aspects of these systems.

APPENDIX A: ACRONYMS AND GLOSSARY

A&S	Acquisition and Sustainment
AIA	Aerospace Industries Association
AM	agile manufacturing
CALMS	Culture, Automation, Lean, Measurement, and Sharing
CID	continuous iterative development
COE	Center of Enablement
DAS	Defense Acquisition System
DE	digital engineering
DevOps	development and operations
DevSecOps	Development, Security, and Operations
DoD	[U.S.] Department of Defense
DoDI	Department of Defense Instruction
DORA	DevOps Research and Assessment
FIST	Fast, Inexpensive, Simple, Tiny
FY	fiscal year
GAO	Government Accountability Office
H.R.	House Report
IIoT	Industrial Internet of Things
INCOSE	International Council on Systems Engineering
ITIL	IT Infrastructure Library
JCIDS	Joint Capability Integration and Design System
MBSE	model-based systems engineering
MTTR	mean time to restore service
NDAA	National Defense Authorization Act
NDIA	National Defense Industrial Association
NearOps	Near Operational Environments
OODA	observe, orient, decide, act
OSD	Office of the Secretary of Defense
PPBE	Planning, Programming, Budgeting, and Execution
PSM	Practical Software and Systems Measurement
PSMSC	Practical Software and Systems Measurement Support Center
RDT&E	Research, Development, Test, and Evaluation
SysML	Systems Modeling Language
WWII	World War II

Agile – *able to improve process flow, rapidly generate functions/capabilities incrementally, and rapidly react to changing customer needs (i.e., constantly deliver some value).*

In terms of acquisition, the fiscal year (FY) 2018 National Defense Authorization Act (NDAA) (House Report [H.R.] 2810, Public Law 115-91) defines "Agile Acquisition" as "acquisition using agile or iterative development." Agility is the ability to reliably deliver customer value in the face of uncertainty and change. While the term "Agile" is most commonly referred to in terms of software development, there is a wider application for Agile in the area of Agile project management. Broadly defined, Agile project management is an iterative process that focuses on customer value first, team interaction over tasks, and adapting to the current business reality rather than following a prescribed plan.

DevSecOps – *an approach to improve processes and reduce bottlenecks in systems and processes. Arose from the need to develop and operate incrementally to continuously deploy initial capabilities early while using operation to inform subsequent improvements.*

Within the DoD, DevSecOps is the preferred term to reference an approach to implement the concept of DevOps. The Department's use of the term reflects the need to ensure that software and information technology deployments are adequately tested for security, and that issues with security post-deployment are addressed within an appropriate cycle time. The emphasis on DevSecOps also responds to the current broad need for improved cybersecurity.

Lean – *an approach to improve every process in an organization by focusing on enhancing the activities that generate the most value for users while removing as many waste activities as possible.*

APPENDIX B: TERMS OF REFERENCE

This study was motivated, in part, by the following statement in the Joint Explanatory Statement of the Committee of Conference, accompanying the FY 2021 NDAA (House of Representatives, 2020, pp. 1761–1762 [formatting added]).

CONGRESSIONAL LANGUAGE

> *Report on agile program and project management*
>
> …The conferees direct the Under Secretary of Defense for Acquisition and Sustainment to direct the Acquisition Innovation Research Center established by section 2361a of title 10, United States Code, to study and develop policy options and recommendations on how the Department of Defense and the services can use agile program and project management concepts in non-software acquisition programs.
>
> The conferees expect the study to
>
> review all statutory provisions enabling the use of agile program and project management within the Department of Defense;
>
> evaluate the implementation of statutory provisions enabling the use of agile program and project management within the Department of Defense and the services;
>
> evaluate the agile program and project methodologies used within the Department of Defense and the services;
>
> evaluate how agile program and project methodologies have enabled efforts to prepare the Department of Defense and the services for the future of work;
>
> evaluate the enterprise scalability of the agile program and project methodologies used within the Department of Defense and the services, including how well agile methods are integrated into the enterprise when used at scale;
>
> analyze the impediments to the further adoption and enterprise scalability of agile program and project management including statutory impediments, as well as existing policy, guidance, and instruction of the Department of Defense and the services;
>
> analyze the impact of further adoption and enterprise scalability of agile program and project management on the future of work within the Department of Defense and the services; and
>
> any other topics the Under Secretary deems appropriate.

