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Improved Forecasting of Defense Acquisition Program Performance Using Digital Twin Models of a Revenue Centric Versus Cost Centered Approach (Enhanced Earned Value Management (E2VM))

COL (Ret., USA) Raymond Jones—is the Chair and Professor of Practice in Defense Program Management in the Department of Defense Management at the Naval Postgraduate School (NPS). Prior to NPS, he was the CEO and co-founder of a strategic consulting company which focused on helping high technology firms improve their innovation strategies. He served as the Deputy Program Executive Officer for the Joint Tactical Radio System (JTRS) and managed three major programs in the DoD. In addition to multiple operational assignments in combat aviation units, he is a 1995 graduate of the U.S. Naval Test Pilot School and a 1983 graduate of the United States Military Academy. He has a Bachelor of Science degree in Aerospace Engineering, a Master of Science degree in Aeronautical Engineering, and a master's in business administration, and is a distinguished graduate with a master's degree in National Resource Strategy from the Industrial College of the Armed Forces.

Abstract

This paper represents a new approach to defense acquisition program forecasting during the development phase of the program life cycle. It will be the first of three research papers that will attempt to improve insight into how a program performs and will offer a method by which future programs offices will be able to simulate their program before beginning in order to develop an optimal acquisition strategy. Specifically, the purpose of this research is to explore if a digital twin of the defense acquisition development phase of an acquisition program of record can enhance a program manager's decision-making ability by revealing unforeseen patterns in program behavior. Additionally, this research will demonstrate a new way of measuring value and return on investment of a defense program of record, to provide decision-makers with an alternative to traditional methods of decision-making that are based upon budget and cost comparisons. This paper represents the initial research proposal and method, which will set the conditions for exploration of new theory and methods of how complex programs could be planned and executed in the future.

Introduction

Background

The Defense Acquisition process is complex and challenging and involves the acquisition of goods and services for the Department of Defense (DoD). The foundation of the DoD Acquisition process is to generate knowledge that is relevant to the development of operationally relevant goods and services. It is fundamentally a risk reduction process that follows a prescribed life cycle that transitions technological insight and development from a low level of maturity to a level sufficient to transition to production and delivery to the customer. The acquisition process involves numerous steps, including research and development, testing and evaluation, production, and sustainment. Despite the importance of the defense acquisition process, it faces several challenges that can impact its effectiveness and efficiency. One of the most significant challenges in the defense acquisition process is transitioning critical technology from a technology base to a program of record organization that has the authorities and resources to develop technologies into viable operational capability. This transition is commonly referred to crossing the "valley of death."

The "valley of death" is a term used to describe the gap between research and development and the commercialization of new technologies. This gap can be particularly challenging in the defense acquisition industry, where the development of new technologies is critical to the success of military operations. Developing new technologies can be expensive, and there is no guarantee that the technology will be successful. This can make it difficult for companies to secure funding for research and development, which can slow the pace of innovation.

The acquisition process can also take years to complete, and it involves numerous stakeholders, including government agencies, contractors, and military services. This lengthy process can result in delays, cost overruns, and the delivery of outdated technology. Crossing the valley of death in defense acquisition is a complex and challenging problem that requires collaboration between stakeholders, increased funding for research and development, and a streamlined acquisition process. Addressing these challenges will require innovative solutions and a willingness to work together to ensure that new technologies are developed and deployed to support military operations.

DoD programs typically follow a prescribed path in which technology solutions are vetted through a complex series of administrative processes. Once budgets are set and vendors are identified, it is extremely difficult for a program manager to stray from the prescribed acquisition strategy, reflecting little agility to adapt to program volatility and integrate new innovative solutions outside of the predetermined acquisition baseline. Additionally, current forecasting models in the management of defense capability solutions provide the program manager limited insight into whether current planning will be successful as the program transitions through the Defense Management program life cycle.

Making decisions in this highly complex and restrictive environment requires new ways of understanding the data and information flowing through the development life-cycle process. Decision-makers need to better understand how knowledge is created and how to make choices among an endless set of options. Knowledge-making is the process of creating new knowledge or insights through research, analysis, and critical thinking. It involves the synthesis of existing knowledge, the identification of gaps in knowledge, and the development of new ideas and perspectives (Choo & Bontis, 2002). The creation of knowledge is useful for improved decision-making before a program under development encounters critical problems. Information networks facilitate the flow of knowledge and communication between individuals and groups, creating the opportunity for choices and feedback within the development life cycle of the defense acquisition process.

The defense acquisition framework can be viewed as an information network with stakeholders as nodes and communication channels as edges. The stakeholders in the network include the DoD, contractors, suppliers, and other entities involved in the acquisition process. Viewing the defense acquisition process as an information network allows stakeholders to identify bottlenecks and inefficiencies in the process. By analyzing the flow of information and communication between discrete events in the process, stakeholders can identify areas where communication paths are overloaded and become inefficient relative to the planned strategy (Scott et al., 2013). Specifically, Scott et al. (2013) address the challenges in which multiple stakeholders allocate tasks for multiple decision criteria while attempting to satisfy multiple groups, confounding the decision-making process. Viewing the defense acquisition process as a complex network of information flow that also represents increasing value in the form of work, requires consideration of multiple conflicting criteria and the consideration of uncertainty.

The theory of information networks in an organization is based on the concept of social network theory and involves understanding of how individuals and groups are connected through communication channels and information flows (Wasserman & Faust, 1994). Additionally, information networks provide a framework by which a more in-depth understanding of decision-making can be understood. This is the foundation upon which this research derives its critical importance. By developing a virtual replica of the defense acquisition environment and the integration and application of decision theory and tools, it may be possible to forecast program management performance of a program as it moves through the development phase of the defense acquisition life cycle.

The development phase in the defense acquisition life cycle is a period in which the designed system or capability is transformed into a tangible and operational product. Critical decisions are made during this phase that influence how well the system is being managed and whether the process is being optimized to provide as much value as possible in results of the management decisions being made. This phase follows the initial stages of concept exploration and technology development and precedes the production and deployment phases. The development phase involves a series of activities, milestones, and assessments to ensure that the system meets the established requirements defined by the user community and is ready for subsequent production.

