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Acknowledgments

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Leadership from all levels in the U.S. Army consistently drive creative effort towards improvement of our products, services, and organizational processes. Those who actively participated in our process development effort are too numerous to mention; however, we would like to specifically acknowledge Mr. Lawrence T. Osiecki for his thorough involvement in the U.S. Army Combat Capabilities Development Command Armaments Center’s pursuit of process improvement.

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Executive Summary

The U.S. Army Combat Capabilities Development Command Armaments Center's (CCDC Armaments Center) Fire Control Systems and Technology Directorate (FCSTD), located at the Picatinny Arsenal in New Jersey, is a weapon system development organization. The main products of the FCSTD are fire control systems, which are software applications that enable weapon systems to accurately point and shoot at designated targets. To give U.S. Army warfighters a competitive edge, the FCSTD developed a process infrastructure that could efficiently and effectively support our creative efforts and our ability to continually build improvements. Our effort and commitment of resources to process development had significant benefits. In 2004, the FCSTD Paladin program produced the first project in the CCDC Armaments Center to achieve an internal assessment of compliance with the stringent software development requirements of the Capability Maturity Model Integration (CMMI) at Maturity Level 5, the CMMI's highest rating. Having gained confidence in the CMMI, the FCSTD and our partner organizations (the Quality Engineering and System Assurance directorate and the Armament Software Engineering Center [ASEC]) prepared for and maintained independent process assessment ratings at CMMI Maturity Level 5 continuously since 2006. Our consistent processes and operational efficiency evolved, leading to significant improvements in product and service quality and adherence to cost and schedule estimates. In 2015, these benefits attracted other organizations within the CCDC Armaments Center, such as Tactical Effects, Protection, and Interactive Technologies, to adopt our process infrastructure.

Training improved the ability of project personnel to conceptualize quality and enabled continued process performance improvement, even after achieving compliance with the CMMI at Maturity Level 5. For example, Paladin integrated project teams learned from analysis of our defect management process that defects created in early software development lifecycle phases often persisted, without remediation, and interfered with development effort in late lifecycle phases. Our realization that defects not being promptly addressed was a risk of poor performance enlightened us to the idea of investing more in peer reviews, in early software development lifecycle phases, to improve the quality of our defect management process. This saved several million dollars in defect remediation costs in late lifecycle phases and also freed up time to further improve software functionality for warfighters. Improvements in our mission-focused organizational culture and, in our system of processes for institutionalizing continual improvement, led to opportunities to communicate and share process improvements within the FCSTD, throughout the CCDC Armaments Center and beyond. In this technical report we will introduce our perspective on quality improvement and share useful highlights of our system of software development processes. We also share our objectives, measurements, improvements, organizational culture, process performance accomplishments, and the benefits to our stakeholders.

Abstract

This report presents a systemic approach to software development process improvement and its impact for the U.S. Army Combat Capabilities Development Command Armaments Center, Fire Control Systems and Technology Directorate (FCSTD) and its stakeholders. The report presents the best practices that improved the FCSTD's ability to meet organizational goals, primarily in the context of the Capability Maturity Model Integration (CMMI). This process improvement effort extended to dozens of projects and earned the FCSTD a CMMI Maturity Level 5 rating. The report discusses how the FCSTED defined strategy, quality, and risk as interrelated elements of a conceptual system and used conceptualizing quality as a thought process to drive product and service design decisions. It also discusses how the use of tools, such as Defect Leak Matrices and Rayleigh Curve Models, drove cost savings, up to nearly $2 million on each Paladin project, and similarly improved costs and efficiency across many projects, enabling the FCSTD to consistently deliver new or improved functionality in less time. Also discussed is how the FCSTD effort to improve software development processes was coupled with significant effort to improve the quality of software-intensive armament systems for the U.S. Army and for allied armed forces worldwide.

1 Introduction

In this technical report we highlight continual quality improvement efforts implemented by the FCSTD to yield significantly improved performance capabilities in our products and services, improved software development process consistency and efficiency, and reduced costs. We discuss how these benefits continued to improve over the last 20 years due to our organizational culture and our infrastructural support for innovation and shared organizational learning. We offer insight intended to help any organization improve creative competencies and performance results.

This report is organized to illustrate how the FCSTD's software development effort, and its rationale for continual process improvement, relates to the satisfaction of stakeholders' strategic needs. Beginning with strategic incentives desired by stakeholders, we describe the development of organizational intentions, objectives, measurements, and a structure for continual improvement. Insights from the FCSTD workforce highlight experiences that motivate our effort and benefit customers. We conclude by discussing creative thought processes that improve quality and reduce risks of poor performance to create strategically focused products and services that, in turn, effectively and efficiently create value for stakeholders.

In Section 1, we introduce our organizational structure, strategic direction, mission and vision, and summarize organizational capabilities. Section 2 introduces our stakeholders – the people in our system who expect to attain valued incentives from the effort of the FCSTD's workforce. In consequence of our stakeholder's incentives, and expectations regarding them, Section 3 introduces our intention to institutionalize a structure for continual improvement and our approach to developing our organizational system. Section 4 introduces the value to the FCSTD of strategic focus in everything we do, and it discusses why our ability to conceptualize quality is a thought process essential for organizational success in performance of leading-edge creative efforts. Section 5 introduces our common organizational goals, objectives, measurements, and improvements which are shared across organizations within the CCDC Armaments Center. We discuss measurement techniques, measured performance improvements over time, and cost savings within the FCSTD. We conclude in Section 6 with a discussion of *coascendance,* a concept that describes how stakeholders in great creative endeavors can organize and work together towards common strategic purposes, drive out risks of poor performance, and attain their valued incentives. Examples of coascendance among the FCSTD's stakeholders are highlighted.

The CCDC Armament Center's Weapons and Software Engineering Center (WSEC) is the FCSTD's parent organization. The organization chart in Figure 1 shows the FCSTD in a heavy blue frame, within the WSEC. A "virtual" organization called the Armament SEC, composed of the FCSTD, the Armament Software Engineering Center (ASEC), QESA directorate, and the Tactical Effects, Protection, and Interactive Technologies (TEPIT) directorate, work on common organizational goals, measurements, lessons learned, and related management activities focused on sustaining our CMMI Maturity Level 5 infrastructure. These organizations are highlighted with blue frames in Figure 1.

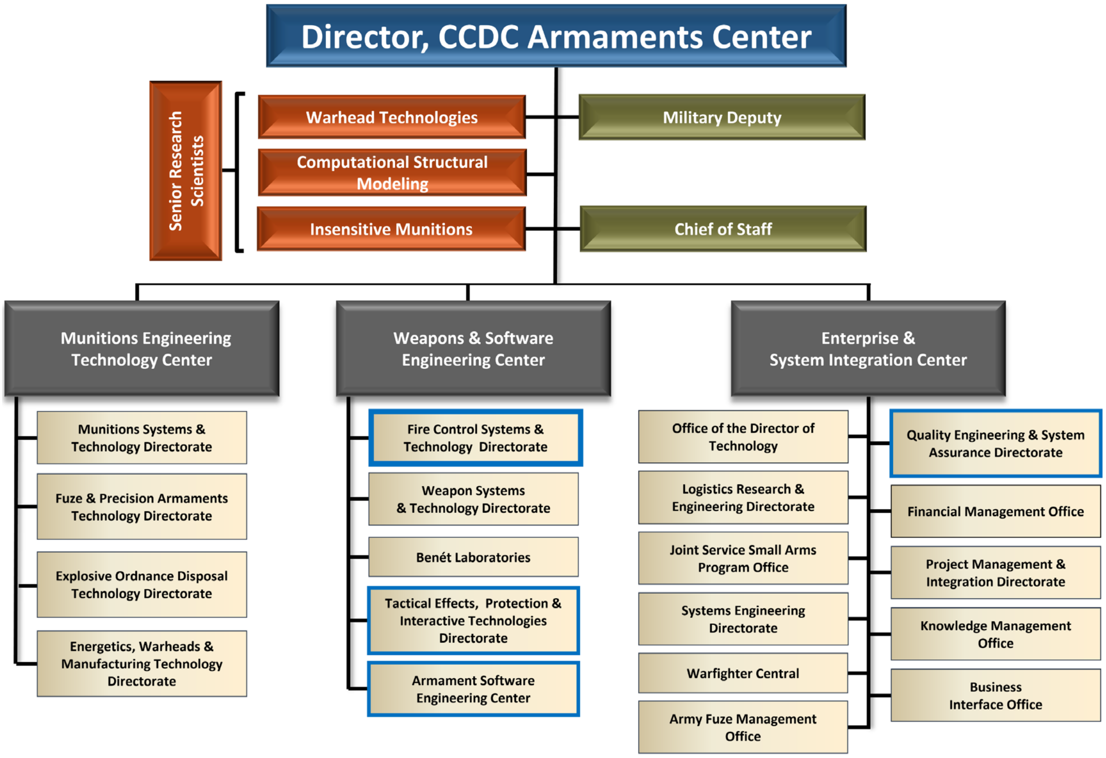


Figure 1: Organizational Structure of the CCDC Armaments Center

The FCSTD consists of six divisions:

- Armored Vehicle Fire Control and Future Systems
- Artillery Fire Control Systems
- Automated Test Systems
- Firing Tables and Ballistics
- Mortar and Common Fire Control Systems
- Small Arms Fire Control and Optics Technology

Each division has from two to four branches differentiated by areas of scientific and engineering expertise. The FCSTD employs 275 scientists and engineers (153 BS, 117 MS, and 5 PhD degrees) on a full-time basis. Our largest contingent of employees works in New Jersey, the rest work in Maryland. Almost half of our employees are contractors from over a dozen firms. The FCSTD manages over two dozen programs, each of which has one or more projects running per year. Some programs have been sustained for our customers for over 50 years. Team sizes vary from one to more than 80 people with a modal value of approximately eight people per team. Many subject-matter experts are shared across multiple projects. Project durations vary widely, with many software development projects lasting two to three years. Almost all of our software is integrated on weapon systems and undergoes live-fire testing at test ranges, such as the Yuma Proving Ground, prior to fielding to warfighters.