MAPPING STUDY FINDINGS TO CONGRESSIONAL STUDY ELEMENTS

Given this study was performed by academia, the DoD asked AIRC to focus our report on the history of agile hardware and software development and the implications for use in the DoD (especially agile hardware development). Thus, our report focuses more deeply on certain aspects of Congress' interest, but the discussion below summarizes our insights across all the congressional study topics.

> (Congress:) Review all statutory provisions enabling the use of agile program and project management within the DoD.

Statutory provisions in Title 10, U.S. Code, relate to the use of Agile for software rather than non-software (i.e., hardware) development. However, this is neither a barrier nor a deficiency. Acquisition policies are explicitly intended to be tailored by program managers and milestone decision authorities. Therefore, the Agile approaches discussed in this report could be leveraged without explicit statutory enablers.

> (Congress:) Evaluate the implementation of statutory provisions enabling the use of agile program and project management within the DoD and the military services.

As mentioned above, there are no statutory provisions related to Agile for hardware development. Thus, we did not review such implementations explicitly, but our report discusses relevant historical uses of Agile for hardware as well as remaining challenges for such implementations.

> (Congress:) Evaluate the agile program and project methodologies used within the DoD and the military services.

Our report discusses Agile program and project methodologies for hardware development generally, but our study was not resourced to perform a comprehensive survey or review of applications in the DoD. However, examples of usage within the DoD includes the exploration and use of additive manufacturing for agile prototyping as well as more agile (rapid) development of systems by such organizations as the rapid capability offices in the Air Force, Space Force, and Army. Also, agile (iterative) hardware development can also be pursued in components using such devices as field-programmable gate arrays that allow for rapid hardware reconfiguration.

> (Congress:) Evaluate how agile program and project methodologies have enabled efforts to prepare the DoD and the military services for the future of work.

Our report extensively discusses how Agile program and project methodologies for hardware development can facilitate positioning the DoD and military services to address future capability needs given rapidly evolving threats.

> (Congress:) Evaluate the enterprise scalability of the agile program and project methodologies used within the DoD and the military services, including how well agile methods are integrated into the enterprise when used at scale.

For software, the DoD is actively pursuing enterprise-scale Agile through the issuance in 2020 of formal policy as well as multiple prototypes and agile software development organizations. For hardware, however, we were not resourced to conduct a comprehensive survey or review of applications within DoD programs. We note, however, that such activities for hardware are generally nascent compared to the DoD's activities for software development.

> (Congress:) Analyze the impediments to the further adoption and enterprise scalability of agile program and project management including statutory impediments, as well as existing policy, guidance, and instruction of the DoD and the military services.

These impediments are discussed in our chapter on Challenges to DoD Implementation, starting on p. 16.

> (Congress:) Analyze the impact of further adoption and enterprise scalability of agile program and project management on the future of work within the DoD and the military services.

These perspectives are discussed in our chapters on Vision and Recommendations, starting on p. 26.

APPENDIX C: AGILE HISTORY - AGILE MANUFACTURING AND ADDITIONAL INFORMATION

SUMMARY

As defined in (Peterson 2021), both software and non-software manufacturing sectors exhibit similar product lifecycles (i.e., product definition, design, prototyping, development/testing, operations, maintenance, and sustainment). The difference is primarily the duration of each lifecycle phase and the domain of work: deterministic vs. emergent. Peterson further notes that there are many new methods under investigation that may offer reductions in duration and effort. For the problem definition phase, specifying requirements at higher levels and implementing modeling techniques such as Systems Modeling Language (SysML) offer promise. In design, focusing initial engineering efforts to architect solution development using generative design should greatly accelerate the processing of change in subsequent iterations. Integrated within the digital thread, virtual reality (VR) offers the ability to rapidly evaluate design in an immersive and realistic experience. Part of I4.0, additive manufacturing (both 3D and 4D printing) offers many new production capabilities and significant reductions in person hours for part fabrication. Finally, the digital twin offers the ability to monitor product performance in operation, identify issues, test resolutions virtually, and potentially fix these using OTA software updates. While this appendix suggests several methods to reduce the effort and duration of iteration, more research is needed to quantify these benefits versus established practice. Quantitative evidence will be of benefit to both the practitioner and researcher and highlight which methods offer the greatest improvement in reducing iteration time if adopted.