Not since Frederick Taylor has there been any significant change in how management and more specifically program management change the way programs are planned and executed. Taylor's work set the conditions upon which modern day development and production programs are structured and conducted. Taylor established standardization and process in the program management field that are still in use today (Taylor, 1911). While these practices provide a good foundation for planning and monitoring a program's process relative to a baseline, they do not provide a complete insight into why programs tend to go astray. In effect, modern day practices are still regressive in nature and provide little opportunity for informed prediction. There is a distinct lack of clarity in program performance in the vast sea of data and information regarding how programs are performing and more importantly, how they will perform in the future. New methods and metrics need to be discovered to begin to address this challenge.

Research Problem

The problem is that the DoD does not have a reliable and measurable forecasting process with which to determine whether capital investment in programs under development is being optimized to produce the desired output within program performance constraints. The DoD focuses on traditional cost theory as a principal driver for assessing program performance, which is exacerbated by historically rigid accounting processes. Current methods rely on the assumption that program cost and schedule can be estimated based upon predetermined frameworks (GAO, 2009). These frameworks rely on historical performance of programs as well as parametric models that presume to predict the complexity of a program under development with regard to its impact on cost and schedule. There is currently no capability that allows decision-makers to simulate future performance of a program under consideration, resulting in best effort analysis based upon subject matter expertise and past performance. Since the DoD has no way to simulate a program of record prior to its inception, using cost predictions relative to expected performance is the best method currently available to program managers.

The purpose of this research is to explore if a digital twin of the defense acquisition development phase of an acquisition program of record can enhance a program manager's decision-making ability by revealing unforeseen patterns in program behavior. A digital twin is a virtual representation of an object, system, or process that spans its life cycle. Digital twins are often used to simulate the "real world," using machine learning, artificial intelligence, and reasoning to improve decision-making (IBM, 2023).

This leads us to the following hypothesis:

> H1: A virtual replica with an integrated artificial intelligence tool has the potential to improve decision-making leading to improved efficiency and cost effectiveness of defense acquisition programs during the development phase of the life cycle.

Using a digital twin of the defense acquisition process offers the potential to provide valuable insight and knowledge that can help improve the acquisition process. For example, a virtual replica of the defense acquisition process can reveal patterns of behavior and information exchange that will allow decision-makers to test different scenarios and strategies without impacting the physical object or system. This will help decision-makers understand the potential outcomes of different decisions allowing for more informed choices. Identification of bottlenecks and inefficiencies will help stakeholders to optimize processes, reduce costs, and improve efficiency. Additionally, patterns not well understood in process documents will facilitate a better understanding of risks and opportunities more effectively.

A virtual replica of the defense acquisition process can simulate the impact of changes in the process and will provide a simulation environment for the actual environment that will reveal potential choke points and alternate paths and courses of action for the decision-maker. This can help stakeholders to understand the potential impact of changes before they are implemented, reducing the risk of unintended consequences and improve decision-making potential. This leads us to our second hypothesis:

> H2: A virtual replica with will provide more certainty in a defense program under development and reduce overall risk in program development, thereby increasing the probability that a program will more closely meet its cost and schedule objectives.

Using a virtual replica of the defense acquisition process can provide valuable insights and knowledge that can help improve the acquisition process. Improved decision-making, identification of bottlenecks and inefficiencies, increased collaboration, improved risk management, and a better understanding of the impact of changes are just some of the knowledge that can be gained by using a digital twin of the defense acquisition process.

Research Objectives

There are three primary research objectives for this dissertation.

1. Develop a conceptual framework for integrating virtual replica technology into the defense acquisition life cycle.
2. Investigate the potential of virtual replicas to improve decision-making in the defense acquisition process.
3. Analyze the impact of virtual replicas on decision-making risk assessment and overall efficiency in defense acquisition.

Significance of the Study

The expected outcomes of this dissertation are to provide a comprehensive understanding of the use of digital twins in a Defense Acquisition Program of Record. The study aims to identify the potential benefits of using a digital twin in this context, including improved decision-making, increased efficiency, reduced costs, and the impact of varying the current acquisition pathways to insert critical technologies after a POR is started. This study is important because there is currently no useful simulation environment in the defense acquisition process that allows program managers to virtually execute their programs and observe them under conditions of ambiguity and change. By allowing the PM to simulate program volatility before a program has even begun, decisions can be made prior to program disruption improving the probability of program success. This study will contribute to the fields of decision-making, program management, and socio-technical theory.

Literature Review

This literature review serves as the foundation upon which to extend existing theory in program management. The intersection between decision-making, program management, and information theory is critical in shaping existing paradigm and challenging the status quo, from which little progress has been made regarding new theoretical constructs and knowledge. A detailed study and analysis of the literature across different, yet complementary theories will play a pivotal role in establishing the existing knowledge landscape, identifying gaps, and positioning the research within the broader academic discourse.

The strategy that will be used for this dissertation study will be to organize and categorize the extensive body of knowledge into meaningful categories. The literature will help to address gaps discovered during model development and experimentation and help to contribute to the field of program management and decision-making through new frameworks. To extend knowledge and create new frameworks from which to improve our insight in program management and decision-making, we will need to examine complimentary theories and processes that intersect the dominant field we are studying. While the literature reviewed for this proposal is simply an initial review, it provides the foundation for a more in-depth study of the significant body of knowledge related to this research. I will scope the literature around four key theories that will be augmented with significant literature from the practice of defense acquisition and program management.

The four theories that are most relevant to better understanding the problem at hand are *decision support systems, socio-technical behavior, economic value, and technology trust*. These theories are intertwined in their relevance to being able extend our knowledge on how decisions are made in a complex management process and perhaps offer insight into the path forward to creating decision support and forecasting tools for program management. Technology trust theory is critical in gaining a sense of understanding into the viability of the recommendation and ultimate adoption of new concepts.

Defense Acquisition Programs

We begin with setting the conditions for this research by examining the current defense acquisition system and how the process is currently managed. It is important to fully understand the nature of how development programs are managed and what methods a manager uses to make decisions and attempt to predict future outcomes. This will inform the research strategy and allow us to examine the relevant theories from which to develop the research design.

Defense acquisition programs constitute complex initiatives involving the development, procurement, and management of military capabilities (Fox, 2016; Sullivan, 2017). These programs are frequently characterized by intricacies, uncertainties, and the necessity for effective decision-making throughout their life cycles (Department of Defense [DoD], 2017). Traditional program management approaches often encounter challenges in addressing these complexities, prompting a need for innovative solutions to enhance decision-making processes. The Defense Acquisition process plays a critical role in ensuring that the U.S. Department of Defense (DoD) acquires and delivers effective and efficient weapon systems and capabilities. Predicting performance in this complex and multifaceted process is of paramount importance to avoid costly delays, budget overruns, and failures in delivering the necessary military capabilities.