An overall strategy guides the work of WSEC, which defines its strategic intent as follows:

> *WSEC is recognized as the preferred provider of innovative and reliable warfighter weapon system solutions and its underlying technical and tactical systems. Our excellence in systems and software development, using mature processes and procedures (e.g., CMMI and ISO) span the full lifecycle. WSEC consistently delivers timely products and solutions to customers within the Army, other Services, government agencies, and industry. WSEC forges strong alliances with strategic partners to conquer the execution of our mission and position ourselves ahead of emerging threats to enhance the warfighter and achieve dominance on the battlefield.*
>
> *Operating within and in support of the WSEC's strategic intent, the FCSTD has defined its own vision and mission:*
>
> - Vision: Recognized foremost provider of fire control and related technologies that transform the battlefield and secure the homeland
> - Mission: Deliver total lifecycle hardware & software engineering solutions for weapon systems control, automated test systems and homeland defense - Rapidly incorporate and field emerging hardware and software technologies into sustainable fire control products - Provide customers with fire control and related domain expertise - Provide sustainment engineering for fielded fire control systems

The CCDC Armaments Center's FCSTD is primarily chartered to initiate and conduct engineering development, prototyping, production, sustainment engineering, and product improvement for fire control systems and subsystems, both hardware and software, for assigned mission systems.

The term *fire control* refers to a system that creates a firing solution to aim a weapon system to fire a projectile on target. The Paladin howitzer, for example (pictured in Figure 3), is designed to operate through either a manual calculation of firing solutions or through a complex software controlled communications system that interoperates with several independently developed systems to rapidly calculate the factors necessary to control firing precisely on a target. The Paladin 155 mm self-propelled howitzer, along with the field artillery ammunition supply vehicle, provides the primary indirect-fire support to armored brigade combat teams, infantry brigade combat teams, and Stryker brigade combat teams. Fire control software is developed and maintained by the FCSTD [U.S. Army 2019].

A firing solution is best when information such as meteorological data, weapon and target coordinates, and ballistic properties for the weapon and ammunition are known. Software and software systems working together and communicating near-real-time data make firing a modern weapon system a very high-tech challenge. Meeting this challenge is especially advantageous for the Paladin howitzer, which is primarily an indirect firing system, meaning it fires at targets that gunners may not even see because they are separated by great distances, hills, or other obstacles.

To meet our assigned challenges, the FCSTD has a particular set of skills. These skills include –

- developing, enhancing, and automating the functions of armament fire control systems for optimal orientation, aiming, and adjustment for target acquisition accuracy of weapon systems out to their effective ranges

- defining system and subsystem concepts and performance requirements for integrated hardware and/or software systems
- developing counter-countermeasure concepts to harden fire control systems against countermeasures
- performing all aspects of software development to attain successful internal testing and independent verification and validation, interoperability verification, and information assurance leading to Materiel Release and fielding
- characterizing the ballistic performance of current, improved, and new munitions and developing aiming data, ballistic fire control information, and ballistics fire control software for all unguided and some guided combat weapon systems in the U.S. Army inventory
- serving as a center of excellence for developing, fielding, and sustaining Automated Test System products in support of weapon systems for Army and DoD elements and providing diagnostic and/or prognostic products, including platform health management, embedded diagnostics, prognostics, and software sustainment tools (software downloaders)
- developing embedded training as an integral part of weapon systems using internal tactical software to simulate the functionality of the weapon and making use of virtual tactical hardware and unmodified tactical software to simulate the environment/event and/or functionality of the weapon system
- institutionalizing and following disciplined software development processes, such as CMMI for Development (CMMI-DEV) and ISO 9001, to allow for efficient and reliable development and fielding

2 Software Process Improvement Incentives

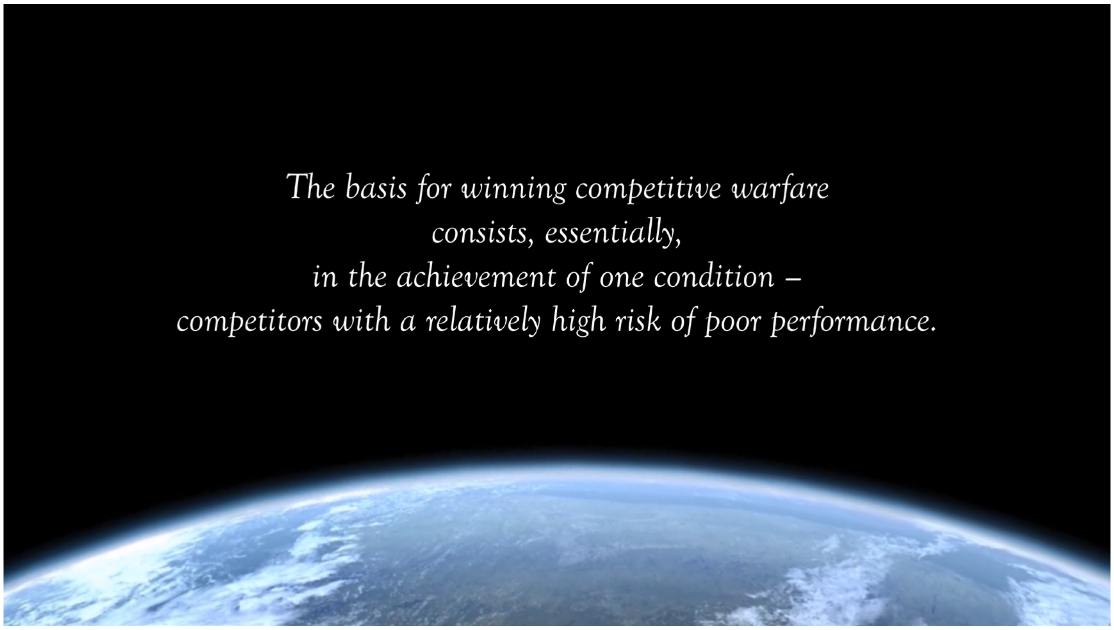


Figure 2: The Basis for Winning Competitive Warfare [Elias 2017]

The goal of providing warfighters superior capabilities relative to potential adversaries incentivizes the FCSTD to develop state-of-the-art technology, build strategically effective systems, and create state-of-the-art organizational processes for developing these systems. Our approach to attaining our incentives is decidedly strategic, collaborative, and committed to success, which includes supporting all of our stakeholders in attaining their incentives as well.

Incentives are the tangible and intangible benefits motivating people to devise strategies to attain them. When a strategy is formulated at the level of quality excellence, it has the ability to attain desired incentives with a minimal risk of poor performance. When quality excellence for a strategy hasn't been achieved, due to a counteracting incentive (e.g., more profitable substandard component) or condition (e.g., unavailable resources or failure of imagination), there is a risk of poor performance. A clear understanding of the incentives a customer or targeted customer market seeks can help product and service designers develop offerings that help customers attain their incentives more easily, at lower cost, with less risk, or in ways customers haven't considered. The ability of suppliers to recognize and, if possible, elevate the standard of quality excellence is what makes them exceptionally valuable to customers. As the principle expressed in Figure 2 implies, innovation and performance improvement toward quality excellence (and beyond) are the basis for winning in competitive warfare and for progressively elevating the standard of quality excellence for the benefit of customers and other stakeholders.

2.1 Stakeholder Incentives

2.1.1 Warfighters

Our nation's warfighters continue to serve in challenging environments worldwide where the safety, efficacy, reliability, and supportability (among other capabilities) of software-intensive weapons systems are greatly valued. The FCSTD is a critical resource to warfighters who depend on our development and support activities to maintain a battlefield edge, wherever that battlefield may be.

2.1.2 The U.S. Army

The U.S. Army is keenly interested in efficient and effective systems engineering processes that enable research and development organizations to respond to the competitive conditions of war, in which circumstances change and risks are exposed. In peacetime, efficient and effective systems engineering processes make the best use of taxpayer dollars while desired weapon systems are developed. For these reasons, the Army sustains the Defense Acquisition University for workforce training and also participated in sponsoring and developing the CMMI along with Watts Humphrey and the SEI.

The FCSTD supports the Army's incentive to affordably attain improved capabilities by developing software applications designed with the modularity and flexibility to manage functions common to several weapon systems. This capability is exemplified in the Automated Test Systems Division's (ATSD) Diagnostics and System Health (DASH) software product line. DASH is an embedded diagnostics application that helps users identify and correct faults present on their systems. DASH was designed with a flexible architecture that allows developers to reuse a core DASH application and easily create platform-specific configurations that include the platform's diagnostic logic. This new product line significantly reduces costs and development time for supported weapon systems. Daniel Tagliente, who serves as the DASH project leader, said in an email to the author on March 12, 2019, that, to date, "DASH has been successfully fielded to users of the M109A7 and M992A3 Family of Vehicles and development is ongoing to implement DASH on a series of additional weapon systems." Modernizing and automating diagnostic functions via DASH applications is expected to extend to more weapons systems in the near future and significantly reduce risks of poor performance.

2.1.3 Scientists and Engineers

The CCDC Armaments Center is motivated to socialize systems engineering practices that help our scientific and engineering community to grow professionally as well as to efficiently develop state-of-the-art weapon systems that are responsive to the mission needs of the U.S. Army. By developing our personnel, we gain a sustainable competitive advantage in our ability to innovate and create better products and services for warfighters.

2.1.4 Industry and Academia

Partnering with industry and academia via cooperative research and development agreements and partnering in Integrated Project Teams (IPTs) enable each partner to benefit from experiencing and contributing to research and development that builds professionalism and capabilities to collaborate on improving the state-of-the-art for armament systems.

2.1.5 Communities of Software Intensive Systems Developers

The challenge of creating software for today's complex weapon systems often requires more than just a team of developers; it often requires an integrated creative effort from teams of developers, and even communities of developers, often dispersed across the country or across borders, building on each other's specialized work. Developers often describe the interrelationships in their systems as being a system in a system of systems. Operating from this viewpoint, with which the U.S. Army has developed significant mastery, creates risks that necessitate common standards, interface protocols, and processes for communicating, synchronizing, and reaching consensus as products develop and evolve. The complex, secure, and often classified nature of weapon systems technology all drive the specialization of software development teams into communities of developers. For example, within the FCSTD, the Artillery Fire Control Systems (AFCS) division develops fire control software for the Paladin howitzer using a component called the NATO Armaments Ballistic Kernel (NABK), a product of the FCSTD's Firing Tables and Ballistics (FTaB) division. The NABK is an essential resource: It resolves the computations necessary to precisely aim the Paladin and several other weapons systems the FCSTD develops. The NABK is sufficiently modular, and its interfaces are so well understood within weapon system development communities that it is capable of interacting with many other systems. Jason Fonner, Competency Manager of the FTaB division, said in an email to the author on March 27, 2019, "The NABK is used in every operational cannon artillery fire control system in service with the United States Army and Marine Corps. The NABK has also been fielded as a component of the fire control systems of at least 20 nations."

There is a strong incentive for sharing development effort across communities of developers: By sharing and integrating desired advanced technologies in their weapon systems, they provide communities of warfighters advantageous strategic capabilities and enhance the warfighters' operational effectiveness. Technology must be selectively developed to attain strategic quality excellence where the newly integrated technology adds a meaningful and desirable strategic capability. This form of strategic focus can avoid integration of unnecessary technology that can overburden a project with unnecessary costs, delays, and risks. Although technology can be very attractive, competition is never a contest of technologies alone, but it is always a contest among different strategies that encompass the broader spectrum of necessary performance [Elias 2017].