HISTORY OF AGILE MANUFACTURING

Industry generally views the agile movement starting in 2001 when a group of software engineers gathered in Utah to develop a methodology (the Agile Manifesto – four values and twelve principles (Fryrear, 2022). The concept and adoption of the non-software agile manufacturing (AM), however, is thought to have been first derived from a report on the 21st Century Manufacturing Enterprise Strategy prepared by the Iacocca Institute of Lehigh University in 1991 (Nagel, 1991). Portions of AM in the manufacturing sector, however, have been around much longer. For example, as reported by Tom Peters in "In Search of Excellence" (Peters, et al. 1982), Harley Davidson implemented (in the 1970s and 1980s) a flexible production line where workers were given the freedom to make production line adjustments to improve efficiency (i.e., Lean Manufacturing, (LM), but also adjustments to meet customer needs and demands (i.e., AM). The fact that many of the production workers were themselves end-users of the product (i.e., motorcycles) no doubt contributed to the success of this approach.

Although early attempts at implementing AM, or at least portions, met with some success, the digital revolution of the 1990s and early 2000s helped launch the beginnings of AM. Increased computing power, storage and cloud computing along with the introduction of the Industrial Internet of Things (IIoT) (Boyes, et. al., 2018) all contributed to the growth of AM. Recognition of the benefits of data-driven decision-making (autonomously or in human-in- or human-on-the-loop applications) led to a reorganization of the manufacturing community. For example, in 2015 GE recognized the growth and importance of data-driven decision-making and spun off GE Digital, which focused on implementing digital technology and data-driven efforts within and outside of GE (General Electric, 2022).

CURRENT-STATE-OF-ART

Although early implementations of Agile Manufacturing (AM) have been in use over the years (e.g., Harley Davidson in the 1980s, etc.), its use (and growth) has evolved considerably over the last decade. For example, advances in additive manufacturing, model-based systems engineering (MBSE), and digital engineering over the past decade have contributed to decreasing manufacturing design and development timelines – mainly in the commercial sector. The following is an overview of where AM approaches are being applied/used in today's non-software manufacturing sector.

Additive Manufacturing (e.g., 3D printing): A critical need in AM is to rapidly adjust to changing customer needs. Rather than "cut metal", which can be expensive, additive manufacturing is employed to produce (multiple) "plastic" or "metal-like" prototypes for testing and evaluation to determine customer value and manufacturing feasibility without the need to develop a full production line. In addition to prototyping, additive manufacturing is often employed to produce small batches of customized versions of products when it is not economically feasible to do so in a mainline production line.

The challenge with additive manufacturing is the suitability of materials used (for small customized batches of product) and the time required to produce the project (days, weeks). That said, there are many companies using additive manufacturing to produce limited production runs of specialized equipment or parts. For example, General Motors (LaReau, 2020) is relying on Agile and DevOps processes in the design, development and production of assembly tools and parts for several of their upcoming automobiles (e.g., Cadillac). Their Additive Industrialization Center (AIC) relies on 3D printing to prototype tools and parts prior to production and to make fine adjustments to these parts during production. Relativity Space's "Stargate Factory" (Relativity Space, 2022) reportedly plans to produce 95% of their rocket using additive manufacturing, allowing them to reduce the build time of a rocket from 24 months to a predicted two months, and the iteration time from 48 months to six. Another advantage of additive manufacturing is that it keeps production closer to the point of need, which may enable faster delivery.

Digital Engineering: An objective of AM is shortening the duration required for each phase of the product lifecycle (e.g., product definition, design, etc.). Digital engineering – specifically model-based systems engineering (MBSE), digital twins, and digital threads – are used to reduce the duration and manpower required to design, prototype, test and react to changes in customer needs and requirements. The key driver here is to digitize and virtualize as much of the lifecycle as possible. MBSE is used to digitally represent the product design to help with visualization, testing, and evaluation before any "metal is cut." Further, MBSE is preferred to traditional paper approaches to design in that these modeling systems can also be used to implement non-physical aspects (e.g., the physics) of a product. For example, if modeling the suspension of an automobile, the physics behind the compression and expansion of system components can be captured within the model. Further, interfaces between systems are automatically maintained and tested as the model is designed or modified. Examples of MBSE tools currently in use include Cameo, Genesys, and OpenMBEE.[6,7,8]

With the continued growth of IIoT and the availability of real-time (performance) data collection and analysis, digital twins (an exact virtual model of an operating product) are useful for predicting future maintenance needs, determining how the product is currently used, and to allow "what-if" analysis to determine impacts to the product due to changes implemented in the design. Digital Twins are a key component of implementing DevOps in the non-software manufacturing sector.

