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Adoption of Digital Twin Within the Department of the Navy

June 2022

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Prepared for the Naval Postgraduate School, Monterey, CA 93943

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ABSTRACT

Digital twins have the potential to support the decision-makers that design, build, operate, and maintain the platforms that the Department of the Navy (DON) relies upon to conduct naval operations. However, the thin body of knowledge on digital twins presents a challenge for the DON as the range of applications and risks associated with onboarding digital twins are still unclear. This thesis conducts a qualitative technology assessment to determine the effects that adopting digital twins has on the DON's enterprise architecture. Analysis of an enterprise-wide adoption identifies opportunities and risks of digital twins within the context of the DON's strategy, processes, people, technology, cyber security, and risk management. The business value provided by digital twins is principally dependent upon the aggregate risk value of the physical platform and the fidelity and frequency of the digital twin's synchronizations.

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LIST OF ACRONYMS AND ABBREVIATIONS

AAV	Amphibious Assault Vehicle
ACAT	Acquisition Category
AI	Artificial Intelligence
AKS	Authoritative Knowledge Source
AR	Augmented Reality
ARG	Amphibious Ready Group
BLT	Battalion Landing Team
CAD	Computer Aided Design
CIO	Chief Information Officer
CNO	Chief of Naval Operations
COCOM	Combatant Command
CPAC	Corrosion Prevention and Control
CPS	Cyber-Physical System
DES	Digital Engineering Strategy
DLA	Defense Logistics Agency
DOD	Department of Defense
DODAF	DOD Architecture Framework
DON	Department of the Navy
DSETS	Digital Systems Engineering Transformation Strategy
DT	Digital Twin
DTA	Digital Twin Aggregate
DTE	Digital Twin Environment
DTI	Digital Twin Instance
EFV	Expeditionary Fighting Vehicle
EMD	Engineering & Manufacturing Development Federal
FCC	Communications Commission
HD	High Definition
HMMWV	High Mobility Multipurpose Wheeled Vehicle
IOT	Internet of Things
IT	Information Technology

JLTV	Joint Light Tactical Vehicle
LAV	Light Armored Vehicle
LCAC	Landing Craft Air Cushion
LCU	Landing Craft Unit
MBPS	Model-Based Product Support
MBSE	Model-Based Systems Engineering
MCEN	Marine Corps Enterprise Network
MCSC	Marine Corps Systems Command
MEU	Marine Expeditionary Unit
ML	Machine Learning
MOV	Measurable Organizational Value
MSA	Material Solutions Analysis
NAVAIR	Naval Air Systems Command
NAVSEA	Naval Sea Systems Command
NDS	National Defense Strategy
NIST	National Institute of Standards and Technology
O&S	Operation and Sustainment
OT	Operational Technology
P&D	Production and Development
PLM	Product Lifecycle Management
PMCS	Preventative Maintenance Checks and Services
POL	Petroleum, Oil, and Lubricants
ROI	Return on Investment
TMRR	Technology Maturation & Risk Reduction
UNREP	Underway Replenishment
USMC	United States Marine Corps
USTRANSCOM	U.S. Transportation Command
VMA	Marine Attack Squadron
VR	Virtual Reality
VSAT	Very Small Aperture Terminal

I. INTRODUCTION

The Naval Service is platform-based (Department of the Navy, 2020c). At the tactical level, naval operations, are conducted by platforms such as ships, aircraft, and submarines among other systems of the Naval Service (Department of the Navy, 2020c). These naval operations are conducted in order to fulfill the enduring functions of the Naval Service.

The Naval Service's dependence on complex systems, such as ships and submarines, to conduct naval operations creates a requirement to effectively manage and develop these products and their related information. These products are developed using a four-phase process of design, develop, operate, and dispose. This process is known as product lifecycle management (PLM). It is essential for the DON to develop and sustain effective PLM. Without sufficient PLM, the DON is unlikely to develop, deploy, and sustain platforms that meet the demands of the evolving maritime environment. The significance of PLM to the naval service is further reinforced in the Chief of Naval Operations (CNO) 2021 NAVPLAN. In his guidance to the U.S. Navy, the CNO explains that "expertly taking care of our platforms is in our DNA" and that "sustaining our ships and aircraft is absolutely critical to meeting future demands" (Chief of Naval Operations [CNO], 2021, p. 7).

In order to sustain the PLM needed, the DON must discover and exploit means of reducing uncertainty. Uncertainty limits a decision-maker's ability to avoid risks and exploit opportunities in the products they manage. Uncertainty manifests as a result of knowledge shortfalls (Kramer, 1999). Consequently, uncertainty can be reduced by decision support tools that provide decision-makers with the timely and relevant information needed to make more informed decisions (Kramer, 1999). Digital twins are an emerging technology capable of supporting DON decision-makers in the PLM process. A digital twin is a digital representation of a real-world system (Gartner, n.d.-a) Unlike similar concepts such as digital modeling, digital twins are fully integrated with data flowing routinely between the physical product and the virtual product in both directions (Grieves & Vickers, 2017). The routine capture and analysis of product data can support decision-making about the physical product. However, the benefits and risks of adoption are not clearly defined in a DON context. This thesis intends to explore how and why digital twins could be adopted by the DON within the context of product lifecycle management (PLM).

A. PROBLEM STATEMENT

Operations in the DON require systems that are collaborative, complex, and costly. Challenges within the DON's product lifecycle management (PLM) result in degraded operational capabilities as well as increased fiscal requirements. Digital twins have the potential to help the DON overcome these challenges by maintaining current data on the status of the DON's systems as well as performing automated data analysis to aid in decision-making. However, the thin body of knowledge on digital twins presents a challenge for the DON as the whole range of applications and risks associated with onboarding digital twins are still unclear. As the DON continues to search for means by which it can extend the useful lifespan of its systems, the computer-supported collection and response to data provided via digital twins become increasingly desirable. As a result, research into how digital twins could be adopted within the DON enterprise and the business value associated with this potential adoption is required.

B. PURPOSE STATEMENT

The purpose of this study is to explore how digital twins could be adopted within the DON. This research will focus on determining (a) the effects of digital twins on the DON's enterprise architecture, (b) the benefits and risks to the DON's PLM associated with the adoption of digital twins, and (c) the business value that digital twins can provide to the DON. The goals of this research are significant because shortfalls in the DON's PLM have a direct negative impact on operational DON capabilities. The results of this study can help the DON better understand how digital twins could be adopted with the end goal of improving PLM thereby providing business value.

C. RESEARCH QUESTIONS

1. How does the adoption of digital twins affect the Department of the Navy’s enterprise architecture?
    1.1. How are business processes altered?
    1.2. What are the positive and negative effects on the Department of the Navy’s cybersecurity?
2. How can digital twins be adopted to support product lifecycle management within the Department of the Navy?
    2.1. What benefits do digital twins introduce to the organization?
    2.2. What risks do digital twins introduce to the organization?
3. What business value can digital twins deliver to the Department of the Navy?
    3.1. Is the value provided worth the cost of adoption?

D. ORGANIZATION OF THESIS

This thesis is organized into four additional chapters. Chapter II is a literature review that investigates the background, components, and applications of digital twins. Chapter III explains the methodology of analysis. Chapter IV presents an analysis of digital twins based on the research questions. Chapter V is a conclusion that provides key insights, recommendations, and opportunities for future research.

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II. LITERATURE REVIEW

A. PRELIMINARY DEFINITIONS

The concept and study of digital twins is still immature and emerging. As a result, there is ambiguity or duplicity in terms used when discussing the topic. For the purpose of this research, the following definitions will be utilized. This list is not all-encompassing of terms that will be utilized during the research but ones that seemed to have some ambiguity throughout the review of the research.

- Digital twin – A digital twin is a virtual representation of a real-world system. A digital twin is synchronized with the physical twin at a specific fidelity and frequency. (Digital Twin Consortium, n.d.-b)
- Digital thread – A digital thread is a means of linking information across multiple states of the digital twin. Sources of differences in the states of the digital twin include (but are not limited to) time, stage of the product lifecycle, type of model, or configuration. (Digital Twin Consortium, n.d.-b)
- Model – A model is a "representation of a group of objects or ideas in some form other than that of the entity itself" (Shannon, 1992, p. 65).
- Simulation – A simulation is "the process of designing a model of a real system and conducting experiments with this model for the purpose of understanding the behavior of the system and /or evaluating various strategies for the operation of the system" (Shannon, 1992, p. 65). Simulations seek to "describe the behavior of a system and uses the model to predict future behavior, i.e., the effects that will be produced by changes in the system or its method of operation" (Shannon, 1992, p. 65).
- Machine Learning (ML) – Machine learning is a subfield of artificial intelligence (AI) (Brown, 2021). ML is a technique that "provides computers the ability to learn without explicitly being programmed"

(Brown, 2021). ML "[uses] statistics and algorithms to enable it to identify patterns in observed data, build models to represent the patterns, and predict things" (Office of Naval Research, n.d.).

- Product – A product is an item (tangible or intangible) or service (Saaksvuori & Immonen, 2008)
- System – A system is a "combination of elements that will function together to produce the capabilities required to fulfill a mission need. The elements may include hardware, equipment, software, or any combination thereof, but excludes construction or other improvements to real property." (Defense Acquisition University, n.d.-a)
- IoT – The Internet of Things (IoT) is any device connected to the internet (West et al., 2018). IoT "allows people and things to be connected any time, any place, with anything and anyone, ideally using any path/network and any service" (Vermesan et al., 2009)

B. BACKGROUND OF DIGITAL TWINS

A digital twin is a digital representation of a real-world system. Emerging in the field of product lifecycle management (PLM) in 2003, the concept of digital twin has recently grown in interest and was listed by Gartner, one of the world's leading research and advisory companies, as a "key strategic technology" in 2017 (Panetta, 2016), 2018 (Panetta, 2017), and 2019 (Panetta, 2018). According to Gartner, a digital twin's "strategic" value is based on its ability to function as a proxy for both traditional monitoring devices and technicians (Panetta, 2016). Moreover, a digital twin can be used to improve an organization's decision-making by providing up-to-date information on reliability as well as insight into how a hardware system can be tuned to perform more effectively (Panetta, 2018).

Origins of digital twins can be traced back to the "Mirrored Spaces Model" discussed by Dr. Michael Grieves in a 2002 presentation on product lifecycle management at the University of Michigan (Grieves & Vickers, 2017). By 2006, in Grieves' book *Product Lifecycle Management: Driving the Next Generation of Lean Thinking*¸ the concept had evolved to the "Information Mirroring Model" (Grieves, 2005). Finally, in 2011 Grieves used the term "digital twin" to reference the concept in his book *Virtually Perfect: Driving Innovative and Lean Products* through product lifecycle management (Jones et al., 2020). The term digital twin has been used to describe the concept from that point on (Grieves & Vickers, 2017). In his 2015 Whitepaper *Digital Twin: Manufacturing Excellence through Virtual Factory Replication*, Grieves describes digital twin as a model consisting of (1) a "physical product in real space" (Grieves, 2015, p. 1), (2) a "virtual product in virtual space" (Grieves, 2015, p. 1), and (3) "connections of data and information that ties the virtual and real products together" (Grieves, 2015, p. 1). An example of a digital twin in a Department of Defense (DOD) context could be (1) a turbine engine aboard a U.S. Navy Vessel embedded with digital sensors, (2) an exact digital replica of the engine "living" in the DOD's cloud, and (3) a fully automatic connection of bidirectional data between the physical engine and the virtual engine. Examples of data from the physical engine to the virtual engine could include current fuel levels and rotations per minute (rpm) speed. Examples of data from the virtual engine to the physical engine could include commands to slow rpm speed in order to conserve fuel or a software update that modifies how the physical components operate.

C. CONCEPT OF DIGITAL TWINS

The basis of the concept of digital twin is that a physical system (physical twin) has a separate and distinct digital representation (digital twin). The physical twin is the physical object or real-world system that is being twinned (Jones et al., 2020). The digital twin is the digital object which is an exact digital replica of a system in the physical world and made possible due to sensors that are networked and gather data from the physical world that can then be reconstructed by machines as a digitally created twin (Marr, 2019). The digital twin routinely receives data about the physical system. In turn, the physical twin routinely receives information from the digital twin. Synchronization between the physical twin and the digital twin occurs at a specific fidelity and frequency (Digital Twin

Consortium, n.d.-a). The physical and digital twins are linked throughout the duration of the physical twin's lifecycle (Grieves & Vickers, 2017). See Figure 1 for a visual depiction of the digital twin model.

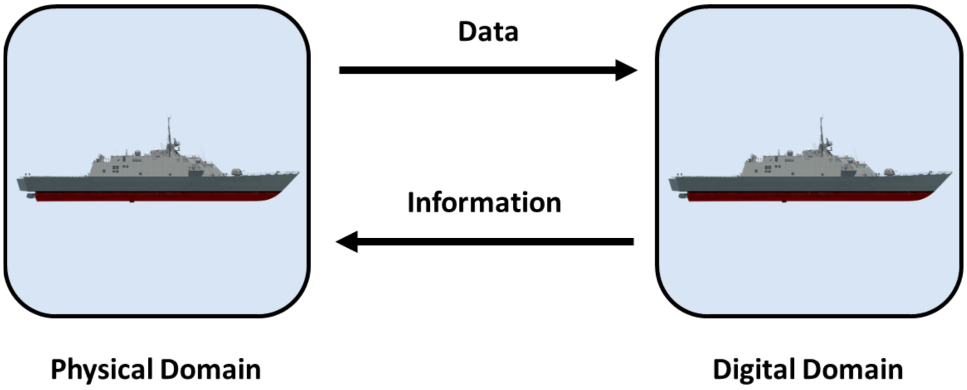

Figure 1. Model of Digital Twin

A digital twin object consists of three important parts (Wright & Davidson, 2020). These three parts are (1) a "model of the object" (Wright & Davidson, 2020, p. 2), (2) an "evolving set of data relating to the object" (Wright & Davidson, 2020, p. 2), and (3) a "means of dynamically updating or adjusting the model in accordance with the data" (Wright & Davidson, 2020, p. 2). A model that is dynamically updated based upon evolving data ensures the digital twin provides an accurate representation of the physical twin that changes over time (Wright & Davidson, 2020).

The model of the object can be any model that is sufficiently accurate to represent the physical system (Wright & Davidson, 2020). In an ideal world with perfect accuracy and instantaneous computations, the model would be physics-based and would account for all measurable environmental phenomena (Wright & Davidson, 2020). In general, the model of the object should be:

1. Accurate enough that updating the values of parameters will be useful. (Wright & Davidson, 2020)

2. Dynamic enough that updating the model's parameters based upon measurement data is meaningful. (Wright & Davidson, 2020)

3. Quick enough to run that it can inform decisions within the required time. (Wright & Davidson, 2020)

Digital twins are both interrogative and predictive. As an interrogative system, digital twins can respond to queries about the historical and current status of the physical twin (Grieves & Vickers, 2017). Examples of details that might be requested via the query include the current fuel status or historical locations. As a predictive system, digital twins can forecast future behavior and performance of the physical twin (Grieves & Vickers, 2017). That said, forecasts are supported by Bayesian Statistics. Bayesian Statistics reduce inferences using unknown parameters and establishes variables that can be utilized to determine probability distributions (Keller, 2014). Although informative, Bayesian Statistics is limited in that it is unable to account for causality (Pearl & Mackenzie, 2018).

D. HOW DIGITAL TWINS DIFFER FROM RELATED CONCEPTS

Cyber-physical systems (CPS) are smart systems that include the interaction of physical components and computational components (Griffor et al., 2017). There are no specific interactions required between the physical and computational components to be considered a CPS. Digital twins are a subset of CPS, which have more specific requirements. There are two factors that distinguish CPS from digital twins. The first is that digital twins require a bi-directional connection between the physical and computational components. In CPSs, the connection between the physical and computational systems is not prescribed. The second is that digital twins require the computational components to store and analyze a virtual representation of the physical components. In CPSs, there is no prescription for the computations performed by the computational components.

Although similar, a key differentiator between a "digital twin" and related concepts such as "digital model" is the degree of integration between the physical product and the virtual product. Specifically, digital twins are integrated with data flowing automatically between the physical product and the virtual product in both directions (Kritzinger et al., 2018). This is unlike "digital models" where the data flow is manual, and unlike "digital shadows" where the automatic data only flows one way from physical to virtual (Kritzinger et al., 2018).

In the simplest terms, a digital twin can be thought of as a digital model plus the relevant data unique to the physical twin (Wright & Davidson, 2020). For example, a digital model of a turbine engine plus data on the current state of that specific engine (e.g., engine temperature, rotations per minute, date of last oil change). Moreover, unlike a digital model, a digital twin must model a physical system in the real world. A digital twin without a corresponding physical twin is just a digital model (Wright & Davidson, 2020). As a result, the digital and physical twins are interdependent.

E. TYPES OF DIGITAL TWINS

Digital twins are a multipurpose tool that can be divided into types. How types are differentiated is dependent upon the needs of the adopting organization. Various levels of abstraction are selected based on the intended use case of the digital twin (Schalkwyk, 2019).

One means of classifying types of digital twins is by time or phase of the product lifecycle. For example, consider these two types of digital twins described by Grieves and Vickers: (1) digital twins prototypes (DTP), and (2) digital twins instances (DTI). A DTP is a type of digital twin that represents a specific product that can be made in the future (e.g., a product in the design or build phase) (Grieves & Vickers, 2016). DTPs could be used to support engineers in designing a product. A DTI is a type of digital twin that represents a specific product that is currently made (e.g., a product in the operate or dispose phase) (Grieves & Vickers, 2016). DTIs can be used to support operators and maintainers in keeping a product in operation.

A second means of classifying types of digital twins is by scale. For example, consider these two types of digital twins described by Grieves and Vickers: (1) digital twin instance, and (2) digital twin aggregates (DTA). As previously mentioned, a DTI is a type of digital twin that represents a specific product (e.g., a single F/A-18). A DTA is an aggregation of all the DTIs, both past and present, of a type of system (e.g., all the F/A-18s in a squadron) (Grieves & Vickers, 2016). DTAs can be used by management to identify trends across a fleet of systems.

A third means of classifying types of digital twins is by scope. For example, consider these three types of digital twins: (1) Component Twin, (2) Sub-System Twin, (3) System Twin. A Component Twin is a type of digital twin that represents a component (e.g., piston). Component Twins can be used to perform analysis related to the durability of the component (Parks, n.d.); (Schalkwyk, 2019). A Sub-System Twin is a type of digital twin that represents a system that is a constituent of a larger system (e.g., engine). Sub-System Twins can be used to perform analysis on the integration of multiple components to determine their effect on one another during the operation of the sub-system (Parks, n.d.); (Schalkwyk, 2019). A System Twin is a type of digital twin that represents a system that may be directly used by an operator (e.g., car). System Twins can be used to monitor and analyze the system in order to identify means of achieving greater efficiency or effectiveness (Parks, n.d.); (Schalkwyk, 2019).

Digital twin types are not mutually exclusive. Depending upon the characteristics of the physical twin, a digital twin could be classified as multiple types of digital twins simultaneously. For example, the digital twin of a Light Armored Vehicle (LAV) currently in operations could be characterized as both a DTI and System Twin. The digital twin can be characterized as a DTI because it represents a specific product that is in the operational phase of its lifecycle. The digital twin can also be characterized as a System Twin because it represents a system directly used by an operator and not a sub-system (the engine of the LAV) or component (the piston in the engine of the LAV).

