Digital Engineering: Expanding the Advantage

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Synopsis

Digital transformation—the pervasive incorporation of digital technology into virtually every process and system—is arguably the greatest force of change within the naval engineering community. Digital innovation is disrupting traditional ship design paradigms and giving rise to new ways of modernizing and sustaining a future integrated force structure. This paper highlights digital transformation as a core strategic initiative that is aligned with the U.S. Department of Defense Digital Engineering Strategy. Recognizing the highly integrated nature of Model Based Systems Engineering, this paper will introduce a multi-factor framework developed by Scheurer (2018) to align traditional processes employed for physical system design and development with a new digital paradigm. Next, foundational elements required to evolve current engineering design and development processes, from event and document-based approaches to a model-based approach will be addressed. Finally, discussion will focus on efforts underway to leverage cutting-edge physics-based computational models to transform ship concept, design, and development processes through investment in high performance computing systems.

Keywords: Shipbuilding and technology; integrating disruptive systems; the engineer at the heart of the system

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1. Introduction

"You're starting to see the era of digital... for the first time ever we have full-up, from the start, digital ship designs."

Hon. James F. Geurts
Assistant Secretary of the Navy (Research, Development, & Acquisition)
WEST Conference, San Diego Convention Center, San Diego, CA, February 2018

The pace of emerging threats is evolving, with increasing range, complexity, and sophistication (Gilday, 2020). Defense against these advanced threats and success in this domain requires multiple, highly coordinated assets acting together, which demands the need for coherent ship system design and development. An essential component of maintaining the warfighting dominance of our ships is updating or installing new systems and equipment aligned with current and projected mission needs (McCullough, 2019). All indications from senior U.S. Navy leadership are that current strategies are insufficient for meeting the needs of the Navy as we enter an era of rapid digital technological development, commonly referred to as the fourth industrial revolution, or Industry 4.0 (Vaidya, et. al., 2018). Unless changes are made in the near term, traditional document-centric engineering and acquisition processes may be unable to efficiently field solutions that can keep pace with these ever-changing future threats.

The naval engineering community is focused on employing new digital tools and methods to leverage advancements in computing, modeling, data management, and analytical capabilities to transform the engineering practices required to develop, characterize, and analyze ship and system-level enhancements within a dynamic digital engineering ecosystem (Doctor, 2019). Systems engineering enabled by an integrated, digital, model-based approach provides the foundation for a digital engineering blueprint. Within this context, formerly disparate model types are integrated with simulations, surrogates, systems, and components at different levels of abstraction and fidelity across the systems engineering lifecycle. This integrated view provides enhanced prediction of ship platform and system-level performance by using dynamic models and surrogates to support continuous and often virtual verification and validation for key trade-space decisions.

2. Navigating the digital future: Establishing a foundation for transformation

"My simple piece on digital transformation is digitize everything. It's got to be in our DNA in terms of how we look at our systems, how we look at our processes."

Admiral Michael M. Gilday
U.S. Chief of Naval Operations
Surface Navy Association Keynote Address, 14 January 2020

Through the use of digital models, the naval engineering community will be able to quickly specify, develop, and deploy solutions in response to a rapidly evolving mission space. Furthermore, digital engineering is transforming ship and ship systems engineering, integration, and sustainment by moving engineering methods from the traditional "design-build-test" paradigm to a "model-analyze-build" methodology. The U.S. Navy seeks to realize the digital representation of surface ships across the lifecycle, where each platform, system, and subsystem is accurately represented via analytical and descriptive models and are easily traced to mission and requirements definitions. The use of such modeling enables informed decision making at the speed of relevance.

In the subsections below, the elements required to implement a digital engineering vision pertinent to surface ships is described – extending from front-line combatants and amphibious assault ships to supply and replenishment vessels. At a high level, policy and guidance provide a construct for developing requirements and investment strategies that enable Model Based Systems Engineering (MBSE) activities.

In order to derive platform and system-level requirements, the naval engineering community must understand the engineering activities and digital engineering capabilities that are needed both in the near term and in the future. Examples include consideration for the use of rapid total ship design synthesis and analysis software suites. These activities are presently conducted throughout government, industry, and academia to help make better decisions (see, for example, Figure 1).

