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Posturing Spares for Strategic Power Competition

December 2022

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ABSTRACT

As the distribution of power evolves across the world and creates new threats, the Department of Defense (DOD) must continually seek ways to maintain a competitive advantage among dimensions of power that enable us to advance our interests and values. America's competitors are becoming more assertive and technologically sound, meaning the Navy must improve readiness and adopt innovative capabilities. In the face of strategic challenges, it is important that there is a shift from legacy platforms to novel weapon system readiness. The purpose of this research was to evaluate the survivability of a primary defense weapon system onboard Arleigh Burke Class guided-missile destroyers (DDGs), the Phalanx Close-in-Weapon-System (CIWS), under continuous operation in a contested environment based on current supply forecasting. Currently, forecast supply models do not consider the increased demand in contested environments or additive manufacturing solution-based delivery. To extend the defense operational availability (A_o) time of primary defense systems, a selection methodology was used to identify the weapon components with the highest failure rates. Through simulation-based modeling, these components were evaluated for additive manufacturing capabilities and potential production onboard. This thesis exposed a critical shortcoming of the supply capacity in a contested environment while offering potential solutions to increase the effectiveness of operational sustainment.

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ACKNOWLEDGMENTS

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On a personal note, we would like to extend gratitude to our families: Kirstin, Caleb, Clara, and Thomas; Kristen, Maverick, and Shelby; and Dalonte, Lauren, and Peyton. Thank you for your sacrifices and support on yet another academic journey. Without your continued support none of this could have been accomplished. We hope our journey teaches you the importance of grit, resilience, and faith.

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LIST OF ACRONYMS AND ABBREVIATIONS

3D	Three-Dimensional
ACIM	Availability Centered Inventory Model
AOR	Area of Responsibility
ASCM	Antiship Cruise Missile
AM	Additive Manufacturing
AML	Additive Manufacturing Laboratories
A_o	Operational Availability
CIMIP	Comprehensive Inventory Management Improvement Plan
CIWS	Close-In-Weapon System
CNO	Chief of Naval Operations
COSAL	Consolidated Shipboard Allowance Listing
DBS	Demand-Based Sparing
DDG	Guided-Missile Destroyer
DOD	Department of Defense
Es	Endurance Supply
FLSIP	Fleet Logistics Support Improvement Program
FRC	Fleet Readiness Centers
JITD	Just in Time Distribution
MDT	Mean Down Time
MLDT	Mean Logistics Down Time
MOADT	Mean Outside Assist Delay Time
MRBD	Material Readiness Database
MSRT	Mean Supply Response Time
MTBF	Mean Time Between Failure
MTTR	Mean Time to Repair
NAVSUP	Naval Supply Systems Command
NAVCIP-M	Naval Inventory Control Point Mechanicsburg
NAVSUP WSS	Naval Supply Systems Command, Weapons Systems Support
NDS	National Defense Strategy
NIF	Navigation Plan Implementation Framework

NPS	Naval Postgraduate School
NSS	National Security Strategy
NSWC	Naval Surface Warfare Center
OR	Operational Readiness
OSD	Office of the Secretary of Defense
PEO IWS	Program Executive Office Integrated Warfare Systems
PRC	People's Republic of China
R&D	Research and Development
RBS	Readiness-Based Sparing
SEA29	Systems Engineering Analysis
U.S.	United States

I. INTRODUCTION

A. PURPOSE

With the largest potential national security threat being a nearing war with peer competitors militarily, the aging Close-In-Weapon System (CIWS), coupled with budget cuts and unsupported parts, puts our fleet at a major disadvantage. Our research aims at demonstrating how to better sustain the CIWS on guided missile destroyers (DDGs) in contested environments by addressing current methods for supplying CIWS parts to the fleet, issues faced by outdated metrics and why they are not a feasible solution to maintaining this primary defense system and others like it. This research will show that with new methods, a more sustainable duration of operations under normal and contested environments, can be achieved until newer weapon systems or manufacturing operations are developed.

B. BACKGROUND

The renewed fear among global threats and the strategic power competition have been at the forefront of national security discussions over several administrations and agencies such as the Biden Administration's 2022 National Security Strategy (NSS) and National Defense Strategy (NDS). In addition, the early 2022 attacks on Ukraine by the Russian Federation resurfaced this focus. As tension mounts over contested land such as the current debate over Taiwanese air and land space with the People's Republic of China (PRC), the stress felt by the U.S. military has been alarmingly evident. Within government defense, continual evaluation and adaptation of strategic military plans is required to ensure sound logic is applied against our technologically advanced near-peer adversaries.

The advances in the U.S. national defense arsenal among deployable assets have been slow to develop as last seen by the emergence of the F-35 fifth generation fighter. The ability to maintain dominance as a controlling superpower requires funding and the continuous production of sustainable warships with advanced capabilities. Without these two elements, current warships, and existing systems onboard are overused. Given the continued use of these warships at sea, the service life of their components becomes an issue with their increased age. Matthew (2013) explains, "The Navy is called upon to continue to maintain weapons systems past their intended life while reconfiguring its depots to meet the maintenance needs of new systems designed for the evolution to the next generation of warfare" (p. 2). The phase reserved in the logistics life cycle for this period past a weapon's serviceable life is the operations and sustainment phase, known to engineers and managers alike as the costliest phase in a systems life. As more of our weapon systems age without being replaced, the sustainment costs to keep these tools operational grows exponentially, making the system itself difficult to keep ready for use as well as each of its subcomponents, contracts, dies, mills, and support facility structures. Coupled with retention of trained personnel qualified to work on each of these, it becomes harder to maintain and manage support.

The military rapidly seeks ways to cut costs as red flags are raised in Congress due to growing spending limits, budget concerns for funding technology advancement and the sustainment of our current fleet. These concerns were evidenced in 2007 when supply redesign funding cutbacks coupled with the 2013 Navy Depot Strategic Plan continued to sequester supply and logistics overspending and potential abuse (Edwards, 2010). The rapid decline in the budget to produce and repair parts contributed to the erosion of the aging fleet's operational availability (A_o). Soon, the decline became unsustainable until funding was brought back to a level sufficient to aid the fleet. The systems most impacted were some of those most critical to ship defense while in contested environments (Apte & Rendon, 2009). A contested environment is defined by U.S. Code Title 10 as "an environment in which the armed forces engage in conflict with an adversary that presents challenges in all domains" (10 U.S. Code § 2926 - Operational energy, 2022).

As this vicious cycle continues, the age of these components steadily raises the logistical support and cost needed to keep these systems operational. The resurgence of lower acceptable system A_o for key systems such as the CIWS is once again plaguing the fleet. The CIWS is nearing its forty-third year of service on warships and is the primary system to deter air and surface attacks on over 90% of all Naval warships. As its A_o decreases, the risk level associated with sending our warships out for deployment increases while our defendable position as a fleet rapidly declines (Arca et al., 2019).

1. CIWS Overview

The MK-15 CIWS is a shipboard mounted weapon system designed to defend surface warships from air and surface threats; a picture of a CIWS is shown in Figure 1. Originally designed and fielded by General Dynamics Pomona Division in 1980 onboard the USS CORAL SEA, the current variant of the CIWS, Block 1B, is owned and produced by Raytheon Missiles and Defense. The Block 1B was introduced into service in 1999 onboard USS UNDERWOOD and has been in continuous service since. The CIWS delivers last line of defense capabilities against numerous enemy threats including missiles, conventional aircraft, small watercraft, and airborne and surface autonomous vehicles. This advanced weapon system can operate autonomously against all engageable threats or perform manual selection of targets by trained shipboard operators. The CIWS uses a combination of radar and forward looking infrared to identify potential targets and can operate independently or jointly with the ship's other organic defense systems. Because the Phalanx is completely self-contained, it is ideally suited on surface platforms that do not possess radar systems in support of other shipboard integrated weapons.

Figure 1. USS CARNEY Firing a CIWS in the Black Sea. Source: Turner (2018).

When the weapon system is placed into automatic control, targets are analyzed at 30,000 feet to identify the six primary antiship threats which are then targeted with destructive fire at 12,000 feet. The CIWS fires the Mark 244 20 mm Armor-Piercing Discarding Sabot round (shown in Figure 2) with a solid tungsten core designed to penetrate today's most advanced antiship cruise missiles (ASCM). While capable of firing at a selectable 3,000 or 4,500 rounds per minute against enemy targets, possible engagement rates are limited by a magazine capacity of 1,550 rounds. The weapon systems' limited magazine capacity is offset by utilizing preloaded magazines that a trained two-person team can change at rate of one every five minutes or less. The ability to mitigate the limited magazine capacity is also found through Block 1B's capability of firing bursts of sixty or one hundred rounds vice full continuous fire.

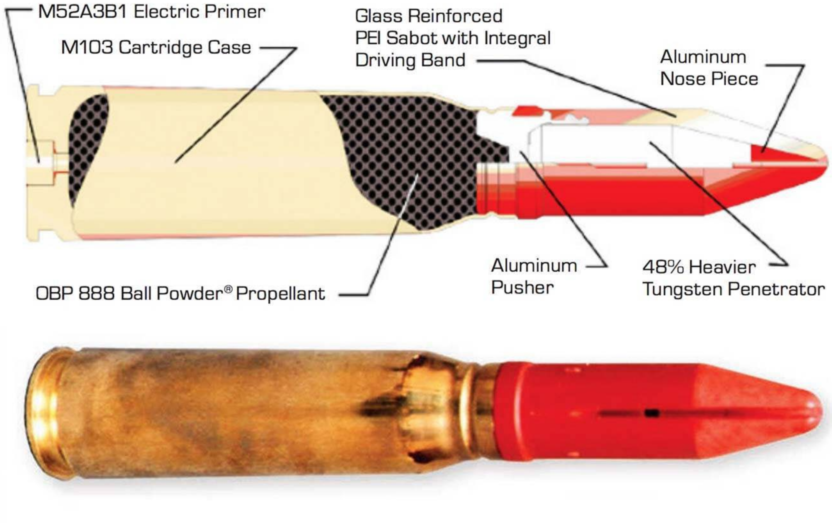


Figure 2. Mark 244 20mm Round. Source: Navy Lookout (2020).

The firing bursts are designed to match designated targets with the intent of increasing the total number of targets that can be engaged between reloads by reducing the round count spent on each target. Overall, the CIWS is a primary defense system capable of engaging multiple threats regardless of whether they originated from the land, sea, or air (Navy Lookout, 2020).

2. CIWS Importance to Defense of the Ship in a Contested Environment

The U.S. Navy relies heavily on the capabilities of the CIWS to provide defense of the ship while transiting through choke points such as the Strait of Hormuz in the United States (U.S.) Fifth Fleet Area of Responsibility (AOR) and the Malacca Strait in the U.S. Seventh Fleet AOR. The U.S. may find itself operating in these choke points and contested environments more often, if they are involved in a strategic power competition. A strategic power competition recognizes that as the distribution of power continues to evolve, new threats are imminent. As the U.S. competitor’s tactics evolve, so will the utilization of the CIWS’s capabilities.

The tactic of overwhelming a ship’s defenses through the deployment of a swarm attack is a very real and likely threat. A swarm attack is “when several units conduct a convergent attack on a target from multiple axes. Attacks can either be long range fires or close-range fires and hit-and-run attacks" (Arquilla & Ronfeldt, 2000, p. 22). Enemy combatants can deploy swarm tactics with small surface and airborne manned, unmanned, and autonomous craft. On several occasions, the Iranians have demonstrated the manned surface ship swarm tactic against U.S. warships transiting the Strait of Hormuz (LaGrone, 2022).

There is an established threat to U.S. Navy warships from small afloat warships and drones. In May of 2021, several warships were harassed by thirteen Islamic Revolutionary Guard small afloat warships carrying crew served weapons (White, 2021). Recently, several DDGs operating approximately 100 miles off the coast of California encountered swarms of airborne unmanned drones. These drones were more advanced than drones available on the commercial market and were able to match the course and speed of the DDGs as well as operate for several hours continuously. The source of the drones has yet to be identified despite investigations by several U.S. agencies but was most likely a state sponsored activity due to the capabilities of the unmanned aerial vehicles (UAV) (Hambling, 2021). The SPY radar, a key weapon system infrastructure found onboard U.S. Navy DDGs, is extremely vulnerable to small arms fire and could be easily handicapped or disabled by explosive charges carried onboard UAVs. In a multitiered attack, enemy states could disable the DDG's ability to defend itself by targeting the SPY radar arrays with a drone or small craft attack, leaving the ship vulnerable to other threats. The CIWS is uniquely equipped to manage the defense of a DDG against a multitiered surface and arial attack. Its capability to target both surface and airborne threats autonomously make the CIWS the ideal defensive weapon to engage threats presented by swarm attacks.

3. Current State of Additive Manufacturing in the DON

Additive manufacturing (AM) is "the process of adding material layer by layer to build the part rather than taking material away" (Sullivan, 2022, para. 2). Using AM to manufacture parts can offer benefits over utilizing traditional machining to manufacture a part. First, the additive manufacturing process also known as three-dimensional (3D) printing has the capability of being simpler than traditional machining and requiring less time training personnel to enable them to utilize the equipment. Second, 3D printing may reduce the overall cost to produce the part by eliminating some of the logistics costs associated with transportation of the personnel capable of machining such part onboard (Sullivan, 2022). The U.S. Navy installed its first 3D printer onboard the USS PRINCETON in 2010. Since then, the U.S. Navy has installed a total of nine 3D printers onboard surface warships. These 3D printers represent a key capability that enables the U.S. Navy's surface combatants to remain actively employed in combat operations by reducing the amount of time required to repair certain equipment through a reduction in the lead time required to receive repair parts (Kitchener, 2022). The latest fielding of 3D printing capability was spear headed by the Naval Postgraduate School (NPS) onboard the USS ESSEX in July 2022. This printer offers the unique capability of printing parts from aluminum and NPS is working to expand this capability to utilize other metal alloys. By printing common parts such as fuel system components from aluminum the USS ESSEX will increase its capacity to operate in contested environments with reliable lines of communication (Lehrfeld, 2022).

The Department of Defense (DOD) Additive Manufacturing Strategy was released in January 2021. This strategy has three goals for AM in the DOD. The first objective is for AM to assist in the modernization of the U.S. weapon systems by increasing the performance and reliability of the systems while reducing cost. The second goal for AM is to increase the material readiness of U.S. forces and the A_o of weapon systems utilized by those forces by reducing obsolescence issues generated by aging platforms. The final objective is for AM to increase the capacity for U.S. service members to develop groundbreaking resolutions for problems that require expeditious resolutions based on their demand levels (Department of Defense Additive Manufacturing Strategy, 2021).