Figure 3: The Paladin 155 mm Self-Propelled Howitzer

2.2 Strategic Incentives for Process Improvement

Wherever the risk of poor performance of a system decreases, system quality and the ability to attain the incentives of a strategy, or achieve mission success, increases. This is true for weapon systems as well as for the system of processes software developers use to create weapon systems. Considering this strategic reasoning, the FCSTD uses assessment of the ability of customers to attain their valued incentives, at a minimal risk of poor performance, as a basis for creating strategically better products and services. Similarly, the FCSTD approaches process improvement by institutionalizing a system of defined processes upon which we can integrate experiential learning and innovation to reduce risks and improve attainment of organizational incentives. These complementary efforts improve our ability to reliably develop and improve weapon systems that effectively help our organizations' stakeholders attain desired incentives.

3 Organizing for Process Improvement

Strategic quality excellence in our products, services, and processes are essential elements of our approach to weapon system development and have been for a long time. The following sections explain how we institutionalized a structure for continual improvement and describe our approach to developing our organizational system.

3.1 The CCDC Armament Center's Process Improvement Journey

3.1.1 The Grand Alliance

Watts Humphrey's pioneering research on software development processes evolved into a multi-industry, multi-government agency, and university collaboration that produced the CMMI. A diverse collection of incentives for various constituents worked to strengthen the model's attractiveness and suitability as well as the commitment to it from a wide range of stakeholders. The FCSTD developed the intention to build a structured system of processes using best practices tailored from the early Capability Maturity Models (CMMs) to the current CMMI models. An advantage our personnel had in using these models was the ability to confer with the Software Engineering Institute (SEI) and the software development community, to contribute ideas, and to screen out ideas that may not have performed best throughout the model's evolution. Dozens of army personnel from the CCDC Armaments Center enjoyed direct involvement with the SEI over the last 20 or more years.

CMMI enabled FCSTD to develop a structure for the work undertaken by our community of software developers. The Armament SEC's 13-year run of successful assessment at CMMI Maturity Level 5 is not only prestigious in its own right, it also shows our customers that we are seriously committed to process improvement.

3.2 Integrating and Implementing Process Improvement Philosophies and Methods

When it comes to approaches to process improvement, you could say the FCSTD's culture is a meritocracy: We will use the best technique that fits a process challenge. Within the CCDC Armaments Center, we developed an organization to teach and certify employees in the philosophy and methods of Lean Six Sigma. We also have an Armament University where employees can take courses in various popular process improvement approaches. The CCDC Armaments Center is also home to the new U.S. Army Armament Graduate School (AGS) at Picatinny Arsenal. The AGS offers a masters and a PhD degree program in Armaments Engineering. Armament Software is a required course in the AGS. This course includes lessons on enterprise process improvement philosophies and methods, including the CMMI, the ISO 9000 series, Process Enrichment, Lean Six Sigma, Shingo principles, Total Quality Management, Baldrige Award Criteria, and Agile software development processes. Most learning opportunities link directly to on-the-job tasks. For example, our students use their Lean Six Sigma green belt and black belt projects to resolve on-the-job challenges and achieve actual cost or time savings. Sometimes a Lean Six Sigma project can lead to organizing and emphasizing process improvement methodologies themselves for best effect, as shown in the Enterprise Excellence Model below.

3.2.1 The Enterprise Excellence Model

The Enterprise Excellence Model was developed by former CCDC Armaments Center Director, Dr. Joseph Lannon, and his Deputy Director, Col John Merkwan, as a Lean Six Sigma Black Belt project. Through the Enterprise Excellence model, the various complementary specializations of enterprise process improvement approaches could be readily understood.

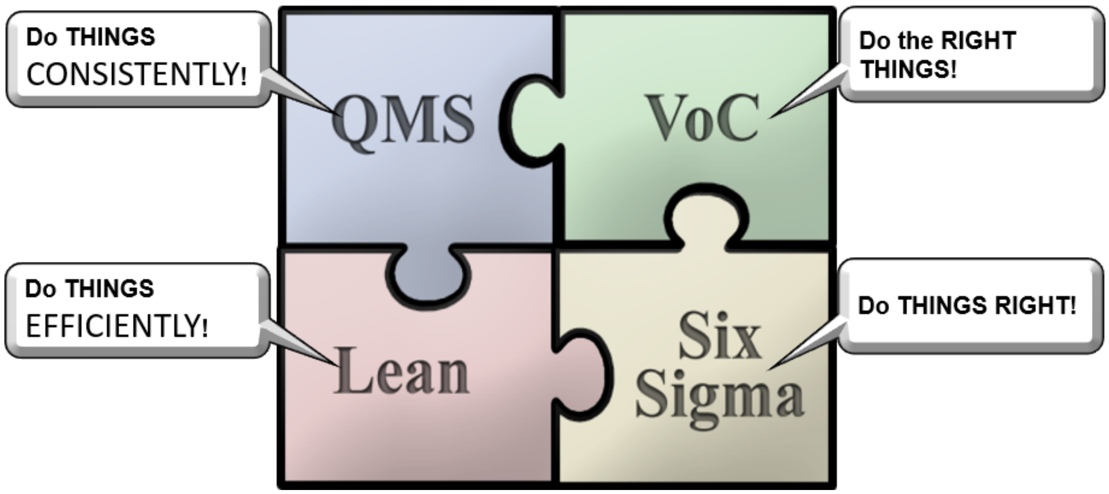


Figure 4: The Four Elements of the Enterprise Excellence Model

- *Do the right things!* Voice of the customer (VOC) facilitates regular, in-depth communication with our customers and/or suppliers to carefully define and understand requirements, create quality proposals and project plans, and obtain feedback before, during, and after project execution.
- *Do things right!* We use Six Sigma tools to ensure that our work processes meet customer requirements effectively.
- *Do things efficiently!* Lean creates higher levels of customer value through the systematic elimination of all forms of waste.

Do things consistently! The Baldrige criteria are the CCDC Armaments Center's over-arching framework for our Quality Management System (QMS). Our QMS integrates industry best practices, including the CMMI and ISO. Beyond a QMS, the Baldrige framework and award criteria shape our business performance system.

3.3 A Structure for Continual Process Improvement

The CMMI's process management premise, "the quality of a system or product is highly influenced by the quality of the process used to develop and maintain it," is a good rationale for improving processes as organizational learning emerges [Humphrey 1989]. As we've experienced, process improvements are able to compound and build on previous improvements when a structure for continual process improvement and a system of well-reviewed processes is established.

Early in our effort to work with the CMMI, the FCSTD (and other partner organizations forming the Armament SEC) began to develop an intranet application that we call our Process Asset Library (PAL). The PAL is used to maintain documentation, such as our policies, procedures, templates, tools, and training. The PAL evolved into an automated repository through which project teams submit monthly measurements to a Process Engineering Group (PEG). The PEG generated monthly reports to communicate process performance status within the Armament SEC. The PAL also became a tracking system for a variety of mechanisms to improve processes.

Organizational Change Requests (OCRs) are a form of proposal initiated if a common organizational policy, procedure, template, or tool may be improved by an incremental change, or if a new common resource must be developed. OCR's are reviewed by a Business Area Managers Council that includes managers from several organizations. The council may recommend process changes or further research.

Project teams submit best practices, lessons learned, and innovations or experimental approaches to process improvement they develop to the PEG via the PAL. Following review, this information is shared across the CCDC Armament Center via the PAL.

The results of process performance measurements and assessments are used to refine performance baselines. These baselines become an expected or predicted level of performance for similar processes in the future.

Resources on the PAL enable projects to develop their defined process (or set of project planning documents) consistently with other similar projects. This makes it easy to have commonality in processes across projects and to assess their performance as they improve based on organizational learning.

3.4 Working with the People in the System

The FCSTD utilizes IPTs to engage functional area team leaders in communicating project needs. IPTs typically consist of government and contractor personnel as well as national guardsmen and retired warfighters, many of whom are veterans of Operation Desert Storm and ongoing defense missions worldwide. IPTs typically include team leaders from software, test, verification and validation, systems integration, safety, and process assurance teams.

IPTs develop milestone meetings to review project progress throughout the software development lifecycle of each project. Milestone meetings typically include System Requirements Reviews, System Functional Reviews, Software Design Reviews, and Test Readiness Reviews. Edward Gilsky, branch chief in the FCSTD AFCS division, noted in an interview with the author on March 7, 2019 that we use stringent, well-defined processes, including requirements analysis, coding standards, peer review oversight, integration testing by warfighters, functional qualification testing, and verification and validation testing by independent agencies so that "we are an open book," inviting people to comment on our products' performance. Our stringent reviews reflect the gravity of developing software for weapon systems. Firing solutions that are in error not only are ineffective but could subject our warfighters to friendly fire, endanger allied forces, or harm innocent civilians in a congested theater of war.

Within the FCSTD, we use two different types of briefing formats to provide higher levels of management insight about project performance. These are Senior Management Reviews (SMRs) and Organizational Level 1 Reports (OL1Rs).

SMRs are quarterly briefings from project team leaders to senior managers and other project stakeholders. In SMRs, project team leaders review project requirements, schedule, risks, Causal Analysis and Resolution (CAR) and Decision Analysis Resolution (DAR) effort, quantitative and statistical measurements, customer feedback, internal as well as independent process assessments, OCRs, best practices, lessons learned, and innovations. SMRs are effective in gaining involvement, feedback, and support from senior managers, which helps motivate continual improvement effort in software development process performance and in related concerns.

OL1Rs are monthly briefings of measurements and analysis aggregated from multiple projects in the Armament SEC. Measurements reported in OL1Rs support organizational process performance baselines and support management intervention as necessary due to evolving conditions or due to innovation proposals.

3.4.1 Strategic Communication

The best way to learn about our customers' missions, besides reading their concept of operations documentation for the equipment they're acquiring, is to meet them out in the field where they're using our equipment and observe and discuss the successes and challenges they encounter. These meetings, which occur with each version of software we deliver, are called User Juries.

Customer feedback from User Juries and from training sessions our developers deliver to warfighters help us adapt our requirements to meet theirs. This feedback also spurs changes to technical manuals that help show warfighters how to benefit from the capabilities of our products and services.

Virtual Trainers are a special type of product that the FCSTD's Automated Test Systems Division produces. Virtual Trainers are computer-based applications that often use animated warfighters to help actual warfighters step through each part of a mission or each part of maintenance operation, each of which are rather complex on today's weapon systems. Virtual Trainers are delivered with many software products the FCSTD produces, enabling warfighters to train or maintain equipment on their own schedule and pace wherever they are stationed.