F. DIGITAL THREAD

As the digital world continues to grow, the use of technology to improve operations in the civilian and military sectors has also increased rapidly. With the increased demand for more complex technology, the use of comprehensive digital technology became one of the primary ways to meet these demands (Kumar et al., 2020). Designers and manufacturers have relied on digital solutions to maximize their output across all forms of product development (Kumar et al., 2020). One of these technologies has been the "digital thread." One of the challenges created by these digital technologies has been the large amount of structurally diverse data that is created across the various development stages that must come together to provide a comprehensive view of the systems (Kumar et al., 2020).

The success of these digital technologies, and more specifically the digital twin, relies heavily on the ability to gather, collate, and access all the data that has been generated about a system throughout its lifecycle (Kumar et al., 2020). Digital thread has been proposed as a way to allow for detailed integration across multi-disciplinary trades which each have its own detailed models and analyses (Kumar et al., 2020). Furthermore, a digital thread establishes the architecture, driven by data, that connects the information across all stages of the product lifecycle (Pang et al., 2021). Digital thread has the desired end state of being the primary source of data from which all other information required in later stages of the product lifecycle management could be derived (Pang et al., 2021). This concept also allows for the needed data to be available in a consumable format when needed by a user (Kumar et al., 2020).

A functional example of a digital thread as it relates to digital twin is found in General Electric's (GE) federated multimodal platform that has been used for its additive manufacturing process. GE's goal was to create a digital twin that used a user-friendly language and terms while also creating a semantic model that allowed for all stages of the digital twin to be understood, and acted upon by machines (Kumar et al., 2020). GE's digital thread architecture consisted of five main components: a domain model designer, data and model polystore, a data ingester, a knowledge graph builder and explorer, and an analytic execution orchestrator. Each of these digital thread components serves a specific purpose to help translate, analyze, and make information available throughout the lifecycle of the digital twin. A pictorial overview of these components can be found in Figure 2.

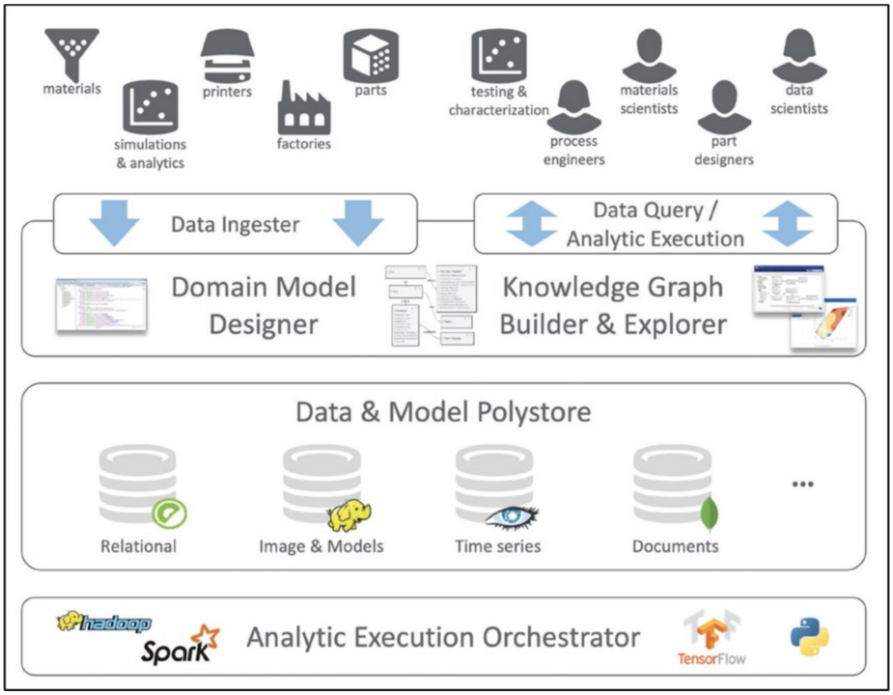

Figure 2. General Electric Digital Thread Architecture. Source: Kumar et al. (2020, p.51).

The domain model designer helps to create a standard for the authoring of a domain ontology in an English-like format that is specific to GE's digital twin (Kumar et al., 2020). This allows for those not familiar with design language to construct semantic domain models in the native language of the digital twin (Kumar et al., 2020).

The data and model polystore has a scalable distributed data store that is optimized for the particular types of data (e.g., time series and images) that are used throughout the digital twin lifecycle (Kumar et al., 2020). These data stores are then logically linked together to allow for the integrity of the individual data types, reduced storage requirements, and enhanced query capabilities for each data type (Kumar et al., 2020).

The data ingestor is what brings the data into the polystores (Kumar et al., 2020). Information is pulled from the source location using message queues and then pushes the data to the correct store at set intervals (Kumar et al., 2020).

The knowledge graph builder and explorer execute the functions the title implies. This takes the semantic stores used to model the data and provides a user interface to explore and examine data (Kumar et al., 2020). Because of the platform used, users do not require special training or knowledge to utilize the query function (Kumar et al., 2020). This links the data across all stages of the digital twin and allows users to easily access and analyze the data in a single location (Kumar et al., 2020).

The final component is the analytic execution orchestrator. The platform combines multiple application programming interfaces (APIs) to allow for both small and big data analytics directly within the platform (Kumar et al., 2020). The GE platform incorporates multiple analytical frameworks which remove the need for manual data analysis that would generally be required with a process as complex as this (Kumar et al., 2020). This GE example could be valuable moving forward as the use of digital twin grow and the data becomes more complex.

G. INDUSTRY 4.0

Industry 4.0, also known as the Fourth Industrial Revolution, is a movement that seeks to fuse physical, digital, and biological technology in order to deliver new products and services (Schwab, 2016). The Fourth Industrial Revolution builds upon the success of previous revolutions. The Third Industrial Revolution often called the "Digital Revolution," shifted industry from mechanical and analog systems to digital systems. These digital systems created the vast amounts of data that Industry 4.0 attempts to harness. The proliferation of automation, the growth of networking, and the miniaturization of electronics have set the conditions needed for harnessing data on an industrial scale (Lasi et al., 2014).

Just as the Second Industrial Revolution manifested in a variety of electricity-driven innovations (e.g., lightbulbs, streetcars, telegraph), the data-driven manifestations of the Fourth Industrial Revolution are broad and varied. Fundamental innovations include cyber-physical systems, smart factories, and increasingly individualized distribution and procurement (Lasi et al., 2014).

Cyber-physical systems (CPS) are "physical and engineered systems whose operations are monitored, coordinated, controlled, and integrated by a computing and communication core" (Rajkumar et al., 2010, p. 731). The integration of physical systems and the computational components of digital systems results in "smart" systems (Griffor et al., 2017). A CPS is capable of sensing, computing, and actuating (Griffor et al., 2017). The combination of information technology (IT) and operational technology (OT) along with associated timing constraints are the new feature provided by CPS (Griffor et al., 2017).

The size of CPSs varies based on the size and scale of the sensors and actuators employed. A CPS can be an individual device, or a CPS can consist of multiple cyber-physical systems that form a system-of-systems (Griffor et al., 2017).

Regardless of scale, the conceptual model of all CPSs remains the same (Griffor et al., 2017). Physical systems send information to digital systems. The digital systems make decisions with this information and then send commands for actions in the physical system. A CPS conceptual model is shown in Figure 3.

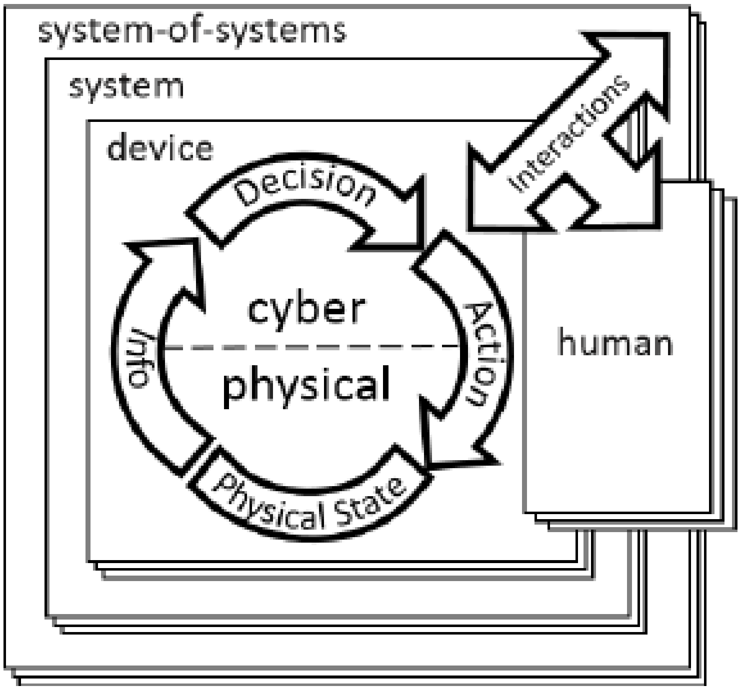

Figure 3. CPS Conceptual Model. Source: Griffor et al. (2017, p.6).

H. DIGITAL TRANSFORMATION

Digital Transformation, abbreviated as “DX,” is a means by which an organization onboards digital technology in order to provide business value (Bloomberg, 2019). Digital transformation is non-specific, and the particulars of the technology required or the value derived depend on the other elements of the organization’s enterprise architecture to include its mission, people, and processes. The concept of Digital Transformation is a broad concept that encompasses several narrower concepts to include digitization and digitalization.

Digitization is the process of taking analog information and encoding it into digital bits (zeros and ones) (Gartner, n.d.-b). Digitization focuses on data or information vice processes or people. An example of digitization is digitally scanning handwritten notes from a meeting and uploading them into a computer so they can be distributed to others. Once digitally scanned and uploaded the information from the handwritten notes has been “digitized.”

Unlike digitization, which can be clearly defined, the specifics of digitalization are more abstract (Bloomberg, 2019). Digitalization is similar to digitization in that organization seeks to leverage digital technology. However, digitalization focuses on processes while digitization focuses on information. An example of digitalization is implementing a digital system of taking and distributing notes throughout the organization. Once the digital notes system is functional and employed by the workforce the digital notes process has been “digitalized.”

Digital transformation includes, but is not limited to, the efforts of digitization and digitalization. Rather than transforming just information or processes, digital transformation seeks to transform business models, architectures, and processes (Kale, 2019). In summary, digitization focuses on the transformation of information, digitalization focuses on the transformation of processes, and digital transformation focuses on the transformation of the enterprise. When organizations undertake a digital transformation, they often focus on digital adoption, the onboarding of digital technology (Digital Adoption Team, 2019). Although digital adoption is important, it is only a single step in the digital transformation process (Digital Adoption Team, 2019). For the digital transformation effort to succeed the organization must also ensure that the new technology is integrated into the workspace (Digital Adoption Team, 2019). The integration of new digital tools into the workspace will result in alterations to business processes. Finally, organizations conducting digital transformations must maximize the utilization and value of the new digital tool (Digital Adoption Team, 2019). For example, instead of using Microsoft Outlook solely for email, it can also be used to manage an organization's tasks and schedules. By effectively integrating and maximizing the utilization of the new technology, the organization increases the value that the new digital tool provides. Organizations that are unable or unwilling to alter their business processes and subsequently maximize the utilization of the new digital tools are likely to stall and fail in their digital transformation efforts (Ramesh, 2019). As result, digital transformations have a high failure rate (up to 90%) in many sectors (Ramesh, 2019).

The implementation of digital twins into an enterprise is an example of a digital transformation effort. Digital twins are a technology that enables changes in an organization's processes, structure, and strategy. For the digital transformation effort to succeed not only must the technology be properly onboarded, but enterprise processes will also need to be changed.

I. DEPARTMENT OF THE NAVY ENTERPRISE ARCHITECTURE

A consideration for digital twins adoption is how it will impact the Department of the Navy's (DON) enterprise architecture. Ross et al. (2006) defined enterprise architecture as a way of organizing the core business process and technological capabilities of the organization through the use of policies, procedures, and governance to achieve both business standardization and integration across the organization (J. W. Ross et al., 2006). A complimentary definition of enterprise architecture is provided by Lin and Dyck (2010) where they defined it as a blueprint of an organization and its technology to meet the organization's needs (Lin & Dyck, 2010). One of the key concerns when implementing new technology is determining if the enterprise architecture has aligned the architecture of the technology to that of the business structure (Bente et al., 2012).

According to the DOD Chief Information Officer (CIO), the current version of the DOD enterprise architecture framework was released in August 2010 (Department of Defense, n.d.). This current version is the DOD architecture framework (DoDAF) 2.02. Through further research of the DOD CIO's webpage, briefs were provided that showed plans for updated versions of the DoDAF that were planned for release in 2012 and then again in 2015. However, these newer versions were never published.

The DON Information Superiority Vision which was published in February 2020 highlights the fact that the current situation of the DON's current enterprise architecture will hinder operational success. The vision states that the DON lacks mastery of its information environment and that the current networks and associated processes do not support efficient decision-making (Department of the Navy, 2020b). Additionally, the antiquated systems used by the DON do not provide adequate security for the Navy to meet the requirements defined by the National Defense Strategy (Department of the Navy, 2020b).

Although the DOD and DON have published multiple policies such as the DON Information Superiority Vision and DOD Digital Modernization Strategy, there have been setbacks in these updates. One of the priorities for modernizing the DOD was the use of cloud storage. One of the ways the DOD was going to implement its cloud priority was through the Joint Enterprise Defense Infrastructure (JEDI) contract (Feiner & Macias, 2021). However, after contracting issues, the contract was canceled in July 2021 (Feiner & Macias, 2021). This contract has been in the works for over a year and a half and was a key way the DOD was going to modernize its information technology operations (Feiner & Macias, 2021). Setbacks such as the failure of the JEDI contract as well as current processes and culture create challenges to implementing improvements to the DON enterprise architecture (Department of the Navy, 2020b).

If the DON is to implement digital twins technology, the impact on the enterprise architecture should first be evaluated. A determination should be made on whether or not the architecture technology capabilities and processes could support the technology. Or will the processes, policies, and procedures need to change to accommodate the system and if so, would the value provided be worth the effort?

J. PRODUCT LIFECYCLE MANAGEMENT

In their 2008 book, *Product Lifecycle Management Third Edition,* authors Antti Saaksvuori and Anselmi Immonen explain that product lifecycle management (PLM) is "a systematic, controlled concept for managing and developing products and product-related information" (Saaksvuori & Immonen, 2008, p. 3). The core of PLM is the "creation, preservation and storage of information relating to the company's products and activities, in order to ensure the fast, easy and trouble-free finding, refining, distribution and reutilization of the data required for daily operations" (Saaksvuori & Immonen, 2008, p. 3). PLM of a product is present from conception through disposal. A "product" can include: (a) tangible object (e.g., engine, battleship), (b) a service (e.g., training, logistics), (c) intangible object (e.g., software, algorithm) (Saaksvuori & Immonen, 2008).

PLM generally includes four phases: creation, production, operation, and disposal (Grieves & Vickers, 2016). The specifics by which these phases are executed depend upon the organization's requirements. In the DON the phases of PLM can follow the phases of the Defense Acquisition Lifecycle: Materiel Solution Analysis (MSA), Technology Maturation & Risk Reduction (TMRR), Engineering & Manufacturing Development (EMD), Production & Development (P&D), Operations & Support (O&S), and Disposal (Rendon & Snider, 2019).

PLM enables organizations to consistently develop and deploy products. This consistency reduces the waste of limited resources and therefore enables superior performance relative to competitors. In a modern environment, capital products such as naval vessels can last over 30 years. At the same time, the time until a product is obsolete continues to shrink. As a result, there is a desire among organizations to develop and deliver products more quickly than in recent history.

PLM is done to ensure that components developed separately can be combined to create a more complex product. Modern products are commonly generated from the collaboration between multiple organizations, which are each responsible for some part of the product's planning, design, or fabrication (Saaksvuori & Immonen, 2008).

As with all processes, PLM is limited by uncertainty. Uncertainty produces risk. In the DOD's PLM context, risk refers to a measure of the "future uncertainties relating to achieving program technical performance goals within defined cost and schedule constraints" (Office of the Deputy Assistant Secretary of Defense for Systems Engineering [ODASD(SE)], 2014, p. 3). Consequently, risk management is substantial to PLM.

K. DIGITAL TWINS IN INDUSTRY

The potential benefits of digital twins have led several organizations to include General Electric, Rolls Royce, Philips, and the government of Singapore to adopt this relatively new technology in their enterprises. By reviewing these real-world examples, appreciation for the potential capabilities and limitations of this technology can be gained.

General Electric employs digital twins of its new wind turbines to create "digital wind farms" (General Electric, 2015). Each digital wind farm starts with the digital twins. A computer model for the wind farm is developed based upon the specifics of the location and the specific wind turbines that will be deployed. This modeling allows for the creation of custom wind turbines that are tailor-made for their environment. Once physically deployed, the digital twins analyze live data from the physical wind turbines. Once the data has been analyzed, the digital twins make decisions about the operations of the wind turbines. As a result, the performance and efficiency of these wind turbines are increased by 20% (General Electric, 2015).

Rolls Royce, which has provided more than 16,000 military aerospace engines to over 100 countries to include the United States (Rolls-Royce, n.d.-a), has incorporated digital twins into its "IntelligentEngine" (Rolls-Royce, n.d.-b). The capabilities of digital twins have allowed Rolls Royce, and its customers, to operate and maintain every engine uniquely. For example, rather than maintenance every 5,000 miles like the old manual suggested, maintenance is conducted as required based upon the information provided via the digital twins. As a result, IntelligentEngine has enabled maintenance time to be extended by up to 50% for certain engines (Olavsrud, 2021). In addition to saving costs, this reduction in maintenance allows customers to reduce their parts inventory.

Philips has been creating digital twins of human hearts as part of their "HeartModel" (Philips, 2018) since 2015. A patient's HeartModel starts as a generic model of a heart. The patient's heart is then scanned with 2D ultrasound and the HeartModel is updated to reflect the unique autonomy of the patient's heart. The HeartModel is then provided additional data about the patient to create a full digital twin. Once established, this digital twin can be examined and even experimented on to identify customized treatment options for the patient's cardiovascular problems. This examination and experimentation can all be done without the need for the patient to be physically present. This not only minimizes risk to the patient but also allows for examination by remote experts who would otherwise be unable to support the patient.

In 2015, Dassault Systems and Singapore's National Research Foundation began the process of creating a digital twin of the entire city of Singapore with its "Virtual Singapore" initiative (Dassault Systemes, 2019). Virtual Singapore will tap into the vast array of sensors already installed throughout the city as well as implement new ones. When complete, Virtual Singapore will enable both public and private organizations to examine live data of the city such as traffic congestion, temperature, air quality, or noise pollution (Singapore, 2017). Virtual Singapore will also enable improved urban planning by providing a platform through which tests can be conducted before physical execution. For example, analyzing the potential for solar energy production if solar equipment were to be installed on new or existing infrastructure (National Research Foundation Singapore, n.d.).

L. SHORTFALLS IN LITERATURE

The concept of digital twins is less than 20 years old. As such, there are still many areas of research about the topic that are being developed and clarified. As the literature was reviewed, multiple areas were found to either have limited information or lacked any information in regard to their effects and relation to the concept of digital twins. First, there are limited examples of the use of digital twins in a military setting. The Defense Acquisitions University (n.d) has a definition for a digital twin (Defense Acquisition University, n.d.-b). Liao et al. (2020) who are part of the National Research Council of Canada discussed the United States Air Force's use of digital twins for their airframes (Liao et al., 2020). Finally, Mendi et al. (2021) who are Turkish academics, conducted a study of digital twins in the military context (Mendi et al., 2021). However, there was a shortage of publications from the DON on the uses or potential uses of this concept whether it be for PLM or other uses.