C. PRACTICAL PROBLEM

The U.S. Navy is over reliant on readiness-based sparing (RBS) and demand-based sparing (DBS) models to manage spare parts inventory for complex weapons systems in contested environments. Since joint operations have emerged as a prominent defense strategy, RBS and DBS display the following weaknesses: each branch of service uses RBS methodology in a different way therefore interoperability and power projection can be negatively impacted. While centralized depots, such as those under the control of Naval Supply Systems Command, Weapon Systems Support (NAVSUP WSS), manage a myriad of spare parts to support DBS, the demand for most items is historically low as annual demand fluctuates. The inconsistencies in demand result in inaccurate demand forecasts. Since NAVSUP WSS must meet the needs of a diverse customer base, they are unable to eradicate the inventory of spare parts for underperformers and space constraints limit the overall inventory capacity, resulting in more complex spare parts not being readily available. This is problematic because at any time, infrequent, yet critical weapon system components could be needed to maintain the operational readiness (OR) of our forces (Ellis, 2019). While both sparing models have the potential to enhance the A_o and OR of weapons systems, these models do not account for the limited storage space on warships or the volatility of the defense budget (Moulder et al., 2011). The reports *Sustaining the Fight: Resilient Maritime Logistics for a New Era and Systems Engineering Analysis (SEA29)* found the current supply chain incapable of supporting more advanced operations against our adversaries such as PRC or the Russian Federation. The Navy's thirty-year shipbuilding plan also calls for a decrease in logistics spending which could create a supply chain less capable of meeting the demand of an expanding fleet (Walton et al., 2019). Timely, evidenced based decision making is imperative to executing logistics in contested environments. A previous study by Den Boer et al. (2020) outlined the benefits of AM in increasing readiness and sustainability while decreasing holding costs, surplus spare parts inventories, delivery lead times and transportation costs of the armed forces during both routine and arduous missions. De Brito et al. (2021) outlined a design approach to integrate AM in supply chains that improved the production and delivery of spare parts given a specific lead time. However, this study did not consider the implementation of AM in contested environments where high demand exists. Coyle (2017) explored centralized AM and Fleet Readiness Centers (FRC) as alternatives to replace on-hand inventory and just in time distribution (JITD) while improving transportation costs, but this study did not consider delivery lead time as an important factor in contested environments.

D. KNOWLEDGE GAP

While previous research provides a foundation for addressing supply chain shortages on surface warships, there is a gap in research that shows the endurance supply (Es) of the CIWS in contested environments. Es is defined as how long a system can sustain its inventory without resupply. AM is a feasible yet unexplored solution that, with increased capabilities (e.g., larger build chambers, broader range of materials, etc.) and increased inventory flexibility, would be able to support many weapons (Ford & Despeisse, 2016). Additionally, AM trained technicians onboard could provide organic assets for complex repairs or production of spare parts which is currently not a capability found on DDGs.

Depot ships are another unexplored solution. The depot ship reduces the length of sea lines of communication to support the warfighter which should, in turn, reduce lead times and increase A_o for downed weapon systems. Depot ships with AM could serve as an agile solution to project power and enhance sustainment to forward-positioned troops. In addition, a floating depot could provide better support for parts or modules that cannot be repaired or built at sea. This reduces the expert skillsets needed since production would occur in a single location rather than on all vessels. However, the asset becomes more valuable and presents a new target (Ford & Despeisse, 2016). AM, whether on a DDG or depot ship, does not negate the need for inventory. The printer that produces the part requires raw material with which to print the part from. However, the ability for the same input material to produce different parts makes AM flexible, assuming the part can be printed.

The CIWS attached to a DDG was chosen for this research due to its unique relationship of survivability tied to the operation of this weapon and how all these factors could affect that survivability. Therefore, this quantitative study will explore the sustainment of the CIWS on DDGs in contested environments.

E. THESIS CONTRIBUTION

This thesis will show multiple additional supply contribution options to allow maximum operational time of primary defensive weapon systems (CIWS) in operational contested environments. The parts availability with current supply forecasting methods versus suggested methods will highlight the impact of CIWS time on station in contested environments and its impact to DDG defense capabilities over sustained operational usage. Findings will add to the development of future supply forecasting models for deployed warships as well as further discussions in fleet integration with onboard AM and potential depot repair ships. The goal of this thesis was to answer the following question:

- How does the Navy better sustain primary defense weapon systems onboard DDGs in contested environments?

II. LITERATURE REVIEW

A. INVENTORY MANAGEMENT

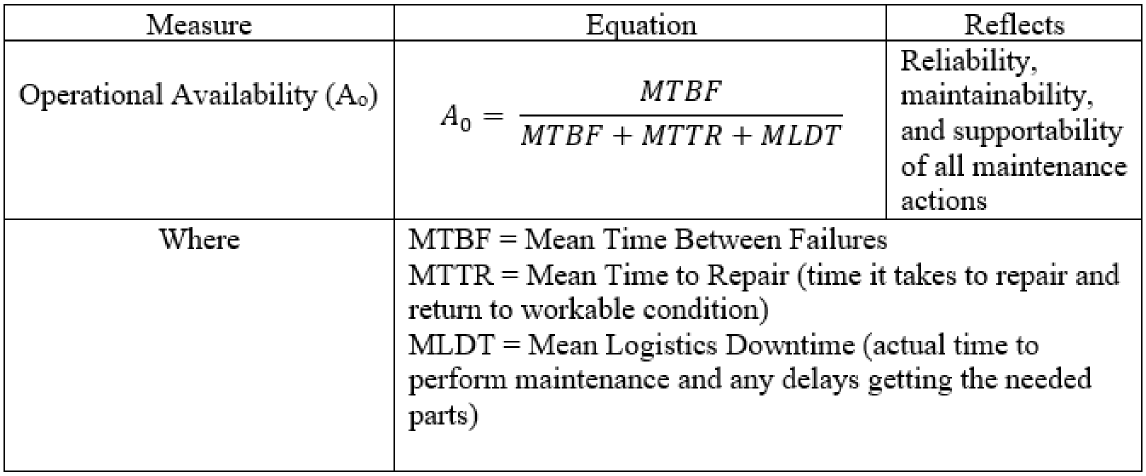
Inventory policy decisions are the hull of the Navy's supply system (Navy Supply Corps Newsletter, 2019). The Office of the Secretary of Defense (OSD) published a Comprehensive Inventory Management Improvement Plan (CIMP) that focused on improving inventory planning. To meet the desired intent of this guidance, Naval Supply Systems Command (NAVSUP) has focused on improving inventory planning through inventory management (Ellis, 2019). Naval Supply Systems Command, Weapons Systems Support (NAVSUP WSS) is the Navy's central inventory control point responsible for providing depot level repairable (DLR) parts, weapon systems components and assemblies that enhance the combat capabilities of the Naval and Joint warfighter. NAVSUP WSS uses a whole-system maintenance approach that requires the simultaneous pursuit of the quadruple aim: the right type of materiel, the right amount, at the right time, to the right place (Ellis, 2019).

The DOD has a broad range of mission essential inventory to include weapon systems that require both extensive and expensive components. When these components require maintenance or replacement, sufficient spare parts inventory is imperative to mission success. The complexities of today's supply chain result in vulnerabilities to the DOD in meeting the demands that affect warfighter readiness. To mitigate the nation's pacing challenges posed by the strategic power competition, building an agile and resilient supply chain by strategically positioning spare parts or spares must be considered. If supply chain management fails, the mission fails. If U.S. forces cannot get resources to the fight in a timely manner, national defense is threatened.

B. INVENTORY SPARING MODELS

1. Forward Positioning

Prior to the 1960s, ship allowances were determined manually. Forward positioning, commonly referred to as pre-positioning, advanced placement or "floating stock" can be defined as the consolidation of inventory in the supply chain to meet future demand (Skipper et al., 2010). Using a forecasting methodology based on historical demand and maintenance history, this strategy decreased delivery times and transportation costs while ensuring inventory was available for rapid use because of theater proximity. In remote environments, forward positioning inventory in the supply chain increases A_o and decreases inventory costs and warfighter lead times (Skipper et al., 2010). Operational availability (A_o) is explained in Figure 3:



Measure	Equation	Reflects
Operational Availability (A_o)	$A_0 = \frac{MTBF}{MTBF + MTTR + MLDT}$	Reliability, maintainability, and supportability of all maintenance actions
Where	MTBF = Mean Time Between Failures MTTR = Mean Time to Repair (time it takes to repair and return to workable condition) MLDT = Mean Logistics Downtime (actual time to perform maintenance and any delays getting the needed parts)	

Figure 3. A_o Summary. Source: Apte and Rendon (2009).

The concept of advanced inventory placement in the supply chain to decrease customer lead times and inventory costs is not a new concept and has been explored in several reports (Sampson et al., 1985; Teulings and van der Vlist, 2001; Dekker et al., 2009). Comparatively, there have been studies of demand in deployable military equipment that have shown the benefits of consolidating equipment for central management in the supply chain (Ho and Perl, 1995; Amouzegar, Tripp, and Galway, 2005; and Ghanmi and Shaw, 2008). While previous research has shown the benefits of forward positioning, there is limited research that explores the unique challenges the U.S. Navy faces in deciding where and how to forecast demand that fluctuates given the system's complexities (Rigoni and Correia de Souza, 2016). In addition, these studies do not account for the restrictions of forward positioning such as space limitations and shipping times in contested environments. Because inventory management is decentralized, there are inconsistencies in the most feasible inventory management approach to forward positioning.

2. Demand-Based Sparing (DBS)

When the Naval Inventory Control Point Mechanicsburg (NAVCIP-M) spearheaded the automated inventory management system in the 1970s, the Fleet Logistics Support Improvement Program (FLSIP) developed demand-based sparing (DBS) (Naval Sea Systems Command, 2010). To estimate the number of spares required onboard warships, DBS was mathematically developed, based on the standardized ninety-day mission or protection period to reach a 90% protection level as defined by the Chief of Naval Operations (CNO). Critical components were defined as components that have a high expected demand rate. Modified FLSIP (MODFLSIP) took this process a step further and provided an additional level of protection for "highly critical" items (Naval Sea Systems Command, 2010). Highly critical items were defined as components that cost more than $1,000. While the DBS model prioritizes high-cost items and items with high failure rates, it does not consider the stock levels of critical components items that may not have a history of demand due to low failure rates. As a result, failure of these components could affect mission readiness and A_o.

3. Availability Centered Inventory Model (ACIM)

To reduce delays in logistics, the CNO directed the implementation of a more advanced sparing technique known as the Availability Centered Inventory Model (ACIM). The ACIM was developed as a steady state model to determine the most cost effective stockage level required to ensure the least amount of delays in logistics (Naval Sea Systems Command, 2010). Given the steady state nomenclature, this model assumed that flow repair and supply would operate at a constant rate over a long period of time. While the model was able to minimize cost and maximize readiness, it was limited in its ability to evaluate multiplex systems and unconventional demand patterns (Naval Sea Systems Command, 2010). ACIM had several underlying assumptions to include:

1. MTBF and Mean Time to Repair (MTTR) are constant

2. Items are individually reordered when issued from stock
3. Failure rates are independent
4. Identical parts at different places indicates distinct items
5. External demands on supply follow the compound-Poisson distribution

These proposals are then used to compute the ACIM by predicting the readiness benefit of a possible part and dividing its Mean Supply Response Time (MSRT). The MSRT is computed by taking the anticipated logistics bottleneck and dividing it by the assumed spare requirements. These assumptions limited the ability to analyze readiness capabilities at the system level and ultimately led to the development of readiness-based sparing (RBS) (Naval Sea Systems Command, 2010).

4. Readiness-based Sparing (RBS)

As the complexities of shipboard systems and components of weapon systems increased, DBS no longer met the readiness requirement of the CNO. OPNAVINST 4442.5 defined RBS as a combination of wargaming and ACIM to select spares and assess critical system readiness. RBS combines design, configuration management, maintenance, and supply support into Readiness Assessment, Sparing Determination and Life Cycle Maintenance (Naval Sea Systems Command, 2010). RBS has been known as a cost-effective strategy to forecast the required inventory levels (Pfaff, 2017). The DOD Manual 4140.0l Volume 2 specifically references RBS as being the model of choice for aligning the operational support of weapon systems (Office of the Under Secretary of Defense for Acquisition and Sustainment, 2019). While RBS combines item-system performance and cost-effective spare parts optimization to systematically recommend a range of products, RBS does not consider the nonstandard approach that each branch of service uses in joint environments as a notable disadvantage.

5. Inventory Model Summary

In summary, while the proposed inventory management approaches enhance the A_o and OR of weapon systems, these approaches do not account for the limited storage space on DDGs and a volatile defense budget (Moulder et al., 2011). Comparatively, while these methods have the potential to improve fill rates, they fail to consider the possibility of an elevated mean down time (MDT) and mean time between failures (MTBF) in contested environments. In addition, the RBS model negatively impacts Mean Outside Assist Delay Time (MOADT), Mean Administrative Delay Time (MADT), and MSRT. These metrics are important because they make up the Mean Logistics Down Time (MLDT) where success is measured by the ability to quickly direct the weapon system parts as needed (Apte & Rendon, 2009; Sherbrooke, 2004). Weapon systems are complex and have specialized parts that sometimes lag in replacement turnaround time. In addition, while joint operations have emerged as a prominent defense strategy, RBS performs poorly in joint environments because each respective branch of service uses this methodology in a different way. The nonstandard approach prohibits the advancement of interoperation that enables power projection. Managing NAVSUP WSS materiel presents challenges that differ from commercial organizations. While the organizations manage a myriad of spare parts, the demand for most items is historically low because demand is nonstandard and instead unique to a fiscal year. The ebb and flow of demand creates inconsistencies in accurately generating demand forecasts which causes inaccuracies in DBS’s forecasts. Because NAVSUP WSS must meet the needs of a diverse customer base, they are unable to eradicate the inventory of spare parts for underperformers. At any time, an infrequent, yet critical component could be needed to maintain the operational readiness (OR) of our forces (Ellis, 2019).

C. ADDITIVE MANUFACTURING (AM)

Integrating AM in supply chain management can improve the current logistics constraints for consumable weapon systems parts and improve readiness (den Boer et al., 2020). In comparison to the normal manufacturing process, AM would be optimal for low-volume production runs and components that have longer lead times. AM could improve reliability for weapon systems that have low failure rates and are outdated due to its unique capabilities in freedom to choose a design, multi-part production capability, unrestrained customization, and part consolidation.

Previous studies such as those of den Boer et al. (2020), outlined the benefits of AM in increasing readiness and sustainability while decreasing holding costs, surplus spare parts inventories, delivery lead times and transportation costs of the armed forces during both routine and arduous missions. The study conducted by de Brito et al. (2021) outlined a design approach to integrate AM in supply chains that improved the production and delivery of spare parts given a specific lead time. Both studies identified a gap in the implementation of AM in complex supply chains where a high demand may exist such as in contested environments. Complex supply chains were defined as interdependent networks that have a ripple effect. A single component being changed impacts other components in the network. Coyle (2017) explored centralized AM and Fleet Readiness Centers (FRC) as solutions that replace on-hand inventory and JITD while improving transportation costs. However, the reoccurring limiting factor of implementing centralized AM on the Navy's current warships is the limited space, and the limiting factor of FRCs is the increased distance from the area of operation which could cause longer lead times in contested environments.

Despite the benefits of AM, there are several drawbacks that prompt the need for further research and development (R&D) and increased technological capabilities. Depending on the size of the part required, the quality of the spare parts produced by AM is inconsistent. While surface finish capabilities for AM continue to evolve, the final product is sometimes not as smooth as traditional production methods and can result in malformed parts or vulnerabilities to corrosion in the case of metal AM. A contradiction to the previously noted benefit of AM producing multiple parts at once is the process could be slower depending on the desired size and shape of components. An often overlooked but important concern the need to ensure Intellectual Property (IP) is protected. Previous research efforts by Ford & Despeisse (2016) and Dietrich et al. (2019) showed that as AM technology continues to develop, there is a growing concern that our adversaries and even competitor companies may duplicate the production of spare parts. If IP is not protected, our abilities to continue to maintain a competitive advantage and ensure national security are threatened.

