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THESIS

CAN AMERICA'S SHIPBUILDERS MEET THE U.S. NAVY'S LONG-RANGE VESSEL CONSTRUCTION PLAN?

by

Rudy Mason, Wyatt J. France, and Connor Darr

June 2020

Thesis Advisor: Geraldo Ferrer
Co-Advisor: Kenneth H. Doerr

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CAN AMERICA'S SHIPBUILDERS MEET THE U.S. NAVY'S LONG-RANGE VESSEL CONSTRUCTION PLAN?

Rudy Mason
Lieutenant Commander, United States Navy
BA, John Jay College of Criminal Justice, 2006

Wyatt J. France
Lieutenant Commander, United States Navy
BBA, University of Wisconsin—Eau Claire, 2002

Connor Darr
Lieutenant Commander, United States Navy
BS, University of Maryland College Park, 2007

Submitted in partial fulfillment of the
requirements for the degree of

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June 2020

Approved by: Geraldo Ferrer
Advisor

Kenneth H. Doerr
Co-Advisor

Eddine Dahel
Academic Associate, Graduate School of Defense Management

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This thesis examined the current capacity of the defense shipbuilding industry in the United States and the need to expand the nation's shipbuilding capabilities to fulfill the Navy's 30-year shipbuilding plan. The authors explored a learning curve model along with a queuing theory capacity model to determine and compare the utilization rate of two industrial-base shipbuilders, Bath Ironworks and Ingalls Shipbuilding. Due to rarely achieved learning curve efficiencies and complex manufacturing processes, the shipbuilding industry is at full effective capacity. Recommendations are to adopt one or more of the logistics principles introduced, including adding redundancy, implementing a more distributed supply chain, introducing "low-road" or shorter-service-life vessels, and reducing the three dimensions of ship variety, ship complexity, and the Navy's demand variability.

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LIST OF ACRONYMS AND ABBREVIATIONS

BBC	block buy contracting
BCNV	Budgeting for Construction of Naval Vessels
BIW	Bath Iron Works
BMD	ballistic missile defense
CGT	compensated gross tonnage
CHAMP	Common Hull Auxiliary Multi-Mission Platform
CLF	combat logistics force
CVN	aircraft carrier, nuclear
DDG	guided missile destroyer
DoD	Department of Defense
FMI	First Marine International
FSA	Force Structure Assessment
FY	fiscal year
GAO	Government Accountability Office
LCS	littoral combat ship
LHA	amphibious landing helicopter assault
LHD	amphibious landing helicopter dock
LPD	amphibious transport docking
LSC	large surface combatant
LSD	dock landing ship
MYP	multi-year procurement
NAVSEA	Naval Sea Systems Command
NVR	Naval Vessel Register
OECD	Organisation for Economic Co-operation and Development
OPNAV	Office of the Chief of Naval Operations
SECDEF	Secretary of Defense
SECNAV	Secretary of the Navy
SSBN	submarine, ballistic missile, nuclear
SSC	small surface combatant

SSN	attack submarine, nuclear
USNS	Unites States Naval Ship
USS	United States Ship

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I. INTRODUCTION

Every few years, the U.S. Navy conducts a force structure assessment (FSA) to determine what number and what mix of ships are required to meet the United States' national security needs in the future. The number of ships in the Navy and combination of ship types have a significant impact on the types of missions the Navy can perform and the ability of the Navy to achieve our nation's strategic goals. The most recent FSA (Secretary of the Navy [SECNAV], 2016b) was conducted in part to assess how the Navy needed to adjust to successfully counter increases in naval aggression and naval power from resurgent and emerging threats, including Russia and China (LaGrone & Eckstein, 2016). When assessing the Navy's current ability to counter these emerging threats, the 2016 FSA identified significant gaps and weaknesses in naval strength. It recommended an increase in fleet size to a total naval battle force of 355 ships. The previous FSA (2014) recommended a battle force of 308 ships (SECNAV, 2016a). Although large surface combatants (LSCs) and attack submarines (SSNs) accounted for the most significant recommended increases, almost all ship classes were recommended for an increase in proportion (SECNAV, 2016b). The 2020 edition of the Navy's long-range shipbuilding plan set a goal of reaching the 355-ship target by 2034 (Office of the Chief of Naval Operations, 2019).