Digital Engineering, when combined with Agile, DevSecOps, and IIoT, is essentially an OODA loop (McKay, et al., 2020) in product manufacturing. Real-time production and operations usage is collected (Observed), analyzed (Orient), decisions are made (Decide), and courses of action are undertaken (Act) based on the collected information and analysis. This OODA process is repeated with various stages of the product lifecycle (e.g., design, development, production, deployment, etc.) undergoing continuous modification to meet a changing development and operational environment. Table 1 provides additional details.

[6] Cameo: https://www.3ds.com/products-services/catia/products/no-magic/magicdraw/

[7] Genesys: https://www.vitechcorp.com/genesys_software/

[8] OpenMBEE: https://www.openmbee.org/

Table 1. OODA Loop and Product Lifecycle

OODA Loop Stage	Targeted Product Lifecycle Area(s)
Observation	Collection entails gathering real-time information from the production line (e.g., via performance measurement IIoT sensors), supply/logistics chain operations, on-going maintenance operations, end-user usage patterns, technological changes, and requirements change.
Orient	This real-time information is analyzed to determine the impact on the lifecycle of the product (e.g., design, development, production, maintenance and usage of the product). Analysis can include running the collected information through a MBSE model or digital twin to determine the impact to the product design and/or predicted performance of the product.
Decide	Courses of action (COAs) are developed based on the analysis of the collected information. Such COAs include adjusting the production line for improved efficiency or changes in the supply chains; and product design changes to meet marketing, user needs and/or to address opportunities due to technology changes.
Act	Once a COA is selected, the specified steps are implemented to the targeted areas of the product lifecycle. Performance information – including user feedback – is collected as part of the OODA loop is repeated.

Industry 4.0: As noted in (Epicor, 2022), "Industry 4.0 refers to a new phase in the Industrial Revolution that focuses heavily on interconnectivity, automation, machine learning, and real-time data collection and analysis to create a connected environment that combines manufacturing, supply chain management and the end-user community." Industry 4.0 is truly the DevOps of the non-software sector. Through IIOT and smart manufacturing technologies, a continuous design, development, integrate, test, and deployment pipeline is realized – all data driven and much of it automated. Changing needs drive design, which drives development and so on.

Agile Manufacturing Services: An evolving area in AM is the outsourcing of AM processes to firms that are usually smaller and more flexible for handling rapid change. These are firms that offer one-stop shopping for product development (usually small batches of product). In many cases, these firms offer small-batch IC design/manufacturing, CNC, and 3D printing capabilities. A sampling of such services include:

- USC/ISI MOSIS – Metal Oxide Semiconductor Implementation System (https://themosisservice.com/) provides IC fabrication services (a mini foundry). The MOSIS Service acts as a silicon prototyping and low volume production service for custom and semicustom ICs.
- FicTiv (Wong, 2018) – Provides a suite of services for vendors who need fast, quality end-use products in volumes ranging from 100-500,000 units. FicTiv has operations across the U.S. as well as in foreign markets including China.

COMPETITORS

Much of the DoD's focus on AM is driven by maintaining a competitive advantage over competitors, especially China. As noted in the media, China is poised to take over as the world's largest economic power and is investing heavily in technology research. AM plays a major role in this effort as it is a major plank in China's China Manufacturing 2050 initiative as well as their "Made in China 2025" initiative (Shaofei, et al. 2016). As reported in (Sun, 2019), China has a slight lead over the U.S. in AM. As also noted in Sun, the Chinese have focused primarily on the introduction of agile-based technologies and organizational structure (especially on supply chain management) into their manufacturing processes. Fortunately, Sun notes that the Chinese have focused less on employee-based enabling technologies (training and augmentation tools being the key focus here). In addition, Sun notes that teamwork is an area in which the U.S. still maintains a considerable edge over China and other competitors. In addition, the U.S. does still maintain a commanding lead in addressing risk management, although the recent chip shortages would suggest that even the U.S. has room for improvement (e.g., establish backup manufacturing capability in another country such as Vietnam). Regardless, agile manufacturing is a key focus of the Chinese as outlined in their Made in China 2025 platform (Shaofei, et al., 2016).

FUTURE OF AM

The need for education and training: Although training has been a focus of the AM movement for several years, there are still considerable challenges to overcome. Many companies speak about being agile and use agile terminology (e.g., sprints, timeboxes, scrums, Kanban, etc.,) to describe their processes, but their processes are far from being agile. Of particular concern is that at the senior level, leadership doesn't fully understand agile and how to implement AM within their production lines. In addition, these vendors often push back on implementing AM due to concern over the initial and long-term costs in implementation (e.g., expenses for implement additive manufacturing, MBSE training, etc.).