D. DEPOT SHIPS

Because current warships have physical space constraints, solutions posed by previous research such as having a surplus of spare parts for critical components, is not always feasible. It is also important to note that during contested operations, physical space is further limited by the increase in personnel, equipment and other supplies needed to sustain operations. Additive manufacturing laboratories (AML) on a floating depot ship are a unique and innovative approach to decreasing current supply chain bottlenecks. AML can potentially solve the physical space constraints problem by enabling distributed manufacturing of multiple weapon systems parts at once. This eliminates the need for large quantities of on-hand inventory. In addition, AML could print customizable complex parts that can reduce the delays associated with receiving spare parts in contested environments.

Likewise, depot ships are auxiliary ships that provide a combination of mobile supply and repair capabilities for warships that have limited space capacity. Because depot ships provide services that would otherwise be unavailable due to the non-proximity of shore facilities to the area of operations, they reduce the distance to support the warfighter which could potentially reduce lead times and increase A_o for downed systems. The concept of depot ships dates to as early as World Wars I and II where destroyer tenders provided maintenance support to a flotilla of DDGs and other small combatant warships. Today, submarine tenders are used for this purpose and the destroyer tenders were eventually eliminated to increase fleet fuel efficiency with many of their systems evolving to be placed onboard the DDG. Depot ships can serve as an agile solution to project power and enhance sustainment in contested environments where traditional AM supply chain management protocol is ineffective against submarine warfare and cyberattacks. A floating AM depot, using AM and traditional manufacturing combined with storage of parts or modules that cannot be repaired or built at sea, could also potentially provide increased support to forward-positioned troops.

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III. DATA

A. SCOPE

The ability to maximize sustainment is integral to maintaining a competitive advantage in maritime operations. History has highlighted that effective supply chain management contributes to deterring and winning strategic power competitions. As the global stage continues to evolve, one of the key concerns in contested environments is the ability for our primary weapon systems to sustain operations in near peer combat. The failure rates of primary weapon systems will inevitably increase as ammunition is expended and a rising number of air threats with minimal radar cross sections (drone swarms) are engaged. To extend the A_o of primary defense systems, this research explored whether the CIWS, could provide for extensive usage in a contested environment where air and surface engagements are likely. By looking at all U.S. Navy DDG's as the control group, a staged set of models was conducted to evaluate the feasibility of newly adapted methods and the best course of action to sustain critical defense system operation within a constrained allotment of time.

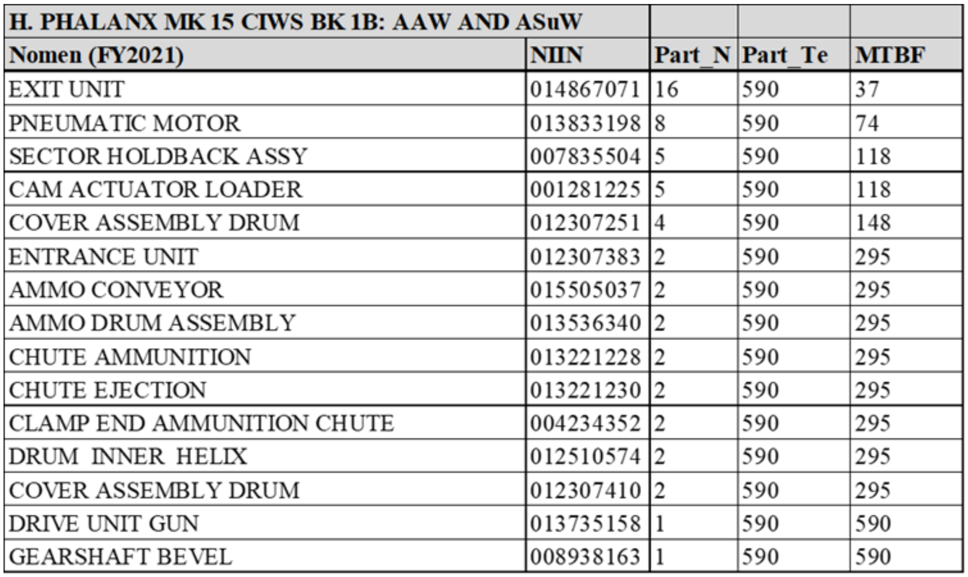
The data contained in this thesis was obtained from Naval Surface Warfare Centers (NSWC), Program Executive Office Integrated Warfare Systems (PEO IWS) and Naval Supply Weapons System Support (NAVSUP WSS). NSWC Corona and NSWC South Beach utilize data analytics and assessment to enhance warfighter readiness. The PEO IWS is responsible for developing and acquiring weapons systems and other equipment for the Navy and Marine Corps. NAVSUP WSS provides Navy, Marine Corps and Joint and Allied Forces with repairable weapon system parts to ensure mission readiness.

B. OVERVIEW OF COMPONENT SELECTION METHODOLOGY

1. Naval Surface Warfare Center (NSWC) Corona and South Beach

NSWC provided five years (2017-2021) of data elements for each DDG containing MTBF component level data failure rates for the CIWS MK 15 1B system currently onboard all DDG platforms (shown in Figure 4). NSWC used their Material Readiness

Database (MRBD) to provide the elements currently in service from DDG’s 51–119. Between 2017 and 2021, the data in each year contained between 178 and 183 components.



H. PHALANX MK 15 CIWS BK 1B: AAW AND ASuW				
Nomen (FY2021)	**NIIN**	**Part_N**	**Part_Te**	**MTBF**
EXIT UNIT	014867071	16	590	37
PNEUMATIC MOTOR	013833198	8	590	74
SECTOR HOLDBACK ASSY	007835504	5	590	118
CAM ACTUATOR LOADER	001281225	5	590	118
COVER ASSEMBLY DRUM	012307251	4	590	148
ENTRANCE UNIT	012307383	2	590	295
AMMO CONVEYOR	015505037	2	590	295
AMMO DRUM ASSEMBLY	013536340	2	590	295
CHUTE AMMUNITION	013221228	2	590	295
CHUTE EJECTION	013221230	2	590	295
CLAMP END AMMUNITION CHUTE	004234352	2	590	295
DRUM INNER HELIX	012510574	2	590	295
COVER ASSEMBLY DRUM	012307410	2	590	295
DRIVE UNIT GUN	013735158	1	590	590
GEARSHAFT BEVEL	008938163	1	590	590

Figure 4. Material Readiness Database (MRBD) FY21 Data. Source: NWSC Corona (2022).

Among the data displayed, the additional information not pictured in Figure 4 was: Nomen (Part Nomenclature), NIIN (National Item Identification Number), Part_*N* (Part Failures), Part_*Te* (Energized Time), and MTBF (Mean Time Between Failure). Each Part Nomenclature summarizes the failure data from DDG’s 51 through 119 where each component’s MTBF was computed by Fiscal Year (FY). For example, the first component which is the Exit Unit had sixteen part failures Navy wide for the DDGs operating in FY21 (shown in the first line of Figure 4). The Exit Unit had an energized (*Te*) of 590 hours in FY21. Using Equation 1, the MTBF for the Exit Unit was calculated as 590 hours/16 failures ≈ 36.9 hours/failure.

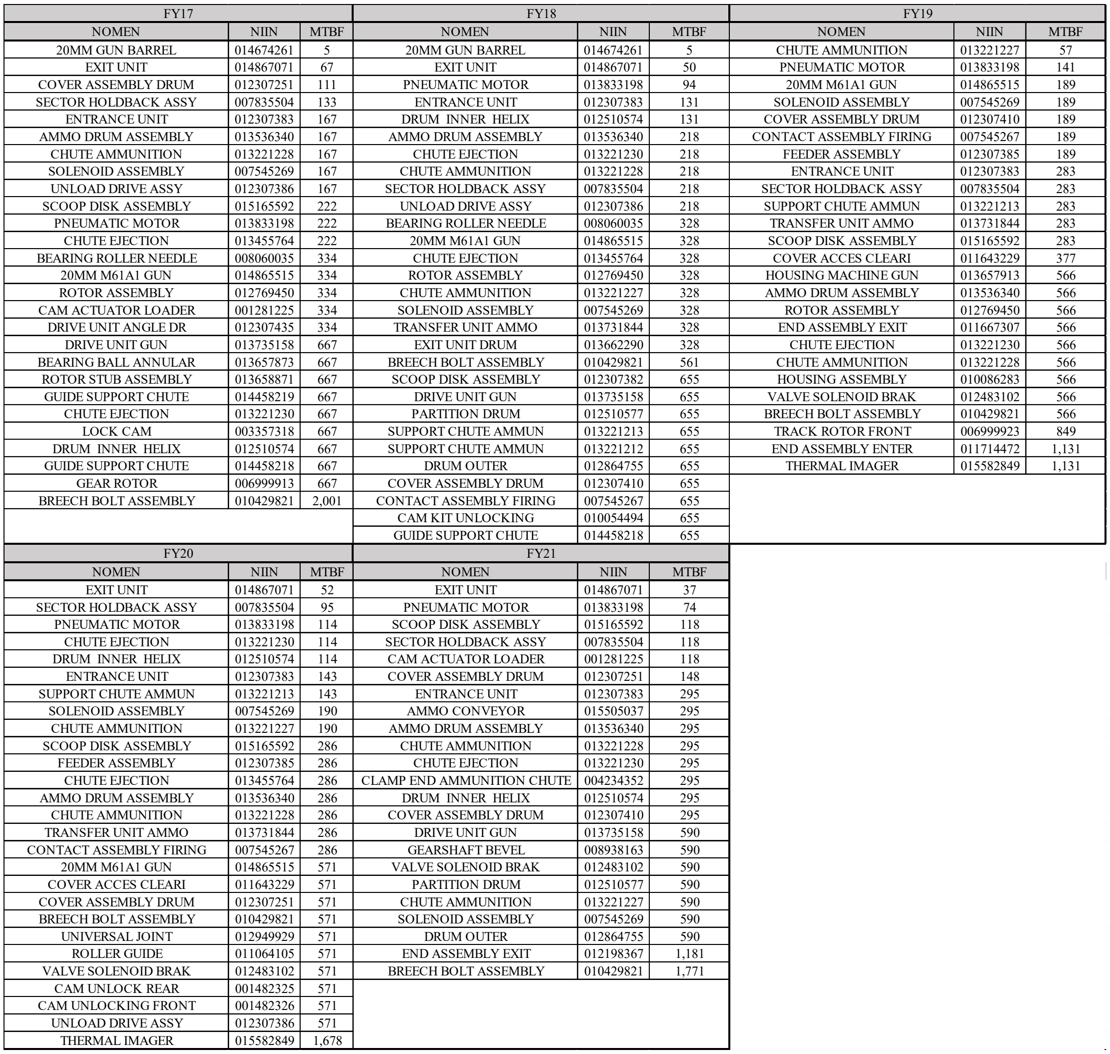
$$MTBF = \frac{Te}{N} \tag{1}$$

Parts from this list were then filtered to ensure that those chosen were CIWS items that could affect sustained usage during an allotted short run time. Our simulations operated on the idea that the CIWS would fire for a sustained period of time until a system disabling part failure occurs. Many of the MTBF's on this list were beyond this timeframe and were therefore extraneous to this study.

The item selection process for this research was based on a top-down selection method in which components were identified and ranked based on their MTBF. The data that became the central focus was any component that had a MTBF under ninety-days (based on a standard twenty-four hour day) or 2,160 hours (based on *Te* for each component). Because this duration would be an extensive time of usage for a machine gun to fire during a deployment period, it was used as the upper limit for the initial analysis of the data filtering process. The analysis conducted on the results of the Real-world Model, examined a different threshold. The data from 2017–2021 ranged from nearly one million hours of MTBF to under fifty hours of MTBF over all the components.

The MTBF metric was important in analyzing individual components in the CIWS's operation because it showed how long the entire system could operate without interruption as a single versus parallel operating system of parts. While a MTBF of under ninety-days was established as the benchmark based on previous correspondence from the CNO for the Navigation Plan Implementation Framework (NIF), this same threshold was used by VADM Williamson, Chief of Naval Operations (CNO) for Fleet Readiness and Logistics, to implement FY22's end-to-end supply chains Endurance Supply (Es) goal (NIF, 2021). The Es goal emphasized that smaller warships, such as DDGs, have a maximum sustainment capability of ninety-days due to logistical constraints and that contested environments impede the receipt of these essential underway components, i.e., food, fuel and parts.

The data consistently showed similar figures with low MTBFs. Using a top-down approach, focus was placed on a group of NIINs for each year that had a MTBF of less than 2,160 hours (ninety day deployment). Figure 5 displays the CIWS Key Components List segmented by FY containing between twenty-three and twenty-eight components filtered for MTBFs of less than 2,160 hours.



FY17		
NOMEN	NIIN	MTBF
20MM GUN BARREL	014674261	5
EXIT UNIT	014867071	67
COVER ASSEMBLY DRUM	012307251	111
SECTOR HOLDBACK ASSY	007835504	133
ENTRANCE UNIT	012307383	167
AMMO DRUM ASSEMBLY	013536340	167
CHUTE AMMUNITION	013221228	167
SOLENOID ASSEMBLY	007545269	167
UNLOAD DRIVE ASSY	012307386	167
SCOOP DISK ASSEMBLY	015165592	222
PNEUMATIC MOTOR	013833198	222
CHUTE EJECTION	013455764	222
BEARING ROLLER NEEDLE	008060035	334
20MM M61A1 GUN	014865515	334
ROTOR ASSEMBLY	012769450	334
CAM ACTUATOR LOADER	001281225	334
DRIVE UNIT ANGLE DR	012307435	334
DRIVE UNIT GUN	013735158	667
BEARING BALL ANNULAR	013657873	667
ROTOR STUB ASSEMBLY	013658871	667
GUIDE SUPPORT CHUTE	014458219	667
CHUTE EJECTION	013221230	667
LOCK CAM	003357318	667
DRUM INNER HELIX	012510574	667
GUIDE SUPPORT CHUTE	014458218	667
GEAR ROTOR	006999913	667
BREECH BOLT ASSEMBLY	010429821	2,001

FY18		
NOMEN	NIIN	MTBF
20MM GUN BARREL	014674261	5
EXIT UNIT	014867071	50
PNEUMATIC MOTOR	013833198	94
ENTRANCE UNIT	012307383	131
DRUM INNER HELIX	012510574	131
AMMO DRUM ASSEMBLY	013536340	218
CHUTE EJECTION	013221230	218
CHUTE AMMUNITION	013221228	218
SECTOR HOLDBACK ASSY	007835504	218
UNLOAD DRIVE ASSY	012307386	218
BEARING ROLLER NEEDLE	008060035	328
20MM M61A1 GUN	014865515	328
CHUTE EJECTION	013455764	328
ROTOR ASSEMBLY	012769450	328
CHUTE AMMUNITION	013221227	328
SOLENOID ASSEMBLY	007545269	328
TRANSFER UNIT AMMO	013731844	328
EXIT UNIT DRUM	013662290	328
BREECH BOLT ASSEMBLY	010429821	561
SCOOP DISK ASSEMBLY	012307382	655
DRIVE UNIT GUN	013735158	655
PARTITION DRUM	012510577	655
SUPPORT CHUTE AMMUN	013221213	655
SUPPORT CHUTE AMMUN	013221212	655
DRUM OUTER	012864755	655
COVER ASSEMBLY DRUM	012307410	655
CONTACT ASSEMBLY FIRING	007545267	655
CAM KIT UNLOCKING	010054494	655
GUIDE SUPPORT CHUTE	014458218	655