4 Strategic Quality Improvement Processes

Quality must be the organization's highest priority.

Watts S. Humphrey
[Humphrey & Over 2010]

When things go wrong on defense programs, the problems are often traceable to the failure to fully grasp the fundamental needs of the user.

Robert Lightsey
[Lightsey 2005]

So, what is quality and why must quality be an organization's highest priority?

If we define quality as the ability of performance (in each Theme of Performance) to enact a strategy, we can see that quality has a relationship with the customer's strategy [Elias 2017]. A customer's strategy enables us to understand the incentives the customer intends to attain through its effort and it gives us a way to establish the types of performance that will achieve quality excellence in attaining those incentives—thus setting product and service performance goals. Gaining an understanding of what quality excellence means for a customer's strategy enables us to see that any deviation from quality excellence is a risk of poor performance. Considering how to minimize risks of poor performance and how to attain the desired incentives of a customer's strategy should enlighten and drive design decisions that help us achieve quality excellence. For whatever we aspire to create, strategy, quality, and risk are interrelated as elements of a conceptual system creative people must understand to develop products, services, or even organizations that can achieve quality excellence for customers.

In the last century, it was reasonable to define quality as conformance to requirements. When much of our industrial production was based on blueprints for products that could be easily measured, the quality of workmanship depended on following requirements. But conformance to requirements was never a proper or even a logical definition of quality, and it has limited utility in helping people to understand quality. These deficiencies are especially acute in creative endeavors, such as software development, in which the ability to conceptualize quality is essential. Requirements defined for software rarely provide the level of specificity needed to design software that properly addresses the complex subtleties of product efficacy, optimal performance, ease of use, and adaptability to diverse conditions that customers hope for the software product to have. To properly implement software requirements and to develop and implement appropriate derived requirements, developers should have insight to the strategic incentives of the customer and may need to exercise significant creative interpretation in order to create software that can provide customers the ability to attain their incentives and mission success through use of the software product. This is why a robust, systemic depiction of quality as an element of a conceptual system, with elements to consider that can provide developers more correct, more contextual, and more strategic insight, that enables them to avoid risks of poor performance, is preferable to operating from an expectation, however valid, that conformance to requirements will be sufficient to achieve quality excellence.

If not for the ability to envision quality as part of a conceptual system, and to refine our understanding of what quality means for our organization, the FCSTD wouldn't be driven to achieve quality improvements beyond the expectations of the CMMI. After the Armament SEC attained assessment at CMMI ML 5, we continued to improve the quality of our processes. These improvements included the following:

- We improved the efficacy of processes by tailoring them. For example, we went beyond measuring and monitoring defects to actively increasing the amount of peer review our work products received early in development, which prevented errors from compounding and saved time and money.
- We developed an intranet application to centralize, build upon, and sustain process resources.
- We developed templates for plans and milestone reviews common to most projects to optimize use of best practices.
- We built applications for our intranet-based PAL to deliver training and to automate collection of data, measurements, good examples, and lessons learned. The accessibility of the PAL enabled our workforce to more readily share ideas and resources.
- We made it possible for programs and organizations throughout the CCDC Armaments Center interested in adopting our processes to join in, as the TEPIT directorate did four years ago.

Organizations as well as individuals perform best when they are skilled at envisioning quality excellence and removing risks of poor performance for their work effort.

In what Watts Humphrey called the "operational processes" (those used by software development teams), excellence in the ability to conceptualize strategy, quality, and risk (and how they interrelate), from the earliest milestones in requirements development processes, is key to recognizing the fundamental needs or incentives of users and to creating products and services that enable users to succeed in their missions.

4.1 Conceptualizing Quality – A Thought Process

> *Today, most sophisticated technical work is more like software: A great deal of the creative effort is done on a computer or in a worker's head, and results are largely invisible to the casual observer... The products, instead of being things you can touch and feel, are ideas. While these ideas may ultimately be embodied in physical products, the bulk of the work, and the true product value, is in the creative effort required to develop these ideas and transform them into marketable products.*
>
> Watts. S. Humphrey
> [CrossTalk 2010]

The intense integration of technology in today's defense and commercial products and services makes understanding quality central to the success of development or acquisition of creative effort. All parties to an acquisition benefit from the ability to conceptualize the forms and degrees of performance that can lead to mission success.

The FCSTD considers quality to be an indication of the ability of the software we develop to serve warfighters (or “users”) in the performance of their mission. This is why we focus on creating software that not only meets specified requirements but is responsive to mission needs, down to each *derived* requirement as well. Derived requirements have to balance quality and risk against the established product strategy, otherwise developers risk altering strategy in ways that do not pair with the product’s concept of operations or with the operational constraints of warfighter missions. On FCSTD’s projects, verification and validation reviews and testing that can capture strategic drift and non-conformances are typically conducted by personnel from the Quality Engineering and Systems Assurance (QESA) directorate, an independent organization within the CCDC Armaments Center’s Enterprise and Systems Integration Center (ESIC). The QESA directorate’s systems engineers are typically members of our IPTs. Managing requirements, performing independent reviews, and testing are significant to the warfighters using our products and services. They depend on our software developers to create safe, efficacious, reliable, and optimally performing software that enhances their ability to achieve mission success, wherever they use our weapon systems.

We don’t ship significantly defective software to our customers. Consequently, our quality improvements are simply the relevant improved functionality available to warfighters in support of their mission. Defects, on the other hand, are mainly a consideration in determining whether software is ready to enter a given test phase or release process rather than an indication of quality. When defects are found, we know we have more work to do to isolate and fix them before we can again test and prepare the software for release. Perfect, defect-free, software that doesn’t serve the customer’s strategic needs should never be mistaken for excellent quality software.

Measurement techniques, such as the Defect Leak Matrix and the Rayleigh Curve model (discussed in Section 5), enable developers to focus on understanding defects and capturing them as early in the development cycle as possible. As Humphrey wrote, “The numbers [of defects] really do come down sharply when people understand their mistakes” [CrossTalk 2010]. The benefits of these measurement techniques compounded over several years and several projects: improving developers’ skills, lowering costs, reducing development cycle time, and freeing resources to perform additional desired product quality improvements.

Software development processes improve towards quality excellence not only by reducing or preventing defects from occurring but also by reducing risks of poor performance for the strategic purposes of people performing the processes. Improved process efficiency, reliability, sustainability, ease of performance, and flexibility to accommodate variation are some of the desired strategic consequences of removing process risks. This is why we are driven as an organization to perform development in the context of best practice models, such as the CMMI-DEV. These models set expectations for processes that serve to reduce risks of poor performance. It is not uncommon for a developer in our organization to transform a training briefing on a CMMI Process Area into a briefing on how the development process was actually performed. This practice is especially evident in procedures involving group effort, such as our CAR and DAR procedures.

> *The whole idea was to motivate people to think about how they’re working and how to improve it, and you want to keep it simple.*
>
> Watts. S. Humphrey
> [Humphrey 2009]

4.2 Simple Process Improvements

The power of working with a process improvement model to influence change shouldn't be underestimated. When quality improvement personnel can reveal to a project leader, developer, or to anyone else that their practices aren't meeting the expectations of the process improvement model, it becomes easier to drive and sustain change and to express the kind of change that's needed. When a Pareto analysis shows that the source of poor performance can be traced to the 20% of features causing 80% of the trouble, people can be motivated to focus their improvement effort. People have a fundamental need to improve things. The progress of civilization over time proves this. Histograms, pie charts, percentages are all simple, revealing, and effective in driving change.

Another common opportunity for improvement can be found in policies and procedures that are so professionally written that only a specialist in the practice can understand them. Although these documents may conform to requirements, they present a risk similar to having *no* policies and procedures—confusion, inconsistency, errors, and inefficiency. A simple way to make policies, procedures, templates, tools, and training understandable to the workforce is to use two statistical techniques available in some word processing software applications. The Flesch Reading Ease and the Flesch-Kincaid Grade Level are readability statistics that can be used on most documents. An organization can set targets for reading ease and grade level and can often improve the measured results by simplifying documentation. An indirect benefit of running these readability statistics is that they are initiated through the spelling and grammar checker, which may improve these attributes of the documentation as well.

4.3 The Paladin Process Optimization Model

The Paladin program developed a Paladin Process Optimization model, as shown in Figure 5, to indicate when a circumstance on a project would benefit from entry into a DAR or a CAR process.

When the criteria to initiate a formal DAR process are satisfied, we begin the DAR from a PowerPoint presentation, with the necessary DAR elements present and organized, along with brief explanations of the details that need to be filled in. DARs are often used to select the set of requirements a software version will contain or to select a software application to use from among competing brands. We occasionally use a DAR procedure to perform make or buy decisions. Completed DAR reports include the whole story of a decision event. DAR reports typically include a decision matrix in which the values of alternatives are weighed and evaluated, and the decision selected is justified.

Similarly, when the criteria to initiate a formal CAR are satisfied, we use an Excel template preconfigured as a CAR Activity Workbook. Typically, a software developer initiates a CAR Activity Workbook and recruits a subset of the projects' IPT to complete the effort. CAR Activity Workbooks contain the whole story of an issue: the root cause(s) discovered, the process improvement(s) initiated, and the effects on performance over time, which are reviewed to confirm that process changes were an improvement. As shown in Figure 5, we used elements of Lean Six Sigma combined with the CMMI's CAR and DAR practices to guide readers to established practices that already had resources, such as templates, they could readily use.

We also wanted to illustrate that a CAR or DAR effort could benefit from applying statistical management techniques to discover performance parameters and areas for performance improvement. The model also illustrates how statistically managed processes don't have to live forever. A process can revert to quantitative management of outputs, or to qualitative evaluation, once the performance variation is stable and within a desirable range.