Navy system owners and associated stakeholders require a trained and technically proficient workforce to establish a digital technical baseline, create an authoritative data source, and develop validated models, simulations, and simulators built on a foundation of relevant data, tools, and other supporting information. Finally, the digital engineering process calls for a technology infrastructure capable of linking models, simulations, and/or simulators. The foundational building blocks for digital engineering are discussed in subsequent subsections.

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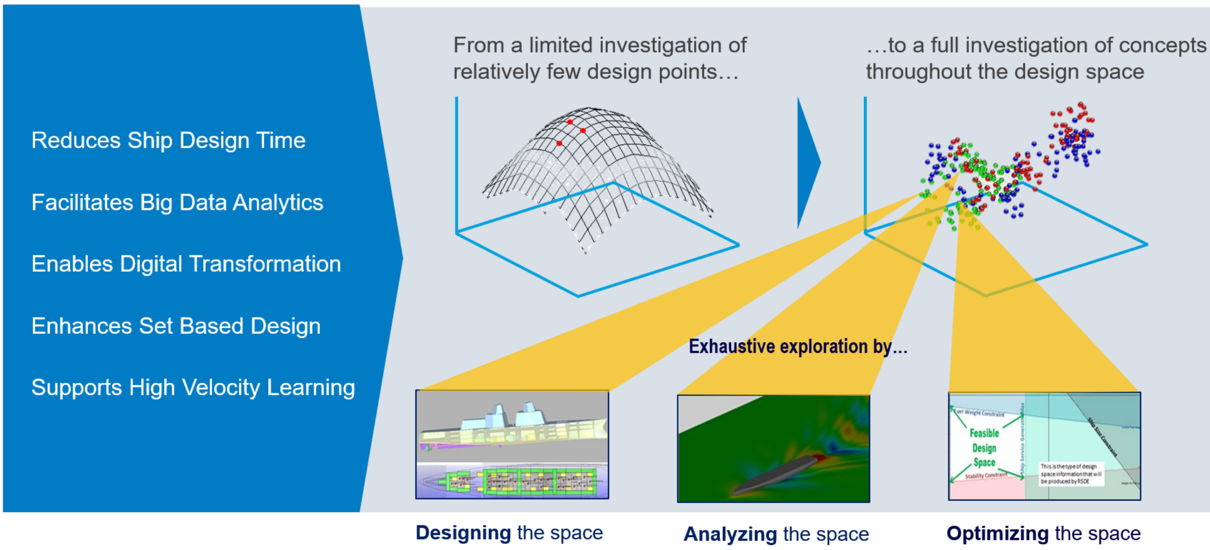

Figure 1. Navigating the digital future

2.1 Driving digital strategy

In June 2018, digital engineering guidelines were released by the U.S. Office of the Deputy Assistant Secretary of Defense for Systems Engineering (ODASD(SE)). The strategy document outlines the foundational elements necessary for a digital engineering ecosystem and aligns with U.S. Department of Defense (DOD) Instruction 5000.02 policy and guidance relating to digital engineering as well as with DOD Instruction 5000.59 that addresses Modeling and Simulation (M&S) Management (DOD, 2018). The *Digital Engineering Strategy* is intended to guide the development of digital engineering implementation plans (Zimmerman, 2019). The capstone U.S. Department of Navy (DON) document, the *Digital Systems Engineering Transformation Strategy*, issued by the Deputy Assistant Secretary of the Navy for Research, Development and Acquisition (DASN RDT&E), addresses the approach for assessment, analysis, design, development, modeling and simulation, testing, and delivery of acquisition program capabilities (DON, 2020).

The U.S. Navy's goal is to evolve current design and development processes from event-based and document-based approaches to a model-based approach. This is consistent with the ODASD (SE) digital engineering ecosystem goals and the NAVSEA Digital Engineering Blueprint for system development (Selby, 2019). Governance, management, and oversight for this effort are aligned with DOD Instruction 5000.02 policy and guidance, DOD M&S governance, and DASN (RDT&E) digital engineering strategy documents. The effort is spearheaded by the U.S. Navy's Systems Engineering Stakeholders Group (SESG) and cross-cutting communities that include leadership from the Chief Engineers from each Systems Command.

