Digital engineering: expanding the advantage

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1. Introduction

‘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

The pace of the threat continues to accelerate, with several nations now contesting the maritime balance of power in key regions around the world (Gilday 2021). Dramatic changes within the global security environment have also disrupted traditional ship design paradigms, giving rise to new ways of modernising and sustaining an integrated force structure. 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 leadership are that current strategies are insufficient for meeting the needs of the U.S. 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, modelling, data management, and analytical capabilities to transform the engineering practices required to develop, characterise, 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.

There is a need to test all critical systems in an environment that models real world operations prior to system activation on ships, as noted by the U.S. Senate Armed Services Committee leadership (Inhofe and Reed 2020). A key focus for the next generation of U.S. Navy surface ships is incorporating the digital engineering capabilities required to introduce Naval Power and Energy Systems (NPES) designed for the future (NAVSEA 2019). Rapid delivery of new disruptive technologies, including the installation or modification of advanced sensor systems and directed-energy weapons is required to deliver integrated all-domain naval power. This paper describes the early-stage development process for NPES, which will provide the U.S. Navy with a relevant means to reduce system risk through the use of persistent digital engineering. The discussion of early-stage NPES development represents an expansion upon the authors’ earlier work, previously presented at the International Naval Engineering Conference, 2020 (Sturtevant et al., 2020).

The remainder of this paper is organised as follows. Section 2 describes the foundational elements required to evolve current engineering design and development processes from event and document-based approaches to a model-based approach. In Section 3 a multi-factor framework developed by Scheurer (2018) is presented, which helps to align traditional processes employed for physical system design and development with a new digital paradigm. Intended use cases for NPES are also described within Section 3, which support investments in high performance computing resources and digital engineering capabilities. Finally, conclusions and recommendations are drawn in Section 4.
2. Navigating the digital future: establishing a foundation for transformation

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 realise the digital representation of surface ships across the lifecycle, where each platform, system, and subsystem is accurately represented via analytical and descriptive models. Further, the digital representation is easily traced to mission and requirements definitions. The use of such modelling 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 activities and digital engineering capabilities that are required, while also focusing on five priorities: (1) drive digital transformation; (2) close the digital competence gap; (3) let data lead the way; (4) demystify models, simulation, and simulators; and (5) increase infrastructure investment.

2.1. Drive digital transformation

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 5000.70 that addresses Modeling and Simulation (M&S) Management (DODD 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, modelling and simulation, testing, and delivery of acquisition programme 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 (Figure 1). 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. Close the digital competence gap

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. 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 is applied within the next section of the paper to further describe the digital engineering design approach and intended uses.

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.

The naval engineering community requires a workforce that understands how to apply digital engineering techniques efficiently and effectively (Leigh and Liu 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 programme 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.

2.3. Let data lead the way

Engineering tools such as modelling, 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 when integrating new disruptive technology.

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

2.4. Demystify models, simulation, 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, behaviour definitions, internal and external interfaces, form, structure, and cost (Figure 2). This data is traced, at a minimum, from operational capabilities through requirements, design, test, training, and sustainment. 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.

Emerging and future capabilities (e.g. unmanned intelligent autonomous systems, next generation high power sensors, directed energy weapons, hypersonics) need to be supported by modelling 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 modelling. 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. Throughout, there is a need to examine and explore digital twin (virtual information) constructs that describe an actual physical product or system relative to current and past design histories, irrespective of where the product/system’s physical counterpart resides.

Multiple instances of products would exist and be available within the M&S environment, which would provide data used and correlated via digital engineering capabilities to anticipate future states. As an example, correlations are possible between component sensor readings for power and propulsion systems and subsequent failures within individual subsystems. When reports of similar sensor patterns emerge then an alert of possible critical system-level failures can be generated, which acts upon documented correlations (Grieves and Vickers 2017). 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.

2.5. Increase infrastructure investment

ODASD(SE) defines the need to establish supporting infrastructure and environments to perform activities, collaborate, and

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**Figure 2.** Demystify models, simulation, and simulators.
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 maximise 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

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 emphasises 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 3). 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 3 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.

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 standardised 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 (DOD) 5000.01, paragraph 4.3.1 and DOD Instruction (DODI) 5000.02, paragraph 5 mandate that the DOD meet the demands of programme 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 customisable 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 3) will continue to serve as a foundation element as the naval engineering community evolves into a new digital engineering ecosystem. Figure 4 represents 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 provides for an evolutionary transformation across the lifecycle.