The next of these areas is the implications and requirements for the enterprise architecture. When adding new technology to the network, there will be required changes as well as requirements to plan out how the system will be implemented. The concept of digital twin looks to gather and collate data from systems across the network in close to real-time. If not properly planned for and implemented, issues could be experienced across the network. Additionally, there was a shortage of information on how this concept would tie in with additional emerging technologies. Concepts such as artificial intelligence and machine learning continue to be popular topics of discussion in both commercial and military sectors. It would seem that the concept of digital twin could be utilized in conjunction with these technologies in the future as they are fully developed. However, there is a lack of literature discussing these possibilities.

In addition to the above-listed shortfalls, there were shortfalls in areas that are of particular concern when considered for military adoption. These shortfalls would need to be studied and courses of action decided on to help enable successful adoption and operationalization. Among the top concerns in the identified shortfalls is literature that addresses the cyber security implications of the digital twin from the aspect of the development and implementation of digital twins. The concept of digital twin is designed to gather information on systems across the enterprise. As digital twins are connected to systems, these systems that may not have been previously connected to a network, are now vulnerable. This growth in connectivity increases the cyber-attack surface. For example, it is possible that high mobility multi-wheeled vehicle (HMMWV) engines could each ultimately have a digital twin. If proper cyber security processes are not considered and integrated into the preliminary stages of development, the enemy could potentially view the location and status of each HMMWV and in turn know the location of troops and other details about them.

A second concern is the governance of the digital twin. As has been experienced, often when integrating a new system, contractor support is heavily depended upon to operate and maintain the technology. Due to limited resident knowledge within the military, the DON will largely be at the mercy of the contractor support for operating the system. Additionally, because the information for digital twins is being collected from across the enterprise, there will be the question of whether a higher headquarters or the using unit is in control of the system. Unit commanders generally maintain their own maintenance operations and decide how to operate their own equipment. If the visibility of how systems are being used is visible at higher levels, unit commanders may feel that they do not have full control over the employment of the equipment they are assigned. Closely related is the issue of who will now control the maintenance of the gear itself as well as the digital twins. With the ability to have a collective view of the readiness of all assets, an argument could be made to have a centralized controlling authority for maintenance activities vice maintaining the control at the local unit.

Closely related to the topic of bandwidth discussed above is the required connectivity to support this level of information exchange. Of the articles reviewed, there was a shortfall of information on the technical requirements for the network at a small unit or enterprise level. An additional concern from the military perspective with the possibility of being in remote locations across the globe is how the concept of digital twin would operate in environments with connections that had high latency and/or low throughput capability. As these systems are adopted and disseminated throughout the DON, specific studies would need to be conducted to find the impact of possible deployed and tactical environments on the use of a digital twin.

As a result of these shortfalls in the current body of knowledge, this thesis's principal objective is to identify the capabilities and limitations of digital twin technology within a naval military context and to highlight the value that could be provided by the adoption of the concept of digital twin within the DON. To address all of the identified shortfalls is outside the scope of this research. However, this research will address some of the concepts that were identified as shortfalls such as possible impacts to the enterprise architecture and concerns related to the tactical environment and the need for stringent cyber security policies and capabilities.

M. CHAPTER SUMMARY

This chapter reviewed the literature currently available on digital twins as well as literature on related topics. The term "digital twin" was coined in 2011 by authors Grieves and Vickers (Jones et al., 2020). The relative novelty of digital twins has led to shortfalls in the current literature. Important literature shortfalls include the potential effects of digital twins on an organization's people, processes, and technology. This chapter helps to establish a baseline understanding of terms and concepts pertinent to the following research. The next chapter introduces and discusses the methodology used during the analysis of this thesis.

III. METHODOLOGY

A. APPROACH

This thesis conducted a qualitative technology assessment to answer the research questions. The researchers developed their understanding of digital twins through a review of the current literature in its many forms. This includes a review of academic papers, practitioner documents (white papers, websites), practitioner discussions (podcasts), and practitioner presentations (webcasts, videos). Once foundational knowledge was developed, the researchers further explored the problem space through real-time discussions with PLM professionals both inside and outside of the DON. Analysis of the potential effects of digital twins on the DON's enterprise architecture was conducted across seven categories: (1) Strategy, (2) Processes, (3) People, (4) Technology, (5) Cyber Security, (6) Risk Management, and (7) Business Value.

Exploring the first research question of this thesis, "How does the adoption of digital twins affect the DON's enterprise architecture?" requires an analysis of the effects of digital twins on the DON's (1) Strategy, (2) Processes, (3) People, (4) Technology, and (5) Cyber Security. Strategy, Process, People, and Technology were analyzed because Leavitt's Model of Organizational Change (aka "Leavitt's Diamond") suggests them as four key components to be considered in analyzing organizational change (Leavitt & Bahrami, 1988). Leavitt's Diamond explains that these four components are interrelated and that a change in one component will have an effect on the other three (Leavitt & Bahrami, 1988). Leavitt's Diamond is "the basis for a sociotechnical view of information systems" (Cornford & Shaikh, 2013, p. 3). The researchers have adjusted Leavitt's original model to better fit the needs of the analysis and the vocabulary of the DON. Specifically, "Strategy" is used instead of "Structure," "Process" is used instead of "Task," and "Technology" is used instead of "Information and Control." See Figure 4 for a visual depiction of the model.

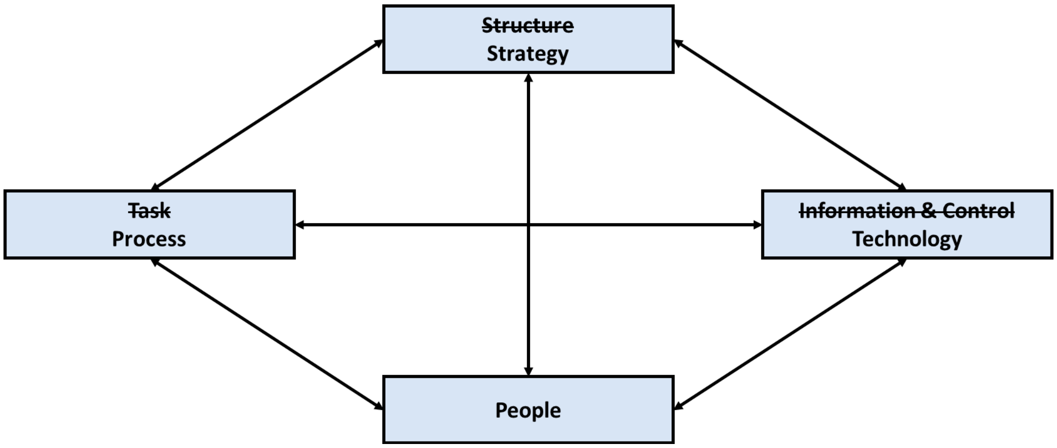

Figure 4. Modified Leavitt's Diamond

Cyber Security was analyzed because digital twins are networked systems and thus have cybersecurity implications. Cyber security has become increasingly important to the DON. The DON's 2020 Information Superiority Vision states that "success in traditional warfighting domains now requires mastering the Information Environment, which includes the … cyber domain, and the data that crosses them" (Department of the Navy, 2020b, p. 1).

Exploring the second research question of this thesis, "How can digital twins be adopted to support product lifecycle management within the Department of the Navy?" requires an analysis of the effects of digital twins on the DON's (6) Risk Management processes. Risk Management was analyzed because it is a vital component of PLM. The manifestation of risk directly affects the "triple constraint" that all projects have (cost, schedule, performance). Moreover, the original vision for the concept of digital twin had a heavy emphasis on Risk Management (Grieves & Vickers, 2017).

Exploring the third and final research question of this thesis, "What business value can digital twins deliver to the Department of the Navy?" requires an analysis of the potential financial and non-financial costs and benefits which explain (7) Business Value associated with the adoption of digital twins by the DON. Business Value was analyzed because the end goal of PLM is to provide business value. Organizations, to include the DON, develop and operate products with the explicit purpose of acquiring business value.

If digital twins, or any technology, fail to provide business value to an organization, they are unlikely to be successfully adopted

B. CHAPTER SUMMARY

This chapter introduced and discussed the methodology used during the analysis portion of this thesis. Seven categories of the DON’s enterprise architecture were identified as requiring analysis: (1) Strategy, (2) Processes, (3) People, (4) Technology, (5) Cyber Security, (6) Risk Management, and (7) Business Value.

Strategy, Process, People, and Technology were deemed to be important for consideration due to Leavitt’s Model of Organizational Change (aka “Leavitt’s Diamond”) which suggests them as four key components to be considered in analyzing organizational change (Leavitt & Bahrami, 1988). Cyber Security was analyzed due to the fact that digital twins are networked systems and thus have cybersecurity implications. Risk Management was identified because it is a vital component of PLM. And Business Value was considered because the end goal of PLM is to provide business value. The next chapter presents an analysis of digital twins based on the research questions.

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IV. ANALYSIS

A. STRATEGY

Strategy is an organization’s plan for how it will achieve its goals (Pearlson et al., 2020). Put another way, strategy is how an organization will move from where it is, to where it wants to be (Pearlson et al., 2020). Strategy is important because it provides a unifying direction to the organization’s efforts. Failure to unify an organization’s efforts can impede achieving the organization’s goals. Changes in an organization’s technology provide opportunities for an organization to alter its strategy. For example, in the early 1900s, the adoption of radio technology provided navies around the globe the opportunity to build strategies around distributed operations because the operations of individual ships could now be coordinated across extended distances.

PLM can be viewed as the execution of an organization’s strategy (Walton et al., 2013). In the context of PLM, strategy “provides the organization’s definition of success” (Walton et al., 2013, p. 4). PLM managers seek to develop and deploy products that enable the organization to reach its objectives. Leavitt’s model of organizational change explains that an organization’s strategy is interconnected with its technology (Tahir, 2020). As a result, if digital twins are adopted within the DON there will be effects on the DON’s strategy.

1. DON Strategy for Digital Twin

The DON is a dynamic functional organization that has shown interest in developing digital twins (Harrison, 2021), but as of this writing, the DON has not published any strategic documents to guide development. As a result, the current development of digital twins within the DON is progressing in a decentralized fashion. The following two sections examine how a DON Strategy for digital twins could provide a unifying direction for the adoption of this new technology.

a. Problem Space

The Department of Defense's (DOD) modern operating environment is heavily influenced by two factors: great power competition and fiscal constraint. These two factors have led to a requirement to adjust how the DOD conducts operations to meet the challenges of these threats. In response to the changing environment, the DOD's 2018 National Defense Strategy (NDS) began changing the course of the DOD with three lines of effort. One of these lines of effort is to "reform the department for greater performance and affordability" (Department of Defense, 2018a, p. 10).

One of the ways the DOD seeks to achieve the desired reform related to performance and affordability from the NDS is through greater use or implementation of digital engineering. In June 2018, five months after the release of the NDS, the DOD published the DOD Digital Engineering Strategy (DES). The DES is intended to provide guidance for the development and implementation of the DOD's digital engineering transformation. Instead of prescribing a way forward that further defines methods and metrics for achieving desired performance and affordability goals the DOD's DES seeks to "foster shared vision and ignite timely and focused action" (Department of Defense, 2018b, p. 2). This strategy is broad and requires more refined details to be provided by the service departments in order for the implementation practices and related performance and metrics guidance to be actionable. The DES describes the "what" while leaving the services the responsibility of determining the "how."

The DON's response to the DOD's DES was the United States Navy/Marine Corps (USN/MC) Digital Systems Engineering Transformation Strategy (DSETS) published in 2020 (Department of the Navy, 2020a). In the DSETS, the DON establishes that it will seek to achieve greater digital engineering through the application of model-based systems engineering (MBSE). MBSE was developed by the International Council on Systems Engineering (INCOSE) and is the formalized application of modeling to support system requirements. MBSE is a ratified methodology that is used to support the development associated with complex systems (Shevchenko, 2020). Although the DSETS provides the "how" to the goals of digital engineering, it fails to provide the level of details needed to achieve specific use-cases such as product lifecycle management (PLM).

DON MBSE concepts such as model-based product support (MBPS) specifically point toward digital twins as a foundational requirement (Harrison, 2021). MBPS is outlined as a way to establish the requirements of logistics support, supportable system design, and cost-effective support over the lifetime of the system (Harrison, 2021). Digital twin is a concept capable of operationalizing MBSE. However, the DON currently lacks a strategy for how the digital twin concept will be adopted by the department in order to achieve its expressed goals.

To address this strategic shortfall, the DON could create and publish a “DON Digital Twin Strategy” (DTS). See Figure 5 for a visual depiction of how a new “DON Digital Twin Strategy” could nest within the broader DOD and DON strategies previously mentioned (DOD’s 2018 National Defense Strategy, DOD’s 2018 Digital Engineering Strategy, DON’s 2020 USN/MC Digital Systems Engineering Transformation Strategy). The DON’s Digital Twin Strategy could provide the DON with a means of adopting the tools necessary to conduct digital engineering and Model-Based Product Support. These tools are important because they provide a means through which digital engineering and Model-Based Product Support are achieved. Moreover, digital twin tools could provide value to the DON by providing: (1) a means of operating and maintaining data models, (2) a means of accessing, managing, protecting, and analyzing the authoritative knowledge source of the DON’s systems, and (3) an end-to-end digital environment for PLM. The end state of the strategy could be to ensure that digital twins are effectively implemented and integrated with the DON’s enterprise architecture and are prepared to provide business value to the DON in the form of enhanced PLM.

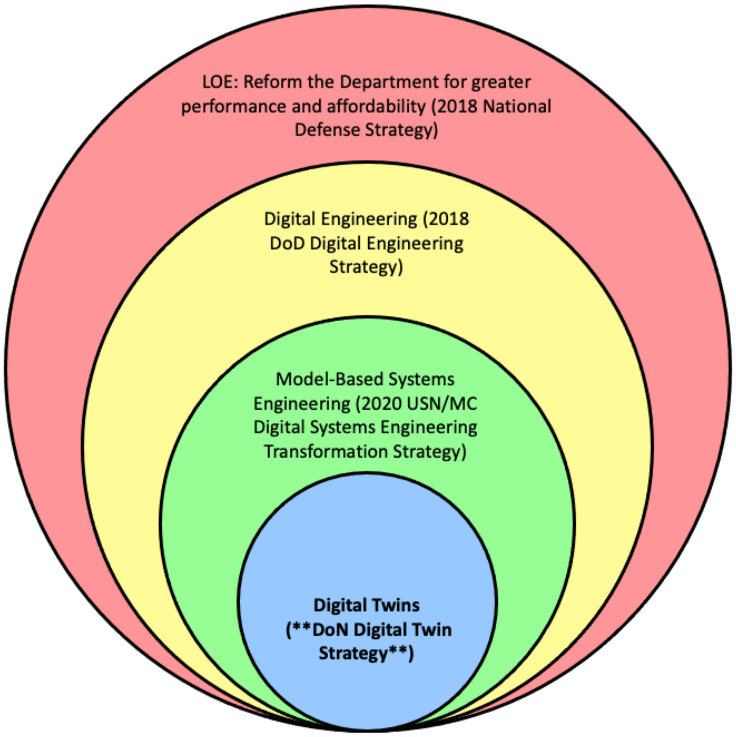


Figure 5. Nested DOD/DON Strategies

b. Expected Outputs of the DON Digital Twin Strategy

One of the goals of the DSETS is to "incorporate technological innovation to improve the engineering practice of the DON" (Department of the Navy, 2020a, p. 7). The DON Digital Twin Strategy could accomplish that goal through the onboarding of digital twin technology. Digital twin technology is a tool that can be harnessed by the DON to conduct the MBPS practices outlined in its strategies. The DES states that "[tools] should be a mix of enterprise-ready solutions that can be scaled to meet the requirements of stakeholders across all disciplines and domains" (Department of Defense, 2018b, p. 16). The DON Digital Twin Strategy could have three specific objectives:

1. Implement digital twins to provide a means of operating and maintaining data models.
2. Implement digital twins to provide a means of accessing, managing, protecting, and analyzing the authoritative knowledge source of the DON's systems.

3. Implement digital twins to provide an end-to-end digital environment for product lifecycle management.

If established in the DON Digital Twin Strategy, these goals could be traced directly back to the goals of the 2020 DSETS and the 2018 DES. See Figure 6 for a depiction of how the objectives of each strategy evolve.

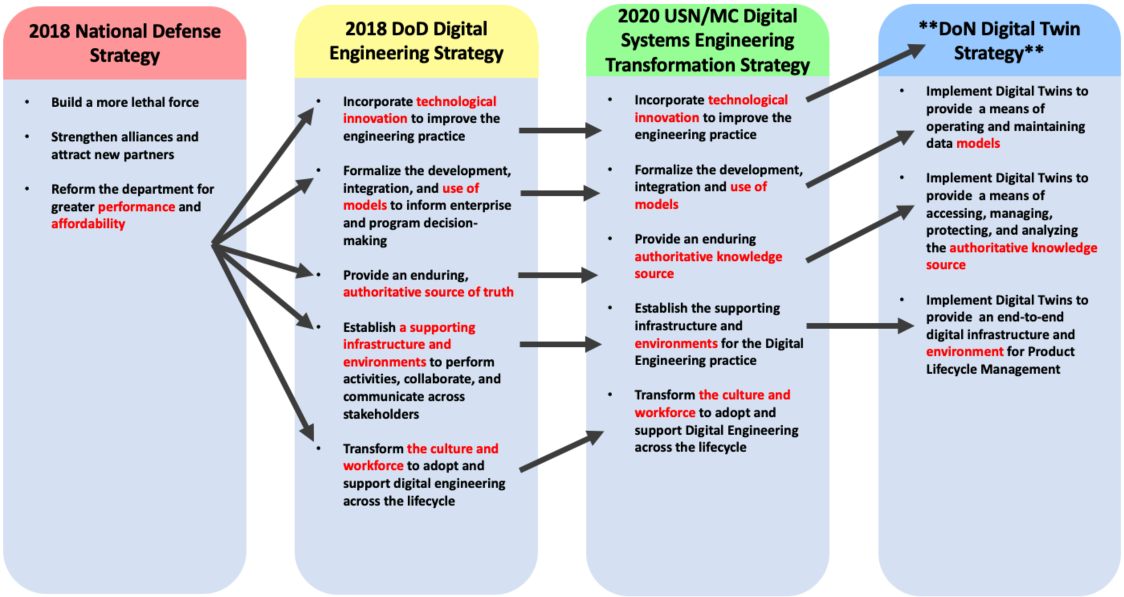


Figure 6. Strategy Connections

First, digital twins provide a means of operating and maintaining data models. Data models are virtual representations of products that exist in the physical world (DOD, 2018b). Data models are valuable to the DON because they can provide a precise and versatile representation of a physical product (e.g., ship, aircraft). In the early phases of the product lifecycle, data models enable virtual exploration and simulations that can be conducted more rapidly, more discretely, in greater quantity, and at less cost than traditional product prototypes (Department of Defense, 2018b). During later phases of the product lifecycle, data models enable the virtual testing of future modifications as well as predictions of future platform performance and logistics requirements (Department of Defense, 2018b).

Second, digital twins provide a means of accessing, managing, protecting, and analyzing the authoritative knowledge source of the DON's systems. An authoritative knowledge source (AKS) is the single authoritative source of knowledge on one of the DON's products (e.g., ship, aircraft). "Knowledge" includes, but is not limited to, data, data models, engineering information, capabilities, and requirements of the product (Department of the Navy, 2020a). The AKS captures both the history and the current state of its product. AKSs are valuable to the DON because they serve as the central reference for data models throughout the product's lifecycle (Department of the Navy, 2020a). As changes are made to a product, the AKS provides a means of tracing these modifications. Changes made to the AKS will replicate throughout the data models affected, thereby ensuring continuity between a product's active artifacts.