2.2 Following the digital thread

Associated with the need for applying digital engineering methods is the critical need to transform internal processes by which surface ships are acquired and sustained (Jennings, et. al., 2020). Fundamentally, there is a need for the naval engineering community to augment existing systems engineering guidance to ensure dynamic models and surrogates are fully employed to support continuous and often virtual verification and validation for key design trade space decisions in the face of evolving mission needs. MBSE offers a solution. MBSE executes a digital thread to link the models and simulations (digital systems) to physical systems throughout the development and acquisition lifecycle. Scheurer's (2018) framework to align digital and physical systems (see, for example, Figure 2) is applied within the next section of the paper to further describe the digital engineering design approach and intended uses.

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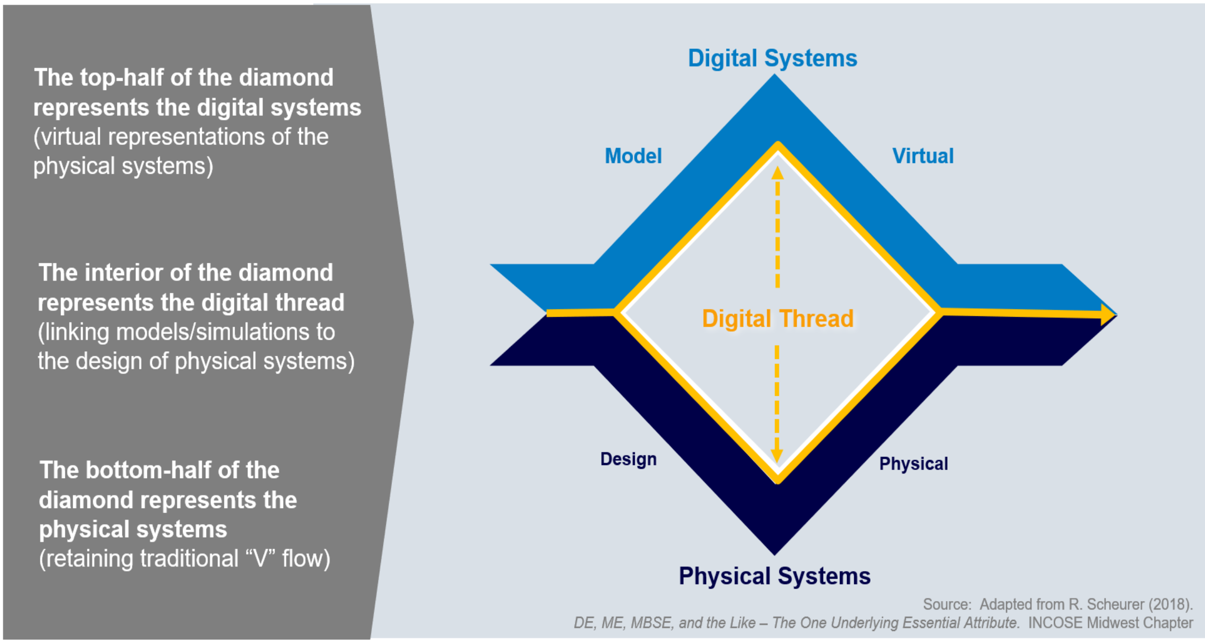

Figure 2. Following the digital thread. Source: Adapted from Scheurer (2018)

The International Council on Systems Engineering (INCOSE) defines MBSE as the "formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later lifecycle phases" (INCOSE, 2007). MBSE used in this context transitions away from traditional document-centric processes of maturing ship systems from initial conception through sustainment in a much more dynamic and flexible systems engineering process. Model-based artifacts effectively enable increased traceability and ultimately de-risk components, interfaces, and systems earlier in the development lifecycle. Section 3 further describes proposed digital engineering activities from initial mission requirements to the design and production of future surface ships.