In addition to training leadership, improved training processes need to be developed to address the overall workforce. Manufacturing is challenged by changing technology and the need to keep the workforce well trained, but also challenged by a transient workforce who at best may spend three or four years at a company before changing jobs. There is an urgent need for training curriculum that supports rapid on-boarding and keeps the workforce skilled on technology advancement across industry. Solutions that combine both in-house and third-party training will need to be created. Training is necessary at all levels for an organization to fully implement/embrace AM (Rigby et al., 2016).

Support for Distributed Manufacturing: As noted in (Peterson 2021), implementing agile/DevOps in distributed manufacturing operations is difficult. Traditionally, much of agile is based on face-to-face meetings and the ability for team members to work any task (i.e., feature) on the project backlog at any time. The ability to support such collaborations and processes assumed that all team members have access to the project backlog and all elements of the production pipeline. Although recent progress has been made in supporting distributed operations due to the COVID-19 pandemic, most of this improvement has occurred with software-based acquisition systems. For example, virtual collaborative solutions such as WebEx and ZoomGov (Zoom for Government) have facilitated, and in some cases enhanced collaborations among distributed team members. That, along with cloud support services have allowed many software-based acquisition efforts to continue despite the COVID-19 pandemic.

For non-software systems, however, additional research into how to apply agile and DevOps methods to distributed operations is needed. Advances in Digital Engineering (DE), where much of the effort is virtual (i.e., digitized) along with advances in distributed additive manufacturing, are some of the areas that can address the distributed manufacturing challenge. This challenge is one of the reasons why Tesla Motors insources production of components likely to change (vertical integration) and moves production onshore (collocating engineering and manufacturing for faster problem resolution) (Van den Steen, 2015).

Artificial Intelligence (AI), Machine Learning (ML): Increased access to production life-cycle operational data, rapid technology change, frequent changing customer demand, and the need to improve production efficiency, has led to the combining of AI/ML, IIoT, and data analytics to maintain an adaptable/flexible production line that meets changing conditions. AI/ML can be applied to many areas of manufacturing, including monitoring and adapting to changing production line environments, operating environments (e.g., detecting product failures due to high use or environmental conditions), material fatigue, and a changing supply chain (e.g., delayed component delivery).

AI is already used to make low-level manufacturing decisions including automated machine tuning and predicting product quality. Advancements in applying AI and ML to higher levels of the production life-cycle are underway. For example, ASSISTANT (Beldiceanu, et al. 2021) relies on predictive and prescriptive analytics to extend the use of AI to higher-level manufacturing decisions, such as process planning, production planning and scheduling. ASSISTANT provides recommendations to human decision-makers on the best courses of action (COAs). ASSISTANT relies on a digital twin that is manipulated to produce possible COAs for a given production-line challenge. Unfortunately, ASSISTANT assumes that the production application includes reconfigurable manufacturing systems or adaptable factories (two areas that need more research and development), IIoT for data collection, and data analytic processes.

Digital Engineering (DE): With the possible exception of the automotive and electronics sectors, most DE tools and processes are often used as documentation tools (i.e., a substitute for paper-based systems) during the traditional product design process. In many situations, contractors fail to use the tools as they were intended due to the high entry cost of transitioning existing design documentation into the DE environment and the perceived high costs (mainly labor) of maintaining those designs throughout the production life-cycle. Addressing this challenge will require advancements in both automated transition tools and training the work force and leadership on the importance digital models and threads on both short- and long-term manufacturing. For example, enhanced economic models that show cost benefits of DE are needed.

Another key area where research is needed is the implementation of a near operational environment as part of the digital engineering environment. For example, in space-based acquisition programs, the hardware side of the program typically lags behind the software side. Space vehicle configurations (SVs) required for full system testing may not be available for a software-based release. For such situations, there is a need for simulators that exhibit behavior of actual SVs, configurations of SVs, and other external systems. These near operational environments serve two purposes: they are used for actual testing of the software generated in the program; and they are used during system design and sustainment to help inform design enhancements (e.g., "what-if" analysis on impacts to the SV and control system if a design change is made).