The defense acquisition environment is characterized by its multifaceted nature, influenced by political, economic, technological, and social factors. Geopolitical considerations, such as regional tensions and international relations, play a pivotal role in shaping defense priorities (Fox, 2016). Additionally, the rapid pace of technological advancements introduces both opportunities and challenges, necessitating constant adaptation in defense acquisition strategies (Elkins, 2019). Budgetary constraints further compound the complexities, requiring efficient resource allocation and strategic decision-making (DoD, 2017) within a complex set of regulatory and statutory constraints.

Stakeholders in the defense acquisition environment encompass a diverse range of actors, including government agencies, defense contractors, military personnel, and the broader public. Government agencies, such as the DoD, formulate policies, set acquisition priorities, and oversee the execution of programs (Elkins, 2019). Defense contractors contribute to the development and production of military systems, fostering collaboration with the government to meet program objectives (Fox, 2016). Military personnel are essential stakeholders, providing input on operational requirements and utilizing the acquired capabilities in the field.

Finally, defense acquisition programs are comprehensive initiatives designed to address the nation's security needs by developing, procuring, and sustaining military capabilities (DoD, 2017). These programs typically follow a structured life cycle that includes requirements definition, system design and development, production, testing, and sustainment (Fox, 2016). The defense acquisition process is governed by regulations and guidelines, such as the Defense Acquisition Guidebook, which outlines best practices and procedures for effective program management (DoD, 2017).

Decision-Making in Program Management

As technology continues to advance, the ability to create digital replicas of both the physical and decision-making environment will allow researchers to accelerate their learning in the virtual space. Digital twins allow for more in-depth analysis and risk-taking in the virtual world allowing the researcher to change the boundary conditions without impacting the real world, thus providing a richer environment for learning and experimentation. Digital twins provide a comprehensive view of the physical system, enabling decision-makers to access real-time data and predictive simulations. Decision-makers can make more informed choices by considering the implications of various alternatives. This aligns with the principles of bounded rationality and the adaptive decision-making models, where individuals aim to achieve the best outcome given their limited cognitive resources and less than perfect information (Simon, 1955).

Decision-making theory also emphasizes the role of risk and uncertainty in choices. Digital twin technology has the potential to facilitate risk assessment and mitigation by providing a platform for scenario analysis and stress testing. Decision-makers can experiment with different scenarios and assess their impact on the physical system or process. This is consistent with the principles of prospect theory, which is based upon behavioral and economic theory that describes how people make decisions under uncertainty (Gremyr et al., 2019). Prospect theory has found applications in various decision-making processes, including public policy, healthcare, and organizational behavior (Camerer, 2005).

The relationship between decision-making theory and digital twins are intertwined and symbiotic. Decision-making theory provides the cognitive and theoretical framework for making effective choices, while digital twin offers the tools and technology to implement these choices in the real world. The integration of these two fields is evident in practical applications across various domains, enabling more informed decisions, improved risk management, and enhanced optimization.

The dynamic interplay between artificial intelligence (AI) and decision-making is perhaps one of the most significant domains in which AI is making a substantial impact. AI systems draw their roots from the advent of computers from which rule-based systems as expert systems evolved. Machine learning algorithms enable AI systems to learn from data, adapt and improve their performance over time. AI systems are designed to augment human decision-making processes by analyzing complex data sets and identifying patterns that may take humans longer to discern (Russell & Norvig, 2010). By integrating AI into decision-making processes, decision-making in complex and chaotic environments has the potential to provide more meaningful results. While AI systems should not be seen as replacements for the human, they should be seen as an integral part of the collaborative process of decision-making (Mittelstadt et al., 2016). Similarly, the digital twin does not replace the “real world” environment but provides a replica in which decisions may be explored from a wide spectrum of views and alternatives, providing a more rich and meaningful set of choices from which the decision-maker can choose.

The success of defense acquisition programs hinges on effective decision-making by program managers who must navigate budget constraints, technical intricacies, and evolving geopolitical landscapes (Schwartz, 2014). Inefficient decision-making can result in delays, cost overruns, and suboptimal outcomes, emphasizing the critical role of advanced technologies in augmenting decision-making capabilities. Systems engineering is a core methodology in the Defense Acquisition process and is often considered the principal method by which defense programs are managed and controlled. While systems engineering attempts to anticipate performance issues early in the acquisition life cycle, leading to improved system performance (Hossain & Jaradat, 2018), current methods are not agile enough to be able to provide reliable forecasting. Historical records bear this out by virtue of the many programs that continue to fail to meet their performance objectives and are often over cost and behind schedule.

Systems engineering primarily focuses on the technical aspects of a project, emphasizing the design, development, and integration of complex systems (Blanchard & Fabrycky, 2011). While this approach is invaluable for ensuring the functionality and reliability of military systems, it tends to neglect broader program management considerations such as budget constraints, political changes, and evolving threat landscapes (DoD, 2017). As a forecasting method, systems engineering may not adequately account for these external factors, leading to inaccurate predictions and suboptimal decision-making in defense acquisition.

Additionally, a key assumption of systems engineering is the stability of project requirements throughout the development life cycle (Blanchard & Fabrycky, 2011). However, in defense acquisition, requirements are often subject to change due to evolving geopolitical situations, emerging threats, and shifts in national security priorities (Oakley, 2019). The rigid nature of systems engineering may struggle to adapt to changing requirements, rendering it less effective as a forecasting method in the unpredictable landscape of defense acquisition.

Current methods of attempting to predict defense acquisition program performance are grounded in the theory of management that suggests that program monitoring and control can be accomplished through a performance measurement baseline (PMB) that measures work accomplished over time. Performance-Based Acquisition (PBA) is a strategic approach that emphasizes the measurement and management of performance outcomes. PBA aligns contracts, incentives, and milestones with desired performance levels. By using PBA, the DoD attempts to predict and influence performance throughout the acquisition process, ensuring that contracts incentivize suppliers to meet or exceed performance expectations. Techniques such as earned value management (EVM) draw heavily from performance measurement theories, particularly those related to assessing project progress and success. The concept of “earned value” itself is rooted in performance measurement, where the value of work performed is compared to the planned value to gauge project efficiency and effectiveness (Fleming & Koppelman, 2016). Additionally, Management Control Systems (MCS) theory, as developed by Robert N. Anthony (1965), emphasizes the need for organizations to implement systems that help manage and control their activities. EVM serves as a management control tool by providing a structured framework for measuring project performance against baselines, enabling proactive decision-making to address deviations from the plan (Fleming & Koppelman, 2016).