2.3 Demystifying models, simulations, and simulators

Live, Virtual, and Constructive (LVC) models and simulations are used individually or together to depict operational environments and different scenarios (NATO, 2020). Essentially, all digital system models are products of system, subsystem, and design engineering efforts. Examples of LVC models include an authoritative technical baseline, parametric descriptions, behavior definitions, internal and external interfaces, form, structure, and cost. This data is traced, at a minimum, from operational capabilities through requirements, design, test, training, and sustainment. Figure 3 depicts a high-level operational concept of a representative environment. The M&S community uses various models, simulations, and simulators at different levels of resolution and fidelity to replicate a wide spectrum of military operations in different functional environments to meet their specific requirements.

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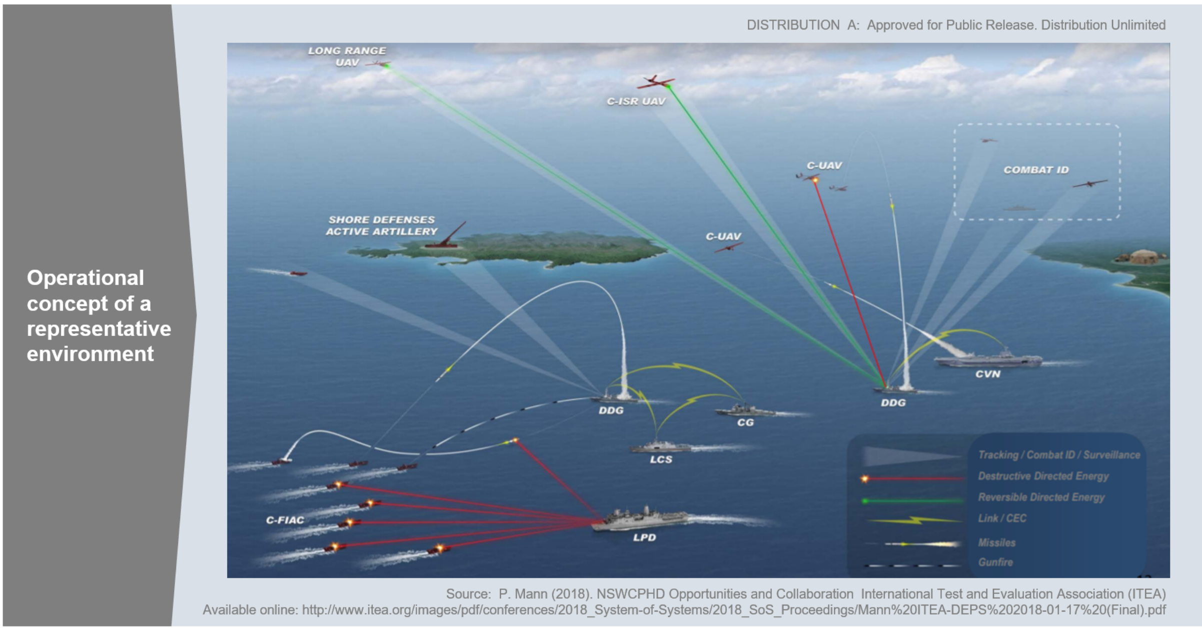

Figure 3. Operational concept of a representative environment. Source: Mann (2018)

Emerging and future capabilities (e.g. unmanned intelligent autonomous systems, next generation high power sensors, directed energy weapons, hypersonics) need to be supported by modeling environments within the digital ecosystem. Additionally, non-traditional aspects of warfare (e.g. effects of stress on decisions under uncertainty) and effects from the natural environment need to be supported by modeling. A critical aspect of the M&S environment is that it supports rapid innovation of both materiel and non-materiel solutions, which provide a decisive advantage in stressful conditions, particularly during combat. M&S environments must also enable joint interdependence, unifying an integrated force structure while maintaining the agility and flexibility to operate in an all-domain battlespace.

2.4 Elevating learning and development to close the digital competence gap

The naval engineering community requires a workforce that understands how to apply digital engineering techniques efficiently and effectively (Leigh, et. at., 2019). For example, senior leadership requires broad awareness and a general appreciation of the capabilities and benefits achieved through the proper application of digital engineering and MBSE techniques. In another example, U.S. Navy Ship Design Managers (SDMs) must understand how specific digital engineering tools can enable them to achieve program requirement thresholds and objectives in a cost-effective manner with an acceptable level of risk. Engineering teams must learn how to expand the use of digital engineering methods to support computational Analysis of Alternatives (AoA) and assess potential changes at the platform and system-level, and they must understand the full scope of the impact.

