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Reducing Complexity in Ship Design

ABSTRACT

One of the characteristics of complex systems is the inability to accurately predict performance. Performance can be in the form of cost, schedule, or technical capability. Small perturbations in the system can result in large changes in outcome; these unpredicted large changes in outcome are considered emergent behavior. Traditional management techniques based on average or median performance are usually not adequate for complex systems. One approach to measuring complexity considers the total number of interacting elements, the number of unique elements, the number of connections among these elements, and the nature of these connections; addressing one or more of these factors reduces complexity. Complicated systems are similar to complex systems, but differ in that they are predictable. Traditional management techniques are usually much more successful with complicated systems as compared to complex systems; therefore, actions to reduce complexity through conversion of a complex system to a complicated system are a key enabler to successful management.

While the design of some commercial ships is complicated, the design of naval warships has historically been complex. This complexity is evident through the management challenges the US Navy has experienced in the design, construction, and operation of warships. Because design is a dominant factor in how ships are operated and maintained, reducing complexity of the design as well as the complexity of the design process itself offers an opportunity to improve the cost, schedule adherence, and technical capability of our warships. This paper explores the complexity of naval warship design, including its impact on operations and maintenance, and offers recommendations for instantiating warship design, maintenance, and operation processes with more complicated attributes and fewer complex attributes; in this way, traditional management practices are more likely to succeed.

INTRODUCTION

While a general consensus exists on what complexity is, a universal precise definition does not exist. Many views exist on what constitutes complexity; often these views are not compatible or even describe entirely different concepts. Suh (2005) for example, states that complexity resides in the "functional domain" and not the "physical domain." For Suh, complexity is defined as:

"A measure of uncertainty in understanding what it is we want to know or in achieving a functional requirement (FR)."

FRs are defined "as a minimum set of independent requirements that completely characterize the functional needs of the product."

Not everyone agrees that complexity only deals with the functional domain and does not have a component in the physical domain. (see Rzevski 2010 for example) These alternate definitions of complexity typically include the number of components, the number of "connections" between the components, and the nature of the behavior of the components and the connections. These same characteristics however, also apply to complicated systems. The difference is in predictability. For complicated systems, if one knows the state of a system within a level of confidence at one time, one can predict the state of the system within a level of confidence at another time. In complex systems, predictions are much more difficult or impossible. Instead, complex systems can exhibit emergent behavior that is not obvious to the observer. This behavior can be positive by providing resilience when exposed to an unexpected environment, or can be negative by being counterproductive to achieving goals or by being self-destructive.

To go one step further, simple systems reduce the number of components and their connections to the minimum needed to meet all of the FRs. With this definition, a simple system can be either complex or complicated. Usually, simplifying a complex or complicated system is desirable since the reduced number of components and connections is expected to result in a lower cost. However, simplifying a complicated system such that it becomes a complex system is usually not desirable.

For engineered systems, the unpredictability of complex systems can be problematic. The down side of inappropriate emergent behavior is generally not desired. Consequently, one often works to transform a complex system into a complicated system. The predictability of the complicated system enables one to engineer it to avoid inappropriate behavior for likely system environments; the ability to ensure all FRs are met is greatly simplified. In complex systems, the discovery of inappropriate emergent behavior results in costly rework and schedule slippage to modify the design; many times, the inappropriate emergent behavior is not discovered until testing late in the construction process or even during operations. The downside of converting the complex system to a complicated system is that beneficial emergent behavior can be lost.

Inserting new technology is often viewed as adding complexity. This is not always the case; new technology can reduce complexity by reducing any one of the characteristics of complexity: number of components, the number of connections between components, and the nature of the behavior. If the new technology improves the predictability of the system, then its incorporation will reduce overall complexity.