Third, digital twins can provide an end-to-end digital environment for product lifecycle management. An end-to-end digital environment for PLM is an environment in which data and predictive models are used throughout the entire product lifecycle to virtually present the system as it exists in the physical world (Department of Defense, 2018b). This means that data models will be adopted during the design phase of operations and continuously updated until the product is retired. If a product is modeled only after it is in operation, or only until it is deployed then it fails to provide an "end-to-end" digital environment. The key idea is that the physical and digital worlds are synchronized throughout the product lifecycle from concept design to disposition. An end-to-end digital environment is valuable to the DON because it will enable consistent analysis and decision-making about the product. Moreover, by continually twinning the data model alongside the physical product, the DON can gain continuous insight from the operational environment (Department of Defense, 2018b).

2. Summary

Changes to an organization's technology provide opportunities for an organization to alter or advance its strategies. digital twin technology is a key enabler to existing DOD and DON strategies including the DOD's 2018 Digital Engineering Strategy and the DON's 2020 USN/MC Digital Systems Engineering Transformation Strategy.

Specifically, digital twins could provide the DON the means of employing data models, maintaining AKSs, and providing an end-to-end digital PLM environment. However, the DON currently lacks the specific digital twin strategy needed to coordinate the efforts of digital twin adoption throughout the enterprise.

B. PROCESSES

Processes are the repeatable procedures that an organization uses to achieve a result. Processes are important for an organization because they help lead to repeatable performance and therefore can elicit the necessary dynamics to study the long-term and predictive behavior of an organization. For example, if an organization needs additional materials, it can execute its procurement process. At the end of the procurement process, the organization will have the required materials.

Changes in an organization's technology affect the means by which an organization's processes are executed. As an example, consider the digital spreadsheet used during an organization's procurement process to document the materials that need to be procured. Originally a digital spreadsheet is stored locally on the supply clerk's computer and can only be accessed by them. As a result, the supply clerk must go around throughout the organization to gather a list of all the needed materials. However, if the organization provides the supply clerk the technology necessary to move the digital spreadsheet to cloud storage and distribute access to employees throughout the workforce, then supply shortfalls can be collected in a distributed manner instead of by the single supply clerk. Of note, if the new technology is not utilized and the supply clerk continues to go around and collect the supply information themselves, then the new technology may fail to provide its maximum potential value to the organization.

1. Effects of Digital Twin Adoption on the DON's Processes

Digital twins have the potential to affect many of the DON's existing processes. In the context of PLM, four of the most significantly affected processes are the product design process, the testing and evaluation process, the maintenance process, and the sustainment process.

a. Product Design Process

Digital twins can serve as AKSs. As AKSs, digital twins can provide a means of reducing knowledge silos during the product design process. By reducing silos early in the development process, digital twins can help to ensure that the subcomponents of the system integrate without issue upon completion of the final system. Providing a means of ensuring subcomponent integration is more efficient from a cost standpoint but may cause time delays upfront as each aspect of the project is planned for and integrated before moving on further in the project development. This also highlights a paradigm shift from a traditional design methodology of "design-build-test" to a "model-analyze-build" methodology which should better enable complex system development (Department of Defense, 2018b, p. 1). For example, an AKS can support the integration of work requirements with available resources.

b. Product Test and Evaluation Process

Digital twins can maintain and provide traceability to historical artifacts. As a result, digital twins can provide product testers with a reliable means of tracing and confirming the requirements for the product test and evaluation processes. Digital twins can also enable simulations via the detailed product models they maintain. This allows product evaluation to be conducted via simulations instead of physical prototypes. Evaluation via physics-based simulations has several advantages relative to traditional physical tests. First, physics-based simulations can evaluate a product in multiple environments concurrently. For example, a new ship model can be virtually tested in both the Indian Ocean and the Arctic Ocean to test the effects of temperature on the ship's performance. Second, physics-based simulations can evaluate multiple product designs at the same time. For example, Marine Corps Systems Command could virtually test two competing helicopter models to determine which design best meets the requirements for a new helicopter program. Third, physics-based simulations can be conducted at a greater scale than traditional physical tests. For example, a simulation of a sea-skimming cruise missile being fired at a moving ship at sea can be conducted 500 times virtually to produce more rigorous results than firing a handful of physical prototypes. Fourth, because simulations are conducted on computers instead of in the physical world, they are less observable by competitors. For example, virtual simulations testing the maximum flight range of a new stealth aircraft are more difficult for competitors to detect than a physical aircraft flying around in the physical world. Finally, because models are relatively easy to duplicate or modify relative to physical prototypes, the advantages mentioned above can be done at less cost per unit.

c. Product Maintenance Process

Digital twins maintain an up-to-date status of their physical twin. Digital twins can also predict the physical twins' future maintenance condition via physics-based simulations. These capabilities empower digital twins to affect both the preventative maintenance processes and the corrective maintenance processes used to maintain the physical twin.

The current preventative maintenance process maintains scheduled times for when systems (e.g., ship, aircraft) are to be inspected and certain maintenance actions such as prevented maintenance checks and service (PMCS) are to be conducted. These time intervals can be weekly, quarterly, and/or annually depending upon the system. These periods were developed to generally apply to all instances of a system type and don't take into account the specifics of individual systems or their operating environments. This time-based process can lead to inefficient use of manpower through conducting inspections of equipment that may not need it. Digital twins can use data models to develop more optimized inspection timelines based upon the individual system and its operating environment. The reduction in time spent executing the preventative maintenance process frees time for the execution of the corrective maintenance process.

The current corrective maintenance process is typically initiated after a maintenance problem has been identified. Digital twins can leverage their physics-based models to predict maintenance issues ahead of time. Moreover, because virtual models can be remotely accessed, advanced troubleshooting can be executed by subject matter experts that are physically removed from the physical twin. The increased time spent executing the corrective maintenance process and the increased efficiency in which it can be executed can reduce the time that a system remains in the maintenance cycle and increase operational availability as a result.

The enhanced ability to know when certain maintenance processes are needed on individual systems is valuable to the DON because it reduces the time wasted performing unnecessary maintenance while also allowing for minor maintenance problems to be addressed early before they become significant maintenance problems. For example, an amphibious ready group (ARG) could use the digital twins of its landing craft air cushions (LCACs) to determine how often the preventative maintenance process should be conducted based upon environmental conditions and operational demand. The ARG could also use the digital twins of its LCACs to identify the need to execute the corrective maintenance process to repair minor damage to an LCAC's turbine engine before the damage is exacerbated.

d. Product Sustainment Process

Digital twins can maintain a history of the physical twins' supply requirements. Digital twins can also maintain a history of the context in which these supplies were required. As a result, digital twins can provide the DON's supply processes with the data needed to predict the future supply requirements of the physical twin. Supply predictions are valuable to the DON because they enable supply processes to be proactive rather than reactive. For example, a Carrier Strike Group's resupply process could incorporate the data from the digital twins of its F/A-18 squadron to predict what repair parts should be ordered now so they are delivered during the underway replenishment (UNREP) next month when the parts will be needed. As a result, the F/A-18 will have the parts arrive "just in time."

Digital twins can also serve as AKSs. As AKSs, digital twins can facilitate the streamlining of the sustainment process. When acting as an AKS, digital twins are the primary source for all information about the physical twin and can inform system maintainers what parts are needed, inform supply personnel how the parts should be procured, and inform supply producers which parts need to be fabricated. As an AKS, digital twins could also help to ensure that only the correct and required items are ordered.

By reducing erroneous supply orders, the digital twin can reduce unnecessary expenditures and free the associated logistics capacity for other operations.

2. Summary

Changes to an organization's technology affect the means by which an organization's processes are executed. By changing how an organization's processes are executed, technology can change the relative value of those processes to the organization. Conversely, if an organization's processes remain unchanged despite the technology changing, then the maximum potential value that the new technology can provide may not be reached.

In the context of DON PLM, four of the most significantly affected processes are the product design process, the testing and evaluation process, the maintenance process, and the sustainment process. Digital twins provide the DON's product design process with a means of reducing information silos, thus providing a means of ensuring subcomponent integration prior to final assembly. Digital twins provide the DON's testing and evaluation process with a means of tracing documented requirements and virtual testing, thus providing a means by which systems can be more rigorously tested and evaluated. Digital twins provide the DON's maintenance process with a means of developing individualized PMCS intervals and predicting maintenance issues, thus providing a means of conducting conditions-based maintenance. Digital twins provide the DON's sustainment process with a means of maintaining a contextualized history of previous supply requirements as well as an AKS from which to manage the supply chain, thus making the sustainment process more proactive.

C. PEOPLE

People are the backbone of an organization. People develop the organization's strategy, conduct the organization's processes, and employ the organization's technology. Changes in an organization's technology affect how the organization's people engage with information and conduct their work. In the context of PLM, people are decision-makers. People must make decisions throughout a system's lifecycle to include if or how the system should be developed when to deploy a system, how to employ a system, and when to take a system out of operations in order to maintain the system. DTs can provide an organization's people with the information they need to make more informed decisions.

1. Effects of Digital Twin Adoption on the DON's People

Digital twins have the potential to affect a wide array of the DON's human workforce. In the context of PLM, some of the individuals most affected are the developers, commanders, operators, maintainers, and suppliers of the physical twins. These individuals will be best positioned to receive the benefits of digital twins. However, they will also be required to cope with the challenges associated with the changes that occur in the processes of adoption.

a. Product Developers

Product developers will be affected by digital twins during the design phase of the product lifecycle. Digital twins have the potential to integrate or replace multiple tools that are currently used during the design and development phase such as computer-aided design (CAD) programs as well as the current document-centric process for gathering system requirements. As a result, the product designers may be able to reduce the number of computer applications that they must interact with in the conduct of their duties. For example, instead of requiring system developers to be advanced users with both MagicDraw and Cameo System Modeler when developing architectural models, system developers could focus on just learning one of the two. However, if the digital twin tool fails to replace existing tools and is treated as just "another tool in the toolbox," it could create an additional burden for these individuals and could lead to resistance to its adoption.

b. Product Commanders

Digital twins will also impact those who are planning for or utilizing the system during the operational phase of the product lifecycle. Digital twins can maintain an up-to-date status of the operational readiness of their physical twin. Operational strategists and unit commanders could leverage this capability when planning in order to make more informed decisions. For example, strike group commanders could query the digital twins of their Arleigh Burke-class destroyers in order to determine which is the most prepared to operate as a vanguard at the head of the strike group.

c. Product Operators

Digital twins can aggregate data from the digital twins of other platforms. Data aggregated from multiple digital twins will contain more data points than a single digital twin can produce. These additional data points have the potential to create more accurate models for determining how to achieve optimal performance. Operators of the physical twin could leverage this capability to better seek their desired goals for the physical twin. For example, if operators wanted to achieve optimal fuel efficiency of their ship, they could reference the digital twin's models to confirm how to achieve this.

d. Product Maintainers

Digital twins can track the physical twin's performance over time. Maintainers of the physical twin can query this information in order to create individualized PMCS periods rather than relying on generic intervals which don't always take environmental factors into consideration. For example, a maintainer could create a corrosion prevention and control (CPAC) plan that inspects its joint light tactical vehicles (JLTVs) every six weeks instead of every four weeks because they are operating in colder less humid conditions.

e. Product Suppliers

Digital twins can maintain a history of previous maintenance and supply requirements that are unique to the physical twin. Historical data can be used to predict future requirements. Supply personnel can use these predictions to better forecast the supply requirements of the physical twins. By supplying the physical twin proactively instead of reactively, the supply personnel can improve the operational availability of the physical twin. For example, supply personnel could query the digital twin of a CH-53E to determine how often it needs to replace one of its seven main rotor blades based upon the current operating environment.

2. Summary

Changes in an organization's technology affect how the organization's people engage with information and conduct their work. Digital twins could provide the DON's personnel with the information they need to make better-informed decisions. In the context of DON PLM, some of the individuals most affected are the product developers, commanders, operators, maintainers, and suppliers of the physical twins.

Digital twins provide system developers with a means of reducing the computer-based applications they interface with, thus enabling them to focus on improving their skills with the tools they use the most. Digital twins provide system commanders with the ability to verify the operational status of their equipment, thus enabling them to make more informed decisions regarding system employment. Digital twins provide system operators with the ability to virtually test how to achieve optimal system performance, thus enabling them to make more informed decisions regarding system operations. Digital twins provide system maintainers with the ability to identify current maintenance concerns and predict future maintenance concerns, thus enabling them to make more informed decisions regarding system maintenance. Digital twins provide system suppliers with the ability to track historical supply requirements and the capability to predict future supply requirements, thus enabling them to make more informed decisions regarding system sustainment.

While each of these users can be positively impacted by the adoption of this technology, if digital twins do not provide timely or accurate information in a usable manner, they will create greater conflict for the user being directed to use this technology. If the workforce does not understand how the system operates or the benefits it can provide, they will resist the change and become a barrier to its adoption. Therefore, action must be taken to create a shared understanding of the benefits of this technology. This understanding must be developed through training so that buy-in is created for the users.

Finally, this technology should not reduce the individual's ability to assess a system and make decisions. While the digital twin tool could certainly be a valuable asset that improves operations and costs to maintain a system, the user must still be able to assess the information and make appropriate decisions. The workforce must be trained to utilize the information but also develop their own understanding of the situation.

D. TECHNOLOGY

Technologies are the tools that organizations leverage to conduct their work. An organization's workforce uses an organization's technologies to execute the organization's processes in pursuit of the organization's strategies. Technologies are often interconnected. As a result, changes to an organization's technology can have an impact on other technologies throughout the organization. For example, if an organization changes its desktop computers from stationary "thick" clients to more mobile "thin" clients it will also need to change its server infrastructure because thin clients lack the ability to conduct process-intensive tasks on their own (McCabe, 2021). In the context of PLM, technology is a tool that enhances peoples' ability to perform their tasks. For example, edge computing technology can enable product maintainers to process product data locally rather than remotely.

1. Effects of Digital Twin Adoption on the DON's Technology

Digital twins are a technology that integrates several other supporting technologies. Without supporting technologies, digital twins may be degraded or denied in their ability to provide value. In the context of PLM, some of the technologies most affected are: (1) sensors, (2) network connectivity, (3) physics-based models, (4) cloud storage, (5) high-performance computers, (6) augmented reality (AR) and virtual reality (VR), and (7) machine learning.

a. Sensors

Digital twins require data that is routinely updated about the physical twin in order to maintain up-to-date data models. Without sensors, data about the physical twin and the environment would not be available. As a result, the adoption of digital twins within the DON may require changes in the DON's sensor technology. The DON already has access to IoT sensors, but new or different sensors may need to be added to physical systems before their digital twins can be established. For example, the DON may need to acquire and deploy sensors capable of measuring the current condition of the sacrificial anodes placed on ships that prevent corrosion.

b. Network Connectivity

Digital twins require bidirectional connectivity with their physical twins. Without connectivity, the digital twin would not be a "twin," it would just be a model. As a result, the adoption of digital twins within the DON may require changes in the DON's network connectivity technology. Previously unnetworked systems will need to be networked in order to connect with their digital twins. Moreover, connectivity throughput may need to be increased in order to allow for the additional network traffic created by the communication between digital twins and their physical twins. For example, the DON may need to upgrade aging telecommunications pathways with higher performance links (e.g., replacing copper with fiber).

c. Physics-based Models

Digital twins use the data they collect from the physical twin to maintain physics-based data models. These data models are then used to analyze/simulate past, current, or future operations of the system. However, simulations can be biased or limited due to the developer's perspectives (Winsberg, 2019). As a result, physics-based digital simulations could be incomplete based upon the DON's understanding of how the physical world operates and interacts with the DON's systems. Therefore, the adoption of digital twins may require the DON to continue to develop its understanding of how, why, and where its systems will operate in order to increase the capability of the corresponding simulations. For example, after significant undersea volcano activity in the Pacific Ocean, the DON may need to better understand how the salinity of water changes such that it can accurately simulate the effects of corrosion on a submarine operating in the Pacific Ocean.

d. Cloud Storage

Digital twins require the storage of large amounts of data. Furthermore, a single digital twin may need to be simultaneously accessed by multiple people and processes throughout the enterprise. According to the 2018 DOD Cloud Strategy, cloud storage provides a means of reliably hosting information for enterprise-wide access (Department of Defense, 2018c). As a result, the adoption of digital twins may require the DON to rely on cloud computer storage rather than local storage. The DON already employs cloud storage technology. However, the adoption of digital twins may limit the DON's flexibility to deploy non-cloud storage technologies in the future.

e. High-performance Computers

Digital twins can use high-fidelity physics-based simulations to predict the performance of the physical twin. These simulations are computationally intensive and require high-performance computer systems to run effectively (U.S. Geological Survey, n.d.). As a result, the adoption of the digital twins may require the DON to change how and where high-performance computers are deployed. Edge computing is the concept of moving computing power closer to the data source (International Business Machines Corporation, 2020). In the context of PLM, this means moving high-performance computers closer to operational platforms (e.g., ships, aircraft). For example, the computational demands of maintaining digital twins may require Gerald R. Ford-class aircraft carriers to acquire additional high-performance computers in order to better service the digital twins of the ship, the carrier's supporting ships (destroyers and cruises), and/or the aircraft onboard (F/A-18, E-2).

f. Augmented Reality (AR) and Virtual Reality (VR)

Digital twins can store data via 3D models instead of traditional documents (e.g., Portable Document Format (PDF)). The high information density of 3D models can make them difficult to view on traditional mediums such as computer monitors (Gorodov & Gubarev, 2013). As a result, the adoption of digital twins may require new technology such as augmented reality (AR) or virtual reality (VR) to effectively convey the information described by the data models.

g. *Machine Learning (ML)*

Digital twins maintain large amounts of data about the physical twin. The large amounts of data provided via data models can be difficult for humans to analyze quickly and effectively. However, machine learning (ML) has demonstrated a greater capability to quickly analyze data and identify meaningful trends (Sarker, 2021). As a result, the adoption of digital twins may require the DON to continue the development of its ML capability. Failure to do so could result in useful trends remaining unidentified by human analysts.

2. Summary

Technologies are often interdependent, and changes to an organization's technology can have an impact on the organization's other technologies. In the context of PLM, some of the technologies most affected by digital twins are:

1. Sensors
2. Network Connectivity
3. Physics-Based Models
4. Cloud Storage
5. High-Performance Computers
6. Augmented Reality (AR) and Virtual Reality (VR)
7. Machine Learning

These technologies are needed to produce, transfer, store, analyze, and display the data that digital twins require to operate as intended.

E. CYBER SECURITY

Digital twins have significant cyber security implications. Some are positive, while others are negative. This section will discuss some potential benefits to cyber security, followed by a discussion of potential risks. This analysis is founded upon the idea that cyber security efforts can be evaluated based upon their effect on the confidentiality, integrity, and availability (CIA) of an organization's cyber assets. See Figure 7 for a visual description of the "CIA triad" Cawthra et al. (2020, p.1).

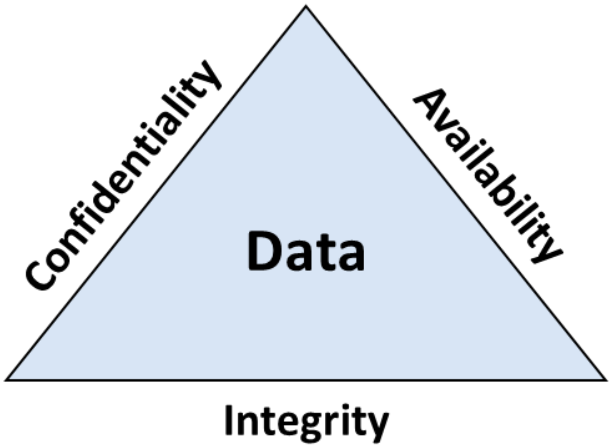


Figure 7. CIA Triad. Adapted from Cawthra et al. (2020).