2.5 Letting data lead the way

Engineering tools such as modeling, simulations, and simulators require data to function. On the front end, data is used to develop and drive M&S. On the back end, data is produced for analysis or as an input to another digital system model. It should be noted that there are several areas of caution surrounding the use of data, including but not limited to its acquisition, validation, security classification, and ownership. Models and simulations require validated and authoritative data to ensure accurate representations (LaPlante, 2015). In this new data-intensive paradigm, the U.S. Navy will need to value and procure data to establish an enterprise capability that will enable insights and achieve faster and better data-driven decisions. A central task for the naval engineering community will be to develop comprehensive data acquisition and data management strategies to fully enable model sharing, traceability, and accountability across ship platforms, lifecycle phases, and warfighting domains. Ship programs will also need to carefully designate the responsibility to oversee the development of data acquisition strategies, tool development, support services, and the hardware and/or software used to develop, maintain, and execute models within the simulation environment. The function of overseeing tool development is distinct from the use of models, simulation, and simulators. While this function is essential to supporting and executing a viable digital engineering plan, it does not directly participate in the simulation environment. Similarly, platform design efforts

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are multidisciplinary and complex engineering challenges that require services supported by experts ranging from ship structural design and assessment to hydrodynamics.

2.6 Increasing infrastructure investment

ODASD(SE) defines the need to "establish supporting infrastructure and environments to perform activities, collaborate, and communicate across stakeholders" in the DOD Digital Engineering Strategy (DOD, 2018). This is especially true as new sets of physics-based high-performance computing engineering tools enable the U.S. Navy to develop innovative systems and more accurately predict system performance in realistic operational environments. These engineering tools can augment select land-based and shipboard testing activities. However, this enhanced engineering capability requires a supporting digital engineering infrastructure that is able to connect geographically disparate work teams while satisfying operational security requirements.

Additionally, demands for computing, data storage, and networking will increase as M&S activities become more prevalent across the ship lifecycle. These infrastructure requirements will be driven by the models, simulations, and simulators required by new platforms. For example, high fidelity, complex simulations require increased speeds in computing to include parallel processing and high-performance computing assets.

Further, the simulation environment for new systems will become increasingly complex. Future forces will operate as integrated force packages that range from an individual ship with multiple off-board systems to multi-ships and systems with a common integrated combat system to maximize the benefits of Distributed Maritime Operations (DMO), Expeditionary Advanced Based Operations (EABO), Littoral Operations in a Contested Environment (LOCE), and the Fleet Tactical Grid. Such integration will create the continuing need for greater bandwidth and decreased latency.

3. Decoding digital transformation

"Our Navy and Marine Corps teams have already started implementing digital approaches within our activities and acquisition programs. We will expand those efforts, working with our industry partners, to provide a standard of practice that delivers affordable, lethal capabilities to the warfighter at the speed of relevance."

Mr. William P. Bray
U.S. Deputy Assistant Secretary of the Navy for Research, Development, Test and Evaluation
United States Navy and Marine Corps Digital Systems Engineering Transformation Strategy (2020)

3.1 Moving beyond the traditional 'one size fits all' approach to systems engineering

The traditional systems engineering process V-shaped model, also referred to as the Vee Diagram, follows a sequential process that tracks the entire lifecycle of system engineering activities and emphasizes the value of requirement-driven design and testing (Baldwin, 2017). Noted for its clear depiction of the complex elements of the systems engineering problem-solving methodology, the Vee Diagram is divided into three primary design process components (Figure 4). The left side of the diagram depicts the decomposition of requirements and establishes the definition of the project. This top-down approach creates the specifications for the system, resulting in detailed designs of all elements required for implementation. The bottom of the diagram defines the boundaries of design execution and assembles the process of system application. The right side of the model represents the implementation and validation stage. The depicted bottom-up approach introduces the testing phase by integrating each left-side component of the model that arises from the operation and maintenance of the incremental system validation sequence. In sum, Figure 4 ultimately represents a V-shaped pattern that showcases the generic lifecycle over a time period *(t)* for various stages of stakeholders, resulting in a product that is based on international systems engineering standards.