Not all types of complexity are the same. Suh distinguishes among four types of complexity:

1. **Real Complexity:** a measure of the time-invariant uncertainty involved in fulfilling a FR. Real complexity can be reduced by improving the ability to predict performance to a FR as well as reducing the coupling of elements with other elements. Lean six sigma methods can also be effective. Predicting performance within a bounding range can also be useful in reducing real complexity.
2. **Imaginary Complexity:** a measure of the lack of understanding about the system design, system architecture and or system behavior. The inability to predict is due to ignorance of the predictor, not the system itself. Training, experience, documentation, activity modeling, creating design structure matrices, improved analysis methods, improved system sensors, and better human-machine interfaces can all reduce imaginary complexity.
3. **Combinatorial Complexity:** uncertainty due to the system (or the environment in which the system operates) changing with time. If the changes are not predictable, then the overall system behavior is also not predictable. Combinatorial complexity can result from equipment wear, misalignments, change of watch standers, changing weather, etc. The uncertainty associated with combinatorial complexity typically, but not always, grows with time.
4. **Periodic Complexity:** like combinatorial complexity, uncertainty due to the system or environment changes with time, except the uncertainty is periodically reset to a lower level. The reset interval need not be at a fixed time increment: the interval could be event based. Typically, once the system is reset, uncertainty grows as time progresses; the reset event restores the ability to predict performance. Acquisition milestones, design iterations, the 36 month optimized fleet response plan are all examples of implementing a systematic resetting to enable periodic

complexity. Converting combinatorial complexity to periodic complexity is one way of reducing overall system complexity.

The design of a warship should seek to reduce complexity of the different parts of a ship's life:

a. Operation, maintenance, and modernization of the ship while in-service,
b. Acquisition and construction of the warship
c. The design process itself.

Suh's four types of complexity can be used as a framework for making recommendations to reduce complexity that are applicable to each of the parts of the ship's life.

COMPLEXITY IN SERVICE – MAINTENANCE PLANNING

U.S. naval warships operate under the Optimized Fleet Response Plan (OFRP) as detailed in COMNAVSURFPAC/COMNAVSURFLANTINST 3502.7. Figure 1 depicts a 36-month repeating cycle for cruisers and destroyers. The OFRP is intended to implement periodic complexity by establishing a high state of readiness at the beginning of each sustainment phase. During the sustainment phase, the ship typically deploys once, possibly twice; while not deployed the ship should be ready for short notice tasking. The ship's readiness slowly decays during the sustainment phase; the maintenance phase, basic phase, and integrated phase are intended to restore the readiness (both material readiness and crew proficiency) to a high level prior to the next sustainment phase.

The U.S. Navy has however, experiences significant challenges in "resetting" the material condition of surface ships. The GAO (2023) reports that these challenges have worsened between 2011 and 2021 as evidenced by increasing depot maintenance delays, growing number of cannibalizations and casualty reports, and fewer steaming hours. This is a clear indicator that the maintenance and modernization of surface ships now constitutes a complex system; the U.S. Navy is not able to accurately predict the condition of the warships to develop a complete Availability Work Package (AWP) that resets the material condition of the ships. Increases in work scope to in the insufficiently defined AWP (inability to properly predict work), coupled with system disturbances such as the inability to source parts in a timely fashion, result in cost over-runs and schedule slippage.