Each of these factors of data, confidentiality, integrity, and availability, are fundamental components of cyber security operations (Cawthra et al., 2020). Confidentiality is "preserving authorized restrictions on information access and disclosure, including means for protecting personal privacy and proprietary information" (Dempsey et al., 2011, p. B-4). Confidentiality is valuable because it limits the access threat agents have to an organization's sensitive information. Integrity means "guarding against improper information modification or destruction and includes ensuring information non-repudiation and authenticity" (Barker, 2003, p. 16). Integrity is crucial because it helps to create trust in the data that is being produced by the systems in use. Without trust, the data's usefulness to the organization is reduced. Availability is the "timely, reliable access to data and information services for authorized users" (deZafra et al., 1998, p. C-3). Availability provides value because it ensures that the users who need the information can access it when needed. Without the reliable availability of data, the systems that are used in conjunction with the data are going to be less effective in support of operations.

Better understanding the effects of digital twins on the DON's cyber security is beneficial because the DON needs to be able to trust the data and systems it uses to operate.

The DON must also be able to ensure that the data is available when needed and that data is protected from being accessed or modified by threat agents. In order to help ensure this, the benefits and the risks associated with digital twins must be understood to allow for proper security measures to be developed to guard against potential threats.

1. Benefits

The principal benefit of digital twins in the context of cyber security is improved cyber resilience. NIST defines cyber resilience as “the ability to anticipate, withstand, recover from, and adapt to adverse conditions, stresses, attacks, or compromises on systems that use or are enabled by cyber resources” (Ross et al., 2021, p. 60). Cyber resiliency is intended to “reduce the mission, business, organizational, or sector risk of depending on cyber resources” (Ross et al., 2021, p. 2). Cyber resilience can be achieved and supported through a variety of activities enabled by digital twins.

a. Digital Twins Can Develop Individualized System Baselines of “Normal” System Performance

Heuristic analysis is often conducted to compare current system performance to a documented baseline of what a product’s “normal” operating behavior is like. This could include things such as an engine’s temperature or power output. However, if platform baselines are developed at a macro-level they may over-generalize. Although still valuable, heuristic analysis conducted against over-generalized product baselines may have an additional variance when compared to individual product baselines. Digital twins provide a means of maintaining and querying data of individual products. This individualized data can be used to develop and maintain individualized heuristics. Understanding what “normal” looks like provides cyber defense assets a means through which abnormal behavior can be discovered. Abnormal product behavior does not directly imply a problem, rather it indicates something that could benefit from further analysis.

For example, digital twins can keep a record of a turbine’s historical RPMs and environmental conditions. If a system’s turbine is operating faster than normal, despite other variables remaining constant, this behavior would deviate from the baseline and could warn the turbine’s operators that the turbine’s RPMs are being maliciously modified in an attempt to damage the system. The digital twin's capability to define these heuristics of a normal system would help to safeguard the integrity of the data received from the system.

b. Digital Twins Can Identify Which Platforms Have or Are Utilizing Compromised Components

In this context, compromised can be defined as "a violation of the security policy of a system in which unauthorized intentional or unintentional disclosure, modification, destruction, or loss of an object may have occurred" (Kuhn et al., 2001, p. 48). Component compromise can occur in two ways. First, threat agents can manufacture components that have intended vulnerabilities. Second, threat agents can discover unmitigated vulnerabilities in components that were intended to be secure. An integrated global economy has allowed national economies to specialize in the products it develops and outsource non-specialized products. Although the DOD seeks to screen its suppliers as much as possible, there are limits to what is feasible. An area of particular concern to the DOD is the potential for compromised computer chips to make their way into DOD products.

Compromised computer chips have the potential to leak DOD information to threat agents (Robertson & Riley, 2018). Compromised computer chips could also degrade, destroy, or otherwise compromise the DOD's computer-based systems (Robertson & Riley, 2018). Digital twins provide a means of querying data about a product. These queries can include data such as the identification of the system's past and current subcomponents. If a subcomponent of a DOD system is found to be compromised, digital twins could provide a means of identifying which products include the compromised components. If threat agents identify a vulnerable component and are able to compromise it, they could potentially disrupt the system operations or modify the data so that it should not be trusted. Identifying possibly compromised components can help to ensure both the integrity and availability of the data.

c. Digital Twins Can Provide a Means of Testing Patches and Pushing Updates

Many of the DON's modern products are hybrid products; being comprised of both physical and software products. For example, the F-35 is an airframe made of metal, but it also includes more than 25 million lines of computer code (Charette, 2012). As with almost all software, the DOD's software products need to be updated over time in order to add additional functionality and to close active vulnerabilities. Digital twins can facilitate software updates in three ways.

First, digital twins can provide a means of testing and validating software updates before they are released. Software updates are modifications to a product. As with all modifications, they should be tested before they are implemented to ensure that they produce the intended result without causing undesirable problems. This is especially important with complex systems where the effects of modifications are not easily predictable.

The extended time period required to develop and manufacture some of the DON's products such as its ships causes each ship to be unique despite coming from the same "blueprint." For example, although DDG-116 the Thomas Hunder and DDG-117 the Paul Ignatius both started construction in late 2015 (Naval Sea System Command Shipbuilding Support Office, n.d.-a); Naval Sea System Command Shipbuilding Support Office, n.d.-b) and are both currently homeported in Mayport that does not indicate they are identical ships. The potential inconsistencies in the product baselines of these two ships make testing essential. Digital twins provide a means by which the current configuration of a product can be queried; thereby helping to confirm if a software update is appropriate. Digital twins also provide a means of conducting digital simulations. These digital simulations could be used to test the results of the software update.

Second, digital twins can provide a means of pushing software updates to active products. Digital twins maintain a bi-directional connection between the virtual twin and the physical twin. The connections from the virtual twin to the physical twin could be utilized to push software updates. The connection from the physical twin to the virtual twin could then be used to confirm the software update was successfully completed.

Thirdly, Digital twins can provide a means of referencing the current software version of the organization's active products. Even urgent software updates sometimes need to be delayed. The ability to query the current software versions of the organization's products allows product managers to validate that software updates are occurring as needed.

d. Digital Twins Can Provide a Means of Penetration Testing

Penetration tests are authorized cyberattacks on a computer system (Scarfone et al., 2008). Penetration tests are conducted in order to evaluate the cyber security of a product. Upon completion of penetration tests, product owners are better equipped to identify the cyber security strengths and weaknesses of their products. Penetration testing can also provide a means of identifying previously unknown vulnerabilities also known as "zero-day vulnerabilities." Understanding a system's weaknesses is a crucial first step in mitigating the vulnerabilities they cause.

Traditionally, penetration tests are conducted against the real product. Digital twins provide a means of simulating actions against the virtual twin instead of against the physical twin. By conducting virtual penetration tests on the virtual twin instead of the physical twin, impacts on real-world operations are minimized. Products can remain in the operation rather than being sequestered for testing.

Penetration tests are also one of the few defense techniques that organizations can employ to prevent supply chain attacks (Holmes et al., 2021). A supply chain attack is when threat actors compromise a network via trusted third parties rather than directly (Holmes et al., 2021). For example, in 2020 a malicious actor used SolarWinds, a trusted third-party software used to help manage networks, to compromise the networks of 18,000 customers including the United States government (Jaikaran, 2021). As the DON continues to increase its reliance on third-party support, it increases its risk of supply chain attacks. By increasing the DON's ability to conduct testing and patching on a system, digital twins help to guarantee the availability of the data when it is needed.

2. Risks

Although digital twins have the ability to provide cyber-related benefits, they also can potentially create cyber-related risks. NIST defines risk as "a measure of the extent to which an entity is threatened by a potential circumstance or event, and typically a function of: (i) the adverse impacts that would arise if the circumstance or event occurs; and (ii) the likelihood of occurrence" (Joint Task Force Transformation Initiative, 2012, p. 6). While these risks are not guaranteed to occur or produce negative effects, they must be properly identified, analyzed, and planned for in order to mitigate the effects that they could have on DON systems.

a. Digital Twins Increase the DON's Cyber-attack Surface

A cyber-attack surface is the "set of points on the boundary of a system, a system element, or an environment where an attacker can try to enter, cause an effect on, or extract data from" (Ross et al., 2021, p. 57). The greater the set of points the larger the cyber-attack surface (Ross et al., 2021). A large cyber-attack surface is undesirable because it represents more attack vectors that threat agents can exploit and that must be protected by an organization. By creating virtual twins of physical systems and networking them, the DON's cyber-attack surface will increase. Although digital twins do not create a directly negative effect on a network, they do increase the risk of cyber-attack. This risk could be exploited to attack the digital twins or used as an entry point and means of attacking the larger enterprise network.

The DON relies on its platforms, such as ships and aircraft, to conduct operations and accomplish its mission. When evaluating systems that would benefit from a digital twin, the DON is likely to use them to support *critical assets*. Critical assets are the essential resources that an organization needs to achieve its mission (Cybersecurity & Security Agency, n.d.). Additionally, digital twins can act as AKSs. If a digital twin is compromised by a threat agent, it can then serve as a blueprint of how to develop the technology and could enable them to reverse engineer the system to use for themselves or to identify vulnerabilities that could be exploited (Walsh, 2019). Due to these factors, digital twins can be high payoff targets for enemy cyber-attacks (Walsh, 2019).

Historically, the United States military has heavily relied on technology to provide a relative advantage in warfare (Garamone, 2018). Digital twins are intentionally detailed so that they can provide additional insight into how to maintain and operate the physical twin. If compromised by a threat agent, the digital twin's data could provide this insight to the DON's adversaries. These insights could reduce the DON's relative technical advantage in multiple ways.

First, adversaries could use the insights gained to better understand the system's technical limitations. For example, an aircraft's maximum speed, a missile's maximum range, or a generator's maximum output. Second, competitors could use the insights gained to employ or reengineer weapons systems capable of exploiting the vulnerabilities of the DON's systems. For example, in *Star Wars: Episode IV - A New Hope*, the Rebel Alliance uses a stolen schematic of the Death Start to identify a critical weakness in the thermal exhaust port that could be used to destroy the entire station (Lucas, 1977). Finally, competitors could use the insights gained to build their own systems using the information gained. Not only could this enable them to field systems comparable to the DON's, but competitors could do so without the cost typically associated with research and development. As a result, the competitor's monetary resources could be used to gain or maintain a relative advantage elsewhere.

The potential for threat agents to access the design of the DON's current systems is a risk that already exists. However, digital twins puts all the information in one place which could make it easier to exploit. Digital twins also provide greater details beyond just the design of the system to include detail of the system's current operational readiness. While the DON already has certain cyber security requirements to protect its current architecture, traditional methods of security such as hardware security and air gapping may not work on digital twins (Walsh, 2019). If not addressed and properly secured, this increased threat surface could be detrimental to the DON.

For example, the Air Force planned to make digital twins of their aircraft (Brackens, 2021). Prior to the implementation of digital twins, the attack concerns for these assets will have been greatest when they were flying missions in enemy spaces and lowest when they were at their home station. Now that there is a virtual twin of this critical asset, they could now be attacked in the cyber domain to allow a threat agent to either compromise or monitor these assets. Digital twins aggregate data about a system. This data can include both how the system was developed as well as how it is currently operating. This would provide threat agents greater knowledge of our systems and could potentially allow for them to be compromised to the point that they could not be trusted to execute missions, rendering them useless. This risk highlights a concern for both the confidentiality and integrity of sensitive data.

b. *Digital Twins Can Be Compromised to Provide Threat Agents with Position, Location, Information (PLI) Data*

Intelligence is critical to military operations (United States Marine Corps, 2003). In a conflict between two adversaries, the opponent with the most complete intelligence will acquire a relative advantage in the conflict. Position, location, information (PLI) data provides both the location and operational status of military platforms. While this information is vital to a commander making a decision regarding their own forces, it is also valuable to an enemy force when assessing the current strength and weakness of an adversary's forces.

Digital twins can store PLI data which includes where a system is located and key information about the system (maintenance readiness, fuel, armament). If adversaries gained access to a digital twin, it could help them to strike where the DON's forces are most vulnerable or avoid DON forces altogether. This could significantly degrade the DON's ability to perform its primary mission "to win conflicts and wars while maintaining security and deterrence through sustained forward presence" (United States Navy, n.d.). If not properly secured, this could compromise the confidentiality of the data and provide an advantage to adversaries.

c. *Digital Twins Can Expand the Scope of Users That Can Access Data on the DON's Platforms*

Digital twins can reduce silos and integrate data throughout the enterprise. Digital twins accomplish this through aggregating product data from multiple enterprise roles (e.g., designer, maintainer, operator, contractors). By reducing silos, the boundaries that previously isolated sensitive product data have also been reduced. When securing data, confidentiality has traditionally been achieved by restricting the number of users that can access sensitive information. If role-based access is not properly managed, there is a risk that sensitive product data could be acquired by users without the authorization or need to know.

For example, in 2010 a former U.S. engineer was caught selling designs of military aircraft propulsion systems to China (Bowes, 2010). If the government had employed digital twins at that time, then this engineer would have likely had access to one so that they could perform their duties. If the digital twins did not have proper role-based access controls in place, then the engineer could have used their trusted access to obtain additional design information which could have led to greater compromise of the platform.

3. Summary

The changes caused by the adoption of digital twins have significant cyber security implications. Some of these changes provide value in the cyber domain while others create cyber risks which must be addressed. Ensuring cyber security helps to enable trust in DON systems which is desired when operationally employing systems in complex environments. Each of these benefits and risks can also impact the confidentiality, integrity, and availability of the system and its data. In the context of cyber security, digital twins provide value by increasing the cyber resiliency of the DON's systems. Cyber resiliency can be increased by leveraging digital twins' capability to simulate attacks, develop heuristics, track compromised components, facilitate patching, and conducting penetration tests. digital twins create risks by increasing the cyber-attack surface, maintaining PLI data, and expanding the scope of users with potential access to sensitive data.

F. RISK MANAGEMENT

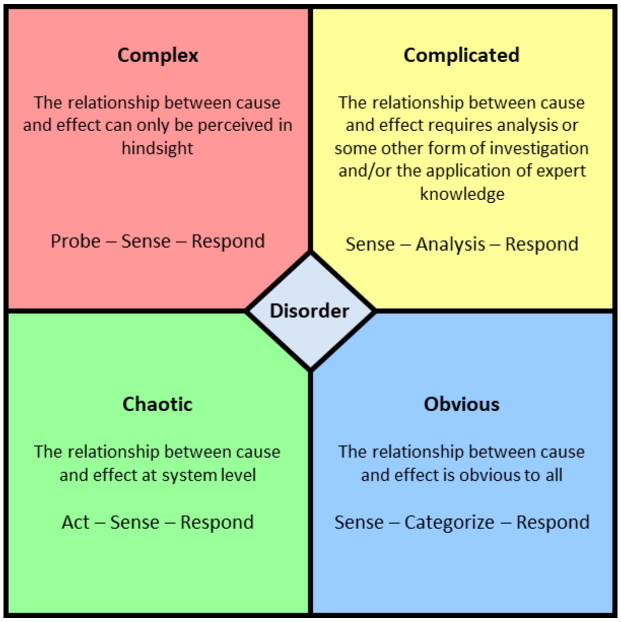
Risk can generally be defined as a "measure of the extent to which an entity is threatened by a potential circumstance or event" (Joint Task Force Transformation Initiative [JTFTI], 2012, p. 6). Risk is a function of "(i) the adverse impacts that would arise if the circumstance or event occurs; and (ii) the likelihood of occurrence" (JTFTI, 2012, p. 6). However, the specific implications of the term "risk" depends upon the context it is being used. For example, risk in a cyber security context refers to "the probability that a particular security threat will exploit a system vulnerability" (deZafra et al., 1998, p. C-7). Risk compromises the confidentiality, integrity, or availability of data (deZafra et al., 1998). While risk in a product management context refers to a measure of the "future uncertainties relating to achieving program technical performance goals within defined cost and schedule constraints" (ODASD(SE), 2014, p. 3).

Risk is generally undesirable because when manifested it can force deviations from planned and/or anticipated outcomes. The manifestation of risk in DON platforms can result in system degradation or system failure. Inhibited system performance can negatively impact mission outcomes and potentially lead to loss of life. The DON conducts risk management in order to attempt to mitigate or avoid the negative impacts of risks.

Before risk can be managed, risk managers must first "make sense" of what they are examining so they can make decisions. The Cynefin Framework is a "sense making device" that provides five decision-making contexts: Obvious, Complicated, Complex, Chaotic, and Disorder (Hasan & Kazlauskas, 2009). See Figure 8 for a visual depiction of the Cynefin Framework and its five domains. See Figure 9 for a Known and Unknown Quad Chart.

- Obvious = "Known Knowns (Things we are aware of and understand)" (Dang, 2021)
- Complicated = "Known Unknowns (Things we are aware of but don't understand)" (Dang, 2021)
- Complex = "Unknown Unknowns (Things we are neither aware of nor understand)" (Dang, 2021)
- Chaos = "Unknown Knowns (Things we understand but are not aware of)" (Dang, 2021)

- Disorder = “Destructive state of not knowing what type of causality exists” (Hasan & Kazlauskas, 2009, p. 7)



Complex

The relationship between cause and effect can only be perceived in hindsight

Probe – Sense – Respond

Complicated

The relationship between cause and effect requires analysis or some other form of investigation and/or the application of expert knowledge

Sense – Analysis – Respond

Disorder

Chaotic

The relationship between cause and effect at system level

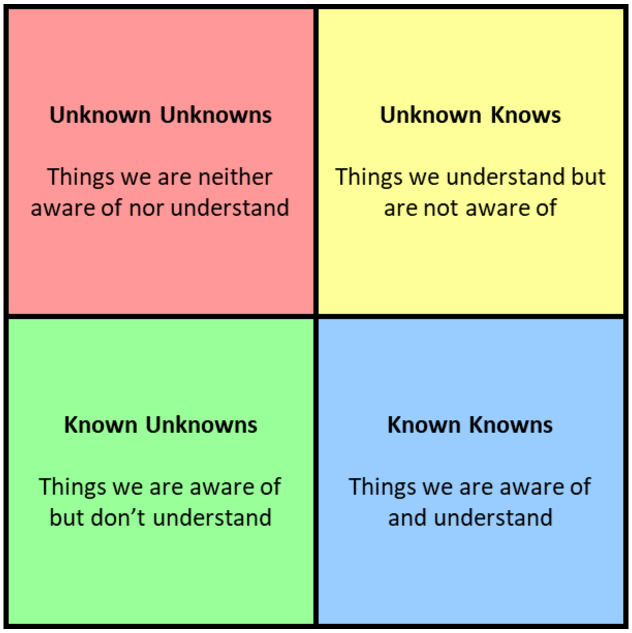
Act – Sense – Respond

Obvious

The relationship between cause and effect is obvious to all

Sense – Categorize – Respond

Figure 8. Cynefin Framework. Adapted from TXM Lean Solutions (2017).



Unknown Unknowns

Things we are neither aware of nor understand

Unknown Knows

Things we understand but are not aware of

Known Unknowns

Things we are aware of but don’t understand

Known Knowns

Things we are aware of and understand

Figure 9. Known Unknown Quad Chart. Adapted from Dang (2021).