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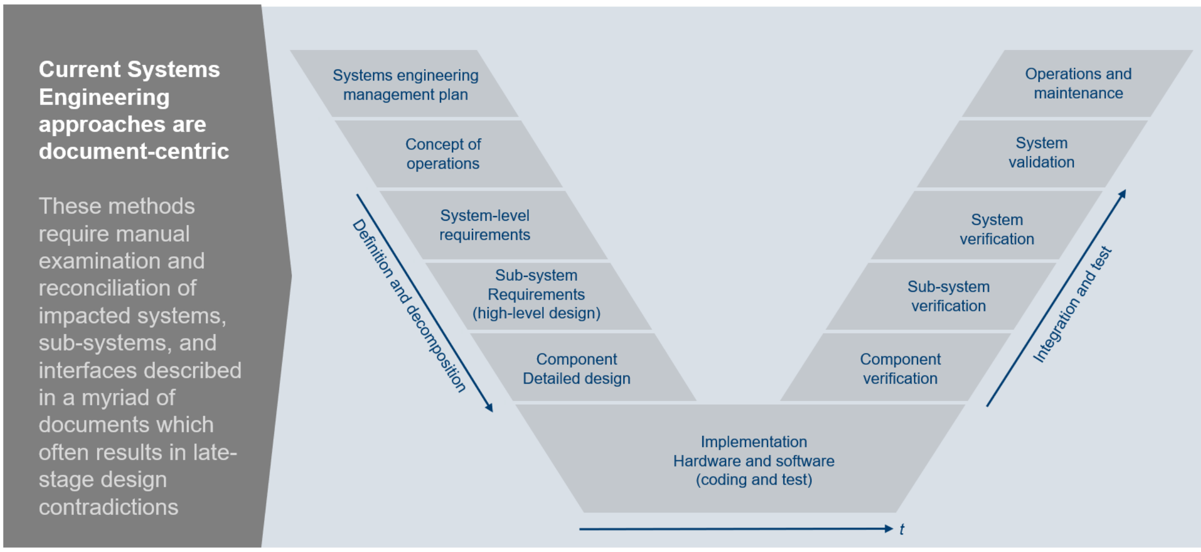

Figure 4. Traditional Systems Engineering Process

The Defense Acquisition Guidebook (DAG) and OSD Guide to Best Practices Using Engineering Standards was released in April 2017. This guide, specifically Chapter 3, set the foundation of standardized system engineering and how it can be incorporated into acquisitions processes across the DOD (DAU, 2017). The Vee Diagram is strategically tiered to effortlessly assess the acquisition process and identify the "process linkages" between the left and right side of the diagram. Successively, this establishes the placement of key stakeholders and their field of responsibility throughout the entire process. The traditional, linear model will continue to serve as the backbone across the DOD. Nevertheless, DOD Directive (DODD) 5000.01, paragraph 4.3.1 and DOD Instruction (DODI) 5000.02, paragraph 5 mandate that the DOD meet the demands of program cost, schedule, and technical performance. Due to its document-focused method that uses several different and often incompatible digital collaboration sites across multiple software systems such as Microsoft Word, Excel, and Visio, the traditional Vee Model is poorly suited to handle multiple variables throughout the entire system engineering lifecycle. The manual examination of each system magnifies cost, time, and resources within the process, resulting in drawbacks in process time, difficulty identifying bottlenecks, and lack of transparency. This leads to extended cycle times with systems that are cumbersome to change and fail to incorporate a real-time interchange of data.

3.2 Engineering the switch to digital: introducing a new framework

The new era of evolving technological alternatives and the potential to turn hundreds of terabytes of incoming data into a strategic advantage highlights the need for technical cohesion. The amalgamation of model-based engineering techniques and application of digital, real-time simulation technologies will enable the naval engineering community to readily assess technical elements, locate critical gaps, and reconfigure existing design approaches via customizable models. As a result, this allows for faster decision making and improves the likelihood of successful outcomes throughout the lifecycle of new ship systems. The Traditional Vee (Figure 4) will continue to serve as a foundation element as the naval engineering community evolves into a new digital engineering ecosystem. Figure 5 represent the use of models and simulations to continuously refine ship systems before a physical platform system is assembled. The new model incorporates digital engineering practices that will represent an evolutionary transformation across the lifecycle.