EVM is a performance measurement methodology that integrates scope, cost, and schedule to assess performance. It provides a structured approach designed to predict and control performance by comparing planned performance against actual progress. EVM is intended to offer insights into whether a program is on track to meet its performance goals (Fleming & Koppelman, 2016). EVM, however, does not account for changes in the overall development environment. It focuses on expected work relative to actual work and assumes that the risk and planning data adequately reflect the realities of the program. While this is a critical component of understanding a program, it is based upon preplanned cost and schedule information and does not provide sufficient clarity in prediction to be considered a viable forecasting method. It simply reaffirms planning processes and has little ability to anticipate the changing nature of the development environment.

New methods are required to better understand program performance and to be able to more reliably forecast program outcomes. This research will leverage theories and methods from other disciplines that provide a more accurate means of prediction. For example, digital twin theory is an emerging theory that is being used in disciplines to predict performance of discrete processes (Glaessgen & Stargel, 2012). Digital twin theory may provide new insight into the defense acquisition management process if coupled with complementary theories such as socio-technical or cyber physical theory, value theory and decision support theory. The concept of creating a virtual replica of a dynamic process such as defense acquisition presents the possibility of discovering the root causes of program challenges. Simply creating a replica of a process, however, is not sufficient. Insight and understanding will be gained through the intersection interpretation and alignment of complementary theories. Additionally, coherence in the model will be increased through the integration of artificial intelligence (AI) algorithms built into what will be referred to as the Acquisition Digital Environment (ADE). The integration of AI will create a learning model that improves its prediction ability as more data flows through the ADE.

Two concepts have emerged as integral components of current industrial and engineering processes: cyber physical systems and digital twins. These concepts represent a paradigm shift in how complex systems are designed, monitored, and optimized. Understanding these systems and the interrelationship between cyber physical systems and digital twins is an important step in being able to create an ADE that accurately represents the true nature of a human-centric business process. A cyber physical system refers to the integration of digital and physical elements where real-world entities interact with digital systems. Cyber physical systems have applications across many domains such as real-time monitoring and control and decision-making systems (Rathore et al., 2018). Digital twins are digital replicas of the physical world or systems. The virtual representation is informed by real-time data through sensors or other sources that provide a representation of the physical world. Digital twins can range from simple replicas to complex models of systems such as business and manufacturing processes to biological systems such as the human body (Glaessgen & Stargel, 2012).

Cyber physical and digital twin theory are related and mutually supporting in that cyber physical systems rely in real-time data for decision-making and control, which is also critical for the operation of digital twins. For example, smart manufacturing uses sensors on machinery to collect data that in turn is integrated into a digital twin to support decision-making and predictive maintenance to improve overall system performance (Tao et al., 2018). When applying this concept to a system such as the defense acquisition process, the cyber physical system is represented by the data collected through testing as well as cost and performance data of a program of record at various points during the developmental life cycle. Specifically, work breakdown structure data is the smallest unit of data of a program by which a program is measured. As a program moves through the life cycle, units of work are accomplished and can be measured and reported on through various program documents. In essence, this reporting data represent the sensor data that can be integrated into the digital twin of the life-cycle process. Digital twins facilitate simulations for understanding how physical systems operate under varying conditions. The data generated by cyber physical system is used to enhance these simulations, making them more accurate and reliable. The interconnectedness allows for the optimization of physical systems and processes in real or near real time (Tao et al., 2018).

Additionally, near real-time optimization of a physical system through a cyber physical system such as the ADE, may improve decision-making and forecasting. Real-time data-driven insight that is informed through learning systems such as artificial intelligence models further reveals the interconnectedness between cyber physical systems and digital twins (Rathore et al., 2018). Better forecasting of the defense acquisition process will improve decision-making, leading to better overall program performance. By forecasting program challenges before they become critical, decision-makers can react sooner and make more fiscally and programmatically sound decisions. Using cyber physical system such as an ADE, decision-makers can also “rehearse” scenarios before investing significant resources to improve acquisition strategy and planning.

Economic Value Theory

Decision-making is a fundamental aspect of human behavior that permeates all aspects of life, and its significance is particularly pronounced in the economic sphere. Current methods by which decisions in defense acquisition are informed are grounded in a cost-based approach that presumes to be able to forecast program performance relative to past estimates. This approach to decision-making excludes the concept of economic value as a key aspect to program performance and outcomes. Work, for example, is simply viewed as a function of cost and time rather than a unit of increasing value. By viewing work from a cost perspective rather than a value perspective, it is not possible to understand the underlying nature of why programs behave as they do. Decisions are focused on strict adherence to a cost-informed baseline, and the question of relevance in the form of value is often dismissed until programs are irreversibly dysfunctional, requiring new planning efforts to create new baselines. This process is inherently inefficient and leads to loss in operational capability to the customer and mismanagement of public resources.

Economic value theory provides a lens through which we can analyze the decisions individuals, businesses, and policymakers make, as these decisions ultimately shape the allocation of resources and contribute to the creation of value within an economy. Economic value theory is deeply rooted in classical and neoclassical economic thought. Adam Smith, often regarded as the father of modern economics, emphasized the role of individual decision-making in his seminal work, *The Wealth of Nations*. The concept of the invisible hand, where individuals pursuing their self-interest unintentionally contribute to the overall well-being of society, underscores the fundamental link between decision-making and economic value creation.

In the realm of microeconomics, consumer decision-making is key to economic value creation. Consumers make choices based on utility maximization, weighing the benefits and costs associated with different options (Samuelson, 1938). In the defense acquisition and program management context, value creation can be derived from work accomplished. If one decouples work from cost for the purpose of better definitizing value as something being created, each unit of work defined in the program work breakdown schedule then takes on a whole new utility by helping to change the framework of program choices from cost to value creation. The concept of marginal utility, derived from the law of diminishing returns, will play a pivotal role in explaining how the individual allocates resources to maximize satisfaction, therefore making decisions that are focused on maximizing value, not minimizing cost.