According to the Cynefin Framework, decision-makers should employ different tests to identify cause and effect relationships based upon the context of the decision. For example, when making decisions in an obvious context, decision-makers should first sense, then categorize, and finally, respond. However, if the decision is in a complex context, then the decision-maker should first probe, then sense, and finally, respond. Through the application of this framework, risk managers can more effectively make sense of the products they manage and are better prepared to manage associated risk as a result.

This leads us to the concept of complexity. The meaning of “complexity” is often debated (Biggiero, 2001). For the purposes of this thesis, there are two types of complexity: Extrinsic Complexity and Intrinsic Complexity.

Extrinsic Complexity is based on human perception. Since this type of complexity is based upon human perception it is subjective rather than objective. Due to its subjectivity, extrinsic complexity can be reduced through modifications of the observer’s understanding. For example, in 1345, during the Bubonic Plaque, early doctors blamed the sickness on a “great pestilence in the air” caused by the conjunction of the planets Mars and Jupiter (Horrox, 1994). Later germ theory was developed which explained the situation and reduced the extrinsic complexity relative to informed observers.

Intrinsic Complexity on the other hand is based upon the interactions and couplings of a system (Perrow, 1999). Unlike extrinsic complexity, intrinsic complexity can be measured and is therefore objective. Intrinsic complexity can only be reduced through changes to the system’s design. For example, by consolidating a web application’s file storage from multiple specialized databases to a single more generalized database the intrinsic complexity of the web application could be reduced.

Both Extrinsic and Intrinsic Complexity are a range rather than a definitive state. The Cynefin framework demonstrates that perceived complexity ranges from obvious (previously simple), to complicated, to complex, to chaos (Kazlauskas & Hasan, 2009). Similarly, the intrinsic complexity of products can range from simple, to complicated, to complex (Grieves & Vickers, 2017).

The DON relies on intrinsically complex system-of-systems such as ships and aircraft to accomplish its mission. Intrinsically complex systems are desired because they can provide more capability relative to systems with less intrinsic complexity (Reeves et al., 2020).

For example, consider the USS Constitution to the USS Zumwalt. As of 2022, both are U.S. Navy ships in active-duty status. A comparison of interactions and coupling of these two platforms reveals that the USS Constitution, although not necessarily simple, is measurably less inherently complex than the USS Zumwalt. As a result of the additional inherent complexity, the USS Zumwalt is a more capable warfighting platform.

1. Emergent Behavior of Complex Systems

Intrinsically complex systems have the capacity for emergent behavior (Grieves & Vickers, 2017). Emergent behavior is the result of the relationship between system components. Emergent behavior can be both desirable and undesirable depending upon the system's intended purpose.

For an example of a desirable emergent behavior, consider a radar system that is comprised of multiple radar arrays. Individually, each array is capable of using radio waves to determine the distance and velocity of an object. However, because each array cannot transmit and receive at the same time it is capable of detecting objects at short-range or long-range, but not both simultaneously (Toomay & Hannen, 2004). By coordinating multiple arrays, a radar system is capable of simultaneously detecting objects at both short-range and long-range. In a military context, this emergent behavior is desirable because the capability to simultaneously detect objects at multiple ranges allows a military force to maintain better awareness of its physical environment.

For an example of undesirable emergent behavior, consider the same radar system as before. However, this time the radar system fails to coordinate its multiple arrays and they all transmit radio waves at the same time and at the same frequency. This could result in destructive interference and as a result, the ability of each array to detect objects is reduced (Toomay & Hannen, 2004). In a military context, this emergent behavior is undesirable because the radar's limited capability to detect objects reduces a military force's ability to maintain awareness of its physical environment.

Emergent behavior gives rise to the general observation that systems are greater than the sum of their parts (Bar-yam, 2018). In the context of military operations, emergent behavior could be desirable if it can lead to increased system capability. For instance, behavior that reduces a platform's ability to be detected by an adversary. This is because increased system capability is necessary to maintain a relative advantage against competitors capable of fielding similar platforms.

In the context of military operations, emergent behavior could be undesirable if it limits the system's ability to execute its desired mission. For example, behavior that requires the platform to need to be restarted every 24 hours. This is because additional system limitations provide competitors opportunities to acquire an advantage.

In systems with high intrinsic complexity, the number of component states and interrelationships is so large that potential emergent behavior may manifest infrequently. As a result, emergent behavior in intrinsically complex systems is often unexpected and therefore not planned for. This innate unpredictability of intrinsically complex systems creates risks throughout the product's lifecycle (Grieves & Vickers, 2017).

Not all emergent behavior is desirable. However, if an undesired emergent behavior can be reliably predicted then risk managers can manage the risk that it represents (Grieves & Vickers, 2017). If the predictable undesired emergent behavior is significant enough, then system redesign may be necessary.

Unpredicted undesired emergent behavior represents a more significant risk to programs because this risk goes unaccounted for (Grieves & Vickers, 2017). In order to be accounted for, the undesired emergent behaviors must first be identified. Digital twins can equip risk managers to identify unpredicted undesired emergent behavior, thus setting conditions for determining the likelihood of the behavior. When the undesired emergent behavior becomes more predictable it also becomes more manageable. Digital twins can facilitate the identification of unpredicted undesired emergent behavior by simulating a wide variety of system states and by testing each of those system states multiple times.

With other tools, emergent behavior can be difficult to identify because it cannot be discovered by looking at the parts individually; a process known as "reductionism" (Bar-yam, 2018). Instead, the parts must be examined in the context of the system as a whole (Bar-yam, 2018). By simulating both the entire physical twin (e.g., ship) as well as the twin's operating environment (e.g., ocean), digital twins are able to examine the system as a whole.

The simulations enabled through digital twins enables a better understanding of the physical twin system. By better understanding the physical twin system, the extrinsic complexity of the system to risk managers can be reduced. If the extrinsic complexity perceived by the risk manager is sufficiently reduced, then risk managers may be able to "make sense of" their decisions in a different Cynefin context than previously possible. For example, a decision once made in a "complex" context could potentially be made in a "complicated" context. By shifting the context in which risk managers make decisions, they are able to use different decision-making processes. For example, instead of identifying cause and effect via "probe, sense, respond" (which Cynefin directs for complex contexts), it could be identified via "sense, analyze, respond" (which Cynefin directs for complicated contexts). "Sense" may be preferred over "probe" as the initial action because sensing can be done passively, whereas probing must be done actively. Passive actions require fewer resources (time, energy, money, people) which can be advantageous.

2. Product Lifecycle Risk Management

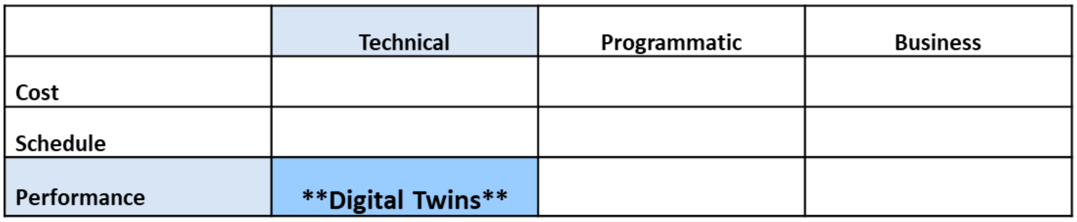
Regardless of the complexity level of a product, Risk management is an important part of product lifecycle management. The DOD program management community defines risk as "potential future events or conditions that may have a negative effect on achieving program objectives for cost, schedule, and performance" (ODASD(SE), 2017). The three objectives of cost, schedule, and performance are tightly coupled and as a result, a negative effect on any of the three objectives will often impose changes in the remaining two objectives (Rendon & Snider, 2019). Moreover, failure to deliver on any of the three objectives can negatively affect the DON. These objectives can impact the DON and projects in the following aspects:

- Cost: The DON operates on a finite budget set annually by Congress. If a program fails to meet completion within the allocated funds available, those funds will have to be taken from somewhere else within the DON in order for the platform to be completed within the desired schedule and performance standards.
- Schedule: DON platforms are interdependent with other DON functions to include training programs and organizational structure. These other DON functions are planned around expected platform completion timelines. If a platform fails to reach completion on time, the DON's interdependent functions may be negatively impacted. Additionally, if one aspect of a project falls behind (e.g., software development and testing) it will cause delays throughout the entire project further impacting DON functions.
- Performance: The requirements of DON platforms are based upon the DON's strategy and operating environment. If a program fails to deliver on all of the defined platform requirements, then the platform may be less valuable in support of DON operations.

In the DON, program managers are responsible for overseeing the entire lifecycle of a product (Rendon & Snider, 2019). A key responsibility of program managers is risk management (ODASD(SE), 2017). Risk is highest at the beginning of the lifecycle; this is when the most uncertainty exists in the program (Rendon & Snider, 2019). Program managers must identify, and control risks as the program matures through its lifecycle.

DOD Program managers have objectives for the program's cost, schedule, and performance (ODASD(SE), 2017). Risk impacts are measured against these three objectives. Of these three impacts, digital twin is most helpful in assessing impacts on a program's performance.

Acquisition risks with performance impacts are grouped broadly into three categories: technical, programmatic, and business (ODASD(SE), 2017). Based upon the tools that DTs provide (e.g., models, simulations, AI/ML) DTs can help with technical risk (system behavior). Thus, out of DON's risk categories, digital twins are best positioned to facilitate the management of technical performance risk. See Figure 10 for a visual description of which risk category digital twins would be best applied.



	Technical	Programmatic	Business
Cost			
Schedule			
Performance	****Digital Twins****		

Figure 10. DOD Risk Categories

The Risk Management Process for DOD Acquisitions consists of four repeating steps: (1) Risk Identification, (2) Risk Analysis, (3) Risk Mitigation, and (4) Risk monitoring (ODASD(SE), 2014). See Figure 11 for a visual depiction. Digital twins can provide value to program managers during the Risk Identification and Risk Analysis steps.

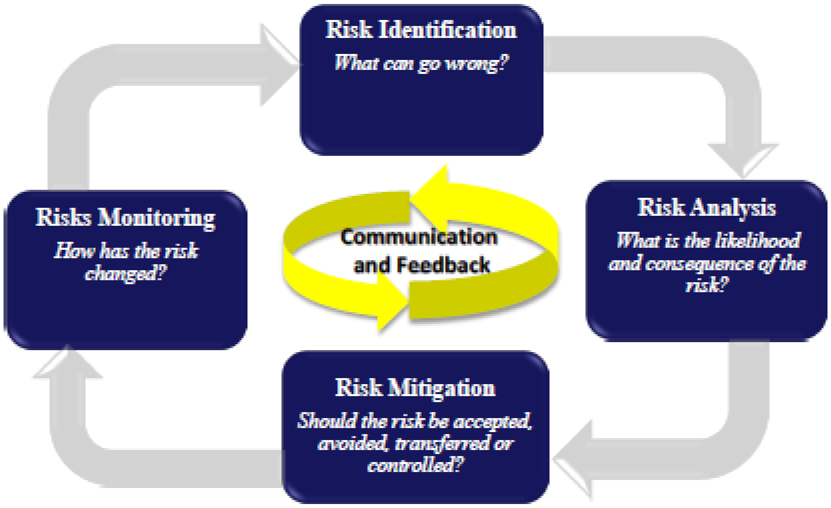


Figure 11. Risk Management Process for DOD Acquisitions. Source: ODASD(SE) (2014, p.19).

The Risk Identifications step seeks to discover "what can go wrong?" (ODASD(SE), 2014). Risk identification is accomplished by evaluating technical facets of the program to determine root causes of risk events that may have an undesirable impact on cost, performance, or schedule (ODASD(SE), 2014). The Risk Analysis Step seeks to discover "how big is the risk?" (ODASD(SE), 2014). This step involves further examining the risk identified in the previous step. This step refines the probability and consequence of the risk. The following is an example of how digital twins could facilitate the identification and analysis of technical performance risk in a DON ship program.

During the Risk Identification phase, the simulations provided via the ship's digital twin can be used to determine the root cause of potential failures. Depending on the fidelity of the digital twin's models, this could include subcomponent causes (e.g., circuit panel failure when two systems are operated simultaneously), environmental causes (e.g., sea state 4 conditions), or manmade causes (e.g., an oil spill in the ship's galley).

Then, during the Risk Analysis phase, the simulations provided via the ship's digital twin can be used to determine a probability of occurrence for root causes previously identified (e.g., event occurred in 1 out of 250 simulations). Risk assessments are probability-based. The machine learning (ML) capability of digital twins can conduct automated statistical learning and then determine risk probabilities more consistently and with less effort than humans (Vapnik, 1999). However, trained humans may still need to validate what the digital twin's ML recommends. Next, physics-based models provided via the ship's digital twin can provide insight into what happens when a risk event occurs (e.g., the event results in 2-inch stress fractures in the ship's keel)

3. Summary

Uncertainty is generally dealt with by a means of information acquisition. Digital twins are fundamentally information tools and can help provide risk managers with the information needed to make informed decisions. The DON employs intrinsically complex systems because of their relative advantage over systems that are less intrinsically complex. However, intrinsically complex systems have the potential for emergent behavior which can create risk throughout the product lifecycle. A digital twin's ability to simulate both an entire physical twin (e.g., ship) as well as the twin's operating environment (e.g., ocean), provides risk managers a means of identifying and predicting undesirable emergent behaviors. Once undesirable emergent behaviors are identified, risk managers can begin to manage their associated risk.

Risk management begins with "sense-making." Digital twins provide risk managers with an improved means of "making sense" of the physical twin. By better understanding the context in which they are making decisions, risk managers could be enabled to employ different decision-making processes. If decision-makers are enabled to identify cause and effect via "sense, analyze, respond" (which Cynefin directs for complicated contexts) instead of "probe, sense, respond" (which Cynefin directs for complex contexts) they may be able, to begin with passive "sensing" rather than active "probing." Passive actions require fewer resources (time, energy, money, human) which can be advantageous.

Of the DOD's risk categories, digital twins are best equipped to support the management of risk to technical performance. When used in the DOD's Risk Management Process, digital twins can assist risk managers in discovering "what can go wrong" during the Risk Identification step. Digital twins can then assist risk managers in determining the likelihood and consequence of those risks during the Risk Analysis step.

G. BUSINESS VALUE

Digital twin is not an engineering concept, it is a project management concept. The goal of project management is to deliver business value. However, what constitutes "business value" depends upon the organization. Unlike many private organizations, the DON does not exist solely to manage projects. That said, the DON is dependent on projects (the unique platforms it develops) to maintain a competitive advantage. Digital twins provide a means of managing the DON's products (e.g., ship, aircraft) and therefore maintaining a competitive advantage.

1. Value Provided by Digital Twins

Digital twins can provide non-financial business value to the DON throughout all phases of the product lifecycle. The specific phases of the product lifecycle depend upon the needs of the organization. For the purpose of this research, there are four sequential product lifecycle phases: (1) design, (2) build, (3) operate, and (4) dispose (Grieves & Vickers, 2017).

a. Non-Financial Value Delivered during Design Phase

During the design phase of the product lifecycle, digital twins provide three key values to the DON. First, digital twins can provide the DON with a means of better understanding the physical twin's operational environment. This value is accessible because digital twins are capable of sensing, modeling, and simulating the environment as well as how the physical twin will react or operate in this environment. Understanding the environment is valuable to the DON because good strategy is based upon a better understanding of the dynamics of the environment. In a competition, the competitor with a better understanding of the environment has an advantage when developing strategy. The DON's strategy helps to determine the defined requirements of its new systems. Thus, understanding the environment will help the DON to design products (e.g., ship, aircraft) that are capable of providing a relative advantage against its competitors. A better understanding of the environment also helps the DON reduce and manage the risk that unforeseen environmental factors will have on the performance of its platforms. For example, a known challenge in the communication community is for satellite communication systems operating above the arctic circle. Due to the extreme northern location of that region, it is a challenge to be able to connect to satellites. Most military satellites that would be used require such a severe takeoff angle that most systems are essentially pointing into the ground which does not allow them to connect. Additionally, the extreme cold of the region adds additional challenges to the operation of the systems. This is an important challenge to overcome when considering our nation's adversaries. Utilizing a digital twin during the development of a new system could allow for cost savings and faster testing. The environmental factors and satellite locations could be programmed into the testing environment. This would allow for prototypes to be developed and tested locally vice the current testing which is completed by having service members go to this region, test the systems, and then provide feedback for corrections that need to be made.

Second, digital twins can provide the DON with a means of collecting, accessing, and achieving the requirements of the system being designed. Large DOD projects (acquisition category (ACAT) I and II) often have broad effects on the service and as a result, have a large number of stakeholders. Maintaining an up-to-date collection of requirements from all the stakeholders is vital to ensuring that the final system can deliver measurable organizational value (MOV). Changes to a system's requirements can have effects on the cost and schedule of the design process. Maintaining an archive of historical requirements can facilitate the justification of new baselines when necessary. As a result, digital twins can reduce the risk of the final product not meeting stakeholder needs. As an example, consider the development of the Bradley Fighting Vehicle which took approximately 30 years and billions of dollars to develop (Burton, 1993). Although there were many factors that impacted this vehicle's development, one key factor was changes in the development of the system's requirements. According to the book *The Pentagon Wars* by Col James Burton (Retired), when he joined the program at the 17-year mark, the program had already spent $14 billion in development (Burton, 2014). Throughout those 17 years, there had been constant requirement changes with no real way to manage, evaluate the feasibility of, or update the different stakeholders of the changes (Burton, 2014). Additionally, due to the long development timeline, there had been multiple changes in the personnel due to the rotational nature of the military. This further exacerbated the challenge of managing requirements and ensuring that all aspects of integrating this system were possible. In today's acquisition process, a digital twin could be used to consolidate all requirements past and present and provide one location for all stakeholders to find and review these requirements to lead to a more efficient and effectively designed system.

Third, digital twins can provide DON program offices with a means of interacting with stakeholders to confirm and refine requirements as the program matures. Agile development methodologies have demonstrated the value of frequent stakeholder involvement while conducting iterative development. However, it can be difficult to facilitate large-scale customer involvement for hardware systems. The digital models provided via digital twins can overcome these limitations and provide a means through which stakeholders can observe the iterative development of hardware systems. As a result of more frequent stakeholder feedback, the final system is more likely to meet stakeholder needs. For example, consider the expeditionary fighting vehicle (EFV) program that the USMC canceled in 2012 after 16 years of development (Committee on Oversight and Government Reform, 2008). In 2006, an operational assessment of the EFV found multiple problems to include excessive weight, excessive noise, limited visibility, and low reliability (Committee on Oversight and Government Reform, 2008). Had digital twins been available and utilized during the development of the EFV, perhaps additional USMC stakeholders could have been involved at a greater scale and frequency, thus reducing the issues that resulted in program failure.

b. Non-Financial Value Delivered during Build Phase

After the physical twin has been designed, digital twins continue to provide value during the build phase of the product lifecycle. First, digital twins can provide the DON with a means of reducing its need for physical prototypes. Historically, physical prototypes have been crucial in ensuring that the final product will perform as expected. However, physical prototypes can be costly and time-consuming to develop. The digital models and simulations accessible via digital twins provide an alternative means of testing and evaluating new systems. Product evaluations conducted via digital models can be conducted in greater breadth and quantity than evaluations via physical prototypes. By testing more product states, life-threatening risks are more likely to be identified. For example, the digital twin of an LCU 1700 could be used to test how the platform performs in various sea states, load capacities, and beach conditions.

Second, by providing a single AKS throughout the build phase of the product, digital twins can facilitate or force the integration of disparate knowledge domains. The sooner and more consistently that disparate domains can be integrated, the less likely it is that there will be unforeseen complications when the final product is assembled. As a result, system builders may be able to reduce trial and error manufacturing. For example, the digital twin of a new ship could be used to deconflict where electrical, water, fuel, and fiber pathways are run.

c. Non-Financial Value Delivered during Operate Phase

After the physical twin has been built, the value delivered by digital twins during the operate phase can be categorized into three areas: the operation of the physical twin, the maintenance of the physical twin, and the supply of the physical twin.