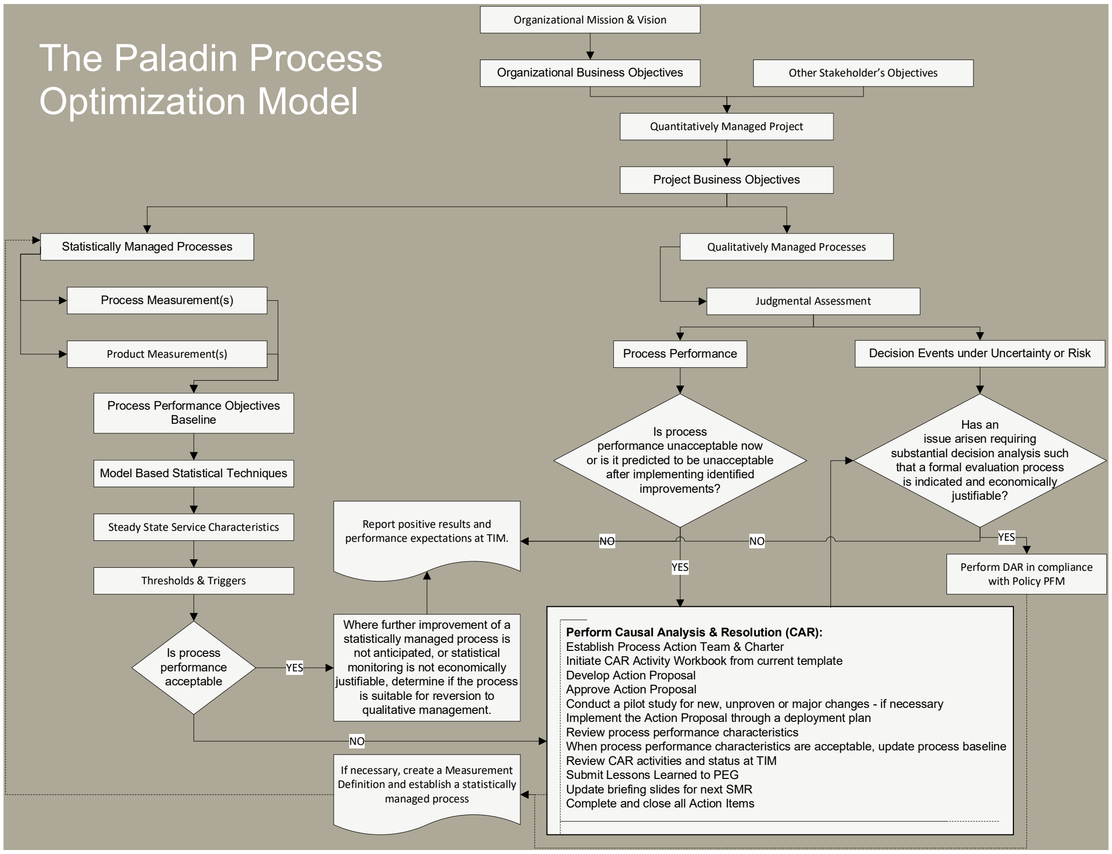


Figure 5: The Paladin Process Optimization Model

Note that the CAR practice in the CMMI evolved to recognize "superior process performance" (unusually good performance of a process) in addition to performance problems. In both cases, CAR is being used on a deviation from quality excellence which, as discussed earlier, is a risk of poor performance. Superior process performance could signal that a process innovation occurred. In this case, someone found a better way to perform a process. If the benefits to stakeholders of this process change truly outweigh any undesirable side effects, the process change should be adopted and shared. As in most innovations, the customers or process stakeholders, must be able to appreciate the beneficial value of changes in performance to sustain and benefit from the innovations and an innovative organizational culture.

4.3.1 Quantitatively Managed Processes

The simpler a quantitative technique is and the clearer the implications of the results are, the better it will be at enabling higher levels of management to understand and influence effort to improve project performance, if necessary. Totals, rates, percentages, and Pareto charts are easily generated and readily understood. These benefits make simpler techniques valuable and prolific.

Some situations warrant more advanced quantitative or statistical techniques, but presenting the results of these studies requires careful planning to clarify the meaning of the results for those not experienced with the measurements.

When measurements are not simple, it's best to describe the conditions for the measurement, what data is or isn't included in the measurement, and the favorable and unfavorable ranges of performance. Current performance should be clearly indicated and, if possible, color coded to indicate good, risky, or deviant performance. If relevant, any trends or corrective actions being taken should be specified for risky or deviant performance.

4.3.2 Statistically Managed Processes

The use of statistical techniques in software development evolved from the use of statistical process control techniques in manufacturing. In manufacturing, for example, a machinist would be given a blueprint for a precision part to be machined to a specific height, width, and depth. Each feature would have a dimension and a tolerance for acceptable variations in size. Statistical Process Control could be conducted for a feature on each of the three axes, x, y, and z, as a representative indicator to determine whether the dimensions on an axis shifted. Under these conditions, conformance to requirements was a useful definition of quality. In the manufacture of hundreds or thousands of identical parts, Statistical Process Control charts provided a way for process operators to see if the parts they were manufacturing showed a trend towards a tolerance limit, thus enabling them to make timely adjustments before defective parts were produced.

Adapting Statistical Process Control from manufacturing to software development has proven challenging because they are different industries; however, statistical management techniques that apply to overall processes have made the transition to software development. Unfortunately, the definition of quality could not make this transition, for the reasons discussed earlier. (Definitions of the elements of quality's conceptual system, according to the Process Enrichment Philosophy, are provided in Appendix A.)

Several statistical techniques may be informative and beneficially influence software development process performance. Some statistical techniques may not satisfy the rigorous prerequisites for mathematical validity. However, this shouldn't preclude use of a measurement if, despite failing to demonstrate mathematical rigor, the technique is still informative and useful to the relevant stakeholders (unless a better technique is identified).

Three statistical techniques stand out as having excellent utility for organizations performing software development: queuing analysis, Earned Value Management (EVM), and the Defect Containment Matrix.

On the Paladin program, we addressed the challenge of optimizing service process efficiency in processing audit questionnaires by using a technique called *queuing analysis*. We adapted queuing analysis, which is more likely to be found in traffic management for toll booths, to our business processes. This novel approach created a statistically managed process that covers the entire software development lifecycle and provided managerially useful statistics. A sample study is summarized below in Section 5.8.

The FCSTD also makes regular use of EVM. An innovation developed by the FCSTD automates the process of calculating EVM statistics from a project schedule. The Defense Acquisition University (DAU) provides an EVM Gold Card (available on a DAU website) summarizing some of the useful statistics, such as cost and schedule variances and estimates at completion. These statistics are predictive and helpful in monitoring and controlling project performance.

We found the Defect Containment Matrix (also called a Defect Leak Matrix) to be an excellent tool for creating a culture focused on defect management in the software development processes. IPTs using Defect Containment Matrices became focused on performing more code reviews and peer reviews of documents early in development activities. This led to significant cost and time savings throughout the software development lifecycle. An example of a Defect Containment Matrix is shown in Section 5.

5 Goals, Objectives, Measurements, and Performance Improvements

In this section, we focus on organizational goals, business- and project-level objectives that were derived from them, and performance measurements. We discuss how measurements, analysis, and innovation led to process performance improvements.

5.1 Common Goals

The FCSTD coordinated with other organizations in the Armament SEC to develop the following top-level organizational goals:

- Improve predictability, consistency, and quality of our services and products.
- Increase productivity and reduce cycle time.
- Maintain and enhance our core competencies.
- Improve customer satisfaction.
- Improve our competitive advantage.

Business objectives designed to support our top-level goals, corresponding supporting processes, and common indicators are tabulated in Table 1 and are discussed in the remainder of this section.

Table 1: Tracing of Organizational Goals to Measurements

Top-level Goals					**Business Objectives**	**Supporting Process**	**Common Indicators**
Improve Predictability, Consistency, and Quality of our Services and Products	**Improve Customer Satisfaction**	**Maintain and Enhance our Core Competencies**	**Increase Productivity & Reduce Cycle Time**	**Improve Our Competitive Advantage**			
X				X	Achieve process compliance of at least 92%.	Organizational project audits	Audit compliance
X	X				Achieve at least 92% defect removal at the time of entry into Record Formal Qualification Testing (FQT) as measured on Rayleigh Curve Model.	Peer review process	Peer review effectiveness (defects detected per unit), defect detection rate
						Defect Discovery through peer reviews	Rayleigh Curve projections of discovery by end of FQT Probability Distribution Function (PDF) Cumulative Distribution Function (CDF)
						Defect containment	Defect Containment Matrix
X	X				Achieve and maintain a cumulative defect containment of at least 83%, otherwise reduce defect leakage by 10% over the current performance baseline.	Defect discovery through peer reviews	Peer review effectiveness (defects detected per unit)
						Defect containment	Defect Containment Matrix
X			X		Reduce estimation variation (planned versus actual) to less than 15%.	Percent of projects complying with estimation	Percent of projects complying with estimation
	X			X	Maintain customer satisfaction survey results above 3.8 (Out of 4) as measured on the CCDC Armaments Center Customer Survey.	Completed customer satisfaction survey	Scores from customer satisfaction surveys
		X	X	X	Maintain at least 90% OSP training compliance within three months of annual OSP Update	Online training	Test results
X	X				Maintain at least 95% organizational asset availability.	Service or hardware availability	Percent asset availability

5.2 Achieve Process Compliance of at Least 92%

Process compliance is a measurement of draft independent internal audits against applicable practices in the CMMI–DEV Version 1.3. Projects with noncompliant practices during the draft audit are required to develop and execute a Corrective Action Plan until 100% compliance is achieved.

Before	After
Projects had significant and valuable training in best practices and methods for software development but often had conflicting strategies, which resulted in successful, yet inconsistent, performance, often accompanied by unnecessary strategic diversions and concomitant inefficiencies and rework.	With the adoption of CMMs about 18 years ago, organizational processes began to evolve in maturity. Currently, performance of Armament SEC projects is regularly assessed internally using the CMMI for Development (currently CMMI-DEV Version 1.3), as shown below. It was found to be efficient at perform incremental audits of a handful of practices at a time. This allows projects to receive feedback and address issues, if necessary, in more manageable sets. Internal audits prepared our organization so effectively that appraisals by external SEI licensed auditors in 2010, 2013, and 2016 not only rated us compliant with the CMMI at Maturity Level 5, they also made no corrective action requests and reported that there were no “Weaknesses” in our organization’s performance. Processes reflecting strategy and accepted best practices are now documented in project plans tailored using common templates which provide ease of implementation and consistency across projects. Regular milestone reviews, quantitative assessments, reporting, and oversight enable projects to be more manageable and successful.