FY19		
NOMEN	NIIN	MTBF
CHUTE AMMUNITION	013221227	57
PNEUMATIC MOTOR	013833198	141
20MM M61A1 GUN	014865515	189
SOLENOID ASSEMBLY	007545269	189
COVER ASSEMBLY DRUM	012307410	189
CONTACT ASSEMBLY FIRING	007545267	189
FEEDER ASSEMBLY	012307385	189
ENTRANCE UNIT	012307383	283
SECTOR HOLDBACK ASSY	007835504	283
SUPPORT CHUTE AMMUN	013221213	283
TRANSFER UNIT AMMO	013731844	283
SCOOP DISK ASSEMBLY	015165592	283
COVER ACCES CLEARI	011643229	377
HOUSING MACHINE GUN	013657913	566
AMMO DRUM ASSEMBLY	013536340	566
ROTOR ASSEMBLY	012769450	566
END ASSEMBLY EXIT	011667307	566
CHUTE EJECTION	013221230	566
CHUTE AMMUNITION	013221228	566
HOUSING ASSEMBLY	010086283	566
VALVE SOLENOID BRAK	012483102	566
BREECH BOLT ASSEMBLY	010429821	566
TRACK ROTOR FRONT	006999923	849
END ASSEMBLY ENTER	011714472	1,131
THERMAL IMAGER	015582849	1,131

FY20		
NOMEN	NIIN	MTBF
EXIT UNIT	014867071	52
SECTOR HOLDBACK ASSY	007835504	95
PNEUMATIC MOTOR	013833198	114
CHUTE EJECTION	013221230	114
DRUM INNER HELIX	012510574	114
ENTRANCE UNIT	012307383	143
SUPPORT CHUTE AMMUN	013221213	143
SOLENOID ASSEMBLY	007545269	190
CHUTE AMMUNITION	013221227	190
SCOOP DISK ASSEMBLY	015165592	286
FEEDER ASSEMBLY	012307385	286
CHUTE EJECTION	013455764	286
AMMO DRUM ASSEMBLY	013536340	286
CHUTE AMMUNITION	013221228	286
TRANSFER UNIT AMMO	013731844	286
CONTACT ASSEMBLY FIRING	007545267	286
20MM M61A1 GUN	014865515	571
COVER ACCES CLEARI	011643229	571
COVER ASSEMBLY DRUM	012307251	571
BREECH BOLT ASSEMBLY	010429821	571
UNIVERSAL JOINT	012949929	571
ROLLER GUIDE	011064105	571
VALVE SOLENOID BRAK	012483102	571
CAM UNLOCK REAR	001482325	571
CAM UNLOCKING FRONT	001482326	571
UNLOAD DRIVE ASSY	012307386	571
THERMAL IMAGER	015582849	1,678

FY21		
NOMEN	NIIN	MTBF
EXIT UNIT	014867071	37
PNEUMATIC MOTOR	013833198	74
SCOOP DISK ASSEMBLY	015165592	118
SECTOR HOLDBACK ASSY	007835504	118
CAM ACTUATOR LOADER	001281225	118
COVER ASSEMBLY DRUM	012307251	148
ENTRANCE UNIT	012307383	295
AMMO CONVEYOR	015505037	295
AMMO DRUM ASSEMBLY	013536340	295
CHUTE AMMUNITION	013221228	295
CHUTE EJECTION	013221230	295
CLAMP END AMMUNITION CHUTE	004234352	295
DRUM INNER HELIX	012510574	295
COVER ASSEMBLY DRUM	012307410	295
DRIVE UNIT GUN	013735158	590
GEARSHAFT BEVEL	008938163	590
VALVE SOLENOID BRAK	012483102	590
PARTITION DRUM	012510577	590
CHUTE AMMUNITION	013221227	590
SOLENOID ASSEMBLY	007545269	590
DRUM OUTER	012864755	590
END ASSEMBLY EXIT	012198367	1,181
BREECH BOLT ASSEMBLY	010429821	1,771

Figure 5. CIWS Key Components List. Source: NWSC Corona (2022).

The list was further filtered to reduce the component list so that the simulations (performed using Oracle® Crystal Ball) were completed within the time restriction of twelve hours. For Real-world Model input data, FY21 data was filtered for components with 590 hours of *Te*, resulting in twenty components (rather than the twenty-three shown in Figure 5). This was done to ensure that all components were a part of the same system block level (parts incorporated in physically firing the CIWS), displayed in Figure 6 and not associated with anything less than mechanical parts directly affecting the firing of the CIWS. Figure 6 is a Reliability Block Diagram for the CIWS. The diagram is a visual representation of the order of operations of the system and is read from block 1 (top left) following the flow of arrows to block 31 (bottom right). The index at the bottom of the diagram denotes which blocks are critical to a specific mission. Only black blocks are critical to all missions. Any failure in a black block will result in a system failure for all missions. The two missions for the CIWS are Anti-Air Warfare and Anti-Surface Warfare.

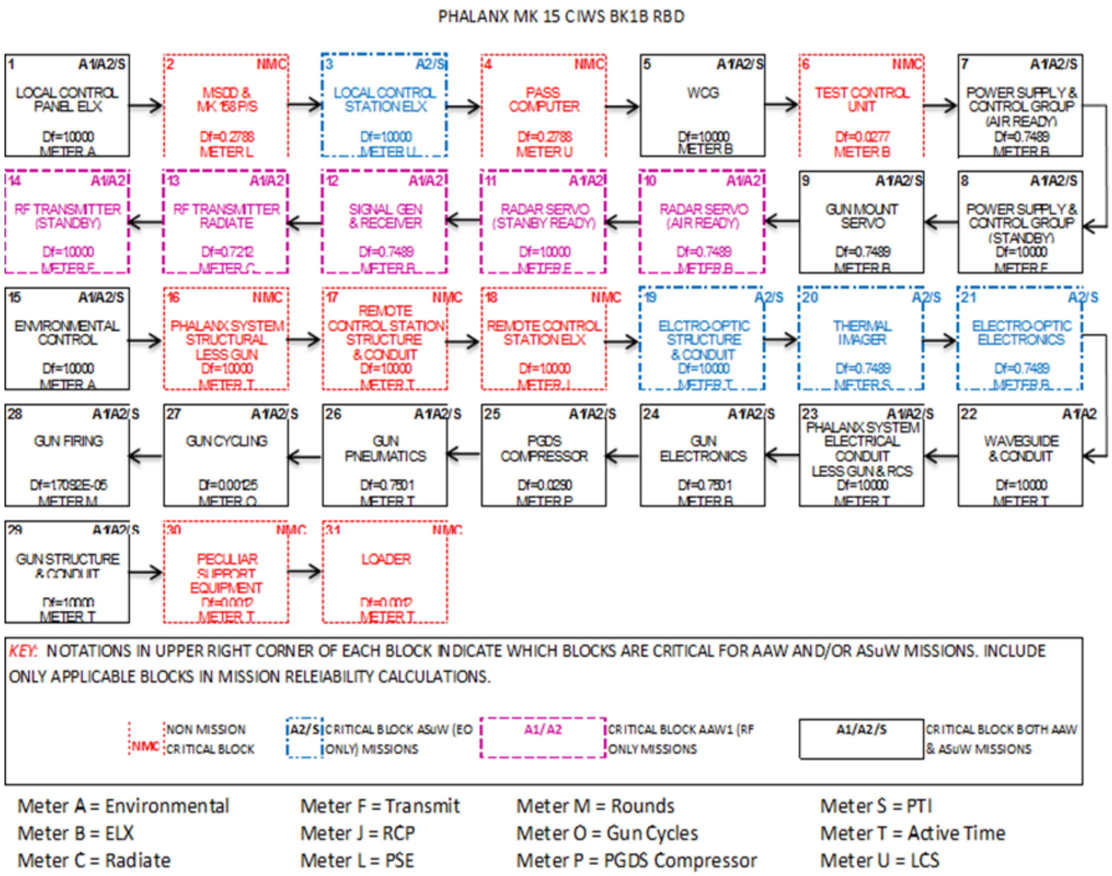


Figure 6. Phalanx MK 15 CIWS BK1B Reliability Block Diagram. Source: NSWC Corona (2022).

In addition to the lists of components with 590 hours or less of *Te*, NSWC Corona Division provided summary numbers for the FY and monthly *Te*. For FY21, the total *Te* for 98 CIWS was 42,072 hours, and the average monthly *Te* of one CIWS in the DDG fleet (69 ships) was 430 hours. These input parameters are used for the Real-world Model.

A demand factor (*Df*) variable seen in the Figure 6 block diagram on each block, was utilized by NSWC Corona Division in conjunction with each *Te* and number of part failures (*N*) given to produce a resulting block level MTBF as shown by Equation 2.

$$MTBF' = (Te/N) * Df \tag{2}$$

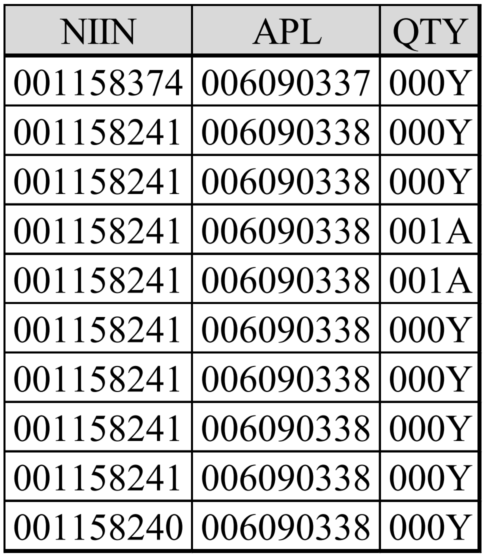
The demand factors (*Df*) are estimates of failure rates based on expected usage in the wartime scenario (A. Dizon, email to authors, August 23, 2022). As components were observed at a parts specific level the *Df* variable was not factored in. Therefore, Equation 1 provided a singular component's MTBF. If the MTBF from Equation 2 total was used for this system, the MTBF of CIWS at a System level, and the block level MTBF would be converted to failure rates for each block and summed up to derive system level metrics (A. Dizon, email to authors, August 23, 2022). Due to the scope of this research, this *Df* variable was used only in the Real-world Model due to NWSC Corona providing numbers that could not separate this factor from summarized totals.

2. Program Executive Office Integrated Warfare Systems (PEO IWS)

The PEO IWS provided Figure 6, the Phalanx MK 15 BK1B Reliability Block Diagram, displaying each block (assortment of parts) as a piece of a series system. As denoted by the flow of arrows, if a single failure occurs within any block, the CIWS ceases to function. This was critical in understanding that a failure of a single component would cause the CIWS to fail. PEO IWS also clarified that Block 28 labeled gun firing (mechanism) were items composed of metal. This was important because this was the focus of our research. Therefore, these items had the potential of being 3D printed to produce spare parts at sea.

3. Naval Supply Weapons System Support

The NAVSUP WSS provided the Consolidated Shipboard Allowance Listing (COSAL) for all DDG CIWS MK 15 1B systems. Figure 7 displays a snapshot of the COSAL released November 2021. This COSAL was used in current uncontested normal naval DDG operations.



NIIN	APL	QTY
001158374	006090337	000Y
001158241	006090338	000Y
001158241	006090338	000Y
001158241	006090338	001A
001158241	006090338	001A
001158241	006090338	000Y
001158241	006090338	000Y
001158241	006090338	000Y
001158241	006090338	000Y
001158240	006090338	000Y

Figure 7. November 2021 COSAL Snapshot. Source: NWSC Corona (2022).

This data was used to enter current naval shipboard deployment spare parts data for the critical CIWS components required by DDG's and crossmatched by the NIIN to display usage sustainability of this list in contested environments. This was done to show how prepared or unprepared a current DDG's CIWS would be in unknowingly encountering a contested environment. The COSAL identified items that were "A" overrides and "Y" underrides to the capacity allowances recommended by the RBS system. Overrides are spares that will deploy with the ship and underrides are spares that will not deploy with the ship. NAVSUP WSS's default system is known as the Weapon System File (WSF) and is based on a DBS model. RBS loadouts are processed into the WSF and the system in return outputs overrides or underrides.

C. DATA ANALYSIS

Utilizing Equation 1, the MTBF was evaluated from the amount of time a component was energized (*Te*) divided by the number of failures recorded in a FY (*N*). Each year from 2017 to 2021, twenty-nine items or less, as displayed in Figure 5, were deemed as "critical" based on the contested environment time constraint of a MTBF < 2,160 hours. Applying these filters, a small number of critical components with both identical energized times (*Te*) and metallic based structure were identified within Figure

6's Block 28. The low MTBF's among these components, given their metallic compositions, were assumed to be caused by the destructive force that the gun exerts while firing. Each part NIIN (of the critical components) was verified as its own assembly with no parent structures or sub-assemblies and no periodic maintenance replacements that affect part failure (*N*) numbers. The *N* reported from NSWC Corona's MRBD were actual failures. Each NIIN's usage was provided on a time meter calculation of the equipment being in theater, excluding in port time (DDG unavailable for operations) and minor part failures.

The CIWS Key Components List data was then used to create a series of models for further analysis. This data was determined to be reasonable for the scope of this research because:

- The data set had not been explored in past studies.
- The data set included a comprehensive set of components identified by NIINs across the fleet.
- The data was obtained from reliable sources.
- A MTBF of less than 2,160 hours (ninety-days) has been identified as a valid point of reference in previous studies.

1. Data Assumptions

To simulate the data, key assumptions were made due to the nonexistence of the following metrics: access to recorded weapon usage based on weapon system firing time and round counts or seconds/hours cycling rounds. The first key assumption made was that damage to CIWS components in this study at individual parts levels was associated with the degradation of an asset that could only come from its firing mechanism. Other variables were negated such as environment, dormant time, mis-installed items, or extraneous entities interfering with the operation of the machine, such as water or foreign material intrusion. The second assumption made was that blocks (parts groups) with similar energy levels within the CIWS operation were utilized during the firing of the weapon and therefore exposed to failures incurred by its usage. By looking at *Te's* representation of separate blocks activated during FY usage, 590 hours was identified as the lowest block of *Te* in a FY. This supported the assumption that these components, given current and standard test and evaluations of deployed CIWS, were directly associated with the firing of the CIWS Block 28 displayed on Figure 6.

2. Data Limitations

This thesis took a unique approach by specifically analyzing DDGs rather than the entire fleet. Given the continuous evolution of 3D printing capabilities, the stock to create a large variety of parts on one machine was an unexplored unknown in this simulation. In many cases, current printers of this nature require large amounts of filament, powder, or product to assemble these items. Currently, the environment and nature of 3D printing being explored by naval warships has not concluded if the unique environment and constant motion of a ship could produce parts at sea that would be within acceptable tolerances.

In a contested environment, time may be a limited commodity. The ability to explore a scenario that generalizes the nature of war in any medium could be a gamble. Our display of the contested environment was one that revolved around layered attacks from the opposing force rather than a full-on force. If a full-on incursion to our force occurs, there will be no time to repair or reload the CIWS asset once a malfunction occurs or all rounds are expended.

The capabilities at the Intermediate Maintenance Depot (IMD) level are often limited regardless of ship or facility. If a part at the subcomponent level can be repaired, it depends heavily on whether the ship has the qualified personnel and is equipped to perform a depot level breakdown of parts to identify the broken component. This was often possible on warships with more robust repair facilities such as CVN's and LHD's but DDG's currently have limited capabilities for this level of repair.

The simulated models may be more cost or space effective than the RBS sparing models that heavily influence the spares allocated to the COSAL. With the limited time and availability to research what each of these components are and how they were stored and shipped, this research had limited ability to answer how effective new sparing practices could be in space reduction or space savings through reduction of spares.