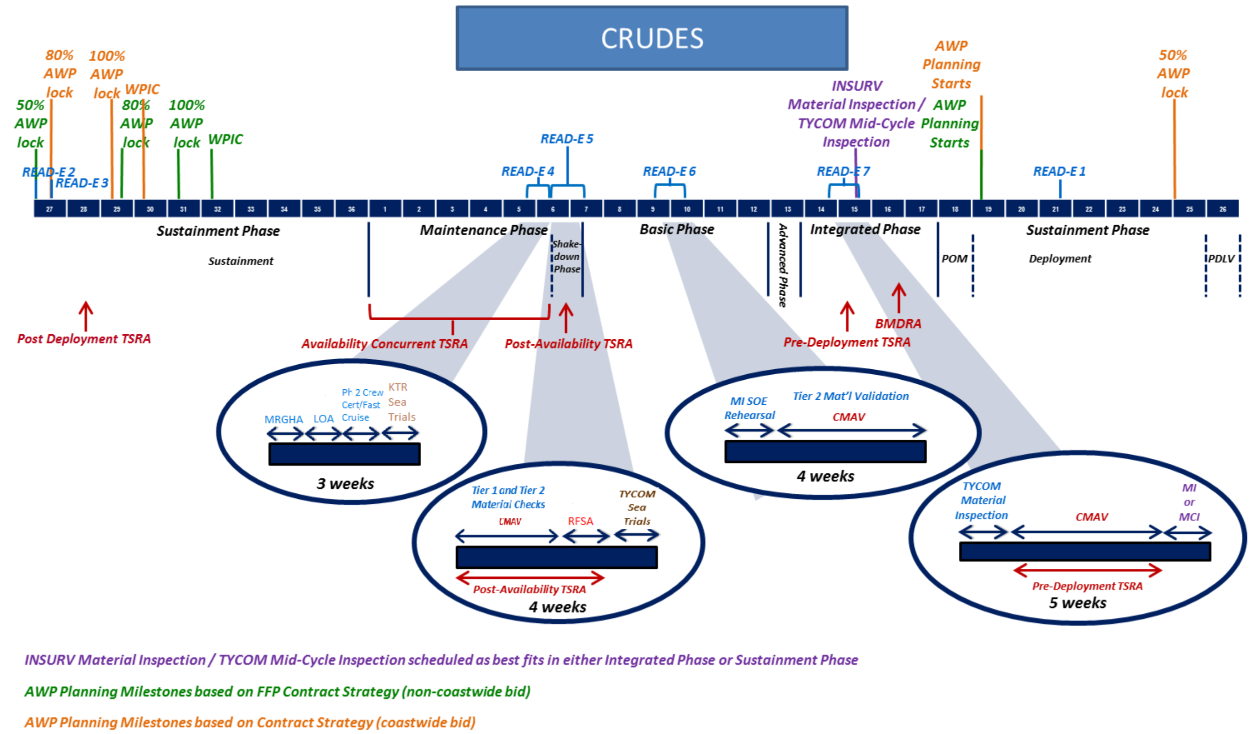

Figure 1: 36-month cruiser-destroyer notional OFRP Schedule (COMNAVSURFPAC/COMNAVSURFLANTINST 3502.7)

The inability to predict the material condition of the ship in the future due to a lack of understanding of the condition of its equipment, is an example of Imaginary Complexity. Features that can be incorporated during the design stage to reduce or eliminate this Imaginary Complexity include:

a. Base the logistics planning on a corrective maintenance free operating period (CMFOP) instead of traditional reliability terms such as mean time between failure (MTBF) or availability (Ao). With CMFOP, work during the maintenance period is designed to reduce the probability of the need for corrective maintenance of critical equipment during the sustainment phase to a very low level. With CMFOP, the material assessments prior to the maintenance phase should not only test the operability of equipment, but perform meaningful predictions that the equipment will, with high probability, continue to operate until the end of the next sustainment phase. Traditional maintenance free operating period theory has generally been applied to aircraft and is not restricted to corrective maintenance of critical equipment. See Hockley 2006 for a clear description of maintenance free operating periods.
b. Incorporate sensors and algorithms necessary to predict the material condition of equipment and structure to eliminate the need for "open and inspect" work items during the maintenance phase. Open and inspect work items are a source of uncertainty of the required work scope and schedule during the maintenance availability.
c. Employ advanced algorithms, including machine learning, to assess the material condition of equipment and their probability of remaining operable during the CMFOP. As described by Patnode et al. (2023) modern feedback controls enable continued operation that appear normal as the equipment degrades; one must look beyond operability to other characteristics such as electrical power consumption and cycling behavior to assess the material condition.
d. Patnode et al. (2023) also detail how non-intrusive load monitoring (NILM) technology can significantly reduce the number and cost of sensors needed to assess the material condition of multiple equipment. During the design of the warship, the material condition assessment sensors and algorithms should be designed around achieving the CMFOP.

e. Develop the shore side and ship side infrastructure to implement a Failure Reporting, Analysis, and Correction Action System (FRACAS) as defined in MIL-HDBK-2155 to create an understanding of the cause of critical equipment failures during the CMFOP and prevent future failures. This infrastructure should ideally contain a ship-wide digital twin that builds off of existing system digital twins. (See Eckstein 2021)

A source of real complexity is the availability of repair parts; the availability of repair parts is currently not predictable. If sufficient repair parts are in stock within the supply system, then the parts can be obtained relatively quickly. However, if the repair parts are not in stock, then it can take months, if not years for parts to become available. During the design stage, it would be beneficial to establish the shore infrastructure for developing parts kits for standard maintenance work items to support maintenance availabilities during the maintenance phase. These parts kits would be reserved from the supply system as soon as the need for the part kits are identified, prior to the finalization of work packages or maintenance availability contract award. (see Rodzewicz et al. 2010) If a parts kit is not available, the supply system (typically the Naval Supply Systems Command or the Defense Logistics Agency) should work to procure the required parts from available stock, the normal parts suppliers, or from an organization capable of rapid manufacturing using techniques such as reverse engineering and additive manufacturing.