Value theory and decision-making are intrinsically linked and influence the choices humans make. The relationship between value theory and decision-making underscores the importance of understanding how individuals assess and prioritize values from both an economics and ethical perspective. Economic value theory provides the conceptual framework for assessing the worth of goods and services, while decision-making involves the process of selecting among competing alternatives. Classical economists such as Adam Smith emphasized the subjective nature of value while future economists included concepts such as individual preference and marginal utility (Mises, 1949). Similarly, decision-making involves assessing and prioritizing alternatives based on individual or collective preferences. The concept of utility, derived from economic value theory, plays an important role in decision-making in that individuals make choices from the perspective of perceived value of a set of options (Samuelson, 1938).

Additionally, economic value theory emphasizes the concept of opportunity cost where the value of the next best alternative is weighed against competing alternatives. Decision-makers weigh opportunity costs of their choices, considering what they must sacrifice in terms of alternative uses of resources. This perspective informs rational decision-making by encouraging individuals to select alternatives that maximize the overall best outcomes (Mises, 1949). This is precisely what program managers are supposed to be doing when making decisions; however, current methods do not provide adequate insight and nuance into the activities of a program under development to allow decisions to be optimized to be consistent with economic value and decision-making theory.

In physics, work is the energy transferred to or from an object via the application of force along a displacement. A force is said to do *positive work* if when applied in the direction of the displacement of the point of application. A force does *negative work* if it has a component opposite to the direction of the displacement (NCERT, 2020). For our purposes, positive work can be interpreted as an increase in overall value. The analogy between physical work and economic value will be developed as part of the overall research effort. However, for now we will draw upon the relationship that a unit of work identified in the program work breakdown structure can be used as a surrogate for a unit of value in that it represents a definitive action required to be accomplished at a specific time and that increasing positive work represents increasing positive value. As work is accomplished, this increases the economic value and provides an opportunity for program managers to weigh the value of the work performed at a certain point relative to the economic need at that moment in time. A virtual replica can simulate the flow of work increasing the choices available to the decision-maker. Additionally, decision tools will be able to learn as workflow is adjusted within the virtual replica, allowing for a smarter decision support system and over time increasing the potential for more accurate forecasting.

Socio-Technical Decision Support Systems

Decision and digital twin theory are becoming more intertwined through advances in technology, data analytics, and artificial intelligence. The two domains share a deep relationship in that decision-making theory focuses on understanding how individuals and organizations make choices, while digital twin theory centers on the creation of virtual replicas of processes that inform the decision-making process. Decision-making encompasses a wide range of concepts, models, and frameworks designed to explain and predict how humans, organizations, and increasingly, AI systems make choices when faced with uncertainty, risk, and complexity (Fraser, 1984). Various models such as rational choice model, bounded rationality, prospect theory, and the multi-attribute utility theory provide insight into the complexity of decision-making. Digital twin theory replicates the decision-making environment in that it aims to create a representation of the physical system or process in which decision theory can be applied.

Because of the interconnected nature of decision theory and digital twin theory, we must understand the relationships between the human and the technical framework within which decisions are made. The socio-technical influence on the decision-making process needs to be explored to make sense of key patterns that emerge during the development and testing of an ADE. As such, we must explore the current literature associated with the socio-technical theory as it relates to the decision-making processes. Socio-technical theory is a multidisciplinary framework that examines the interactions between social and technical elements within complex systems. Socio-technical theory originated in the field of organizational studies and has been applied in a variety of contexts such as information systems, health care, and transportation. Socio-technical theory can also be applied in the defense acquisition process in that the social and technical aspects of the process are interconnected and are considered a unified system which is influenced by context, culture, and the mutual influence of technology and human behavior (Trist & Bamforth, 1951). Trist and Bamforth argue that increasing technological advances integrated into the human centric process has shown to lead to improved efficiency and performance. We will explore whether increasing socio-technical integration through an AI-informed replica of the defense acquisition process has the same impact with regard to management decision-making and improved performance. Historical trends seem to suggest that there may be a positive correlation between the two. Many of the decision points within the defense acquisition process are informed by technologically driven data and require the integration of humans and technology to produce data that allows the process to function. Understanding this relationship is necessary to create an AI-informed digital replica of the defense acquisition process.

Additionally, socio-technical theory emphasizes the importance of human factors in technology and system design. A digital twin provides a platform for modeling and simulating human interactions with technology and data-driven processes that impact the overall system performance. This human-centric approach is necessary for ensuring that the technical solution or process design aligns with human needs, behaviors, and organizations priorities. To understand the significance of this, it is essential to explore how human-centric design fosters a harmonious relationship between technology and its users, thereby ensuring optimal functionality and long-term success. Adopting a user-centered approach enhances usability and overall satisfaction, ultimately contributing to the success of technological solutions (van Velsen et al., 2022). Human-centric design also extends to the organizational level. By aligning organizational priorities with design strategies, levels of efficiency can be gained by reducing waste and tasks that distract from value optimization. A study by Davenport (1993) in "Process Innovation: Reengineering Work Through Information Technology" emphasizes the need for technology to be an enabler of organizational objectives, emphasizing that a disconnect between technology and organizational goals can lead to inefficiencies. Davenport suggests that the business environment demands significant change and simply formulating strategy is no longer sufficient. He argues that we must also design the processes to implement it effectively by fusing information technology and human resource management to improve business performance (Davenport, 1993).

Understanding the socio-technical process involves recognizing the technological elements, such as hardware, software, and infrastructure, as well as the social aspects, including human participants, organizational structures, and culture. By comprehensively understanding these components and their interdependencies, one can provide a foundational framework for explaining the process (Trist & Bamforth, 1951). Socio-technical processes are dynamic and subject to continuous feedback and adaptation. Like other socio-technical processes, the defense acquisition process responds to feedback and changes and is intended to address issues, optimize performance, and align processes with evolving goals and objectives (Wong, 2022).

By replicating the defense acquisition process using a digital twin approach, greater clarity and alignment between organizational goals and outcomes can be achieved. The relationship between socio-technical and decision theory is inextricably linked and necessary to provide an opportunity to create a new way of examining defense acquisition that provides improved opportunities to forecast outcomes. Current management theory does not appear to reflect any research that attempts to replicate the defense acquisition process during the development phase of a program life cycle. This leaves us with a significant gap in knowledge on the relationship between the human and technical framework of the defense acquisition process that might provide insight into why defense programs under development tend to veer off track regarding meeting their cost, schedule, and performance objectives.