The number of battle-force ships in the Navy has been steadily decreasing since the end of the Cold War. From a high of nearly 600 ships in the early 1980s, the current battle force has been reduced to 299 ships as of 2020 (NAVSEA Shipbuilding Support Office, 2020). After the fall of the Soviet Union, the United States no longer faced a military equivalent peer adversary. This change in the early 1990s, along with the sweeping pivot to anti-terrorism operations by the U.S. military in the 2000s, made it difficult for naval planners to justify large naval fleets and, ultimately, along with other factors that are discussed later, led to the atrophy of U.S. naval strength and atrophy of U.S. naval shipbuilding capacity. The current operational age of many active naval ships presents another challenge. Many naval ships currently in service were built during the 1980s and early 1990s, and will be reaching the end of their service lives in the near future. Achieving the 2016 FSA recommendation of 355 ships by 2034 requires not only the addition of 66 ships to the battle force but also the replacement of dozens of ships that are scheduled to be decommissioned over the next 10 to 15 years.

Similar to the atrophy of U.S. naval strength over the past two decades, the American commercial ocean-going shipbuilding industry has also experienced substantial production reductions over the last 40 years (Klein, 2015). Following the end of the Second World War, the United States was ranked first in the world in commercial shipbuilding and built most of the world's commercial fleets. Today, the United States ranks 19th and produces less than 1% of the world's ocean-going commercial ships (Klein, 2015). U.S. large commercial shipbuilders have not received ship orders to support the infrastructure needed for technological advancement and efficient large volume production. The factors that contributed to this decline are explored in detail in this thesis, as the erosion of the commercial sector's production capacity also presents a variety of risks to the defense sector's ability to maintain and build the Navy the United States needs.

In this report, we discuss some of the many challenges facing the American shipbuilding industry and discuss what the Navy can do to support shipbuilding capacity and capability to reach its 355-ship battle force goal.

A. RESEARCH QUESTION

The primary research question answered in this thesis is as follows: What does the Navy need to do to expand the nation's shipbuilding capabilities to fulfill the Navy's 30-year shipbuilding plan? In doing so, this thesis answers two supporting research questions:

1. What are some of the ways the Navy's acquisition process has influenced the defense sector of the American shipbuilding industry?
2. How have contraction and consolidation trends within the American shipbuilding industry impacted production capacity?

B. METHODOLOGY

This thesis project uses a mixed-method index approach for a comparative macro-quantitative analysis to assess the production capacity of the defense shipbuilding sector. The first approach of this index is based on the concept of production efficiency as it relates to the design complexities of a naval vessel. As employed in this project, production efficiency is modeled based on the complexities of each vessel design and the degree in which learning occurs during production of each vessel. The stated goal is to create a macro-uniform aggregated measure of productivity for defense-sector shipbuilding efficiencies correlated to specific designs. The Naval Vessel Register (NVR) provided the shipyard production data used in this model.

The second methodology is derived from queueing theory. A capacity-risk model using a multi-server model was developed to determine a utilization rate. The inputs were extracted from historical shipbuilding data from each of the current seven American shipbuilders. The inputs were then used to determine the time between keel-laying dates (inter-arrival time) and days under construction (service time) to arrive at a utilization rate. By determining utilization rate, a shipbuilder can assess where the variability lies to make strides toward cost-effectiveness, efficiency, and possible expansion.

The third methodology addresses several commonly held logistics principles inspired by Danzig's 2011 Center for a New American Security report. These principles include the value of redundancy, the advantages of distributed construction processes, and the usefulness of building for the short-term, among others. Both the Navy and the shipbuilding industry are examined and analyzed to see how well they adhere to these principles and where there is room from improvement.