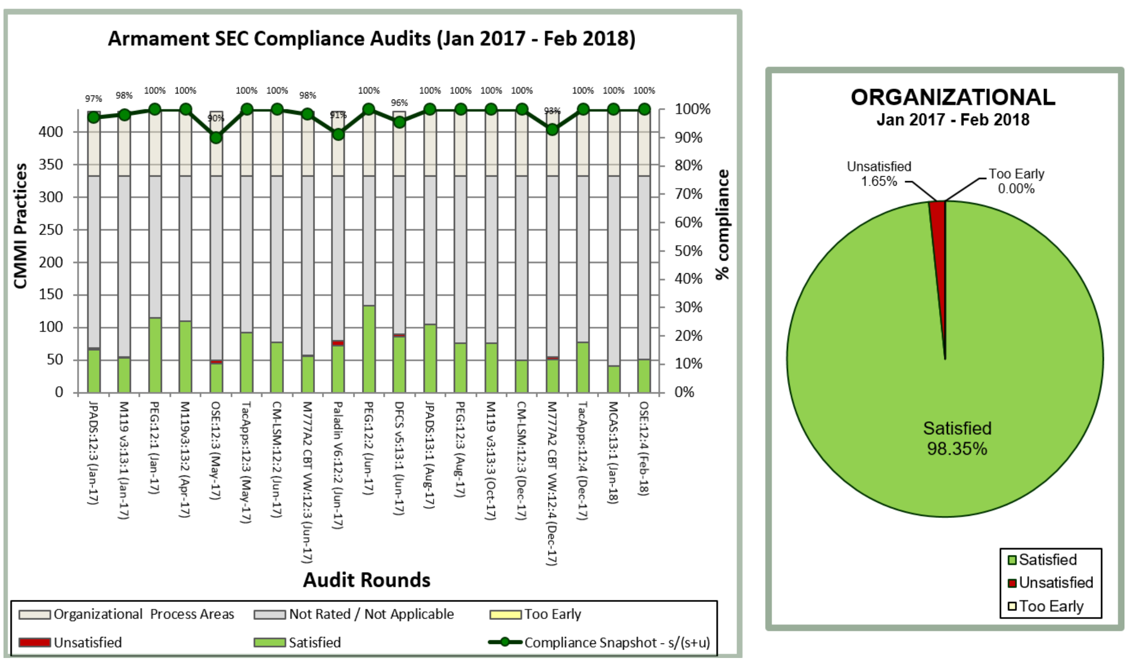


Figure 6: Organizational Process Compliance Audit Results (by Project)

5.3 Achieve at Least 92% Defect Removal at the Time of Entry into Formal Qualification Testing (FQT) as Measured Using the Rayleigh Curve Model

The Rayleigh Curve Model estimates the pattern of the count of defects, as they are discovered, over the course of a project. Rayleigh Curve charts are presented as a Cumulative Distribution Function and a Probability Distribution Function upon which actual defect volume is plotted. The Paladin project data presented below includes defects discovered in software testing and document peer review in all completed project phases. Rayleigh Curve estimates are among the factors considered when deciding to start Record FQT.

Before	**After**
Readiness for FQT and software release depended on subjective assessments that were poorly informed with regard to quantitative measures of software performance.	In addition to milestone meetings and senior management reviews, the FCSTD introduced Test Readiness Reviews (TRR) as a checklist for use prior to FQT. During TRRs projects review Rayleigh Curve charts to confirm that discovery of new defects has diminished to an acceptable volume for entry into FQT. TRRs, including review of Rayleigh Curve chart data, helped reduce the risk of unexpected defect resolution effort in both software and technical documentation. An example of Rayleigh Curve charts is shown below. In the PDF chart there are three spikes in defect volume. The first spike was caused by documentation peer reviews, the second by code and unit testing, and the third by system integration testing. Our custom is to chart only the more significant level 1, 2, and 3 defects (out of 5 levels of defects). Based on the Rayleigh Curve, current defect removal is estimated to be at 98.75% prior to FQT.

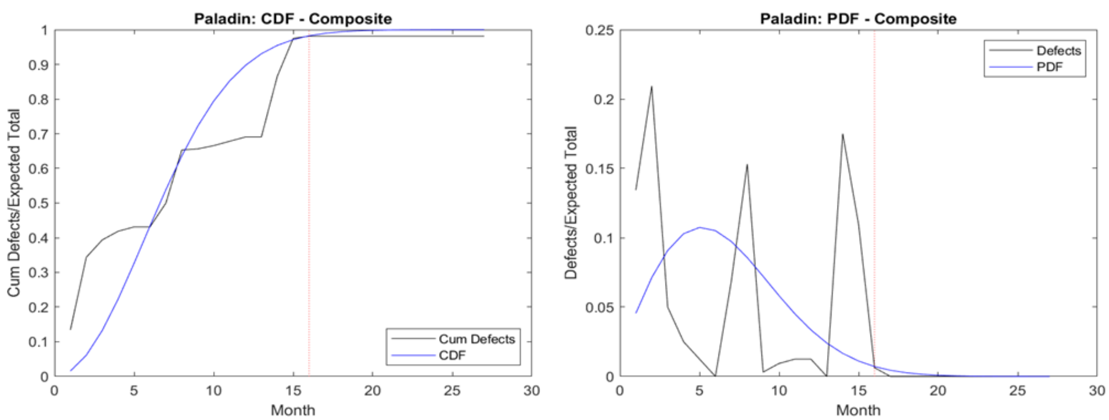
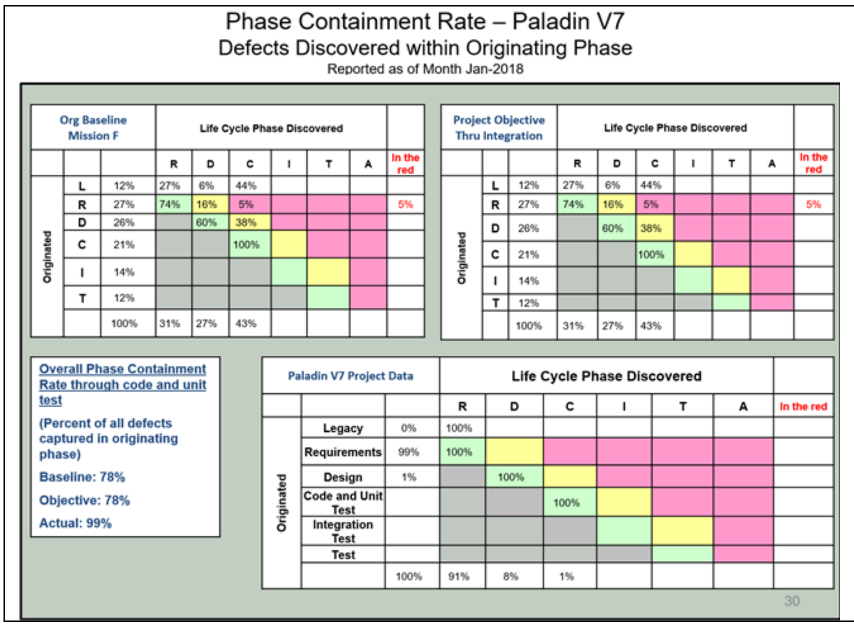


Figure 7: The Rayleigh Curve Model

5.4 Achieve and Maintain a Cumulative Defect Containment of at Least 83%, Otherwise Reduce Defect Leakage by 10% over the Current Performance Baseline

This objective is monitored using a Defect Containment Matrix (DCM). If a project's baseline cumulative defect containment is already 83% or better, the project should strive to continue to reduce defect leakage by 10% (or by a percentage set by the project). Defect containment baselines are developed based on actual project performance and they are reviewed annually. This measurement is used to prevent defects from persisting from their phase of origin to subsequent phases, where they would be significantly costlier and more time consuming to address.

Before	After
Special attention was not given to the stage at which defects were found; however, software developers had to meet the requirement of no level 1 or 2 defects (on a 5-level scale) prior to software release.	Developers planned for code evaluations or peer reviews at the earliest feasible time in order to detect and address defects early. Figures 8 and 9 show how the cost of resolving a project's defects, documented in Problem Change Reports (PCRs), has dropped by almost $2 million per project over 15 years and continues to decline on projects with requirements (RSLs) requiring similar effort in the Paladin program. On the current Paladin project, the return on investment for peer reviews is about 15.5:1, or about $38,600 per peer review. Favorable improvements in efficiency, which create the ability to integrate additional desired functionality, have been shown throughout the FCSTD for projects utilizing the DCM.



This DCM was documented in Paladin V7's Code & Unit Test (C) phase. Note that in the baseline's Requirements (R) row, 5% of the requirements defects are usually not discovered in the Requirements or Design (D) phases. Thus, at 100% containment, Paladin V7 is doing much better than the baseline--for now.

Figure 8: A Defect Containment Matrix (DCM)

Project Version	Start Date	RSL Count	PCR Count per Project	PCRs per RSL	Cost to Resolve PCRs
Paladin (baseline project)	2000	27	660	24.44	$3,894,000
Paladin V2	2004	17	591	34.76	$3,486,900
Paladin V3	2006	23	541	23.52	$3,191,900
Paladin V5	2009	13	396	30.46	$2,336,400
Paladin V6	2015	19	324	17.05	$1,911,600

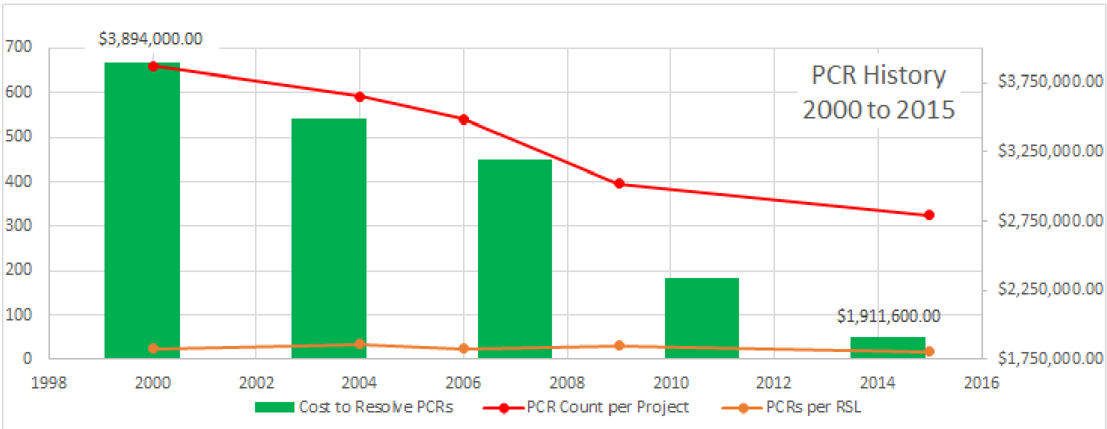


Figure 9: Effects on PCR Resolution Cost due to PCR Management

Because the V7 project is doing much better than previous Paladin software versions, we initiated a CAR event to assess the process improvements that were made to determine whether there were beneficial process changes that could be used going forward. We decided that in the next Paladin project we will include Level 4 defects in tabulation of the DCM; currently, we include only levels 1, 2, and 3. This process change may extend the benefits we gained for Level 1, 2, and 3 defects to level 4 defects. Once an improvement can be confirmed, the change will be shared with other projects via a CAR Activity Workbook and a “Lessons Learned” report that we will post to the PAL.