If parts for critical equipment fail during the MFOP, and the parts are not available from the supply system, the Naval Sea Systems Command should have an organization that can rapidly acquire or manufacture limited life repair parts. These limited life repair parts should have sufficient certifications to meet functional needs, but are certified to only have a service life of at least 36 months – enough to last until the next maintenance phase. These parts should be required to be replaced with fully certified repair parts during the next maintenance phase; the limited life repair parts provide the supply system time to procure the required repair part. A requisition for the fully certified repair part should have been submitted to the supply system prior to installation of the limited life repair part. Methods for tracking these limited life repair parts should be incorporated into the design of the ship and the shore infrastructure.

COMPLEXITY IN SERVICE – DAMAGE CONTROL

One of the biggest challenges a crew may face is responding to weapons induced damage in combat. In this situation, detrimental emergent behavior of a complex system can be fatal to the ship and crew. Real complexity, imaginary complexity, and combinatorial complexity can all occur at the same time.

The weapons induced damage and the manner in which the damage effects propagate can obviously change the operability of the systems and therefore represent the time dependent combinatorial complexity. Designing in the ability to prevent progressive fires and progressive flooding can help reduce this type of complexity. Similarly, the design of computer networks should also be designed to prevent progressive loss of functionality due to cyber-attacks.

Zonal ship design, detailed by Doerry (2005) (2006) offers an approach to design that eliminates many of the connections between components in different zones; real complexity is thereby reduced. Damage or a fault in one zone or two adjacent zones should not impact the operation of equipment in undamaged zones. The connection between in-zone distribution and longitudinal buses that span multiple zones should provide isolation such that faults on the bus do not result in a loss of functionality within the zones, and faults within zones do not impact functionality on the longitudinal bus. The ship design should minimize the chance that progressive fire or flooding will cross zone boundaries.

A common set of zones should be defined for all mission systems and distributed systems (including control systems). For most surface combatants, five to seven zones are usually appropriate; weapons effects will generally not impact more than two adjacent zones. Redundant equipment should have at least one full zone between them; non redundant equipment needed for a common FR should reside in a single zone. The zone boundaries should be watertight and serve as fire boundaries. Because fires typically spread vertically, the zones should normally not be stacked upon each other; if zones are stacked, considerable attention should be paid to preventing fire spread across the zone boundary. Where possible the longitudinal bus should be protected from damage that occurs within a zone. Having sufficient source (generation) capacity to supply all surviving loads following damage to two adjacent zones is facilitated if sources of adequate rating are located in the forwardmost zone having a load, and in the aftmost zone having a load.

Reducing complexity through zonal design provides the watch standers with better situational awareness. If a zone is not damaged, then everything in that zone should be operational. Hence if a component becomes inoperable during combat, there is a high probability that the zone the component is in has suffered weapons induced damage and that fire or flooding is also possible. Without zonal design, it could be possible for cascading damage to impact multiple systems across the entire ship in unanticipated ways. This detrimental emergent behavior could easily confuse the watch stander as to the actual location of the damage; resources could be expended inappropriately, leading to loss of the ship.

The proper integration of energy storage and power conditioning facilitates zonal design by increasing the range of power disturbances outside a zone that do not impact the functionality of loads within the zone. Eliminating the impact of external power disturbances reduces the overall system complexity; one is better able to predict that the system in the undamaged zones will meet its FRs. Energy storage with a run time capacity on the order of seconds enable continuous power while faults are cleared and if necessary, the power system is reconfigured. Energy storage with a run time capacity on the order of 5 to 10 minutes enable continuous power while a standby generator set starts and comes online. If a casualty power system is installed, energy storage with a run time capacity on the order of 30 to 60 minutes enable continuous power while the casualty power system is rigged and activated.