This thesis was developed using publicly available data, including the NVR, Congressional Budget Office reports, Government Accountability Office (GAO) reports, Office of the Chief of Naval Operations reports, Secretary of the Navy instructions, and reports from various think tanks.

C. SCOPE

The scope is limited to two major stakeholders: the U.S. Navy and U.S. naval shipbuilders. Although commercial shipbuilding in the United States is mentioned occasionally, we do not provide an in-depth analysis of commercial shipbuilding in the United States. We also focus only on ship construction as opposed to ship repair and maintenance. From a time perspective, this thesis is limited to actions that can be taken in the next 10 to 15 years, as this is the time frame in which the Navy desires to reach the 355–ship battle force goal. Last, this thesis is limited to publicly available information and does not discuss classified information.

II. BACKGROUND

The following chapter provides a brief background on the composition of the current naval battle force, required numbers to meet statute, and the Navy's plan to achieve a fleet of 355 ships in the next 30 years.

A. COMPOSITION OF CURRENT NAVAL BATTLE FORCE

Our understanding of the Navy's current battle force construct helps in determining the defense shipbuilding industrial base's capabilities. The Navy derives its authority to hold a battle force from 10 U.S.C. § 8062 (United States Navy, 2018). Paragraph (b) states the naval combat forces of the Navy "shall include not less than 11 operational aircraft carriers" (United States Navy, 2018). SECNAVINST 5030.8C (Secretary of the Navy [SECNAV], 2016a) defines "battle force inventory" as "commissioned United States Ship (USS) warships capable of contributing to combat operations, or a United States Naval Ship (USNS) that contributes directly to Navy warfighting or support missions, and shall be maintained in the Naval Vessel Register" (p. 1). The instruction issues guidance for establishing official counting procedures of Navy battle force ships, including combat-capable ships that contribute to warfighting missions, specified combat-support missions, or service-support missions (SECNAV, 2016a).

An accurate battle force count is necessary to support the requirements set forth in 10 U.S.C. § 231 (Budgeting for Construction of Naval Vessels [BCNV], 2018). This code establishes the annual plan and certification for budgeting for construction of naval vessels. Section 231 states that the secretary of defense (SECDEF) shall submit an annual plan for the construction of naval vessels to include combatant, support, and auxiliary vessels. The annual naval vessel construction plan shall include a detailed program for the construction of combatant, support, and auxiliary vessels over the next 30 fiscal years (BCNV, 2018). It is important to note how 10 U.S.C. § 231(f)(4) defines *combatant and support vessel*: "any commissioned ship built or armed for naval combat or any naval ship designed to provide support to combatant ships and other naval operations" (f)(4). The term does not include patrol coastal ships, noncommissioned combatant craft specifically designed for combat roles, or ships that are designated for potential mobilization (BCNV, 2018). The annual naval vessel construction plan also provides detailed estimated levels of funding by ship class to meet the requirements of the National Security Strategy (BCNV, 2018). Table 1 shows the current naval battle force compiled by the NVR as of April 27, 2020.

Table 1. Battle Force Size. Source: NAVSEA (2020).

Ship Type	**2020**
Aircraft Carriers	11
Surface Combatants	112
Submarines	70
Amphibious Warfare Ships	33
Mine Warfare Ships	11
Combat Logistics Ships	30
Fleet Support	31
Auxiliary Support	1
Combatant Craft	0
Other	0
Total	**299**

B. CLASSES OF SHIPS AND REQUIRED NUMBERS

In December 2016, the Navy promulgated its latest version of the FSA. The FSA is developed in an effort to determine the right balance of existing forces. It recommended a 355-ship battle force comprised of 12 aircraft carriers (CVN), 104 large surface combatants (LSC), 52 small surface combatants (SSC), 38 amphibious ships, 66 attack submarines, 12 ballistic missile submarines, 32 combat logistics force (CLF) ships, 10 expeditionary/high speed transport ships, six expeditionary support base ships, and 23 command and support ships (SECNAV, 2016b). The next FSA is expected to be released in Spring 2020. Until then, the 2016 FSA continues to define the framework for the Navy’s battle force requirements.