5.5 Reduce Estimation Variation (Planned Versus Actual) to Less than 15%

This objective is measured by projects using EVM statistics. The Defense Acquisition University produces an EVM Gold Card providing the formulas for EVM statistics. Several EVM statistics have proven useful at the project level. The Cost Performance Index (CPI) indicates how well budgeted expenditures match actual costs. The Schedule Performance Index (SPI) tracks how well the amount of work done matches the scheduled amount of work. An SPI or CPI greater than 1 is a favorable indication. An SPI or CPI less than 1 is an unfavorable indication.

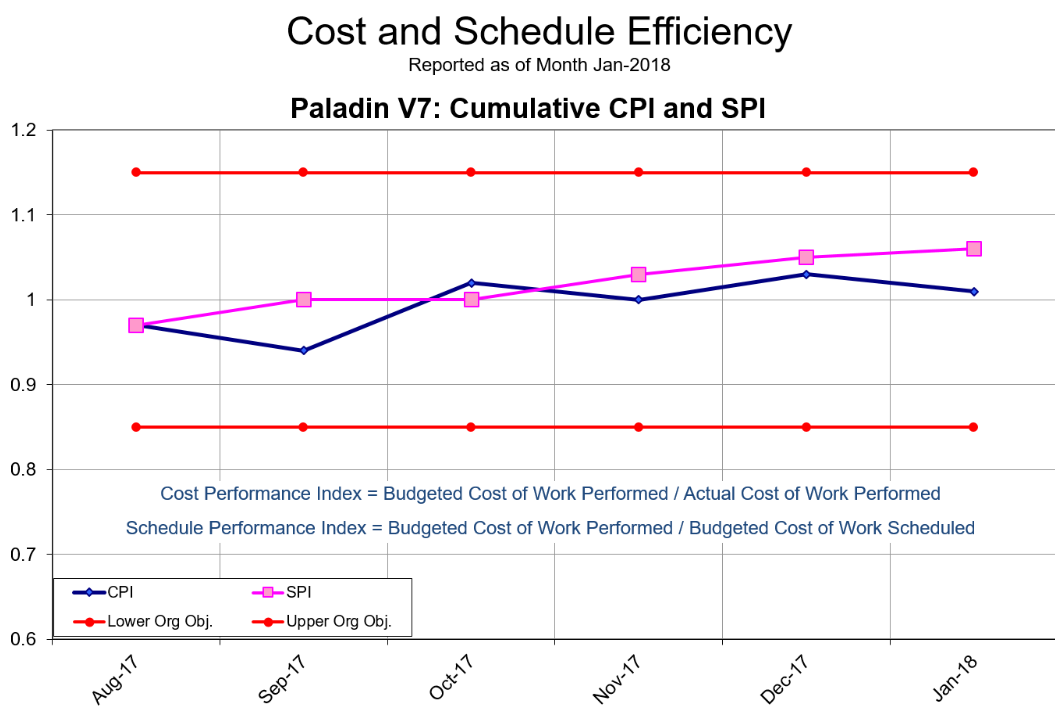


Figure 10: Statistical Process Control (SPC) Chart for Cost and Schedule Performance

Before	After
Budgets were established using heuristics based on historical assumptions about employee count, cost, availability, and effort.	Schedules are regularly maintained in Microsoft Project along with basic task and resource details. The MS Project records serve as the data source used to calculate EVM statistics as well as to track project progress and evolving critical paths. Regular monitoring and reporting of EVM statistics enables IPTs to improve efficiency in cost and task completion by applying resources effectively, where needed, and in a timely manner.

5.6 Maintain Customer Satisfaction Survey Results above 3.8 (Out of 4) as Measured on the CCDC Armaments Center Customer Survey

This objective is measured on the basis of quarterly Customer Rating Data.

Before	After
The assumption that customers were satisfied because they returned for business drove contentment with the perceived level of customer satisfaction.	Returning customers are still a strong consideration in customer satisfaction; however, the use of customer surveys provided insight about each program's competitiveness and desirability as a source of necessary products and services. The surveys also drove improved focus on quality improvement. At the project level, a technique called a User Jury was developed to enable project personnel to interact directly with warfighters as they evaluated the performance of newly released software intensive systems. As the voice of the customer, warfighter, product and program manager's comments could become new requirements for the current or a subsequent software version.

5.7 Maintain at Least 90% OSP Training Compliance within Three Months of Each Annual OSP Update

The incentive for this objective is to maintain and enhance Organizational Standard Process (OSP) institutionalization that provides a common understanding of policies and procedures.

Before	After
Personnel were well educated and aware of contemporary processes and procedures but there was little ability to communicate or enforce common forms of performance of systems engineering practices across the organization.	The FCSTD's OSP, consisting of policies and procedures enhanced by standard templates, tools, and training are all heavily influenced by the CMMI-DEV. Training in the OSP helps to institutionalize policy and process improvements and enables projects to operate consistently in the manner of best practices. Each employee must achieve a passing score on an OSP quiz to be credited with OSP training compliance.

5.8 Maintain at Least 95% Organizational Asset Availability

A tailored version of this objective was set for the Paladin Program in which we initially used a queuing study. Our goal was to establish a service level that optimized service process efficiency of our internal auditing process based on demand for service, process capability, economic analysis, and project needs.

Before	After
Process audits using older CMMI models could be done by a single server (auditor) in roughly 14 days.	Queuing analysis is a very useful statistically managed process because it provides managers many useful, easy-to-understand statistics. Table 2 provides queue statistics for the processes relating to receiving requests for process audits. Requests for audits arrived almost randomly and were for different projects. The service time varied by the extent of preparedness of each project. We considered this an M/M/1 (in Kendall notation) queuing system: Markov (M) (exponentially distributed) inter-arrival and service times with a single server and a single stage. The M/M/1 model is pictured in Figure 11 and the results of our queuing study are presented in Table 2. For organizations seeking CMMI compliance, the queuing model is an excellent way to satisfy many practices at once. Analysis of service levels continues to enable process optimization, and it supports the use of heuristics to staff audits appropriately when the queue becomes congested. Understanding process performance characteristics has worked to eliminate late deliveries of completed audits and also has relieved some of the time pressures for audit personnel.

Table 2: Expected Process Performance Characteristics with a Single Server Queuing System

Characteristic	Actual Value	Threshold	Units
Arrival Rate (λ)	0.023715	>= 00.04	Audits/ Workday
Inter-arrival time ($1/\lambda$)	42.166667	<= 25	Workdays
Service Rate (μ)	0.094340	<= 00.05	Audits/ Workday
Service Time ($1/\mu$)	10.5999999	>= 20.00	Workdays
Server Utilization (ρ)	0.251383 * 100 = 25	>= 35	%
Length in system (L_S)	0.335797	>= 00.60	Audits
Length in queue (L_Q)	0.084414	>= 00.12	Audits
Length in busy queue (L_B)	0.335797	>= 00.60	Audits
Wait in system (Cycle Time) (W_S)	14.159451	>= 25	Workdays /Audit
Wait in queue (W_Q)	3.559451	>= 6	Workdays /Audit
Wait in busy queue (W_B)	14.159451	>= 25	Workdays /Audit
Variance, Std-Dev., of length in system	0.449, 0.66974	>= 00.60, >= 00.90	
Variance, Std-Dev., of wait in system	200, 14.159	>= 275, >= 25	
Probability of no arrivals to system (P_0)	0.748617 * 100 = 75	<= 40	%
Probability of busy system (P_B)	0.251383 * 100 = 25	>= 45	%

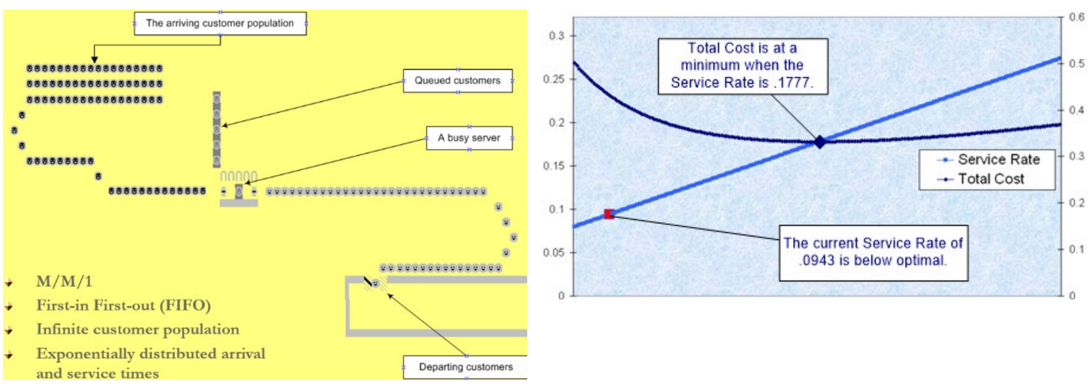


Figure 11: Economic Optimization of an M/M/1 Queuing System

5.9 Organizational Performance

Indications that the FCSTD's process improvement work met our goals and had a positive effect are evident in measurements of our organizational capabilities:

- Monthly Task Completion, compared to estimates, is above 85%.
- EVM statistics of CPI and SPI show variation (planned versus actual) is less than 15%.
- Software development projects maintain cumulative defect containment of at least 83%.
- Software development projects achieve at least 92% defect removal at the time of entry into FQT as measured with the Rayleigh Curve Model.
- Support projects maintain at least 95% organizational asset availability.
- Assessed projects achieve preliminary process compliance of at least 92%. Audits are not complete until the project achieves 100% process compliance through corrective action, if necessary.
- Organizational customer satisfaction survey ratings are maintained above 3.8 (on a 1 to 4 scale).

- 90% of personnel receive Organizational Standard Process (OSP) training within three months of annual OSP updates.

Most new projects that maintain CMMI ML 5 tend to achieve significantly better performance than these organizational minimum expectations. Mr. Steven Liss, Director of the ASEC, said in an email to the author on March 19, 2019 that our measured performance results show “the strength of our Organizational Standard Processes and the dedication of all of our team members toward the goal of continuous and systematic improvement. It is the result of years of building a culture of software excellence.”

6 Coascendance

The issue is how we really can learn as a society to work together to do really effective very high quality creative work in a way that will help advance mankind.

Watts S. Humphrey
[National Science and Technology
Medals Foundation 2015]

The FCSTD's collaboration with warfighters, the U.S. Army, scientists and engineers, industry and academia, and communities of software-intensive systems developers on the common cause of creating strategically excellent products and services, with a workforce that is continually learning and growing and creating new sciences as well as innovations in technology that support our national interests, is *coascendant*. It's a professional experience we've been fortunate to experience.