Technology Trust

The integration of Digital Twin technology and AI has revolutionized various industries, offering unprecedented opportunities for innovation and efficiency. However, the widespread adoption of these technologies is contingent upon the establishment of trust, both in the theoretical underpinnings and practical implementations. Equally important is gaining cultural acceptance of the technology to rely upon it to support critical decision-making. Due to the complexity and significant number of stakeholders in the defense acquisition process, the program manager is often influenced by competing information and priorities. Having a predictive model needs to account for the many priorities and stakeholder influences with a high degree of reliability for the capability to be adopted as a viable source by which to make decisions. Current decision support systems are slow and outdated due to the legacy data analysis approaches, such as EVM, that support these systems. An intelligent digital twin that allows for iterative scenario analysis and real-time forecasting would significantly improve the professional and theoretical foundation of program management.

Trust in digital twins and AI technology is anchored in a multidimensional theoretical framework that encompasses aspects of reliability, transparency, accountability, and ethical considerations. The theoretical foundation of trust in digital twins and AI hinges on their ability to provide reliable and accurate representations of the physical world. Digital twins, as virtual replicas of physical systems, must mirror reality while AI algorithms embedded in these twins must be capable of generating accurate predictions or simulations. These technologies are being used in other disciplines today with increasing success; however, they have never been used to replicate the program management process to improve program development performance outcomes. Product development leaders expect digital twins to accelerate product development processes and improve cost and schedule outcomes. Organizations are investing in the concept, with the global market for digital-twin technologies forecasted to grow at about 60% annually over the next 5 years, reaching $73.5 billion by 2027 (Argolini, 2023). This investment, however, does not represent a digitizing of the actual program management life cycle. It is predominantly focused on mechanical, test and evaluation, and manufacturing process to optimize these subordinate processes within the life cycle of a program under development (Argolini, 2023).

Trust in AI and digital twins requires transparency and explainability in their operations. Without good models and the right tools to interpret them, data scientists risk making decisions based on hidden biases, spurious correlations, and false generalizations. This has led to a rallying cry for model interpretability (Hohman et al., 2019). Theoretical frameworks such as interpretability in machine learning (Caruana et al., 2015) and explainable AI (XAI) methodologies emphasize the importance of making AI decisions understandable to humans. Transparency engenders trust by demystifying the nature of AI algorithms, fostering a clearer understanding of how decisions are made within digital twins. Creating a greater understanding of the intricate pathways with which information flows through the defense acquisition process, creating or reducing value, and gaining a sense of trust in the relationship between the digital version of reality will not only increase adoption of digital twin replicas of the defense acquisition process, but will further the theory and knowledge base of digital trust in general.

Scope

The defense acquisition process is a complex and multifaceted system designed to ensure the DoD acquires and sustains the most capable and cost-effective military capabilities. This process spans several distinct phases, each playing a critical role in the development, procurement, and sustainment of defense systems. Figure 1 shows a visual framework of the entire defense acquisition life cycle.

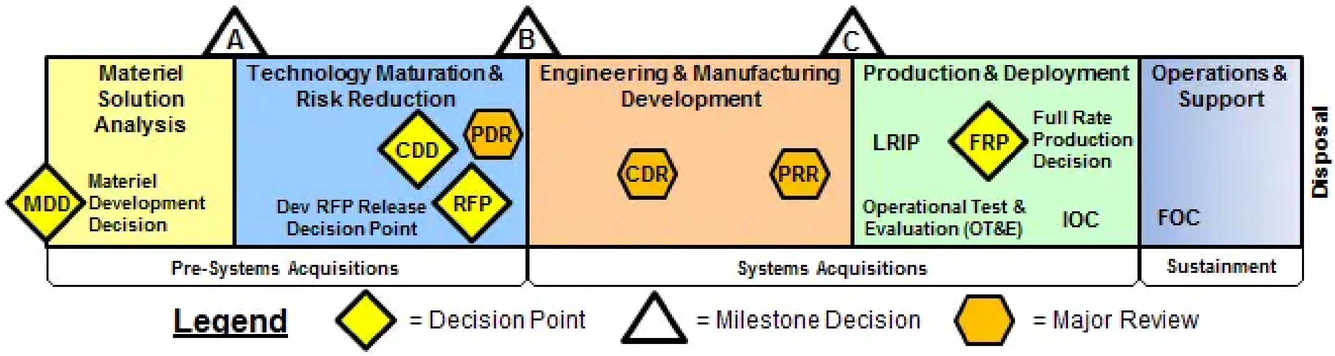

Figure 1. Defense Acquisition Life Cycle (AcqNotes)

The acquisition process begins with the identification of a capability gap or a need within the military, commonly referred to as a requirement. During the Concept and Technology Development phase, potential solutions are explored, and the feasibility of developing new technologies or adapting existing ones is assessed. This phase involves research, prototyping, and concept validation. Once viable concepts emerge, the Materiel Solution Analysis (MSA) phase focuses on refining and evaluating these options. This involves a detailed analysis of the potential solutions, cost estimates, and the development of an initial acquisition strategy. The goal is to identify the most suitable solution that meets the requirement within budget and time constraints. The Technology Maturation Risk Reduction (TMRR) phase is dedicated to advancing technologies and mitigating risks associated with the potential technology strategy. Prototypes are further developed and tested, and risk reduction measures are implemented. This phase aims to enhance the maturity of the technology and reduce uncertainties before entering development. The Engineering Manufacturing and Development (EMD) phase solidifies the design and development strategy and executes development of the product according to a budget and schedule baseline. Detailed engineering, manufacturing, and testing activities occur during this phase. The focus is on refining the design, ensuring manufacturability, and preparing for production. Successful completion of the EMD phase results in a system that is ready for production and deployment. This phase involves the mass production and deployment of the defense system. Manufacturing processes are optimized for large-scale production, and the system is fielded to military units. The Production and Deployment phase also includes ongoing logistics support to ensure the operational readiness and sustainment of the deployed systems (DoDI 5000.02, 2020)

This research will focus on the EMD phase of the defense acquisition process. While this phase might seem unique to the defense department, it is generalizable to the program management discipline at large. Choosing this phase is critical in that is represents the phase in which the organization commits to procurement of a capability and invests resources to its development. This phase also represents the phase in which program execution is grounded in prior predictions and measured against historical cost and schedule targets. In effect, this is the phase in which the "hype" for a project begins to decline either through poor program performance or ill-conceived requirements that were not well understood at the beginning of a project. This research will be divided into three phases. Each phase will culminate in a seminal paper that builds upon each other and supports the underlying research question.