Digital twins can provide value by monitoring the operations of the physical twin and predicting future states of the system. If an undesirable state is likely in the future, the digital twin can warn the operators of the physical twin so that they can intervene. For example, the digital twin of an oil platform could use its models to predict if a rupture is likely. If a rupture is likely, operators of the oil platform could temporarily reduce speed or pressure in order to avoid a catastrophic failure.

Digital twins model the operations and performance of the physical twin. These models can be used to optimize the performance of the physical twin towards a specific goal or outcome. For example, the digital twin of an engine could be used to determine the parameters needed to achieve optimal fuel efficiency or optimal power output.

Digital twins can maintain a complete and up-to-date model of the physical twin. These models can be used during corrective and preventative maintenance processes to determine how to maintain the physical twin more effectively or efficiently. For example, the digital twin of an SH-60 helicopter could potentially be used to identify a means of extending the lifespan of its rotor blades.

Digital twins can be used to support the modification or retrofit of a physical twin in the operational phase of its lifecycle. Instead of conducting in-person inspections, system designers can inspect the up-to-date models of the physical twin. Designers can use the knowledge gleaned from the models to develop any necessary modifications. For example, the digital twin of a Wind-class icebreaker could be used by system designers to plan and develop an engine modification from Virginia while the ships themselves remain in operations in the Arctic Ocean.

Digital twins maintain a history of the physical twin. This history can include the history of individual parts as well. Suppliers of the physical twin can use this history to predict future supply requirements. For example, a logistics planner for a marine expeditionary unit (MEU) could use the digital twins of the MEU’s light armed vehicles (LAVs) to predict the quantity of petroleum, oil, and lubricants (POL) that should be ordered during the next resupply.

d. Non-Financial Value Delivered during Dispose Phase

When the physical twin is removed from operations, it no longer provides value to the organization. Digital twins on the other hand continue to provide value during the disposal phase of the product lifecycle. This is because data is immortal. The data collected and maintained by the digital twin can be used as long as the organization wants it.

First, when acting as an AKS, digital twins can provide tactical units with a single clear source of instruction on how and when to dispose of the physical twin. Clear disposition plans will provide tactical units with a means of more rapidly disposing of obsolete equipment; thus, providing them more time to manage the equipment essential to their current operations. For example, the USMC is currently in the process of replacing a portion of this high mobility multipurpose wheeled vehicle (HMMWV) fleet with joint light tactical vehicles (JLTVs). However, USMC units are ineligible to receive their new JLTVs until their HHMWVs have been properly disposed of. The exact disposal instructions of a HMMWV can vary based upon the type and series of the HMMWV, thus providing a source of potential confusion and delay. If the USMC had digital twins for each of his HMMWV, they could be used to distribute clear disposal guidance based upon the characters of each specific HMMWV.

Second, by maintaining a complete history of the physical twin, digital twins can provide the organization with an understanding of how the system was designed. By understanding how the system was designed, the organization can prepare to retire the system as safely as possible. These safety processes could protect the health of the organization's workforce and the environment. For example, between 1930 and 1990, asbestos was commonly used to provide fireproofing insulation for navy ships. The DON now recognizes that exposure to asbestos can have negative health effects (Office of Public Health, 2013). If the Navy had digital twins of these ships, they could be used to confirm the details of how and where asbestos was used to develop the ship. Knowledge of these details could help the Navy to dispose of the old platforms more safely.

Third, the digital artifacts stored by the digital twin can be used to obtain an improved understanding of the physical twin if it is ever reactivated. Rather than being buried in a landfill or converted into scrap, many DON platforms to include ships and aircraft are simply "mothballed." When older platforms are reactivated, they can present problems to the operators who have been trained and accustomed to working on newer equipment. The digital artifacts retained by the platform's digital twin may provide the operators the insight needed to effectively operate the platform. For example, in the 1980s, the Navy desired to increase the size of its fleet as part of its Cold War strategy. This included the reactivation of four Iowa class battleships that had originally been built in the 1940s. Had digital twins been present at the time, they could have assisted the crews of these ships to get them operationally ready.

Fourth, the data retained by the digital twins of retired systems can be harvested and used to aid in the design and operation of future systems. The operational data accrued over the life of the physical twin does not become irrelevant just because the physical twin is no longer in service. This data, which could include a history of environmental conditions or common maintenance defects, could be useful in creating replacement systems. For example, the USMC is currently in the process of replacing the AV-8Bs in its marine attack squadrons (VMAs) with F-35Bs. If the USMC had digital twins of its remaining AV-8Bs, the data they collect over their last few years of active service would still be relevant to the F-35B program.

2. Costs Created by Digital Twins

To fully understand the potential value of a product, the associated costs must also be considered. Costs are the resources an organization must expend in order to acquire and utilize something. As with almost all changes to enterprise architecture, the adoption of digital twins also generates costs for the DON. These costs include both financial (e.g., money) and non-financial resources (e.g., humans, time, effort)

a. Financial Cost

The adoption of digital twins will have upfront financial costs. Financial costs are especially significant to the DON because revenue cannot be generated and instead the DON operates from a fixed budget which is established annually. If the DON invests its finite budget into adopting digital twins, it will have less budget to allocate towards other initiatives or requirements. These fiscal costs could be significant if the technology is adopted in the near future before the technology has become more diffused in industry. The fiscal costs per unit of a new technology are usually highest for the "Innovators" and "Early Adopters" who onboard the technology early in the technology diffusion process (Rogers, 2003). Costs are usually higher in this phase of the technology diffusion lifecycle because production capacity and technology literacy are relatively low compared to later stages of the lifecycle.

Digital twins could also require the DON to commit additional financial resources to the supporting technologies that digital twins rely upon. For example, the adoption of digital twins may require the DON to purchase more IoT sensors. The adoption of digital twins could also require the DON to purchase additional cloud storage.

b. Non-Financial Cost

The adoption of digital twins will also generate non-financial costs as the DON's enterprise architecture is altered. Change requires the expenditure of resources (e.g., time, effort, leadership) and can therefore be identified as a cost. These non-financial costs can be categorized based upon which portion of the enterprise architecture is affected (i.e., strategy, processes, people, or technology).

(1) Strategy

The adoption of digital twins could trigger the DON to change the means by which it will achieve its strategic objectives. These changes may lead to existing DON projects becoming obsolete and thus ended prematurely or before their return on investment (ROI) goals are met. As a result, the proposed business value of these projects will never be fully achieved, and the resources expended on the project thus far may be perceived as wasted. For an example of a technology that directly altered Navy strategy consider the adoption of aircraft carriers. Prior to carrier-based aviation, naval superiority was often determined by which force could field the most naval guns. As a result, battleships were often a navy's most valuable assets. This changed during World War II when "fleet carriers" were introduced (Porch & Wirtz, 2002). The Battle of Midway was the "turning point of the Pacific" in part because the United States sunk four Japanese carriers while only losing one of its own (Porch & Wirtz, 2002). At this point in the war, the Japanese still retained most of their battleships, to include both of their Yamato-class battleships. However, these ships had been made partially obsolete based upon a new naval strategy.

Digital twins are enterprise solutions. Enterprise solutions have the potential to limit the flexibility of organizational strategy. As a result, the adoption of digital twins could also limit the flexibility of future DON strategies. As an example of an enterprise solution limiting flexibility, consider the difference between Tactical – Marine Corps Enterprise Network (T-MCEN) and Deployed – Marine Corps Enterprise Network (D-MCEN). T-MCEN is a sub-domain of the USMC's enterprise-level MCEN domain. D-MCEN on the other hand is the USMC's enterprise-level domain. The USMC's current goal is to move to D-MCEN as the primary network for deployments, operations, and training exercises. USMC units that operate on T-MCEN don't have access to all of the resources that are on the MCEN, but they are able to administer their networks locally. This local administrative access gives these units the flexibility to partially tailor their network resources based upon their needs at the time. Units that operate on D-MCEN gain access to all of the sources that MCEN provides but lack the flexibility to make adjustments locally.

(2) People

The adoption of digital twins could force changes in the requirements of current billets throughout the DON. As a new technology, digital twins enables the DON to develop new or different processes. It's the DON's human workforce that will primarily execute these new processes. Unfortunately, changing billet requirements and position descriptions within the DON can be time consuming and difficult. As an example of a billet that may be changed by the adoption of digital twins, consider the DON's data analysts. Many data analysts use manual techniques to clean, analyze, interpret, and share data from the DON's systems. The machine learning elements inherent to digital twins provide a means of partially or fully automating many of these data analytics steps. If digital twins are employed to analyze data, then data analysts may need to spend their time managing their digital twins instead of manually analyzing data themselves. This could require retraining of these individuals to understand how to manage the digital twins or could change the personal requirement completely leaving these analysts without a job.

In addition to forcing changes in existing positions, the adoption of digital twins could force the DON to modify portions of its current manpower structure in order to create new positions for the personnel that will operate and maintain the DON's digital twins. The DOD's manpower size is set by Congress. As a result, if the DON wants to increase manpower in one area, it will need to make an equal reduction in another area. For example, the DON may require more data analysts and IT support personnel at the strategic level to maintain the digital twin. This may require the DON to make an equal amount of reduction in the operators and maintainers of the physical twin found at the tactical level.

The adoption of digital twins will almost certainly create a requirement for the DON to modify its training requirements. Like all technology, the DON's workforce will need to be trained on how to use digital twins if they are going to be used successfully. There are a limited number of hours in a workweek. If part of the DON's workforce is required to operate and receive training on digital twins, this will decrease the time they have to conduct other training and operations. For example, if a maintenance Marine spends four hours a week operating and training on digital twins, that is four hours less time they have to conduct physical training, safety training, or PMCS.

(3) Process

While acting as an AKS, digital twins have the potential to reduce information silos and thus integrate DON processes. Although process integration is often desirable, it comes with several associated costs. First, integrated processes typically involve the interactions of a larger number of personnel than siloed processes do. As a result, the interactions are more complex. Second, because integrated processes often involve a larger number of personnel, they can require more time to complete. A combination of greater complexity and time requirements results in integrated processes being harder to expedite when needed. For example, the resupply process for a Naval ship at sea could involve several different organizations to include the ship, the Task Group the ship is sailing with, the Fleet the Task Group is currently assigned to, U.S. Transportation Command (TRANSCOM), and potentially even the Combatant Command (COCOM). If all of these organizations want to be involved in the resupply process because they now have access via the digital twin, it could be difficult for the ship to expedite a last-minute supply request.

Process integration can increase the scope of personnel that are involved in a process. As more personnel from more of the DON's functional departments become involved in the integrated process, conflict may arise. This conflict could give rise to a need for the process to be centralized at a single higher echelon in order to arbitrate the concerns of the various organizations. Centralized processes may be efficient from an enterprise level, but at the unit level, they may be less flexible and thereby potentially less effective. For example, strategic-level logistics is coordinated via the Defense Logistics Agency

(DLA) instead of individual services. The bulk that DLA can purchase and transport allows for efficiencies that a single service couldn't match. The downside is that DLA may only deliver logistic supplies in quantities that are too large (e.g., crate instead of a box).

(4) Technology

The adoption of digital twins will create additional network traffic on the DON's tactical and garrison networks. Digital twins maintain a bi-directional connection with their physical twin. The added volume of network traffic will depend upon the fidelity and synchronization rate that the digital twin maintains. This added network volume could reduce the performance of other systems on the DON's network. Alternatively, the added burden may force the DOD to invest in additional network capacity. For example, the very small aperture terminal (VSAT) used by a USMC battalion landing team (BLT) can provide a maximum bandwidth of 6 Mbps assuming optimal conditions. For comparison, according to the Federal Communications Commission (FCC) that is the bandwidth needed to stream a single high definition (HD) movie (Federal Communications Commission, 2020). If the digital twin of the BLT's howitzers, amphibious assault vehicles (AAVs), and light armored vehicles (LAVs) use that bandwidth, then there will be less bandwidth available for other tactical and business systems.

Digital twins require sensors to gather data on the physical twin and its environment. Unfortunately, many of the DON's physical systems were not built with digital twins in mind. As a result, there may be a deficiency of potentially vital sensors. To make the most out of its digital twins, the DON may need to buy and install sensors on its physical twins. These installations will take time, money, and effort. For example, in order to gather additional data for the digital twin of a landing craft unit (LCU), the Navy would likely need to add additional sensors to the engines and hull.

3. Summary

The net business value of digital twins to the DON depends upon how the time period is bounded. This is because the costs and benefits of digital twins will be delivered to the DON at different times. The results of cost-benefit analyses may be different depending on the scope of the time evaluated.

As with almost all new technologies, there are heavy upfront fiscal costs. Conversely, business value isn't delivered until after the digital twin technology is operational and integrated with the DON's enterprise architecture. Moreover, the business value of a digital twin is spread over the lifespan of the physical twin. For large platforms such as naval ships, that lifespan could be several decades. As a result, the full value of a digital twin may take a long time to be fully realized.

If digital twins are to be adopted by the DON, the DON must first identify if the potential value of digital twins is worth the costs. In order to complete this business value determination, the costs and benefits of digital twin adoption must be integrated. However, this integration can be difficult because both the costs and benefits are measured in terms of many different resources (time, money, people). Moreover, each resource may be weighted differently depending upon the current needs of the DON. Historically, the culture of the DON has been significantly weighted in cost-benefit determinations. Stated simply, the DON's culture doesn't readily embrace change. The high "weight" of change when evaluating disruptive technologies, like digital twins, often skews cost-benefit analysis towards inaction.

H. CHAPTER SUMMARY

This chapter presented an analysis of digital twins. The potential effects of the DON's adoption of digital twins were analyzed across seven categories:

1. Strategy – Digital twin technology is a key enabler to existing DOD and DON strategies including the DOD's 2018 Digital Engineering Strategy and the DON's 2020 USN/MC Digital Systems Engineering Transformation Strategy. However, the DON currently lacks the specific digital twin strategy needed to coordinate the efforts of digital twin adoption throughout the enterprise.
2. Processes – Digital twins could affect the means by which an organization's processes are executed. In the context of DON PLM, four of the most significantly affected processes are the product design process,

the testing and evaluation process, the maintenance process, and the sustainment process.

3. People – Digital twins could provide the DON's personnel with the information they need to make more-informed decisions. In the context of DON PLM, some of the individuals most affected are the product developers, commanders, operators, maintainers, and suppliers of the physical twins.

4. Technology – Digital twins are dependent on other technologies to produce, transfer, store, analyze, and display the data that is required for digital twins to operate as intended. In the context of DON PLM, some of the technologies most interrelated with digital twins are: Sensors, Network Connectivity, Physics-Based Models, Cloud Storage, High-Performance Computers, Augmented Reality (AR) and Virtual Reality (VR), and Machine Learning

5. Cyber Security - The changes caused by the adoption of digital twins have significant cyber security implications. In the context of cyber security, digital twins provide value by increasing the cyber resiliency of the DON's systems. Cyber resiliency can be increased by leveraging digital twins' capability to simulate attacks, develop heuristics, track compromised components, facilitate patching, and conducting penetration tests. Digital twins create risks by increasing the cyber-attack surface, maintaining PLI data, and expanding the scope of users with potential access to sensitive data.

6. Risk Management – Of the DOD's risk categories, digital twins are best equipped to support the management of risk to technical performance. A digital twin's ability to simulate both an entire physical twin (e.g., ship) as well as the twin's operating environment (e.g., ocean), provides risk managers a means of identifying and predicting undesirable emergent

behaviors. Once undesirable emergent behaviors are identified, risk managers can begin to manage their associated risk.

7. Business Value. – The net business value of digital twins to the DON depends upon how the time period is bounded. This is because the costs and benefits of digital twins will be delivered to the DON at different times. As with almost all new technologies, there are heavy upfront fiscal costs. Conversely, business value isn't delivered until after the digital twin technology is operational and integrated with the DON's enterprise architecture. Moreover, the business value of a digital twin is spread over the lifespan of the physical twin. For large platforms such as naval ships, that lifespan could be several decades. As a result, the full value of a digital twin may take a long time to be fully realized.

The next chapter is the conclusion of this thesis. The conclusion provides key insights, recommendations, and opportunities for future research.

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V. CONCLUSION

The fourth industrial revolution, often called Industry 4.0, is a movement that seeks to fuse physical and digital technology in order to deliver new products and services (Schwab, 2016). In this paradigm, “data is the new oil” and organizations need to run their operations based upon data (The Economist, 2017). Digital twins provide the DON with the capability to generate, store, and analyze the data of its platforms throughout their lifecycle.

The concept of digital twin overlaps with other technology concepts that are gaining prevalence in the DOD to include Machine Learning, Big Data, Cloud Computing, and Enterprise Solutions. See Figure 12 for a visual depiction.

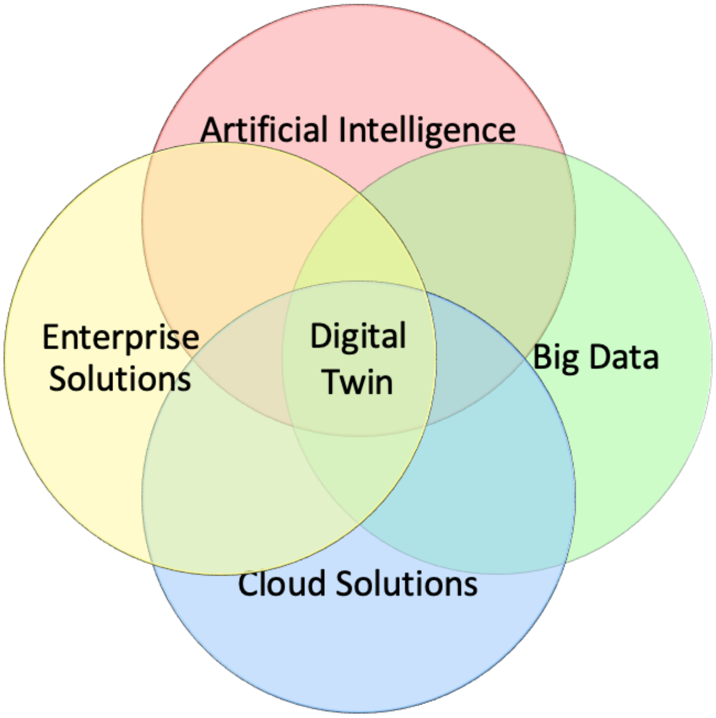

Figure 12. Technology Overlap

However, the specific details of the concept of digital twin are not clearly understood. A lack of detailed understanding can cause decision-makers to over assume capabilities while under assuming shortfalls of technology. Moreover, the initial resemblance of digital twins to computer-aided design (CAD) models can lead some to believe that digital twins are not a new concept. Those that believe digital twins are not a new concept are unprepared to capture the value that digital twins can provide. Moreover, those that fail to understand the effects of the adoption of digital twins will be unprepared to cope with the associated changes to the enterprise.

A. KEY RESULTS AND INSIGHTS

The following three sections will attempt to summarize the answers to our three research questions. The fourth section will address some challenges that have been identified over the course of the research.

1. Effects of Digital Twin on the Department of the Navy's Enterprise Architecture

Four major elements of any enterprise architecture are its Strategy, Processes, People, and Technology. If one of these four elements changes, the others will be forced to change as well. In addition to the four general elements, the DON's enterprise architecture includes an element of cyber security. Digital twins are enterprise-level technology, as such the adoption of digital twins would affect all five of these elements across the enterprise.