Additive Manufacturing: Three major challenges with additive manufacturing are scale, speed, and durability (and sustainability). Most 3D printers are limited to producing prototypes or working end-parts that are small in dimensions. In some cases, scaling challenges can be overcome by modularizing the design of the end-part (via MBSE tools) and using 3D printers to produce multiple components that are later fabricated into a finished (and large) end-product. In many other cases, this may not be possible, although as noted in (Relativity Space, 2022; Zastrow et. al, 2020), Relativity Space is planning to produce rocket engines capable of lifting 1,250 kgs of cargo into low Earth orbit (LEO). As noted in (Zastrow 2020), large-scaled 3D printing is an active area of research.

Speed is also a limiting factor, as it can take days or weeks to produce end-parts. For prototyping, speed may not be an issue as in many cases: it is preferrable to take the time to prototype to ensure the end-part is what the market demands. However, speed to market is a critical consideration in many cases. In addition, for small lot production runs, the need for rapid 3D printing to meet customer demand is also a major driver behind enhancing additive manufacturing technologies.

Another area of active research is in the material sciences. Additive manufacturing is highly dependent on the materials used for producing the end-product. Durability, speed of application, and sustainability of the end-product are all driven by the characteristics of the material used in 3D printing. On-going investments in materials for use in additive manufacturing (Shahrubudin, et al. 2019) are on-going, including research into advanced metals, polymers, ceramics, composites, and smart materials (such as shape memory alloys (Van Humbeeck, 2018) and polymers (Yang, et al., 2016)).

Finally, another active area of research is 4D printing, in which movement is added to a 3D printed product. As noted in (Zastrow, 2020), researchers at the Swiss Federal Institute of Technology and the California Institute of Technology reported using 3D printing to develop a submarine that relies on paddles to propel itself in underwater applications.

Modularity/Plug-and-Play Platforms: Although modular hardware platforms have been around for decades (e.g., automotive manufacturing has relied on such platforms, much of this hardware based, for over a century), advances in electronics, standardized bus designs/standards, and the use of on-board software interfaces have enabled more modular/plug-and-play architectures to be used in industry. For example, (Azoulay, 2021) discusses how software-enabled data nodes can serve as an interface layer between the on-board computer (OBC) and sub-system/payload hardware systems in space vehicle design. In this case, the OBC serves as an off-the-shelf commodity component that can be used for a variety of space vehicle designs. To add or change a payload, all that is required is a software upgrade to the on-board data node.

Virtual/Augmented Reality: Often multi-dimensional views of end-products are not sufficient to fully define and evaluate a design or prototype. An area of active research is in the use of virtual reality prototyping (Peterson 2021). In many cases, VR offers a low cost and easy to use method for customer evaluation of a design or prototype. In addition, marrying VR with DE allows for the designer, engineer, and customer to visually see and understand the non-physical characteristics of an end-product (e.g., spring motion for an automobile).

APPENDIX D: DETAILS OF LEAN

As noted in the body of this report, Lean principles have generally been incorporated into agile approaches and are therefore discussed as part of the narrative on agile. This appendix provides additional detail on Lean for reference.

LEAN ACQUISITION

The term "lean" often arises in discussions about continuous improvement. The modern history of Lean can be traced to Henry Ford's implementation of the first assembly line in 1913, and the concept flourished in post-WWII Japan. The application of Lean principles led to a resurgence in manufacturing in Japan; subsequent attempts to apply it to U.S. manufacturing were met with mixed results.

In brief, Lean is based on seven principles (or situations) to cultivate, and seven wastes (or situations) to avoid. Though not the focus of this report, Lean principles are included when relevant to the discussion of Agile or DevSecOps.

The Seven Principles:

1. Eliminate waste
2. Build quality into the product
3. Create knowledge and amplify learning through experimentation
4. Defer commitment
5. Deliver fast
6. Respect people
7. Optimize

The Seven Wastes:

1. Partially done work
2. Extra features
3. Relearning decisions
4. Handoffs
5. Delays
6. Task Switching
7. Defects

Lean and agile, with a common root in post-World War II Japan, have a lot in common. Such as a focus on building quality in, value, flow, respect for people, a pull-based system of work and a kaizen process of continuous improvement and visualizing work. However, a key area they differ is the focus on "standardized work" in lean. Mass production looks for "good enough," and lean production looks for perfection. This is desirable for repetitive production; however, for unique, unknowable, emergent domain of [software] product development, "perfect is the enemy of good," to quote Voltaire (Smart 2006, p 25).

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