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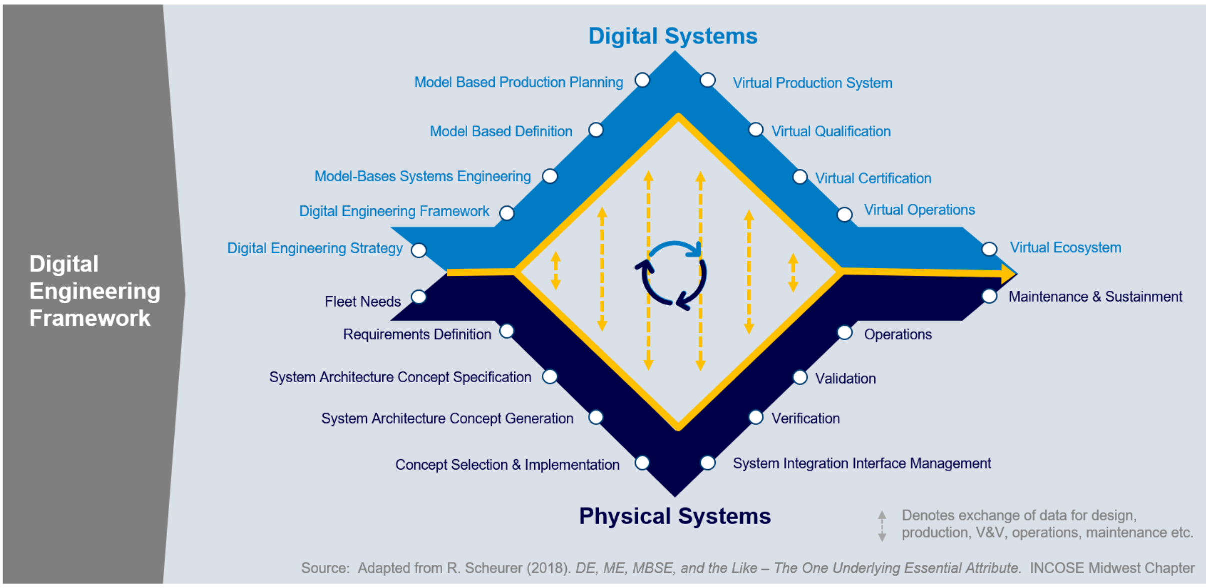

Figure 5. Digital Engineering Framework. Adapted from Scheurer (2018)

Figure 5 highlights a notional digital engineering framework that incorporates the multi-directional activity flow of development efforts from definition through top-level mission requirements to builders' trials. The diamond provides a useful framework for understanding the alignment between digital and physical systems (Scheurer, 2018) as well as Grieves and Vicker's (2017) definition of Digital Twin as a set of virtual information constructs that fully describe an actual physical product or system. Here, the Digital Twin is illustrated by the top half of the diamond and represents the digital and virtual representation of a physical system in a high-fidelity model. The bottom-half of the diamond incorporates the traditional Vee Model that depicts the physical system. There is a need for information exchange between the concurrent paths of the digital and physical systems throughout the process lifecycle (Hoheb, 2019).

Because the Digital Twin emulates the actual system before a physical testing phase is conducted, the DOD now has the ability to rapidly test different solutions virtually in order to evaluate and design the best possible solutions with real-time feedback via models and simulations (Perry, 2019). In turn, this increases the confidence level of the project's outcome by applying optimization techniques that reduce the cycle time of development, project cost and associated risk while ensuring quality under a complex construction process (Biehn, 2019).