1. Model Development – an initial digital twin model, which we will here forward refer to as the Program Management Acquisition Digital Twin (PMAD), will be developed that replicates the EMD phase of the life cycle. This model will be an exact replica with

machine learning integrated into the model. A subset of artificial intelligence, the machine learning algorithms will learn from the data and improve performance automatically over time. This learning will be compared with past programs during phase two of the research to begin to establish a sense of confidence through increased reliability. This first paper will describe the process, development, validation, and complexity of building a new model of a complex business process system.

2. PMAD Forecasting Assessment – data from past programs will be used to mature the PMAD. Additionally, this phase will examine the actual information pathways relative to those predicted at program initiation and attempt to reveal root cause for differences. This root cause analysis will provide insight into relevant theory and practice that will extend the knowledge for these disciplines. Root cause understanding will also allow the machine learning tools to become more accurate in their predictions improving the potential for adoption of this process as a more accurate means of decision-making and forecasting. Additionally, data from the model will be compared to current decision-making and forecasting tools to assess the level of improvement in predicting program outcomes.

3. Current program assessment – the third phase of this research will take data from an existing program of record and use the PMAD to assess the approved acquisition strategy and program documents to provide insight into how the PMAD can improve real-world program performance and forecasting. This phase is necessary to increase the PMAD and underlying theory adoption. Additionally, this is a critical step in demonstrating generalizability of the results of this research across a larger population of program management environments.

Method

The defense acquisition process is a complex and resource-intensive endeavor that plays a pivotal role in ensuring the national security of the country. As technology advances, the integration of digital twin technology offers significant potential to enhance decision-making, efficiency, and cost effectiveness within the process.

This dissertation is a quantitative approach and will use an AI model developed for the purpose of this research to better understand the unstructured patterns of decision-making that occur within the defense acquisition process. The AI model will assess the patterns and decisions of actual historical programs of being replicated in a digital twin of the defense acquisition process. A digital twin is a virtual replica of a physical object or system that can be used for simulation, analysis, and testing. In the context of defense acquisition, an experiential twin can be used to simulate, analyze, and test real-world processes and experiences of the acquisition process to identify areas for improvement and optimize the process. The AI model helps to identify patterns within the defense acquisition process while simulating a program execution from the start of a contract award to a production decision. By integrating AI into a virtual twin of the defense acquisition framework, novel insight can be gained into how decisions are being made and the impacts of those decisions, leading to more informed decisions leading to improved outcomes of a Defense Acquisition Program of Record.

Research Design

Phase I. Conceptual Framework and Model Development

The defense acquisition process conceptual framework refers to the structured set of principles, guidelines, and procedures that govern how goods and services are acquired and managed for defense systems and capabilities. This process is crucial for ensuring that military organizations obtain the necessary resources and technologies to meet national security requirements effectively. The defense acquisition process typically involves several stages, and the conceptual framework provides a roadmap for decision-making and management throughout these stages.

Requirements Definition**:** The process begins with the identification and definition of the military capabilities needed to fulfill national security objectives. This involves assessing threats, analyzing operational needs, and specifying the desired capabilities.

Acquisition Planning**:** This stage involves developing a comprehensive plan for acquiring the necessary defense capabilities. It includes considerations such as budgeting, scheduling, risk management, and determining the acquisition strategy.

Contracting and Procurement**:** The acquisition process typically involves contracting with private companies or government agencies to design, develop, and produce the required defense systems. Procurement activities may include competitive bidding, negotiation, and contract award.

Development and Testing**:** Defense systems undergo design, development, and testing to ensure they meet performance, reliability, and safety standards. This stage may involve prototypes, testing in simulated environments, and eventually field testing.

Production and Deployment**:** Once a defense system successfully completes testing, it enters the production phase. This stage involves manufacturing the systems in larger quantities and deploying them to military units.

Life-Cycle Management**:** The defense acquisition process extends beyond initial deployment. It includes ongoing maintenance, upgrades, and eventual retirement or replacement of systems as they become obsolete or reach the end of their operational life.

Regulatory Compliance**:** Throughout the acquisition process, adherence to legal and regulatory frameworks is crucial. This may include compliance with procurement laws, export controls, and other relevant regulations.

Cost Management**:** Cost considerations play a significant role in defense acquisition. This includes estimating, budgeting, and managing costs throughout the life cycle of a defense system.

Risk Management**:** Identifying and managing risks is essential to ensure the success of the acquisition process. This involves assessing potential challenges and implementing strategies to mitigate or address them.

While the defense acquisition process is designed to be systematic, transparent, and accountable, its complexity lends itself to a process that is difficult to manage due to the lack of deep understanding of the interdependencies of the ties between the elements of the framework from both a human and technical perspective. A virtual replica model of the defense acquisition process will be constructed using relevant data sources, including historical acquisition data, stakeholder interviews, and existing process documentation. While the model itself is not the primary intent of this research, it is necessary to understand the complex socio-technical environment of the defense acquisition process. By developing a virtual replica that mimics the "real world," the researcher will be able to gain insight into how information flows through the process and how decisions are made. This in turn will help to improve the model and eventually facilitate the creation of a tool that can improve forecasting and provide a reliable method by which program performance can be predicted. Key steps in developing the model include:

Define Objectives and Scope - Clearly define the objectives of the virtual replica model. Determine the specific aspects of the defense acquisition process you want to simulate. Identify the scope of the model, including the stages of acquisition, key stakeholders, decision points, and relevant environmental factors.

Gather Data and Information - Collect data on the defense acquisition process, including historical information, regulations, policies, and procedures. Consult with subject matter experts (SMEs) who have experience in defense acquisition to ensure accuracy and relevance.

Identify Key Components and Relationships - Break down the defense acquisition process into its key components, such as requirements definition, contracting, testing, and deployment. Identify the relationships and dependencies between these components to accurately represent the flow of activities.

Select Modeling Tools and Develop Model - Choose appropriate modeling tools for creating the virtual replica. This could include simulation software, 3D modeling tools, data visualization platforms and artificial intelligence models. Define the logic and rules governing the interactions between different elements in the virtual environment.

The model will be designed to capture the dynamic and interconnected nature of the defense acquisition life cycle.