COMPLEXITY IN SERVICE – NORMAL OPERATION

The design process should also strive to eliminate unintentional connections between equipment under normal operation. Electromagnetic Interference (EMI) is one such connection. EMI can be radiated emissions through the air, or conducted emissions through power cables.

On May 4, 1982, onboard *HMS Sheffield*, a transmission on the ship's satellite communication system interfered with the ship's electronic warfare system. Consequently, the ship did not detect two incoming Exocet missiles and did not deploy any counter measures. Following impact of one of the missiles, fires grew out of control, resulting in the loss of the ship and 20 of her crew. It was certainly an undesirable emergent behavior. (Woodward 1992)

The loss of *HMS Sheffield* is a grim reminder of the importance of topside arrangements of all radio frequency (RF) antennas onboard ship to reduce or eliminate EMI. Even with a relatively small fixed set of antennas, locating them all in feasible locations while avoiding blockages and EMI is challenging. Applying modularity features to RF antennas and their shipboard integration in the form of aperture stations as described by Doerry (2012) is one possible way to avoid the complexity associated with radiated emission related EMI.

Another source of complexity in shipboard operations involves conducted emissions in the form of common mode (CM) currents. In a set of conductors, such as a feeder cable, the CM current is the sum of the instantaneous currents of each conductor. The return path of the CM current to the source is outside the set of conductors, typically through the ship's hull. If not adequately controlled, CM currents can manifest themselves anywhere in the ship, with potential adverse impacts on sensors, munitions, and personnel safety. Onboard ship, the most troublesome CM sources are due to power electronics and circuit asymmetry; CM currents couple to the hull through parasitic capacitances. If unshielded transformers are used, CM currents can couple between primary and secondary windings through winding-to-winding parasitic capacitance. IEEE 45.1 provides guidance for reducing the impact of CM currents on a power system, as well as techniques for measuring the Thevenin Equivalent circuit and predicting bounding values for CM voltages and currents. This guidance should be incorporated into the ship design process.

The process for restarting systems following complete loss of electrical power with energy storage remaining (dark ship) and with energy storage exhausted (dead ship) can also exhibit real complexity. For example, if power electronic converters require cooling water, but the cooling water is supplied from pumps powered by the power electronic converters, then careful sequencing is needed to start up the system without overheating the power electronics. The potential for a system to lock-up as components are not able to operate because they each depend on the other is also possible in the integration of other systems and components. During the design process, the interaction of different systems should be modelled to identify the complexity and highlight the need for design changes. It is insufficient to design the electrical system in complete isolation from the cooling water systems.

COMPLEXITY IN SERVICE – MODERNIZATION

Naval warships have long service lives as compared to many commercial ships; often naval warships are expected to remain in commission for thirty to fifty years. A substantial fraction of the equipment installed during construction can be expected to be replaced during the ship's life due to normal wear and tear, loss of logistics support, or through obsolescence. The ship design should facilitate the removal and replacement of equipment not expected to last the ship's service life. The need for hull cuts and extensive interference removal should be avoided to minimize the real complexity of the modernization availability. For equipment that is intended to be upgraded often, modularity techniques as described by Doerry (2012) should be incorporated.

Service Life Allowance (SLA) is additional capacity (space, weight, center of gravity, electrical power, cooling water, etc.) provided to enable installation of new equipment during the ship's service life. SLA can reduce real complexity by reducing coupling between the new equipment and the need for change to distribution systems it requires. For distributed systems, the additional capacity should not only be provided at the generation level, but also provided through out the distribution system. Consideration should be made to allocating the SLA to distribution system components based to a degree on where the new equipment is anticipated to be located; examination of modernization related growth on previous classes of ships may provide some insight on how to allocate the SLA.

COMPLEXITY IN ACQUISITION AND CONSTRUCTION

The acquisition process itself often includes unnecessary real and imaginary complexity. For example, shipbuilding contracts usually include a long list of government furnished information (GFI). Much of this GFI is available at the time of the request for proposal (RFP) release, but it is listed as being provided by the government to the contractor a month or two after contract award. Furthermore, the contents of the

GFI are not listed, nor is their intended purpose. Consequently, although the Government has full insight as to the knowledge contained in the GFI, the contractor does not; the impact of this GFI on the cost and schedule of the ship acquisition estimates by the contractor has significant uncertainty. This imaginary complexity can be quickly eliminated by including the available GFI into the RFP, and providing in the RFP details on the content and purpose of GFI that will be provided after contract award.