The DOD's 2018 National Defense Strategy recognizes the need to reform the department's way of operating (to include the DON) for greater performance (effectiveness) and affordability (efficiency). Digital twins are specifically called out as a means of achieving the DON's current Model-Based Systems Engineering and Digital Engineering strategies. That said, the DON currently has no strategy for how digital twins would be adopted. If the DON does develop a strategy, it could address three goals. These three goals can be traced back to the goals of the 2020 United States Navy/Marine Corps Digital Systems Engineering Transformation Strategy and the 2018 DOD Digital Engineering Strategy. First, digital twins could provide a means of operating and maintaining data models. Second, digital twins could provide a means of accessing, managing, protecting, and analyzing the AKS of the DON's systems. Third, digital twins could provide an end-to-end digital environment for product lifecycle management.

In the context of DON PLM, four of the most significantly affected processes are (1) the product design process, (2) the testing and evaluation process, (3) the maintenance process, and (4) the sustainment process. Digital twins provide the DON's product design process with a means of reducing information silos, thus providing a means of ensuring subcomponent integration prior to final assembly. Digital twins provide the DON's testing and evaluation process with a means of tracing documented requirements and virtual testing, thus providing a means by which systems can be more rigorously tested and evaluated. Digital twins provide the DON's maintenance process with a means to develop PMCS intervals individualized to a specific system and the ability to predict maintenance issues, thus providing a means of conducting conditions-based maintenance. Digital twins provide the DON's sustainment process with a means of maintaining a contextualized history of previous supply requirements as well as an AKS from which to manage the supply chain, thus making the sustainment process more proactive and less of a burden to the enterprise.

Digital twins are a tool that could be used by people at all levels of the DON's enterprise and throughout all phases of the product's lifecycle. Some of the key individuals affected by digital twins include (1) system developers, (2) commanders, (3) operators, (4) maintainers, and (5) logistics suppliers. Digital twins provide system developers with a means of reducing the computer-based applications they interface with, therefore providing them the ability to focus on improving their skills with the tools they use the most. Digital twins provide system commanders with the ability to verify the operational status of their equipment, consequently enabling them to make more informed decisions regarding system employment. Digital twins provide system operators with the ability to virtually test how to achieve optimal system performance, thus enabling them to make more informed decisions regarding system operations. Digital twins provide system maintainers with the ability to identify current maintenance concerns and predict future maintenance concerns, thus enabling them to make more informed decisions regarding system maintenance. Digital twins provide system suppliers with the ability to track past supply requirements and the ability to predict future supply requirements, thus enabling them to make more informed decisions regarding system sustainment.

Digital twins are dependent on other technology to perform as expected. If digital twins are adopted by the DON, the DON may need to also invest more heavily in these supporting technologies. In the context of DON PLM, some of the technologies most affected by digital twins are (1) sensors, (2) network connectivity, (3) physics-based models, (4) cloud storage, (5) high-performance computers, (6) augmented reality (AR) and virtual reality (VR), and (7) machine learning. These technologies are needed to produce, transfer, store, analyze, and display the data that digital twins require to operate as intended. Digital twins rely on the DON's sensors to gather and relay data on the physical twin and the physical twin's environment. Digital twins rely on the DON's network connectivity to maintain a bi-directional connection with the physical twin. Digital twins rely on physics-based models to anticipate future states of the physical twin. Digital twins rely on cloud storage to store and share data about the physical twin. Digital twins rely on high-performance computers to process the data about physical twins in a timely manner. Digital twins rely on machine learning to identify data trends and optimize models. Finally, digital twins could be supported by AR and VR technology in order to overcome the data visualization issues associated with traditional displays such as computer monitors.

Digital twins are a network-dependent technology. The adoption of digital twins provides value in the cyber domain while simultaneously creating cyber risks which must be addressed. In the context of cyber security, digital twins provide value by increasing the cyber resiliency of the DON's systems. Cyber resiliency can be increased by leveraging digital twins' capability to simulate attacks, develop heuristics, track compromised components, facilitate patching, and conducting penetration tests. However, digital twins create risks by increasing the cyber-attack surface, maintaining position location information (PLI) data, and expanding the scope of users with potential access to sensitive data. If left unmitigated, these cyber risks could inhibit the DON's operations and reduce the effectiveness and capabilities of the enterprise.

2. Adoption of Digital Twins to Support Product Lifecycle Management within the Department of the Navy

The concept of digital twin was conceived with the intent of being utilized to support PLM (Grieves & Vickers, 2017). Support of PLM is accomplished by providing organizations with additional information about their physical systems. Additional information about the physical twin can reduce the uncertainty of decisions involving the physical twin. In the DOD, uncertainty is predominantly associated with risk (ODASD(SE), 2017). Thus, the reduction of uncertainty provided by digital twins can be seen as a form of risk management. By increasing the certainty of (1) the chance of a risk occurrence and (2) the impact of a risk occurrence, digital twins support decision-makers with the information needed to make more informed decisions. Moreover, in the DOD, risk management is not a stand-alone PLM process (ODASD(SE), 2017). Rather, risk management is integral to other PLM processes to include product design, product testing, product management, and product sustainment (ODASD(SE), 2017).

If digital twins are adopted by the DON to support risk management throughout the product lifecycle there are two key benefits. The first benefit is that digital twins can help risk managers to better understand the physical twin. By better understanding the physical twin system, the extrinsic complexity of the system to risk managers can be reduced. If the extrinsic complexity perceived by the risk manager is reduced enough, then risk managers may be able to better "make sense of" the physical twin and are supported to make more informed decisions as a result. The second benefit is that digital twins can be used to support the management of technical performance risk. When used in the DOD's Risk Management Process, digital twins can assist risk managers in discovering "what can go wrong" during the Risk Identification step. Digital twins can then assist risk managers in determining the likelihood and consequence of those risks during the Risk Analysis step.

There are also three prominent dangers of adopting digital twins to support risk management in the DON. The first risk is digital twins create and store large amounts of data. If not properly managed and analyzed, this data could become noise to decision-makers. Noise can prevent decision-makers from quickly or accurately assessing a situation. Thus, digital twins may reduce a decision-maker's ability to make desirable decisions instead of supporting decision-making if they are not properly designed. The second risk is that even properly designed digital twins could inadvertently mislead decision-makers. Misleading could result from inadequate data or inappropriate analysis. Inadequate data could result from inadequate fidelity or synchronization of the digital twin. Inappropriate analysis could result from the shortfalls of Machine Learning algorithms. Arguably the most significant shortfall in Machine Learning is that Machine Learning is based upon probabilistic simulations and is therefore not capable of understanding cause and effect relationships (Pearl & Mackenzie, 2018). The third risk is that properly designed digital twins that reliably produce useful information could become a tool that decision-makers become over-reliant upon. An over-reliance on decision support tools, to include digital twins, may reduce the ability of decision-makers to critically think through decisions. Lack of critical thinking skills reduces the decision-maker's ability to make decisions in a context where the decision support tools are unavailable.

Regardless of the benefits and risks of digital twins as a whole, some of the DON's platforms are better suited to pair with digital twins than others. This is because the information that a digital twin can provide about its physical twin is a function of the level of fidelity and synchronization rate that the digital twin can achieve. If there is a mismatch between the fidelity and synchronization needed relative to the fidelity and synchronization available due to environmental constraints, then a digital twin may not provide the value expected or needed. Potential environmental constraints that could limit a physical twin's ability to be effectively twinned include:

- Lack of sensors or ability to retrofit sensors onto the physical twin
- Lack of ability to effectively connect sensors to a communications network
- Lack of bandwidth available to effectively maintain a bi-directional connection between the physical twin and its digital twin.
- Lack of processing power available to analyze sensor data locally in a timely manner

3. Business Value Delivered to Department of the Navy by Digital Twin

If the DON adopts digital twins, there are three associated costs. First is the time and effort needed to plan and execute the adoption of digital twins. Second, are the upfront fiscal costs needed to purchase or develop the technology. Third, are the change cost associated with the integration of digital twins into the DON’s enterprise architecture.

Conversely, business value is not delivered until after the digital twin technology is operational. Once integrated, digital twins provide two sources of value. The first source of value is the digital twin as a decision support tool. The second source of value is the enhancement provided to the physical twin.

For the business value of digital twins to overcome the associated costs, significant resources (e.g., time, effort, money) will need to be recovered. The considerable number of resources required to operate large DON platforms to include ships, submarines, and aircraft will likely provide a greater opportunity to recover the resources needed to break even relative to smaller DON products such as joint light tactical vehicles (JLTVs) or diesel generators. Moreover, the business value of a digital twin is delivered over the lifespan of the physical twin. For large platforms such as naval ships, that lifespan could be several decades.

That said, there are challenges in precisely determining the net business value of digital twins to the DON. The cost and benefits of digital twins will be delivered to the DON at different times. Thus, the results of a net business value analysis will change depending on the boundaries of the time evaluated. Additionally, both costs and benefits are measured in a variety of resources (e.g., time, money, people). The value of each resource (e.g., time, money, people) is context-dependent and changes over time. As a result, the value of one resource relative to another is difficult to assess.

4. Challenges

Should the DON decide to adopt digital twins, there are six sequential challenges of increasing difficulty that must be overcome. Failure to overcome these challenges could result in digital twins failing to provide all of their potential value or an eventual rejection of digital twins from the DON's enterprise. See Figure 13 for a visual depiction of these six challenges for adoption.

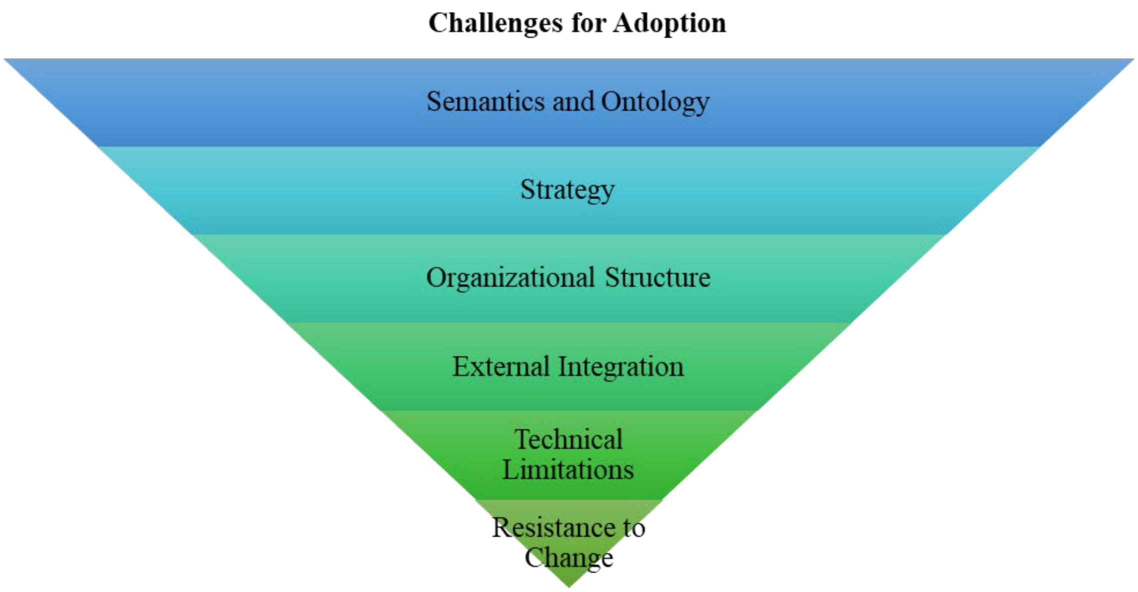

Figure 13. Challenges for Adoption

(1) Challenge 1 – Understanding of Digital Twins

The initial challenge is that the DON currently lacks a clear understanding of the semantics and ontology of digital twins. Digital twins are enterprise tools as such there needs to be a unified understanding of what digital twins are across the enterprise. Without a uniform enterprise-wide understanding of what digital twins are and are not, the DON will be unable to develop an integrated plan for acquiring and employing digital twins.

(2) Challenge 2 – Planning for Digital Twins

The second challenge is that the DON currently lacks a plan or strategy to onboard or make use of digital twins. Without an enterprise strategy, the DON may not be able to integrate the efforts and resources needed to successfully adopt digital twins. Furthermore, a sponsor with enterprise-wide influence or authority may be necessary to overcome any institutional resistance. Without an integrated strategy, the DON's functional managers may fail to provide the resources needed to ensure the successful adoption of digital twins.

(3) Challenge 3 – Organizational Structure

The third challenge is that the DON is structured as a functional organization. While functional organizations may efficiently group and develop employees with specialized skills, they have long lines of communication which can impede the flow of information (Schwalbe, 2018). Functional organizations also limit the authority of project managers like those that would manage the adoption of digital twins. The DON is unlikely to transition away from being a functional organization. However, by recognizing the shortfalls of its organizational structure, the DON will be better prepared to counter the potentially negative effects. Without integrating the digital twin endeavors of its internal organizations, the DON will have difficulty integrating its digital twin endeavors with external organizations.

(4) Challenge 4 – External Integration

The fourth challenge is integrating the DON’s digital twins with external organizations such as the joint force or the defense industry. The DON purchases different platforms from different vendors. A lack of standardization will inhibit the DON’s ability to efficiently manage and make use of digital twins.

(5) Challenge 5 – Technical Limitations

The fifth challenge is the technical limitations of the DON’s current networking and processing systems. Digital twins will place an additional burden on network connectivity in order to maintain a bi-directional connection with the physical twin. Moreover, some of the DON’s most recent operating concepts (e.g., DMO, EABO) place an emphasis on the potential need for platforms to operate disconnected from the rest of the enterprise (Commandant of the Marine Corps, 2019). The need for wide area network (WAN) connectivity could be reduced if the local processing power of platforms is increased. However, doing so may affect the size, weight, and power (SWaP) requirements of those platforms.

(6) Challenge 6 – Organizational Resistance to Change

The sixth and final challenge is that the DON is a large and diverse organization. Moreover, it is an organization that is often perceived as slow to change (Dew et al., 2017). The adoption of digital twins will create changes to the DON's enterprise architecture and all changes have associated costs. The specifics of the associated cost are often subjective and based upon the perspective of the observer. If stakeholders are not convinced that the benefits of adoption out way the costs of adoption, they will resist and potentially undermine the change process.

B. RECOMMENDATIONS

The authors have three recommendations for the DON when it decides to adopt digital twins. The first is to develop a more specific understanding of digital twins (Challenge 1). The second is to develop an enterprise strategy for digital twins (Challenge 2). The third is to develop a method of evaluating the suitability of a physical twin to be paired with a digital twin. If the DON wants to successfully adopt digital twins, then eventually all the challenges mentioned above will need to be solved, but the first two challenges provide a foundation that can be built upon. Moreover, the first two challenges can be resolved by a relatively small portion of the DON. Once the DON has refined its understanding and published a strategy, the enterprise can take a more decentralized approach towards overcoming the remaining challenges.

1. Recommendation 1 – Develop the Semantics and Ontology of Digital Twins

The first recommendation is for the DON to develop the semantics and ontology of digital twins and its related concepts (e.g., digital thread, Model, Simulation). Semantics are necessary to communicate clearly about digital twins (Thomas & McDonagh, 2013). Ontology is necessary to understand the parts of a digital twin and the relationship between those parts (Bao et al., 2020). The DON does not need to, nor should it, develop the semantics and ontology from nothing. Instead, the DON can build upon the ideas of others to include the DOD, industry, and academia.

Digital twins is a PLM concept. The semantics and ontology of digital twins should be developed accordingly. In order to ensure the development of the semantics and ontology of digital twins are applicable across the enterprise and remain rooted in PLM, these efforts should be overseen within the Assistant Secretary of the Navy for Research, Development and Acquisitions (ASD RD&A). The effort in developing the semantics and ontology can be completed by the Navy Systems Commands to include Naval Sea System Command (NAVSEA), Naval Air Systems Command (NAVAIR), and Marine Corps Systems Command (MCSC).

2. Recommendation 2 – Develop an Enterprise Strategy for Digital Twins

The second recommendation is for the DON to develop an enterprise strategy for digital twins. Digital twins are enterprise systems, and enterprise systems should be deployed via a top-down approach. If digital twins are adopted via a bottom-up approach, there is a strong possibility that the digital twins developed would not integrate effectively once they reached the top of the organization. Moreover, the adoption of digital twins may require more resources (e.g., time, effort) than any single subordinate organization could afford. A centralized adoption allows for resources to be pooled and for costs to be distributed. Finally, an enterprise strategy can be more easily integrated with other enterprise strategies. In this case, a digital twins strategy could effectively integrate with the DOD's 2018 Digital Engineering Strategy and the DON's 2020 USN/MC Digital Systems Engineering Transformation Strategy.

3. Recommendation 3 – Develop a Digital Twin Suitability Evaluation

Digital twins have the potential to provide a net value to the DON. That said, the value that a digital twin provides depends upon the physical twin that is being twinned. The lack of value provided by twinning certain DON systems results in the DON not being able to overcome the costs associated with deploying and managing a digital twin of that system.

In order to ensure that digital twins are providing a net value to the DON, the DON should develop a digital twin suitability evaluation (DTSE). Prior to a digital twin being created for a physical system, the physical twin must first undergo the DTSE. If the DTSE is passed then, and only then, will a digital twin be created.

The potential value of a digital twin is largely determined by three factors: (1) synchronization fidelity, (2) synchronization frequency, and (3) aggregate risk value. The fidelity and frequency of synchronization are dependent upon the bandwidth available to maintain the bi-directional connection, and the processing power available to perform computations on the data in a timely manner. The aggregate risk value is based upon the intrinsic and extrinsic complexity of the physical twin. These three factors and their root causes should be considered when developing a DTSE.

C. AREAS FOR FUTURE RESEARCH

The researchers believe there are opportunities for future digital twins related research in four areas: (1) digital twins support of digital products, (2) digital twin support of physical assets outside the scope of PLM, (3) digital twin support of wargaming, and (4) digital twin support of additive manufacturing.

1. Digital Twin Support of Digital Products

There are two categories of DON products, hardware products (e.g., ship, aircraft) and software products (e.g., network, software application). This thesis focused on how digital twins could support hardware products (e.g., ship, aircraft) that exist in the physical domain. Future research could be conducted to identify how digital twins could potentially be used to support PLM of the DON’s software products (e.g., networks, software applications) which exist in the digital domain.

2. Digital Twin Support of Physical Assets Outside the Scope of PLM

If the DON adopts digital twins, there are physical assets outside the scope of PLM where digital twins could potentially have an effect. Future research could be conducted to identify the effects of adoption on these other assets. Three physical assets worth consideration are installations (e.g., shipyards, air stations, camps, bases), structures (e.g., hangars, buildings, warehouses, factories), and personnel (e.g., sailors, marines, government civilians).

3. Digital Twin Support of Wargaming

Wargaming provides the DON's decision-makers the ability to practice their decision-making skills and to test operational concepts. A challenge with wargames is that they can have limited access to up-to-date data of the organization's equipment (Mittal & Davidson, 2021). A second challenge with wargames is that they can lack the data needed to conduct detailed simulations of specific events (e.g., effects of a missile strike on a naval ship) (Mittal & Davidson, 2021). Future research could be conducted to identify how digital twins could be used to support the DON's wargaming efforts.

4. Digital Twin Support of Additive Manufacturing

Additive manufacturing provides the DON the capability to print parts on-demand; thus, avoiding the shortfalls of the traditional parts ordering method. A challenge with additive manufacturing is maintaining an inventory of detailed part models. A second challenge with additive manufacturing is testing the manufactured part prior to installation. Future research could be conducted to identify how digital twins could be used to support the DON's additive manufacturing capability.

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