Phase II. PMAD Forecasting Assessment

The virtual replica model will be subjected to simulations using real-time and historical data. Validation of the model will be conducted by comparing the simulation results with actual acquisition outcomes. This step aims to ensure the accuracy and reliability of the digital twin in replicating the complexities of the defense acquisition process. Having a validated virtual replica that can be used to inform decision-making and resource priorities has many benefits such as:

Variables and Data Analysis

In program management, variables can significantly impact the effectiveness of program performance. These variables are often interconnected and need to be carefully managed to ensure successful outcomes. While variables such as quality, communication, and leadership are critical to program performance, the purpose of this research is to explore the ability to forecast outcomes. Program performance outcomes are typically measured by a program's cost and schedule during execution relative to the initial program plan. Currently, the principal method by which major development programs are measured in terms of program execution is EVM, a project management technique that integrates cost, schedule, and scope to assess project performance and progress. It provides a standardized and objective method for project managers to measure a project's performance against its baseline plan. EVM is typically used for tracking and forecasting project costs and schedule performance.

Rather than focusing on traditional metrics, this research will measure a program's performance through value and workflow. Every development program starts with a pre-approved work breakdown structure that represents work over time. Each of these work packages was developed according to a specific criterion designed to complete the project in a specified period of performance. If the planned work is correct and it is performed exactly according to plan, then the output meets the needs of the customer and can be said to provide 100% value. As a unit of work is performed, it provides a unit of value to the program. If this unit of value is performed at a predetermined time, this is the highest level of efficiency a program might be able to achieve. We will need to assess all the units of work simultaneously over time, comparing actual to planned to provide a more accurate assessment of how much value a program is generating. The key variables we will use for comparison to current methods are:

Dependent Variable: Value (expected work completed relative to planned outcomes throughout the program life cycle)

Independent Variable: Workflow (Work Breakdown Structure)

The reality is that no program accomplishes every work package according to the work breakdown structure plan, resulting in program inefficiencies and loss. Additionally, there is no method available to assess program value and subsequently generate accurate program performance predictions. By using units of work to inform value, we can decouple cost from the analysis and focus on value and time (Schedule) relative to workflow. A sample two by two comparison helps illustrate how different scenarios or approaches may be classified based on these dimensions.

	High Value	**Low Value**
Efficient Workflow		
Inefficient Workflow		

- High Value (Efficient Workflow) - Programs in this quadrant exhibit both high value and efficiency in workflow. They deliver significant value within a relatively short timeframe, indicating effectiveness in resource utilization and project management.
- Low Value (Efficient Workflow) - This quadrant represents programs that deliver high value but may take a longer time to complete. While the workflow is efficient, the complexity or scope of the program requires a more extended timeline for successful execution.
- High Value (Inefficient Workflow) - Programs in this quadrant have a quick workflow but deliver low value. The focus may be on completing tasks rapidly, but the overall impact or benefits are limited.
- Low Value (Inefficient Workflow) - This quadrant represents programs with both low value and an inefficient workflow. These programs may take a long time to complete, and the outcomes may not justify the time and resources invested.

The virtual replica/AI model developed for this research will allow for an analysis of large value variables simultaneously and will provide the structure by which we can learn from actual data, creating the conditions for a predictive tool that will enhance program management insight and decision-making.

Validating a digital model of a program management process often involves the use of statistical tools to assess the accuracy, reliability, and effectiveness of the model. Validation will begin by validating the requirements for the model. Ensuring that the twin accurately represents the key elements of the program management process and aligns with the goals set by stakeholders is critical to ensuring the model is an accurate representation of the actual process. Additionally, testing of the digital twin under various scenarios and conditions and comparing the digital twin's predictions with actual outcomes or historical data will help to verify its reliability.

Using Value as the dependent variable, a comparison will be made to EVM performance metrics to assess correlation between the model and actual program performance. This will help assess how well the twin replicates the behavior and outcomes of real-world scenarios, providing a basis for validating its reliability. Statistical tools such as regression analysis, hypothesis testing, and goodness-of-fit tests will help to evaluate the performance of the digital twin and assess whether the twin's predictions align with the observed data of actual program performance. Additionally, a sensitivity analysis to understand how changes in work package input parameters impact the outputs of the digital twin will identify the robustness of the twin under varying conditions, contributing to its reliability.

This research is focused on understanding knowledge from new methods that will improve the decision support process of program management. Therefore, once the validity of the digital twin is sufficiently determined, the data from the model will be used to compare with existing methods of decision-making and forecasting in development programs. Current methods used to manage development programs are based upon EVM techniques, which produce key performance variables that are based on cost, schedule, and work performed. EVM is a project management technique that integrates cost, schedule, and scope to assess project performance and progress. It provides a standardized and objective method for project managers to measure a project's performance against its baseline plan. EVM is typically used for tracking and forecasting project costs and schedule performance.

Data

Data for the digital twin model will be sourced from a variety of channels, including historical defense acquisition data from relevant government agencies, stakeholder interviews, and expert opinions to capture qualitative insights, and technical specifications and documentation related to defense acquisitions. Historical defense acquisition data will primarily be drawn from existing program work breakdown structure data, in that this represents the lowest level of work defined for a program under development. This data represents a sample of the type of data available and the level of detail that will inform the research process. Other data sets will include program schedule data, earned value metrics, and selected acquisition reports.

Ethical Considerations

This research will adhere to ethical guidelines, ensuring the confidentiality of sensitive information and obtaining informed consent from stakeholders involved in interviews. All data will be anonymized to protect the identity of individuals and organizations. An IRB determination will be obtained prior to conducting any interviews.

Expected Results

The anticipated results include a validated virtual replica of the defense acquisition process that provides improved decision-making methods and a level of forecasting that does not currently exist in the program management profession. Additionally, this research will provide insight into potential improvements of the defense acquisition process facilitated by a virtual replica, and recommendations for implementing this technology in defense acquisition strategies. This dissertation's methodology combines literature review, conceptual framework development, data collection, simulation, and analysis to explore the application of digital twins in studying and improving the defense acquisition process. The results of this research aim to contribute to a more efficient, transparent, and adaptive defense acquisition framework.

This study is important because there is currently no useful simulation environment in the defense acquisition process that allows program managers to virtually execute their programs and observe them under conditions of ambiguity and change. By allowing the PM to simulate program volatility before a program has even begun, decisions can be made prior to program disruption, improving the probability of program success.

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Acquisition Research Program
Department of Defense Management
Naval Postgraduate School
555 Dyer Road, Ingersoll Hall
Monterey, CA 93943

www.acquisitionresearch.net