A source of real complexity is that the design of mission system and distributed systems does not consider the assembly block boundaries used to actually produce the ship. To reduce complexity, the number of system interfaces at the assembly block boundaries should be minimized. Where possible, a FR should be fulfilled within the boundaries of the assembly block; doing so enables testing of the FR before assembly is integrated with the rest of the ship. It may also be possible to use the ship's lighting and ventilation systems during construction, thereby reducing the need for temporary services. The installation of casualty power connections and manual bus transfers at specific power panels may facilitate connecting the power panels to shore power before the power system construction has been completed. Consideration should also be given to installing extra electrical outlets to the ship design for the sole purpose of powering welding machines during construction.

The use of integrated power systems (IPS) where the main propulsion motors are located aft enables shorter shaft lines and requires the shaft to cross fewer construction boundaries; survivability of propulsion would be provided by a forward retractable propulsor. The shorter shafts could also simplify and shorten the erection schedule of construction blocks.

Warship designs for a class of ships are often updated in groups of ships called flights. Sometimes, the desired addition of new capability in a new flight requires increasing the ship's displacement by inserting a parallel midbody near the center of the ship. If a propulsion motor or engine is located forward of this parallel midbody, there is considerable design linkage (and complexity) between the design of the parallel midbody and the propulsion system. Eliminating shafting through the parallel midbody reduces complexity. In particular, if shafting passes through the parallel midbody, the change in propulsion system design results in a significantly larger number of production drawings that must be altered for the new flight.

COMPLEXITY IN THE DESIGN PROCESS

While the complexity of how a ship is acquired and operated is based on decisions made during the design process, the design process itself can be complex. The inability to predict how long it takes to design a warship, as well as how much it costs is a symptom of both real and imaginary complexity. Ship design is typically performed by a number of different teams under the direction of the ship design manager (SDM) and the SDM's design integration team.

One aspect of the imaginary complexity is that the SDM team many times does not have a full understanding of the various design activities and how they inter-relate. This inter-relationship results in the design iterating. Unfortunately, many existing scheduling tools do not have the capability of understanding the impact of design iteration on cost and schedule. Doerry et al. (2022) proposes the use of a quality metric along with design activity modeling to gain an understanding of how fast designs converge during the design process. With this understanding, the imaginary complexity can be reduced.

Viewing the design process through the use of a design structure matrix can provide insight on design activities that are highly coupled. Reducing the coupling through design process re-engineering is one method of reducing the overall design process complexity. See Doerry (2009).

Modeling and simulation activities frequently are major components of the power and propulsion design of an overall ship design effort. Modeling and simulation activities may also be a major component of a ship acquisition program risk reduction plan. In Doerry et al. (2022), dynamic analysis (modeling and simulation) activities have a “strong” influence on the resulting propulsion system design, electric and propulsion control system design and design space characterization, which amounts to the ultimate design selection. The parameters which characterize the power and propulsion equipment being modelled are not accurately known until the equipment has been manufactured and integrated, if ever. Prempraneerach et al (2008) discuss a probabilistic approach to identifying and quantifying which design parameters have the greatest effect on design performance, in a electric power and propulsion context. Through the earlier stages of design, the accuracy of the values used for these parameters is uncertain. Hence, it is apparent that, through the entirety of the design and acquisition portion of a ship’s life cycle, consequences of great gravity turn on modeling and simulation in the presence of significant uncertainty. Use of design structure matrices coupled with a quantified understanding of first-order design performance determining parameters can mitigate this source of complexity by focusing the design on the most important details.

Another approach to changing the nature of iteration is to employ set-based design (SBD) as described in Singer et al. (2017). In SBD, small changes do not typically result in large impacts to the overall design process; decisions are not made if there is a likelihood that the decision will have to be revisited.

Zonal design also simplifies the design process by improving the ability to predict how systems performs during the design stage. Through allocation of FRs to zones, then ensuring the zones are not tightly coupled, both the overall system and the design process for the overall system become less complex. For the electrical power system, newer approaches employing power electronics, energy storage, and CM current control can reduce this coupling and thereby reduce the overall system complexity.