Figure 4 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 Vickers'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 optimisation techniques that reduce the cycle time of development, project cost and associated risk, while ensuring quality under a complex construction process (Biehn et al. 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 Lifecycle 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:

- Organise engineering data within a central, authoritative source – a definitive source of data providing continuous insight within a digital collaborative environment
- Represent all elements of the ship acquisition lifecycle in a manner that is fully interconnected and integrated with real-time feedback (e.g. emphasising 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 modelling and simulation to physical implementation
- Ensure an inclusive PLM relationship from physics-based simulation methods through production system characterisation 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 tenets 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 4 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.

### 3.3. Exploring the digital frontier

The U.S. Navy has been collaborating with Sandia National Laboratories (SNL) to leverage U.S. 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 Programme to further develop these advanced design and analysis tools in the areas of sea-keeping hydrodynamics, structural response to weapons effects, compartment arrangement and density optimisation, ship damged 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 et al. 2010; Wilson 2016).

The Rapid Ship Design Environment (RSDE) tool is being used extensively for new ship acquisition programmes 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 optimisation is one example of the significant benefits that are being realised today due to the power of digital engineering (Post et al. 2016).

### 3.4. Digital engineering intended application and use case: Naval Power and Energy Systems (NPES)

The increasing connectivity of systems and data is rapidly transforming how NPES impacts capability enhancements for future surface ship platforms. Within combat systems and command and control, communications, computers, cyber, intelligence, surveillance, reconnaissance, and targeting (C5ISR) development communities, digital engineering, MBSE techniques, architectural frameworks, and System Modelling Language (SysML) – a general-purpose architecture modelling language for systems engineering applications, have become common tools to manage increasing levels of complexity and mitigate system integration risk.

Instances of digital modelling have been implemented by the U.S. Navy that have shown potential to achieve greater performance and affordability across the lifecycle, while providing continuous access to authoritative data. The U.S. Navy continues to mature advanced M&S applications and has begun to incorporate additional performance and systems models. However, the Navy is only beginning to unlock the full potential of model-based systems engineering techniques, which will be much more deeply integrated with new ship and system designs.

The digital system model is anticipated to evolve into the standard medium through which requirements will be communicated, analysed, traded, and balanced. Early-stage NPES development will continue to rely heavily on digital engineering tools augmented with available data from historical and surrogate hardware testing. In later development phases there will be continued focus on tactical hardware and integration tests being conducted within the relevant system context long before the rest of the system becomes available together with an overall reduction in the time needed to properly test key components.

NPES testing will increasingly be tied to early acquisition process activities. There will be a continued increase in NPES test results being assessed against work products emanating from specification readiness reviews, specification functional reviews and preliminary design reviews. The phased testing and risk reduction inherent with the NPES development approach builds assurance that each new power and propulsion system can be installed and activated efficiently by the shipbuilder with performance characteristics that are well understood.

In support of NPES development, a modelling and simulation articulation of the latest power system architecture has been established at Florida State University’s Center for Advanced Power Systems (FSU CAPS) running in Real-Time (RT) to better define capabilities, identify issues, mitigate risks, and facilitate Hardware-in-the-Loop (HIL) based testing (Markle et al. 2021). Capturing the system-level effects of HIL much earlier in the design cycle is a primary result and critical advantage of the advanced modelling and simulation techniques being employed as part of NPES development (Steurer et al. 2020). Control algorithms – with Controller Hardware-in-the-Loop (CHIL) simulation – are being tested and de-risked long before full-scale hardware becomes available (Ogilvie et al. 2020). This advancement has accelerated the introduction of key hardware and software updates within the system development lifecycle. Similarly, implementing Power Hardware-in-the-Loop (PHIL) has further reduced the time and cost required to test power hardware components in a realistic environment (Langston et al. 2018). As the U.S. Navy continues to invest in methods to advance the state of practice, the digital thread will become a model-based link between mission capabilities described at the platform-level and system-level capability.

Section 3.5 below discusses approaches that are currently being applied by the U.S. Navy notably in the development of NPES. The section further describes the deployment of MBSE and SysML to de-risk power and propulsion architectures in early-stage ship design.

### 3.5. Evolution of U.S. Navy system modeling

U.S. Navy design will increasingly make use of the models described in Table 1. Through the use of these models, the U.S. Navy seeks to achieve a more seamless integration of future warfighting capabilities with fielded platforms. Design approaches and intended uses will also align with the tenants described this paper, leveraging available tools and repositories within the Department of Navy (DON) Integrated Modelling Environment (IME).