IV. METHODOLOGY

A. SIMULATION CONSTRUCTION

Using a method of staged logic, four models were created for a comparative analysis of the following: the Navy's current position and trend for CIWS critical parts carried onboard (Five-Year Model with Current COSAL), the idea of a ship without space limitations for spares (Depot Repair Ship Model), the effects of AM on CIWS survivability given unlimited production of spares (AM Model), and the last model determined the number of critical parts needed to sustain CIWS primary operations for a constrained time (Real-world Model). The analysis culminates in a simulation that demonstrates the best desired effect of spares modeling within a contested environment. The models compared the Navy's current performance to future performance sustainment of the primary defense system onboard DDG's in contested environments.

Each model was similarly constructed with the first three models sharing the following design details and the fourth model (Real-world) adding to it. Using the program Oracle® Crystal Ball add-in in Microsoft Excel®, a Monte Carlo simulation of endurance supply (Es) was executed using the CIWS Key Component List data against the current COSAL for each of the five years of data. The model was designed to assess and record the survivability of a ship in a contested environment for that FY. This was then recorded as the minimum days a ship could defend itself with an operating CIWS under the ninety-day constraint by utilizing an Erlang Distribution, where x (from COSAL) was the number of spares available. Erlang-k Distributions were derived for each NIIN by estimating two parameters, one for shape and one for scale. Factors for its shape were based on the Navy's current allocated spare allowance (x) for each NIIN being simulated (where 1 means no spare, the only part that was in the operating CIWS) and scale that was based on using each NIIN's MTBF. The simulation generated a random number for each of the NIINs. Each year was ran as its own independent simulation to allow for comparative analysis. Each simulation consists of 30,000 trials, as any trial after this number made no further change to the model's outcome. The simulation stopped once it achieved a 95% confidence interval level (an internal threshold set within Crystal Ball) of the solution or 30,000 run trials. The

95% confidence threshold was set at this level with a 5% chance of the solution being incorrect. This meant that the simulations would, within its trials, estimate solutions to reach its goal being 2,160 hours, with the exception of the Real-world Model, set to two-hours. All simulations in this research found solutions at the 95% confidence level never reaching 30,000 trials in any of the four models.

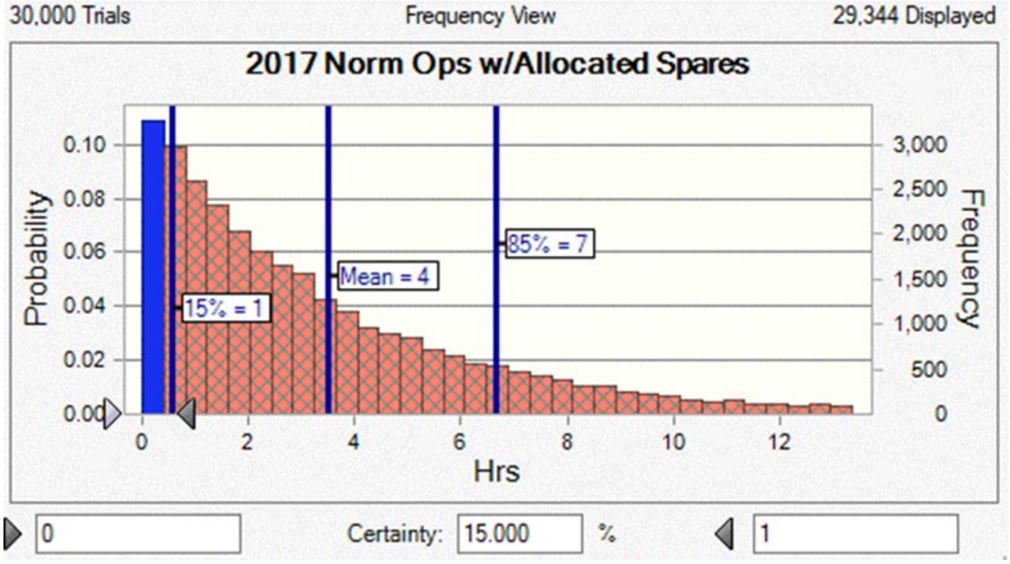
An Erlang-*k* Distribution, a variation of a Gamma Distribution, was used in this simulation due to the relationship the parts had in a singular operating path (shown in Figure 6's block diagram flow). In a singular operating path if one component fails the system fails. Effectively, if one part fails, the system no longer operates. An Erlang-*k* Distribution summarizes its use of true spares needed to repair the system to fully operational given a single path. The models operated on the assumption that the next spare begins when the previous spare ends with no repair time between.

Each of the models was evaluated at the 15% certainty level, as this would be the minimal amount of risk to provide an 85% assurance the number produced would occur given the output (hours). For each NIIN's allocated spare that was above two spares, the risk was reduced significantly. Figure 8 was a sample of this simulation's structure before running (the green area indicates zero as it has not begun its analysis). Figure 9 displayed the results generated by Oracle® Crystal Ball for FY17 for this simulation. In Figure 9, the results that were displayed included a blue shaded area to the left (area of most importance) and its associated number of hours survived at the 15% certainty line (the left most line). The single digit hours of survivability, are explained in the analysis section.

Simulation FY17				
Nomenclature	NIIN	MTBF (Hrs)	Allocated Spares	Normal Ops w/ Allocated Spares
20MM GUN BARREL	014674261	5	1	0
EXIT UNIT	014867071	67	1	0
COVER ASSEMBLY DRUM	012307251	111	1	0
SECTOR HOLDBACK ASSY	007835504	133	3	0
ENTRANCE UNIT	012307383	167	1	0
AMMO DRUM ASSEMBLY	013536340	167	1	0
CHUTE AMMUNITION	013221228	167	1	0
SOLENOID ASSEMBLY	007545269	167	2	0
UNLOAD DRIVE ASSY	012307386	167	1	0
SCOOP DISK ASSEMBLY	015165592	222	1	0
PNEUMATIC MOTOR	013833198	222	1	0
CHUTE EJECTION	013455764	222	1	0
BEARING ROLLER NEEDLE	008060035	334	1	0
20MM M61A1 GUN	014865515	334	1	0
ROTOR ASSEMBLY	012769450	334	1	0
CAM ACTUATOR LOADER	001281225	334	1	0
DRIVE UNIT ANGLE DR	012307435	334	1	0
DRIVE UNIT GUN	013735158	667	1	0
BEARING BALL ANNULAR	013657873	667	2	0
ROTOR STUB ASSEMBLY	013658871	667	2	0
GUIDE SUPPORT CHUTE	014458219	667	1	0
CHUTE EJECTION	013221230	667	1	0
LOCK CAM	003357318	667	3	0
DRUM INNER HELIX	012510574	667	1	0
GUIDE SUPPORT CHUTE	014458218	667	1	0
GEAR ROTOR	006999913	667	2	0
BREECH BOLT ASSEMBLY	010429821	2,001	8	0
Normal Operations		0		
Normal Operations with Allocated Spares		Chances of ship survival on 90 day deployment with no logistical support and current allowance.		

Figure 8. Five-Year Model with Current COSAL Structure

A forecast (in bright blue near the bottom in Figure 8) was defined for each column of assumptions (rows of green) to evaluate and record the days survived at the first part failure without an available spare. The results displayed in Figure 9 were viewed in frequency (shown as the y-Axis, on the right side) with statistics of 0.05 absolute units set for precision, probability (y-Axis, left side) and hours (x-Axis, bottom). All other inputs were set to standard. The simulation ended once the distribution's solution value reached a 95% confidence interval which occurred before the 30,000 trials were reached, displayed in Figure 9 by the number in the top right-hand corner. For example, FY17 in Figure 9 below, 29,344 of 30,000 trials were completed to reach its 95% confidence interval.



0

Certainty: 15.000 %

1

Figure 9. Five-Year Model with Current COSAL Output (FY17)

1. Model Assumptions

The models were based on the assumption that a failed, metallic component or mechanism can be removed from the CIWS and printed by a machine now or in the near future. The models did not account for the time to design a digital model of the failed part, the time to print and post-process the part, nor the time a CIWS would be down for repair. The models also did not account for maintenance times in-between cycling rounds or tests needed to evaluate if the CIWS was fully operational and safe to fire. The survivability metric was also based on a single CIWS per ship model as the super majority of those operating in the fleet are still in this current configuration. If a two CIWS per ship model was used, it would further exasperate the scenario as spare parts would become depleted at a faster rate.

2. Model Limitations

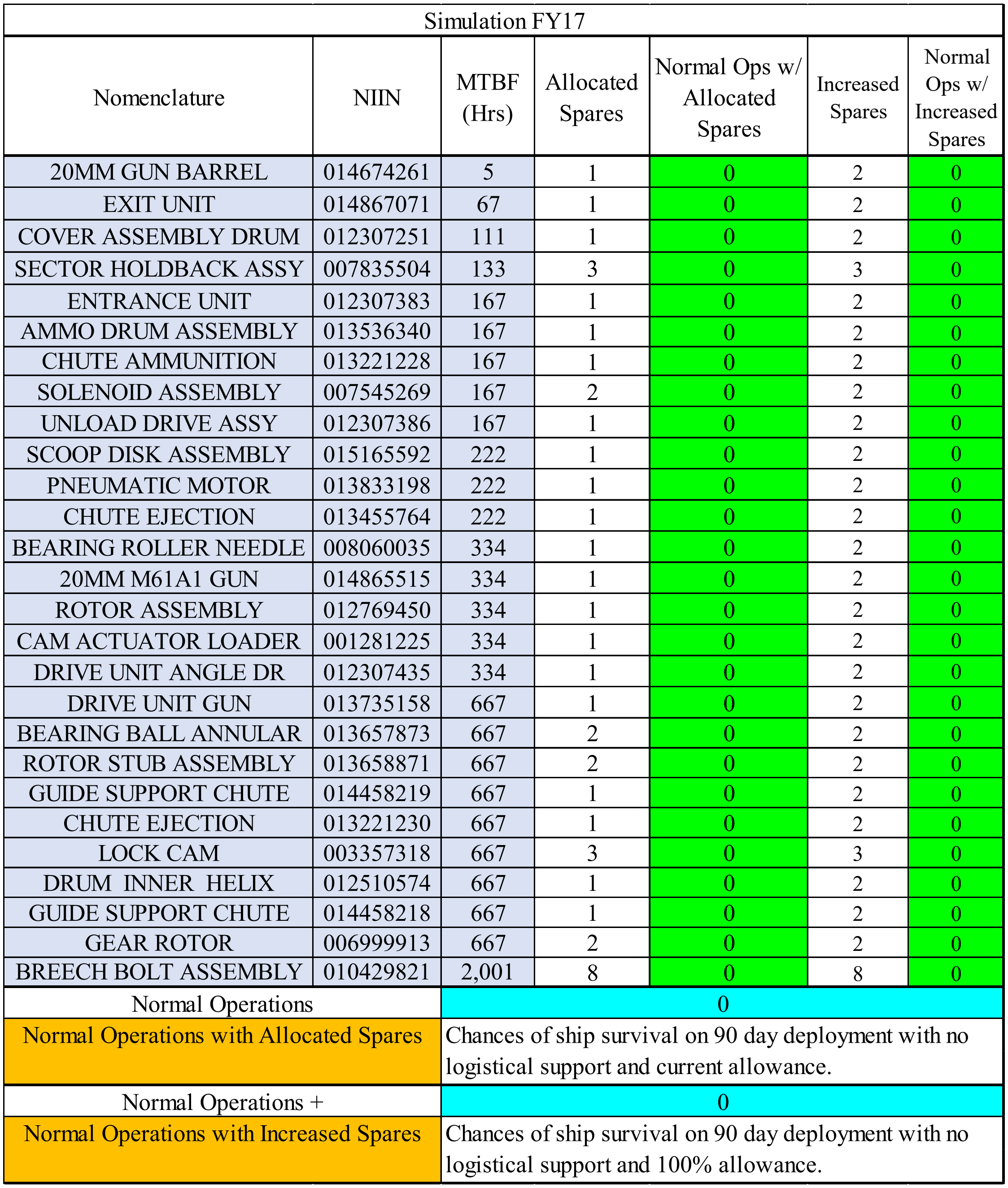
Firing limitations for the scenario needed to be set in a condition suitable for the narrative and within reason for our current DDG fleet's operational deployment status. The ninety-day window was critical to this model to ensure a small enough amount of data was ran through Oracle® Crystal Ball. This allowed for a more feasible and conclusive result. Without the cap at ninety-days, the model's simulation computation would not produce results within a reasonable amount of time, under five-hours of actual computing time.

B. FIVE-YEAR MODEL WITH CURRENT COSAL

The first model created was labeled "Five-Year Model with Current COSAL." It analyzes five years of data from the CIWS Key Component List compared against the current COSAL. This model evaluates the Navy's current position through the lens of a contested environment for CIWS critical part's MTBF versus sparing models to determine if the Navy's position had improved over a five-year time frame. Figure 9 displayed the model for FY17. The other four models differing only in critical components selected for the respective FY.

C. DEPOT REPAIR SHIP MODEL

Similar to the Five-Year Model with Current COSAL Model, a second model was created to eliminate the current sparing model's logic restriction: space onboard. The purpose of this model was to display the idea of a secondary, depot, or auxiliary ship that could build, repair, or store spare parts with no space limitations due to its primary function to assist the first ship with repairs. This model was called Depot Repair Ship Model (Figure 10).



Simulation FY17						
Nomenclature	NIIN	MTBF (Hrs)	Allocated Spares	Normal Ops w/ Allocated Spares	Increased Spares	Normal Ops w/ Increased Spares
20MM GUN BARREL	014674261	5	1	0	2	0
EXIT UNIT	014867071	67	1	0	2	0
COVER ASSEMBLY DRUM	012307251	111	1	0	2	0
SECTOR HOLDBACK ASSY	007835504	133	3	0	3	0
ENTRANCE UNIT	012307383	167	1	0	2	0
AMMO DRUM ASSEMBLY	013536340	167	1	0	2	0
CHUTE AMMUNITION	013221228	167	1	0	2	0
SOLENOID ASSEMBLY	007545269	167	2	0	2	0
UNLOAD DRIVE ASSY	012307386	167	1	0	2	0
SCOOP DISK ASSEMBLY	015165592	222	1	0	2	0
PNEUMATIC MOTOR	013833198	222	1	0	2	0
CHUTE EJECTION	013455764	222	1	0	2	0
BEARING ROLLER NEEDLE	008060035	334	1	0	2	0
20MM M61A1 GUN	014865515	334	1	0	2	0
ROTOR ASSEMBLY	012769450	334	1	0	2	0
CAM ACTUATOR LOADER	001281225	334	1	0	2	0
DRIVE UNIT ANGLE DR	012307435	334	1	0	2	0
DRIVE UNIT GUN	013735158	667	1	0	2	0
BEARING BALL ANNULAR	013657873	667	2	0	2	0
ROTOR STUB ASSEMBLY	013658871	667	2	0	2	0
GUIDE SUPPORT CHUTE	014458219	667	1	0	2	0
CHUTE EJECTION	013221230	667	1	0	2	0
LOCK CAM	003357318	667	3	0	3	0
DRUM INNER HELIX	012510574	667	1	0	2	0
GUIDE SUPPORT CHUTE	014458218	667	1	0	2	0
GEAR ROTOR	006999913	667	2	0	2	0
BREECH BOLT ASSEMBLY	010429821	2,001	8	0	8	0

Normal Operations	0
Normal Operations with Allocated Spares	Chances of ship survival on 90 day deployment with no logistical support and current allowance.
Normal Operations +	0
Normal Operations with Increased Spares	Chances of ship survival on 90 day deployment with no logistical support and 100% allowance.