Of particular note, ship designs with a high voltage (medium voltage) ac distribution system that is connected to low voltage ac distribution via transformers are often perceived as not being complex. This is not entirely true; power faults on the high voltage side are coupled to the low voltage side, and the maximum ratings of the transformers are sensitive to the total amount of installed electrical power generation on the high voltage bus (Dalton 2019). The use of energy storage and a power electronics interface between the high voltage bus and the low voltage distribution can reduce this complexity. See Doerry and Amy (2018) for an approach using medium voltage direct current for the main distribution.

Real complexity can be reduced by limiting the number of systems within each space. Ideally, each space should only have a limited number of FRs assigned to it; only those systems that fulfill those FRs should reside in the space. Often distributed systems not serving a space are routed through this space. Complexity can be reduced by routing distributed system in a dedicated system volume that is configuration managed separately. In this manner, changes to distributed systems do not impact the design of spaces an vice versa. A dedicated power corridor is part of the Office of Naval Research (ONR) Power Electronic Power Distribution System (PEPDS) project. Details of PEPDS are described in Petersen et al. (2020).

Effective use of margins can also reduce design complexity. In contrast to service life allowances that are intended to be used during the ship’s service life, margins are intended to be consumed prior to ship delivery. For example, electrical margins account for:

- Uncertainty as to the specific loads onboard the ship; many loads are only estimated in the aggregate and not individually. Furthermore, the selection of specific equipment may be deferred until detail design; different equipment may have different electrical power requirements.

- For different operational conditions, uncertainty as to how frequently specific loads are used, as well as the actual power consumed by the load when on.
- Uncertainty as to how a particular load connects to the power system (which load centers?).

Margins enable the power system to meet its FRs despite these uncertainties; the uncertainty in meeting the FRs is greatly reduced. Similar types of uncertainties apply to the other margins (weight, center of gravity, cooling, area, powering, etc.)

The ability of design tools to predict performance impacts the imaginary complexity of the system. Imaginary complexity can be reduced if better design methods and tools are used that can reliably reduce the uncertainty as to whether FRs are met. In many cases these methods and tools require the capture and curation of shipboard data. The use of the digital twin coupled with onboard sensors can provide this data.

In many cases, the inability to accurately predict whether a FR can be met is due to one or more knowledge gaps. Eliminating these knowledge gaps as early as possible through research or experimentation can be effective at reducing imaginary complexity. Unfortunately, these knowledge gaps are often relegated to risk management programs where they are ineffectively addressed. (see Doerry 2018)

Imaginary complexity can also be reduced if the design of the ship is constrained to regions of the design space where existing design tools can accurately predict performance. For an example in the aviation industry, the faceted shape of the F-117 Nighthawk stealth fighter is reported to correspond to the stealth analysis methods available when the aircraft was designed. (Crickmore and Crickmore 1999)

CONCLUSION

Managing or eliminating complexity in the design, operation, maintenance, and modernization of warships should begin during the earliest stages of design and continue through the entire life of the ship. Real complexity is a function of the number of components, the number of "connections" between the components, and the nature of the behavior of the components and the connections. Imaginary complexity is a function of our knowledge of the systems and the ability to use this knowledge to accurately predict whether FRs are met. Systems that are complex are differentiated from systems that are complicated in that it is difficult or impossible to accurately predict if FRs are met in complex systems, while such predictions are possible in complicated systems. While traditional management techniques can work well with complicated systems, they often perform poorly with complex systems. Consequently, reducing complexity is desirable. The selection of architectures, components, and processes impacts both the real and imaginary complexity; both real and imaginary complexity should be reduced.

While new technology is often viewed as the source of complexity, if used properly, can reduce the real complexity through the elimination of components, elimination of intentional and unintentional (typically parasitic) connections, and by changing the behavior of components and systems such that they are more predictable. New technology can reduce imaginary complexity by enabling the use of analytic methods that improve the ability to predict performance.

Investment in design and analysis methods, tools, and collecting and curating supporting data can reduce imaginary complexity by providing a better understanding of systems and enabling accurate predictions of performance.

Systems commands, warfare centers, program offices and ship design teams should actively concentrate on reducing complexity throughout the design and service life of naval warships; doing so should improve the ability to deliver capability on budget and on schedule.

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