The traditional Vee Diagram is inherently flexible and has evolved over time to incorporate the subsets of digital engineering frameworks such as MBSE and Product Life Cycle Management (PLM). Although distinct from the digital engineering design approach, the legacy Vee Model remains the central pillar of Scheurer's (2018) framework. The parallels between the physical and digital diagrams include:

- Organize engineering data within a central, authoritative source – a "single source of truth" providing continuous insight within a digital collaborative environment
- Represent all elements of the ship acquisition life-cycle in a manner that is fully interconnected and integrated with real-time feedback (e.g., emphasizing the exchange of data for design, production, verification, validation, and computing infrastructure)
- Depict a multi-dimensional and iterative feedback process of continual improvement from requirements through modeling and simulation to physical implementation
- Ensure an inclusive Product Life-cycle Management (PLM) relationship from physics-based simulation methods through production system characterization of factory hardware to builders'/acceptance trials and Fleet support
- Incorporate digital twins for development and refinement of physical shipboard systems

This dual, "best of both worlds" approach seamlessly integrates the advantages of digital engineering while reflecting the proven effectiveness of the three core tenants of the physical model design process: (1) the continuous improvement of in-depth definition and decomposition, (2) the application of physical hardware, and (3) the integration of test activities. Figure 5 reflects a multifunctional framework that allows deliberate design decisions based on the real-time interchange of data in a progressive digital system engineering environment. This positions the DOD and DON to continuously adapt and maintain a consistent competitive design advantage in an era of constrained resources.

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3.3 Exploring the digital frontier

The US Navy has been collaborating with Sandia National Laboratories (SNL) to leverage Department of Energy (DOE) investments in high performance computing resources (machines, codes, and people) to advance the development of physics-based computational models for more efficient ship acquisition (ship design and shipbuilding) and sustainment of naval ships. Adoption of these advanced algorithms enable the acquisition community to converge on optimal designs and make informed decisions further to the left of acquisition and with less cycle time (Kendall, 2016). Additional benefits of digital engineering include, requirements traceability, distributed work, streamlining technical authority review and approval, elimination of physical interferences in early stage design, developing affordable engineering change proposals, and workforce training and skills development.

As part of the aforementioned partnership between the U.S. Navy and SNL, the U.S. Office of Naval Research (ONR) is leading the Computational Research & Engineering Acquisition Tools & Environments (CREATE) Ships Program to further develop these advanced design and analysis tools in the areas of seakeeping hydrodynamics, structural response to weapons effects, compartment arrangement and density optimization, ship damaged stability assessments, and rapid hull form concept formulation (Moyer, 2016). The digital engineering processes enabled by physics-based computational models permit the early discovery of design flaws and systems integration challenges that historically would have resulted in costly and lengthy rework cycles when using legacy "analog engineering" processes (Wilson, 2010, Wilson, et. al, 2016).

The Rapid Ship Design Environment (RSDE) tool is being used extensively for new ship acquisition programs to create and analyze thousands of ship design concept iterations in a fraction of the time it took only a few years ago. The results are generated in decision maker-friendly visual representations early in the design space exploration phase. This early-stage, multi-discipline design optimization is one example of the significant benefits that are being realized today due to the power of digital engineering (Post, et. al, 2016). Primary functions and selected design concept features of RSDE are further described in Table 1.

Table 1: Rapid Ship Design Environment

Objective	*Primary functions*	*Selected design concept features*
Provide high-end toolset integrating ship design generation tools with physics-based analysis tools, enabling increasingly informed decisions	Concept design, balancing, and analysis Enable design space exploration Facilitate set-based design process	Structural optimization Equipment arrangements Intact and damaged stability Hull form geometry optimization Zonal payload laydown arrangements Space, Weight, and Power, Cooling (SWAP-C) margins

The DOD Digital Engineering Strategy identifies key elements to strategy implementation and is improving awareness of these new high-performance tools across senior leadership (Zimmerman, 2019). Without broad, committed support from senior leadership, extensive workforce training, and dedicated resources, this initiative will likely stall at the current phase of maturity.

4. Conclusion

Industry 4.0 has expanded the possibilities of digital transformation while increasing its importance across the naval engineering community by impacting the entire process from ship acquisition to sustainment. The change carries with it seemingly limitless opportunity to combine and connect digital and physical technologies. It enables the rapid generation and analysis of computational prototypes that more accurately predict system performance in realistic operational environments and drive informed decision making. Building on established systems engineering principles, the multi-factor digital engineering framework could be an ideal approach for mitigating program risk by closing the digital divide and establishing a design flow that addresses exploration, design, verification, and validation of complex ship and weapon systems functions.

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