At a high-level, Figure 5 depicts how development teams are converting legacy and new models into SysML leveraging available Navy Marine Corps Intranet (NMCI) workstation licenses for Cameo System Modeler within the DON IME. The top left of Figure 5 begins by defining capability and operational requirements for a selected surface ship platform. Capability and operational requirements are right sized and then flowed down to high-level system specifications for NPES product lines and are rebalanced, as necessary, based on the progression of mission system requirements. The second element is the instantiation of the system specification in a model.
### Table 1. Modelling categories, model type and purpose.

| Modelling Category | Type                           | Purpose                                                                                                                              |
|--------------------|--------------------------------|-------------------------------------------------------------------------------------------------------------------------------------|
| Operational Models | OV-01 (DoDAF)                  | - Represents operations that the surface ship platform will undertake<br>- Enables the team to explore top-level capability requirements for the platform. |
|                    | Use Case Diagrams (SysML)      | - Represents operations that Naval Power and Energy Systems need to undertake and how it impacts overall system-level and ship dynamics. |
|                    | Textual Use Cases (SysML)      | - Matures the requirements set and helps set the functional context.                                                                  |
| Requirements Models| Requirement Decomposition Diagrams | - Traces key requirements from the front-end design to ship integration and test                                                    |
|                    | Activity Diagrams (SysML)      | - Decomposes the requirements set to ensure consistency and completeness.                                                             |
| Functional/Logical Models | System Inter-Relationship Diagrams (SysML) | - Describes dynamic behaviour of the system. <br>- Depicts how functionality is achieved by providing sequencing and logical flow between sub-systems/equipment |
|                    | 3D CAD Model                   | - Assesses the physical integration and the delivery of manufacturing outputs using a detailed geometric representation of the physical ship design |
| Physical Models    | Integrated Bill of Materials   | - Provides a full list of parts, items, assemblies and other materials required to construct the ship.                             |
|                    | General Arrangement            | - Representation of the overall composition of the ship.                                                                            |
| Performance Models | Power System Models (MATLAB/Simulink) | - Primary interchange media for component and power system simulations <br>- Mathematical models used to analyze power requirements, load flows, fault levels, dynamic performance, and operating state transitions <br>- Time-variant model used to understand transient performance, harmonic behaviour and micro- second level performance. Provides assurance that the platform can meet dynamic performance requirements. |
|                    | Real-Time (RT) Simulation      | - Special purpose multi-processor computer system optimised for real-time power system simulations. Relevant examples include the demonstration of modular multilevel converter technology (Steurer et al. 2016), evaluating system-level controls (Schoder et al. 2018), and exploring advanced energy storage functions (Langston et al. 2021). |

**Figure 5.** Requirements decomposition within U.S. Navy Integrated Modelling Environment.

By developing a digital system model, development teams capture and correlate the use cases, functions, expected behaviour, interfaces, validation techniques, and constraints in a model that serves as a central, authoritative source. From the use of this digital systems model, the U.S. Navy is able to further decompose requirements from SysML diagrams within the third element and provide a rich
context for development of NPES, highlighted on the bottom right of Figure 5.

4. Conclusion

The U.S. Navy has demonstrated the efficacy of employing digital engineering capabilities in the form of advanced modelling and simulation to de-risk complex power components and systems, such as power converters, energy storage, circuit breakers, and controls. Capabilities have included system emulations running in real-time and hardware-in-the-loop emulations. Digital system models have initially been used to reduce risk on power and propulsion components, subsystems and the system through advanced prototyping. Ultimately, the U.S. Navy will confirm power and propulsion system performance, interoperability and integration through the phased build-up of subsystems.

In order to expand the advantage, the naval engineering community should employ a disciplined approach to digital engineering, where risk is incrementally reduced to the necessary level to support performance of follow-on design and construction activities. Early phases should rely more heavily on digital engineering tools augmented by available data from historical testing and surrogate hardware and integration testing. Later phases should be characterised by the use of tactical hardware and integration testing. This phased testing and risk reduction approach will build assurance that new systems can be installed and activated efficiently by the shipbuilder with performance characteristics that are well understood.

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. Applying the multi-factor digital engineering framework, which builds on established systems engineering principles, can mitigate programme risk by closing the digital divide and establish a design flow that addresses exploration, design, verification, and validation of complex ship and weapon systems functions.

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