Figure 10. Depot Repair Ship Model Structure

The Depot Repair Ship Model took the construction of the Five-Year Model with Current COSAL, but any spare with the number one (no existing on-board spare) was increased to two (carrying a spare onboard), see difference in "Allocated Spares" column to "Increased Spares" column in Figure 11. The increase represented a depot repair ship within the contested environment that could give immediate limited logistical support and resulted in the AM Model (Figure 12), which is further discussed in Chapter 5: Model Analysis. Due to the limitations of funding for spare parts and space constraints on DDGs, this option would be worth exploring to see if these constraints limit the primary defense of the DDG in a contested environment and the overall survivability of the ship.

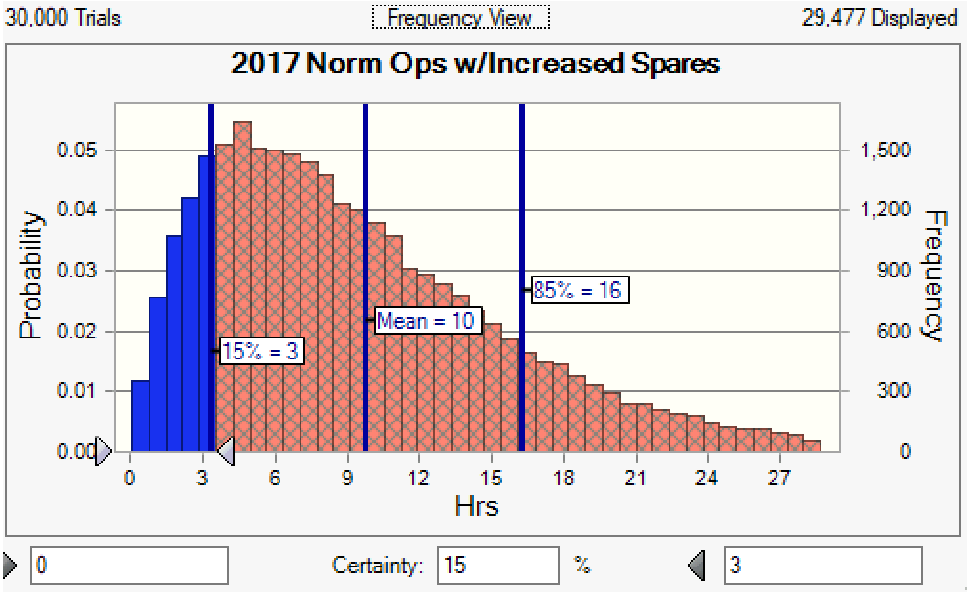


Figure 11. Depot Repair Ship Model Output (FY17)

The most notable difference from the Five-Year Model with Current COSAL model was the significant jump at the 15% probability of days survived that overall effected the shape of the result. This was due to the Erlang distribution factor used to structure the model but also directly links supply of this asset to risk associated with contested environments, lowering the risk as more spares are utilized.

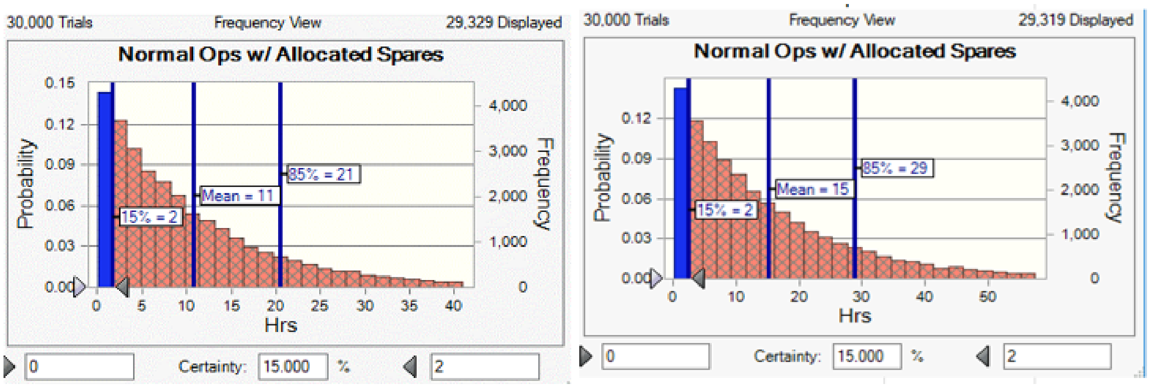
D. AM MODEL

The third model, "AM Model," was established to provide input on how AM could affect survivability. Due to the metallic structure of the identified critical components within Block 28, the feasibility that several components could be printed underway in a contested environment without logistics support is likely. The AM Model was identical in its parameters and selections to the Five-Year Model with Current COSAL, with the exception that it was ran only using FY21 data. Essentially, the CIWS Key Component List for FY21 was compared against the current COSAL.

Trial 1A (Standard)

Trial 1B

(Most Critical AM Components)



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Trial 1C

(Top 2 Crictical AM Components)

Trial 1D

(Top 3 Crictical AM Components)

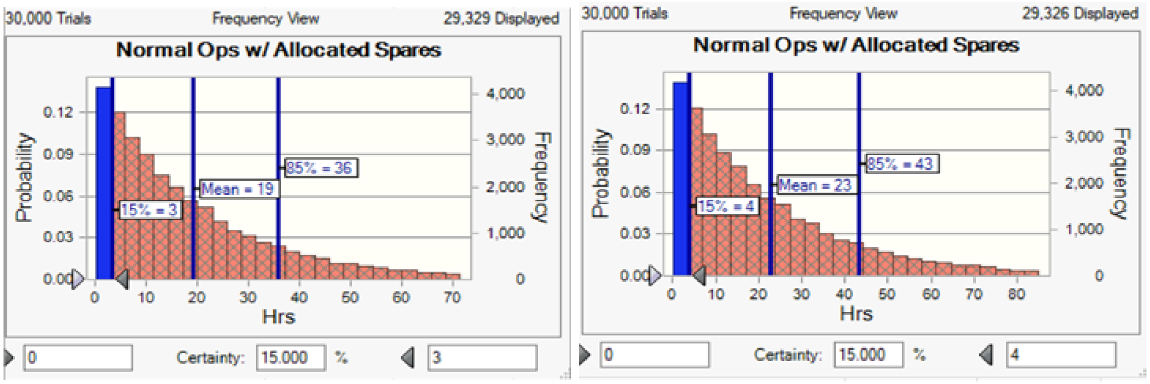

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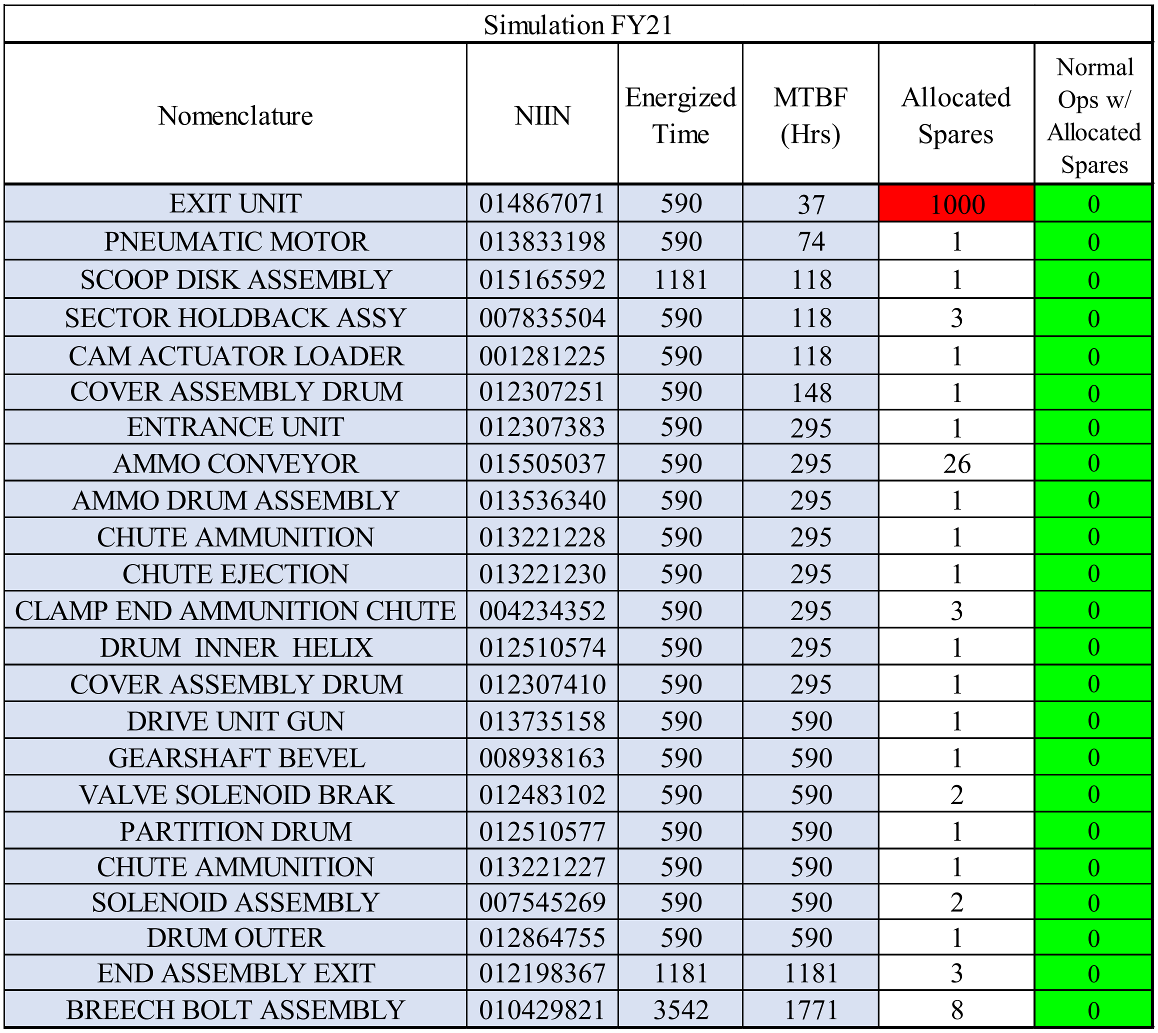
Figure 12. AM Model Structure

The FY21 data in this model was ran four times while changing a single factor for the last three trials. FY21 data was used vice other FY data, as it was the most relatable to present day. Results are displayed in Figure 12 as trials 1A through 1D. The Trial 1B simulation was identical to Trial 1A with the exception of removing the most critical component (NIIN with the lowest MTBF) from the equation. This was done by replacing its spares number of one with the number 1,000 to replicate a situation when the AM process could continually print this part as many times as necessary, highlighted in red in Figure 13.



Simulation FY21					
Nomenclature	NIIN	Energized Time	MTBF (Hrs)	Allocated Spares	Normal Ops w/ Allocated Spares
EXIT UNIT	014867071	590	37	1000	0
PNEUMATIC MOTOR	013833198	590	74	1	0
SCOOP DISK ASSEMBLY	015165592	1181	118	1	0
SECTOR HOLDBACK ASSY	007835504	590	118	3	0
CAM ACTUATOR LOADER	001281225	590	118	1	0
COVER ASSEMBLY DRUM	012307251	590	148	1	0
ENTRANCE UNIT	012307383	590	295	1	0
AMMO CONVEYOR	015505037	590	295	26	0
AMMO DRUM ASSEMBLY	013536340	590	295	1	0
CHUTE AMMUNITION	013221228	590	295	1	0
CHUTE EJECTION	013221230	590	295	1	0
CLAMP END AMMUNITION CHUTE	004234352	590	295	3	0
DRUM INNER HELIX	012510574	590	295	1	0
COVER ASSEMBLY DRUM	012307410	590	295	1	0
DRIVE UNIT GUN	013735158	590	590	1	0
GEARSHAFT BEVEL	008938163	590	590	1	0
VALVE SOLENOID BRAK	012483102	590	590	2	0
PARTITION DRUM	012510577	590	590	1	0
CHUTE AMMUNITION	013221227	590	590	1	0
SOLENOID ASSEMBLY	007545269	590	590	2	0
DRUM OUTER	012864755	590	590	1	0
END ASSEMBLY EXIT	012198367	1181	1181	3	0
BREECH BOLT ASSEMBLY	010429821	3542	1771	8	0

Figure 13. AM Model Output

Trial 1C and Trial 1D follow the same logic except instead of replacing the most critical component (least MTBF) it replaced the top two and top three components respectively, simulating the ability to produce on station one critical component, then two and three. These were identified as the components that would affect the CIWS time available for operation (firing time) the most, on station in a contested environment.

E. REAL-WORLD MODEL

A realistic approach was taken for the last model. Several assumptions were altered, compared to the other models, including firing time and space constraints; parameters based on how the CIWS would operate given the energization (*Te*) of components (rounds used) were generated. There were two key modifications to the model data assumptions. First, the ninety-day threshold was reduced to a more realistic firing time. Second, optimal sparing can achieve a more realistic threshold around a weight factor (given storage space constraints onboard DDGs) of rounds fired.

A realistic firing time estimate was needed for the CIWS in a contested environment over ninety-days. It was unrealistic to assume that 2,160 hours of firing is sustainable mechanically and physically without considering that the CIWS will need to be reloaded, which takes roughly five minutes. The chosen upper bound of ammunition carried onboard provides four reloads per day. Four reloads per day was used as a realistic number of rounds expended by a warship against an adversary given the required duration of time at sea. The following scenario was illustrated to calculate the pounds of rounds required to fire the CIWS for two-hours (upper limit of firing time):

Rate of Fire = 4,500 Rounds/Minute = 75 Rounds/Second

Magazine Capacity = 1,550 Rounds

100 Rounds Shipping Weight = 100 lbs.

Estimate 1 Round = 1 lb.

4 reloads per day for 90 days:

1,550 Rounds / (75 Rounds/Second) = 20.67 Seconds of Sustained Fire per Magazine

4 reloads/day * 90 days * 20.67 seconds of sustained fire per magazine = 7,440.0 seconds or 2.067 Hours of firing time

4,500 Rounds/Minute * 2.067 Hours = 558,000 Rounds or 558,000 lbs.

The purpose of the Real-world Model is to determine the number of critical spare parts needed to remain functional for two-hours. This scenario showed that two-hours of energized time (*Te)* for the entire system exceeded the current firing capacity (where the machine was test fired monthly). The scenario also shows how dynamic two-hours of operational time can be. With approximately two-hours of firing time, the CIWS would expend 558,000 rounds that could not realistically be stored on a DDG. Two-hours was used as an upper bound in the Real-world Model.