6.1 Stakeholder Value

6.1.1 Warfighters

Irvin Spencer, a systems engineer with the FCSTD, served in the U.S. Army as a Sergeant First Class from 1982 to 2004. Mr. Spencer served on a howitzer crew operating the M109A5 howitzer during the Gulf War in Operation Desert Shield and in combat during Operation Desert Storm. After the Gulf war, in 1994, the upgraded M109A6 Paladin howitzer (now configured with a digital fire control system) was fielded to the army unit in which Mr. Spencer was serving. The software in the new Paladin howitzer introduced dramatic changes. In an interview with the author on March 6, 2019, Mr. Spencer observed, "It was faster to do everything." The computer display made it easy to emplace the howitzer and prepare a firing mission. Automated calculation processes made the howitzer safer by eliminating human error in targeting calculations. Commands that used to be communicated via radio were now appearing on a computer display. Software gave Paladin crews the ability to compute their own firing solutions independent of a Fire Direction Center, and the firing solutions became more accurate as more factors could be considered. Software driven processes brought speed, accuracy, and ease of use to the army's howitzers. Mr. Spencer brought the FCSTD insight from the field to ensure that our developers create the functionality that provides warfighters a battlefield edge.

One of the things humans do best is integrate technology in our strategies, and we often do so to improve performance beyond the state of the art. Henry Nguyen is a software engineer on the FCSTD's Extended Range Cannon Artillery (ERCA) project – part of "the Army's number one modernization priority" [U.S. Army 2019]. Mr. Nguyen said of his work on ERCA "Our new radar sensor projectile tracking system will greatly increase lethality by improving the accuracy and targeting speed for enemy positions." An interesting aspect of Mr. Nguyen's work is that he and the ERCA team were able to reuse code from a years-old program because the code was properly commented and maintained in a configuration management system. Strategically, the ERCA program will create improved capabilities for the Paladin system and related weapon platforms "through a combination of an increased range, increased rate of fire, increased lethality, increased reliability, and a greater survivability" [U.S. Army 2019].

The incentives or value in products and services warfighters receive on the field are the product of great commitment and the ability to conceptualize and create strategic quality in these products and services. When a development organization is efficient enough to reliably create desirable products and services and promptly respond to urgent fielding requests, the organizational system and its development processes are a strong link in the strategy for mission success.

6.1.2 The U.S. Army

If you pit a good performer against a bad system, the system will win almost every time.

Rummler and Brache
[Rummler 2013]

It often seems as though if there's one best way to develop a weapon system, the Army will try to find it or create it. The many complementary process improvement approaches in the Enterprise Excellence model and the sponsorship of Watts Humphrey's CMMI, reveal a motivated Army senior management with intentions to continually improve and to institutionalize consistent best practices. It takes a great system to enable talented people to create great products and services.

6.1.3 Scientists and Engineers

Process improvement effort that is culturally and structurally supported, and independently assessed against a process maturity model, promotes an environment in which developers gain a deep and useful understanding of industry best practices. Regular offerings in Defense Acquisition University courses, the QESA directorate's courses in Lean Six Sigma, Organizational Standard Process Training (delivered to project personnel by Armament SEC managers), and Armament Graduate School degree programs taught by qualified CCDC Armament Center scientists and engineers, transfer unique aspects of armament technologies to students and create a culture among system developers that is strong in the capabilities necessary to perform process improvements.

In addition to winning the 2018 IEEE Computer Society/Software Engineering Institute Watts S. Humphrey Software Process Achievement Award, the FCSTD's progressive growth in software development process maturity, as part of the Armament SEC, gave rise to an organizational culture that supported several recognized achievements:

- 2016: sole U.S. government organization to assess at ML 5 using the CMMI-DEV V1.3
- 2013: sole U.S. government organization to assess three times at CMMI ML 5
- 2010: first U.S. government organization to achieve ML 5 in CMMI-DEV V1.2
- 2006: sole DoD organization to achieve CMMI ML 5 in Systems Engineering, Software Engineering, and Supplier Sourcing (CMMI-SE/SW/SS)
- 2002: among the world's first organizations to achieve CMMI ML3 in CMMI-SE/SW/SS

6.1.4 Industry and Academia

The FCSTD's work with universities often involves developing or exploiting state-of-the-art or newly invented technologies. At least two FCSTD divisions are currently performing classified contracts with universities. The benefit to universities and also to our industry partners is the ability to share our research labs, research personnel, and patented technology to create research, products, and processes that advance the state of the art and give our warfighters competitive advantages.

6.1.5 Communities of Software-Intensive-Systems Developers

Planning to develop weapon systems across multiple organizations enables independent teams to build products that are interoperable and work together to provide necessary system capabilities. The FCSTD,

> *supporting the respective Program Management Offices, has digitized all of the Army's gun-based indirect fire systems including M109A6 Paladin self-propelled and the M777A1 and M119A3 towed howitzers; dismounted 120mm mortars, M1064 mortar platforms and M577 fire direction center and STRYKER mortar carrier variants... In addition to advantages in increased weapon accuracy, responsiveness and survivability, these software-intensive fire control systems have also facilitated the incorporation of smart munitions within the fire control systems such as the artillery's Excalibur and precision guidance kit (PGK) munitions, the mortar's advanced precision mortar initiative (APMI) munition and the tank advanced multipurpose (AMP) round. Additionally, since the efforts are performed in house with government owned intellectual property, significant advantages result from hardware and software commonality and the associated cost, schedule and sustainment benefits [U.S. Army 2014].*

The FCSTD's process improvements are an essential element in our organization's drive to consistently create and support state-of-the-art, effective, reliable, easy-to-use, defect free, software-intensive weapon systems and services for the warfighters who depend on them to attain mission success.

> *I just wanted to tell you that the MCV B [Stryker—M1129 Mortar Carrier Vehicle, version B] is doing a great job here. We recently shot 17 rounds of 120mm HE [high explosive] in close proximity to our own troops. The MFCS was dead on and we took out two buildings that were housing two enemy sniper teams. I wanted to thank you again for such an accurate mortar system ….*
>
> [name redacted], Baghdad, Iraq

The success of our process improvement work, initially with a handful of projects, and now shared by over a dozen projects, continues to attract interest throughout the FCSTD and among our customers and with other DoD components. The FCSTD continues to implement the latest customer requirements through our development processes to create effective, state-of-the-art products and services that dominate the battlefield. The processes that were once a daunting challenge to implement are now simply described as "how we do business."

Appendix A Abbreviations and Definitions

Table 3: Organizational Abbreviations

Abbreviation	Full Term
AGS	U.S. Army Armament Graduate School
ASEC	Armament Software Engineering Center
ATSD	Automated Test Systems Division
CCDC Armaments Center	U.S. Army Combat Capabilities Development Command Armaments Center
DAU	Defense Acquisition University
FCSTD	Fire Control Systems and Technology Directorate
ESIC	CCDC Armaments Center’s Enterprise and Systems Integration Center
IEEE	Formerly the Institute of Electrical and Electronics Engineers, this organization now simply operates under the name IEEE (I triple E)
PEG	Process Engineering Group
QESA	Quality Engineering and System Assurance directorate
SEI	Software Engineering Institute
TEPIT	Tactical Effects, Protection, and Interactive Technologies directorate
WSEC	CCDC Armament Center’s Weapons and Software Engineering Center

Table 4: Definitions of Key Concepts in the Process Enrichment Philosophy

Concept	Definition
Coascendant / Coascendance	A concept that describes the condition in which stakeholders in great creative endeavors are attracted to common strategic purposes, work to drive out risks of poor performance wherever they appear, and attain their respective valued incentives.
Quality	Quality is the ability of performance, in each Theme of Performance, to enact a strategy. Quality's six Themes of Performance are a hierarchical model that can be used to comprehensively describe the strategic quality of any thing or idea, including products, services, organizations, processes, and projects. Quality's six Themes of Performance are the Acceptance, Efficacy, Sustainment, Optimization, Process Enrichment, and World-class Themes of Performance. The hierarchical construct can be understood through an example. A pen that is acceptable can write, a pen that is efficacious has permanent ink that dries fast, a pen that is sustainable can be refilled, a pen that is optimal has a fine point (assuming that the user likes a fine point), a pen that satisfies the Process Enrichment Theme of Performance is comfortable for the customer to use, a pen that is world-class can be used beneficially anywhere the customer intends to use it.
Quality Excellence	Quality excellence is the absence of the risk of poor performance in each Theme of Performance for a valued strategy. In this construct, considering the customer's strategy, and what the customer is ready, willing, and able to pay for, and what is profitable for the producer to provide, creates a target market that defines performance at the level of quality excellence. Any deviation from quality excellence, as is created by an innovation or by the absence of desired capabilities, creates a risk of poor performance. For example, the benefits of an innovation may not be adequately understood by the customer, which creates a risk that the innovation may make the product or service undesirable. A deviation from quality excellence with poor performance caused by missing desired features or inferior materials is a risk because the product or service may have, or the customer may perceive that it has, diminished ability to reliably perform its strategy.
Risk	Risk is an influence affecting strategy caused by an incentive or condition that inhibits transformation to quality excellence. An incentive that inhibits transformation to quality excellence could be, for example, the profit to a supplier of using a cheaper or a more poorly developed resource than would be warranted at the level of quality excellence. The other cause of risk is a condition that a strategist may or may not be able to prevent. For example, if the milk in your refrigerator is on its expiration date, and you plan to enjoy milk and cereal, even though the expiring milk conforms to the requirements for still being good, to avoid the condition of risk, and to attain quality excellence in the ability to attain your incentive of an enjoyable breakfast, you may be influenced to alter your strategy and go out and buy a fresher container of milk.

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13. **ABSTRACT (MAXIMUM 200 WORDS)**

This report presents a systemic approach to software development process improvement and its impact for the U.S. Army Combat Capabilities Development Command Armaments Center, Fire Control Systems and Technology Directorate (FCSTD) and its stakeholders. The report presents the best practices that improved the FCSTD's ability to meet organizational goals, primarily in the context of the Capability Maturity Model Integration (CMMI). This process improvement effort extended to dozens of projects and earned the FCSTD a CMMI Maturity Level 5. The report discusses how the FCSTED defined strategy, quality, and risk as interrelated elements of a conceptual system and used conceptualizing quality as a thought process to drive product and service design decisions. It also discusses how the use of tools, such as Defect Leak Matrices and Rayleigh Curve Models, drove cost savings, up to nearly $2 million on each Paladin project, and similarly improved costs and efficiency across many projects, enabling the FCSTD to consistently deliver new or improved functionality in less time. Also discussed is how the FCSTD effort to improve software development processes was coupled with significant effort to improve the quality of software-intensive armament systems for the U.S. Army and for allied armed forces worldwide.

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