Further selection of critical components resulted in identifying all major critical components that had *Te* of 590 hours. The operation time of 590 hours equaled the least usage of all displayed components with accompanied low MTBF. The *Te* factor identified those components that were exposed directly to the destructive forces of the firing mechanisms and therefore highly apt to failure. Given the new constraint of 590 hours of component time energized (*Te*), the following lower bound of CIWS operation time was determined:

42,072 Hours = Average *Te* All CIWS DDG's Runs /FY

430 Hours = Average CIWS *Te* 1 CIWS Runs/Month

590 FY *Te* of Major Critical Components

42,072 Hours / 430 Hours = 97.8 or Roughly 98 CIWS Currently Operating in FY21

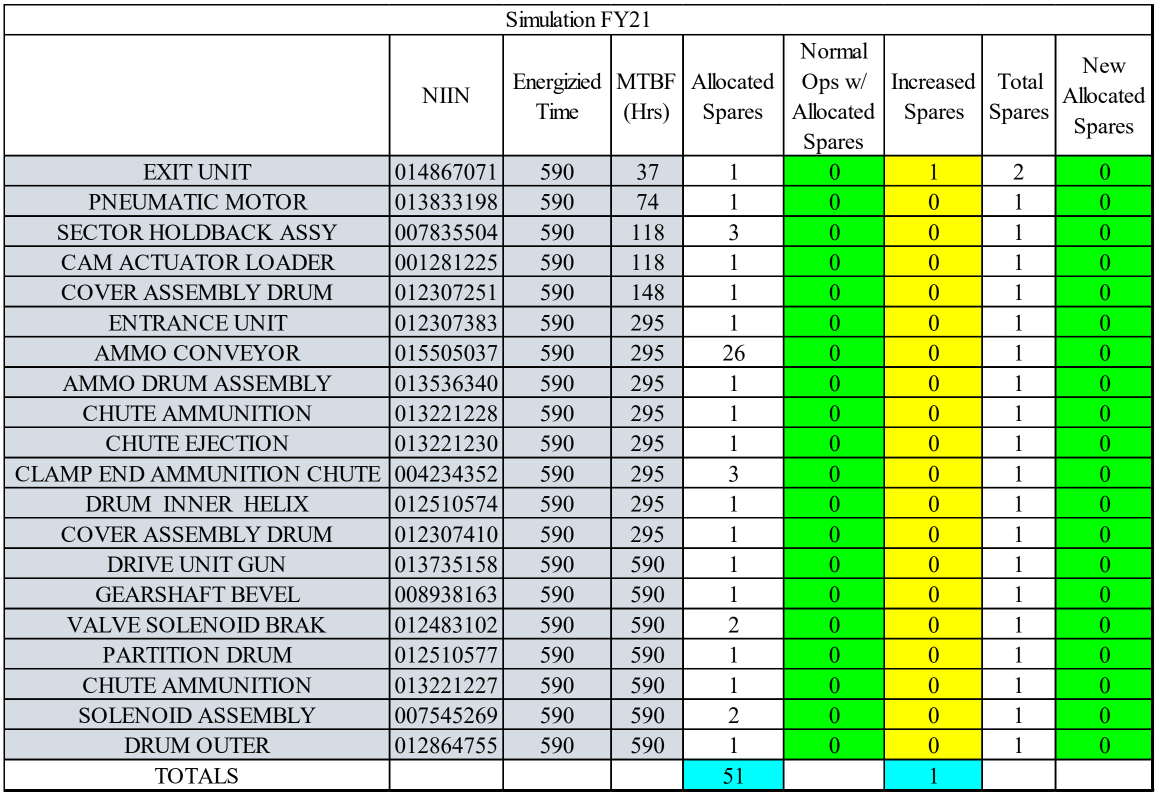
590 Hours / 12 Months = 49.16 *Te* Hours/Month

(49.16 Te Hours/Month) / 98 CIWS = 0.501 Hours / Month CIWS Operation

Because each DDG CIWS in the fleet fails, on average, on or before 0.501 hours within a month of usage, this data control point was used to show the operation or energization evaluated at the major critical component level.

The Monte Carlo simulation ran a revised critical components list (all items with 590 = *Te*) utilizing inputs from the Five-Year Model with Current COSAL while using only FY21 data. These two models utilized identical inputs for all other simulations ran within these models.

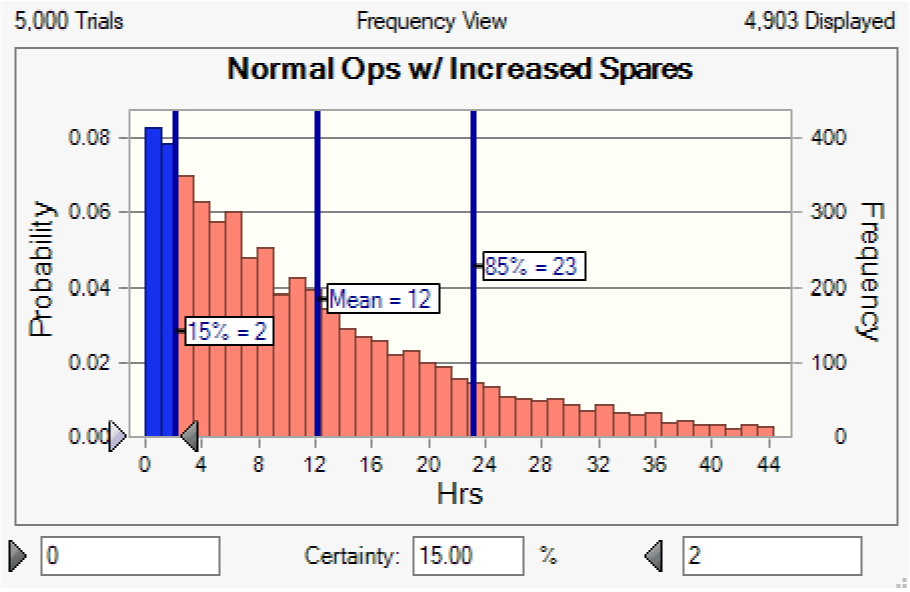
A stochastic search to determine the minimum quantity of each NIIN needed to achieve at least 85% probability that the system would endure two-hours or more given FY21 data was performed with an optimization model (Figure 14) within the Real-world Model, denoted by the yellow column. The objective of the optimization model was to achieve two-hours of firing time while minimizing the number of total spares carried onboard. In Figure 14, the number fifty-one in the bottom row represents the number of spares onboard DDGs within the current COSAL of these critical parts. Also in Figure 14, the light blue highlighted box displayed the minimal number of spares needed to achieve a two-hour firing time onboard a DDG with a single CIWS. The decision variables in this optimization model were the number of spare parts carried onboard for each part ("Increased Spares" column). The optimization of the "Increased Spares" column only varied the number of spare parts carried onboard from zero spares or greater with no upper bound to meet the two-hour firing time in order to achieve less than fifty-one total parts carried onboard (the current allocated spares total). The constraints for this model were no more than fifty-one total allocated spares carried onboard, no less than two-hours of firing time, and all spares greater than or equal to zero.



Simulation FY21								
	NIIN	Energizied Time	MTBF (Hrs)	Allocated Spares	Normal Ops w/ Allocated Spares	Increased Spares	Total Spares	New Allocated Spares
EXIT UNIT	014867071	590	37	1	0	1	2	0
PNEUMATIC MOTOR	013833198	590	74	1	0	0	1	0
SECTOR HOLDBACK ASSY	007835504	590	118	3	0	0	1	0
CAM ACTUATOR LOADER	001281225	590	118	1	0	0	1	0
COVER ASSEMBLY DRUM	012307251	590	148	1	0	0	1	0
ENTRANCE UNIT	012307383	590	295	1	0	0	1	0
AMMO CONVEYOR	015505037	590	295	26	0	0	1	0
AMMO DRUM ASSEMBLY	013536340	590	295	1	0	0	1	0
CHUTE AMMUNITION	013221228	590	295	1	0	0	1	0
CHUTE EJECTION	013221230	590	295	1	0	0	1	0
CLAMP END AMMUNITION CHUTE	004234352	590	295	3	0	0	1	0
DRUM INNER HELIX	012510574	590	295	1	0	0	1	0
COVER ASSEMBLY DRUM	012307410	590	295	1	0	0	1	0
DRIVE UNIT GUN	013735158	590	590	1	0	0	1	0
GEARSHAFT BEVEL	008938163	590	590	1	0	0	1	0
VALVE SOLENOID BRAK	012483102	590	590	2	0	0	1	0
PARTITION DRUM	012510577	590	590	1	0	0	1	0
CHUTE AMMUNITION	013221227	590	590	1	0	0	1	0
SOLENOID ASSEMBLY	007545269	590	590	2	0	0	1	0
DRUM OUTER	012864755	590	590	1	0	0	1	0
TOTALS				51		1		

Figure 14. Real-World Model Structure

This simulation executed 5,000 trials with 30,000 iterations in each trial, to achieve a 95% confidence interval that the CIWS could fire for [1.95-2.05] hours without resupply. The simulation completed well under 5,000 trials, and Figure 15 displays the compiled results analysis verifying the targeted two-hour run time by the displayed line at 15% (right of the blue shaded region) and the results as the left most portion of the graph shaded solid blue.



0 Certainty: 15.00 % 2

Figure 15. Real-World Model Output

F. APPLICATION OF THE METHODOLOGY

The following four models were compared: Five-Year Model with Current COSAL, Depot Repair Ship Model, AM Model, and Real-world Model. These models evaluated the amount of firing time they could provide a CIWS onboard a DDG. For models Depot Repair Ship and AM, the longer the duration of firing time achieved from the thesis standard (results of the Five-Year Model with Current COSAL), the more feasible the method to create sparing model improvements became. The Real-world model was set to evaluate the least number of parts that could be carried to achieve two-hours of firing time, the smaller number of parts, the better the result. These models worked as building blocks with each model adding depth to ultimately improve operational firing time. If one model could improve the firing time, what if two models were applied? This process was repeated, and each model represented an additional method to ensure that adequate firing time of the CIWS was achieved and how much time was truly needed given normal operation.

The staged analysis of these models evaluated critical parts being spared and different ways to find a total amount required to be carried onboard a DDG. The variation of four results established how evaluation of this data can lead to an improved Navy sparing model and how depot ships, AM, or system operation priority (hours of CIWS firing time) can largely affect how the Navy spares parts for systems onboard DDGs. Superior sparing methods could increase survivability of DDG assets in future contested environments giving the U.S. Navy an advantage in the threat environment created by strategic power competition.

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V. MODEL ANALYSIS

A. FIVE-YEAR MODEL WITH CURRENT COSAL

The CIWS has had its ups and downs over its forty plus years of service and several factors largely affect its sustainment as the Navy's premier defense weapon onboard warships. Previous studies, such as the critical material failures of the CIWS study conducted by Arca et al. (2019), demonstrated the decline in the A_o of the CIWS leading into 2019 due to the misuse of the Thermal Imager and human error causing premature failure of the Exit Unit. The spare parts selected in this research were meant to expand upon previous research efforts to gain a better understanding of the effectiveness of the supply of CIWS spare parts onboard DDGs.

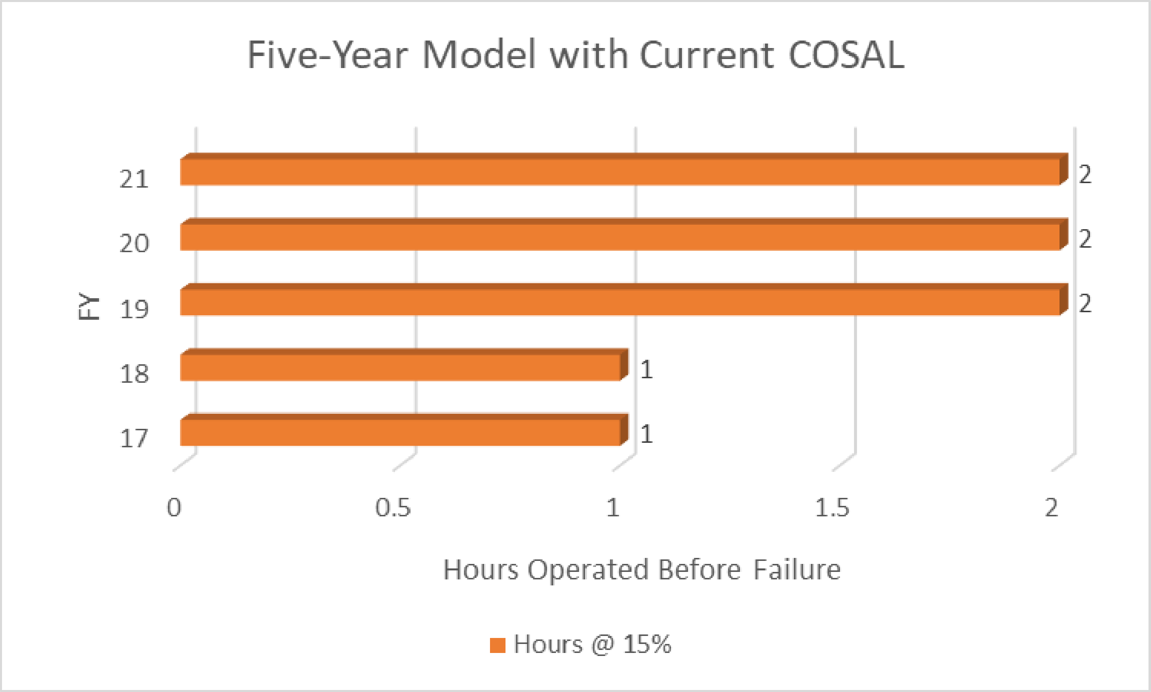

Figure 16. Five-Year Model with Current COSAL Results

The results of the Five-Year Model with Current COSAL are displayed in Figure 16 above. Figure 16 showed that with the fleet wide elimination of a single critical component (the 20 MM Gun Barrel, replaced by the Optimized Gun Barrel in 2019) the survivability increased 200%. This was displayed by one-hour of potential continual use at 15% certainty in FY18 above, displayed in the orange columns, versus the two-hours of firing time before failure at 15% confidence in FY19. This evaluation of a five-year period showed that assessing critical components based on desired usage has a large effect on how the ship will perform in an environment that will utilize its defense system. One-hour of defense in a contested environment may be the difference between failure or success of a mission, highlighting that critical components become substantial to mission success. Finding alternative solutions to either produce, increase spares, or improve these designs should remain a top priority among logisticians and engineers alike.

B. DEPOT REPAIR SHIP MODEL

Eliminating the cost and space constraint variables from the sparing equation, the Depot Repair Ship Model was created to showcase potential additional firing time achieved with extra resources at sea. In Figure 17 (Depot Repair Ship Model Results Versus Five-Year Model with Current COSAL), the results of carrying a single spare for each critical component, plus those already on the COSAL, resulted in a 300% increase in weapon operation time at the 15% certainty level in 2017, compared to the previous simulation in that year. Years 2017 and 2018 remained at three hours due to the same critical component across both years affecting the simulation, while the large spike in 2019 was due to the changeover in the new Exit Unit barrel previously mentioned. Survivability in 2019 was 1,400% greater than its previous simulation with declining results, but improved overall in 2020 and 2021, surpassing three hours operation by large amounts. The hours of operation in relation to the goal of 2,160 hours was inconsequential due to the space utilized by rounds expended during approximately two-hours of firing time equating to 558,000 lbs. of rounds. Therefore, FY19's twenty-eight hours of firing time, 1,400% greater than two-hours, would never be supported by rounds carried onboard a DDG. The exorbitant percentage increases over the Five-Year Model with Current COSAL, used as a benchmark, shows the sparing model limitations on the capacity to operate at a much higher firing duration.

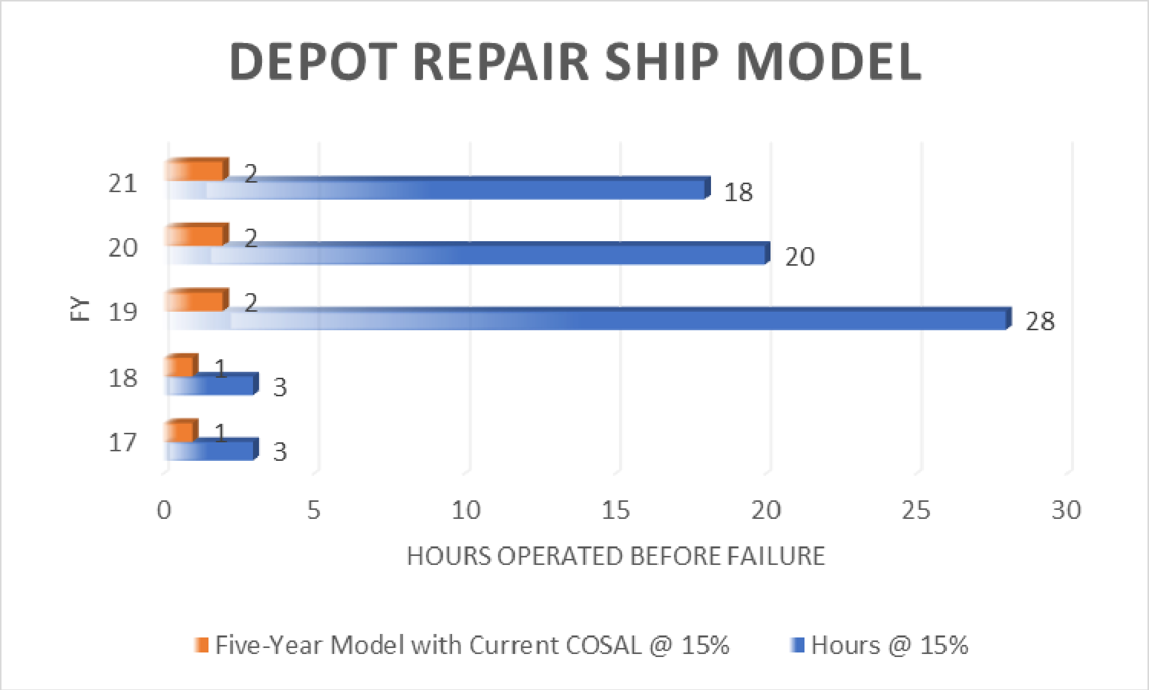

Figure 17. Depot Repair Ship Model Results Versus Five-Year Model with Current COSAL

The Depot Repair Ship Model was an effective means of quantifying the positive effect sparing models can have on the survivability of a ship and how more spares for a critical primary defensive weapon result in an increase in the chances of survival in an operational contested environment if the CIWS must be used for defense. The Navy limits its capability in operation of the CIWS by the number of components spares carried onboard. The Depot Repair Ship Model highlights the importance of upper bound operational goals to establish a working defense system designed for protection of the ship, as well as why carrying all critical spares is unrealistic and unnecessary.

C. AM MODEL

Sequentially removing the most critical component affecting firing time of the CIWS, the AM Model was ran to display the effect of AM production onboard if aimed toward CIWS operation given FY21 metrics. Mirroring the Depot Ship Model with a narrower focus, the AM Model was constructed to find how much firing time could be gained by AM of the top three critical components, given the current COSAL. The results in Figure 18 show that the AM of critical components on DDGs increases the firing time of the CIWS with less total spares carried onboard. As shown in Figure 18, Trial 1C and 1D, depicted a potentially enhanced operational firing time that would be 150–200% greater than the "Five-Year Model with Current COSAL" for FY21 results, where the CIWS was only operable for two-hours. The ability to AM onboard a ship with only three components doubles the survivability of this defense asset during critical operations and reduces risk to inherent probable threats with a high potential to greatly reduce logistics down time and cost to replace critical components. The benefit of the AM process not only potentially scales down the MDT but nearly eliminates MLDT as the most critical factor in a logistically unsupported contested environment. The elimination of spares onboard DDG could potentially free up space to store other non-printable assets that logistically constrain the deployment time of DDGs.

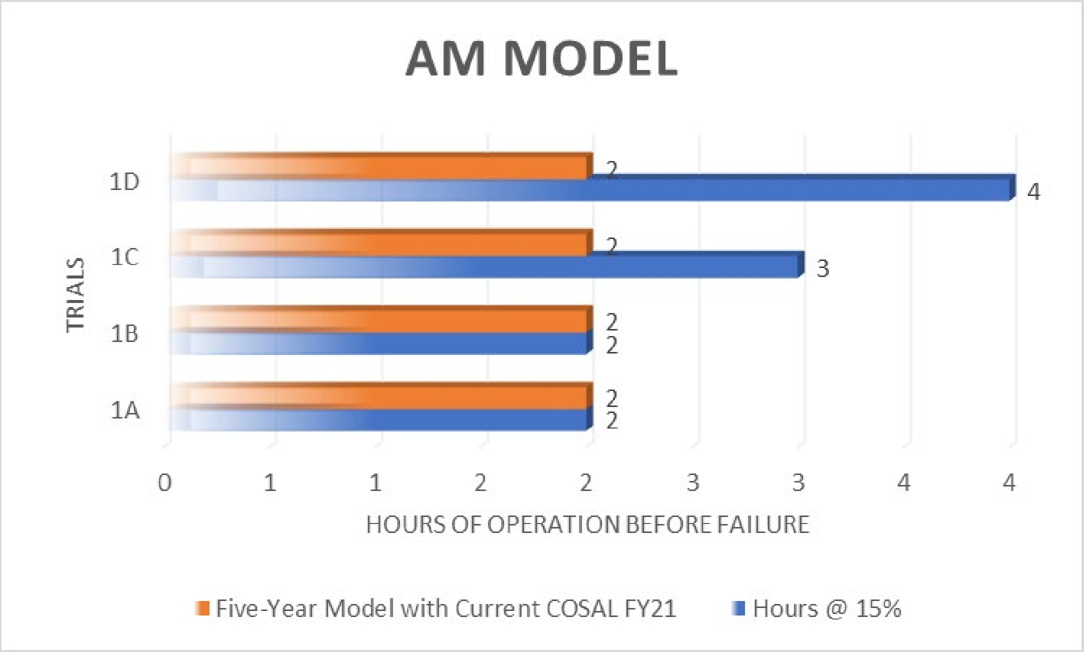

Figure 18. AM Model Results Versus Five-Year Model with Current COSAL

Given the Real-world Model structure and restriction to the firing time variable, the result of two-hours of firing time is a significant result across all trials of the AM Model. As discussed previously, two-hours of firing time is critical within a contested environment. In the Real-world model, the maximum and minimum firing times are calculated conclusions explaining why anything more than two-hours of firing time is unnecessary, while the AM model supports a longer duration increasing validity to improve reliability in that desired two-hours of firing time.

D. REAL-WORLD MODEL

The Real-world model was created to give value to the limits of this weapon based on space and weight constraints, which may be inherently an issue for all weapon system consumables onboard naval warships. With this, the two-hour firing time limit became a very tangible number in its placement of the upper bound for this experiment. The simulation's optimization computational results were displayed in Figure 14's increased spares column (highlighted yellow) showing up as a sum of one, for the entire column, which combined with Figure 15, presenting that Real-world optimization was met within the following constraints:

- Meeting two-hours of firing time
- 95% confidence interval
- 15% certainty (as other models have observed)
- Within 5,000 trials of 30,000 simulations

The model demonstrated that with the addition of a single spare, not RBS's 51 spares, it could enable the potential firing time of two-hours for the CIWS weapon.

More finitely, only a single spare of the most critical major component will result in survivability of the CIWS under extreme usage during a ninety-day period, negating all suggestions made under current RBS sparing model algorithms. This scenario prioritized operation of the CIWS in a contested environment above all to achieve this result.

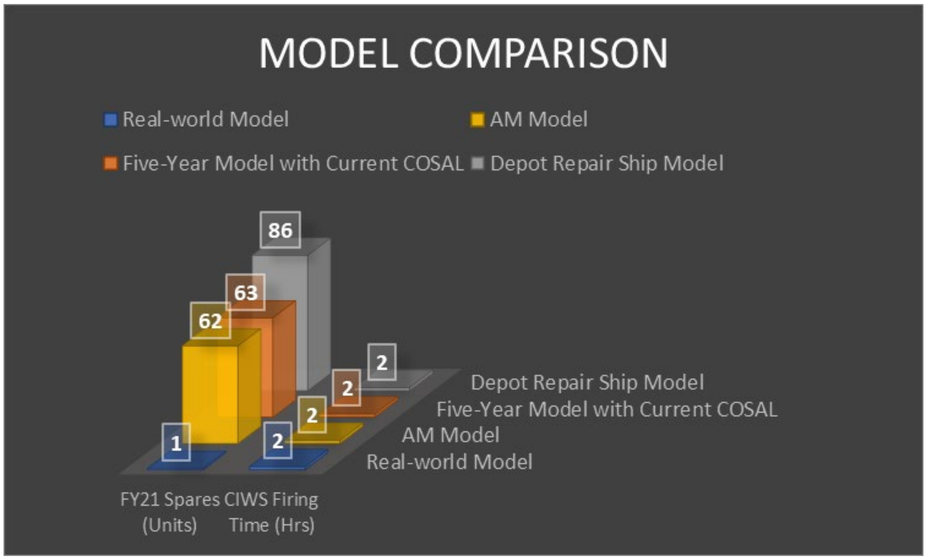

Figure 19. Comparison of Four Models

The results from the Real-world model further validated the increased firing times exhibited in Figure 18's comparison between all four trials of AM simulations. The ability to print critical components at sea vastly increases usage rates and firing sustainability of the CIWS defense weapon system. This point is graphically represented in the Comparison of Four Models (Figure 19) above, comparing all the models by the number of spares held by each model to achieve a two-hour firing time. In comparison to the other models, the optimization model demonstrated how the weapons' primary function is grossly overlooked. The only spare that mattered to the prolonged use of the CIWS could either be printed or stored onboard, but has been neglected by current models that focus on other targets affected by cost, availability, and size constraints.

Although the current Navy RBS sparing model generates a number of total parts for deploying CIWS, based on this research those quantities appear to be excessive. The extra spare parts generated by the Navy RBS sparing model exist due to factors, such as cost, availability, and storage constraints. This research evaluated the CIWS given its primary function, firing rounds, and what the most likely failure would be. The order of operation in operating a machine onboard is superfluous. The critical parts, those that fail most often, need to be spared accordingly especially if this operation provides essential survivability and protection of Navy assets and crew.

VI. CONCLUSION AND RECOMMENDATIONS

A. DISCUSSION

This thesis attempted to answer the question “How does the Navy better sustain primary defense weapon systems onboard DDGs in contested environments?” The motivation behind the thesis question was to improve the notional operational time of the CIWS. Through modeling, the thesis strived to demonstrate the possible impact of additive manufacturing (AM) and depot ships on the availability of spares and how improved sparing could positively impact the available firing time of the CIWS. Through the creation of four models supported by Oracle® Crystal Ball software, the thesis evaluated the Navy’s current potential firing time of the CIWS onboard DDGs. The models first showed how much firing time current sparing models provided, then introduced concepts for AM and depot repair ships to evaluate if these methods could provide additional firing time of the CIWS. The Real-world model then provided perspective on what an appropriate firing time in a contested environment should be. It also delivered a tailored list of spare parts to ensure a determined length of firing time was supported.

Although 3D printing is still in its infancy in the Navy, further development will open the door to additional discussions on its integration in support of other platforms outside of primary weapon systems. The capabilities of 3D printing offer the Navy the opportunity to shorten sea lines of communication and provide critical repair parts to surface combatants engaged in near peer combat in contested environments. In a time of fiscal constraints coupled with unreliable support provided by defense contractors the reduced turnaround time of parts repaired utilizing 3D printing can offer increased sustainability of the CIWS found onboard DDGs.

The importance of integrating 3D printing into the supply and repair pipeline for spare parts will be measured in terms of A_o and readiness of weapon platforms. The improved A_o and readiness will offer the warfighter the ability to maintain reliable deployment and maintenance availability schedules. Consistent and reliable schedules avail the warfighter of suffering from symptoms of unstable deployment and repair schedules and in turn has the potential added benefit of improved warfighter moral and increased retention. One of the most important benefits of 3D printing is the improvement to readiness and sustainability of the DDG fleet. In a period of strategic competition, the demands placed on surface combatants will increase placing greater pressure on the fleet to maintain readiness through improved sustainability. By integrating 3D printing into fleet sustainment models DDG readiness can be maintained at obligatory levels.

B. RECOMMENDATIONS

The primary recommendation of this research aligns with the most recent National Security Strategy (NSS) guidance that states that the global distribution of power continues to create and evolve the level of threats that will require a better equipped force. Given the current threat analysis, U.S. forces must prepare and adapt to deter threats from advanced weapon systems. While supply chain management and logistics alone cannot win a war, these factors can enhance the DOD's inherent ability to protect and defend America.

Next, based on the four models in this research, there are opportunities to improve the design of our current defense system. The "Five-Year Model with Current COSAL Results Model" and "Depot Repair Ship Model" showed that instead of carrying a surplus of critical spares, the process for determining the number of critical components included on a COSAL should consider continuous usage in contested environments. The Navy must shift its readiness focus from dispensable legacy systems to prioritize advancement in weapon system speed and agility. Tactically and strategically, our forces must prepare to operate our current weapon systems for longer periods of time to counter adversaries in contested environments. If the Navy continues to carry current levels of spares onboard without considering continuous operations, it will limit its CIWS operation capabilities in contested environments. The "AM Model" and "Real-world Model" further supported the previous models and showed that the Navy should AM critical components on DDGs. This would increase the firing time of the CIWS and decrease the number of total spares carried onboard. With the reinvention of an old idea, depot repair ships that have AM capabilities could support longer operational firing of primary weapons onboard warships in contested environments. Much like the concept that depot repair ships supported during World War

I and II, AM to posture spares can nearly eliminate logistic down time and increase the amount of operational time at sea for DDGs and naval warships alike. Understanding that making changes to the defense budget process is complicated, analyzing spaces onboard DDGs, such as those that contain test benches, could potentially make space for new AM machines.

Lastly, to limit the scope of this research effort, a subgroup of critical components was assessed. Due to computational complexity, the number of variables in this research effort was limited. A thorough analysis of all critical components would be beneficial in evaluating the endurance times of critical components that may not fail as often but still have the potential to fail.

C. AREAS OF FUTURE RESEARCH

Spares modeling has only just recently begun exploring endurance logistics regarding contested environments as a weakness of the Navy's deployed supply network. The simulations ran within this study demonstrate the effect of targeted replenishment to critical components of the CIWS onboard DDG's and the effect that AM could produce if no logistical support existed during a heightened battle scenario. There are many factors that go into how the Navy orders, distributes, and stores these assets onboard warships but with space and cost being the largest factors the future of expedient replenishment at sea could take many forms that the RBS model does not yet account for. Those currently available without supported data are drone deliveries by air or submersible, storage ships or fully capable depot ships, and current industry small scale AM produced parts of other materials, such as those used in automotive racing production and Automated Intelligence printed parts. Using these future available platforms could critically affect the cost overall of parts and how the Navy logically thinks of storage availability within a DDG haul.

Previously mentioned was the USS Essex's successful test of aluminum AM onboard, sponsored by Xerox that substantiated the claim that 3D printing could be performed at sea. Materials such as inconel, copper, stainless steel, tool steel, onyx (carbon composite) and aramid fibers are printable and able to withstand the extreme environments encountered in the marine environment. The industries leaders in these materials should be brought into the conversation for new tests onboard warships, integrated with current DOD manufactures to ensure that parts onboard warships are not only capable of being printed but intended to be by their design and conception. The integration and utilization of these design and manufacturing advancements could single handily change the conversation on parts constraints onboard warships and how sparing models are implemented.

Given the current state and algorithms that enable RBS systems and allow placement of spares onboard all Naval warships, a production capability at sea would ultimately change the relationship that warships in need of parts could have with the logistics network. Clean labs using stable power, distilled water and dehumidified air would be ideal sterile conditions to continue research of high caliber AM. Recreating proven industry printing method results, but at sea, is the next step for the Navy to take to ensure AM success in ocean environments.

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