The 2016 FSA considered existing ships, ships under construction, and future procurement plans. The number and mix of ships reflect an assessment of the Navy’s force structure requirements. These force structure requirements are derived from all combatant commanders' unconstrained desires for Navy forces in their respective theaters. The Navy's battle force requirements were generated under the premise of retaining the "capacity and the capability … to defeat one adversary while denying the objectives of a second adversary" (SECNAV, 2016b, p. 1). It is interesting to note that in order to meet these unconstrained desires the Navy would require a 635-ship force (SECNAV, 2016b).

A force this size would require the Navy to double its current annual budget, which is clearly unrealistic. Navy component commanders were engaged in each theater to provide a realistic assessment. They eliminated redundant missions, transitory forces, and introduced presence risk. The number was reduced to a 459-ship force. This, too, far exceeds the Navy's annual budget. Further assessment was conducted on areas to absorb risk and accomplish missions in new ways. After extensive review and analysis, Table 2 shows the results of the 2016 FSA.

The final number of 355 ships was determined to meet objectives, align with the resources available, and comply with defense planning guidance while providing the shipbuilding industry with a baseline acquisition profile of new-ship construction requirements with an acceptable degree of risk (SECNAV, 2016b).

Table 2. Results of the 2016 FSA. Source: SECNAV (2016b).

Type/Class	**2014**	**2016**
Aircraft Carriers	11	12
Large Surface Combatants	88	104
Small Surface Combatants	52	52
Amphibious Warfare Ships	34	38
Attack Submarines	48	66
Guided Missile Submarines	0	0
Ballistic Missile Submarines	12	12
Combat Logistics Force	29	32
Expeditionary Fast Transport/High Speed Transport	10	10
Expeditionary Support Base	3	6
Command and Support	21	23
Total	**308**	**355**

Each ship class level attempts to meet the requirements for the minimum force structure to comply with strategic guidance.

> - A minimum of 12 aircraft carriers are required to meet the increased warfighting response requirements of the defense planning guidance defeat/deny force-sizing direction.
> - 104 large surface combatants deliver increased air defense and expeditionary ballistic missile defense capacity and provide escorts for the additional aircraft carrier.
> - 52 small surface combatants are required to meet defeat/deny challenges and support ongoing counterterrorism, counter–illicit trafficking, and theater security cooperation/building partnerships efforts.
> - 66 attack submarines provide the global presence required to support national tasking and prompt warfighting response.
> - The additional logistics ships support the additional aircraft carrier and large surface combatants.
> - Six expeditionary support bases provide persistent and flexible capabilities for counterterrorism and counter–illicit trafficking efforts.
> - The command and support inventory are mostly driven by platform-specific studies of presence and warfighting requirements for the unique missions of these ships. The rise to 23 represents two additional surveillance ships. (SECNAV, 2016b)

C. OVERVIEW OF THE NAVY’S 30-YEAR SHIPBUILDING PLAN

The Office of the Chief of Naval Operations (OPNAV) submits a report to Congress on the annual long-range plan for construction of naval vessels. The most recent report (March 2019) addresses the Department of Navy’s 30-year shipbuilding plan for Fiscal Year (FY) 2020 to FY2049. The National Defense Strategy (Mattis, 2018) and National Security Strategy (White House, 2017) provide the overarching high-level requirements. A healthy and efficient industrial base serves as a fundamental driver for achieving and sustaining the United States’ national security importance (OPNAV, 2019). This 30-year plan uses the FSA mentioned above, as its baseline for a 355-ship battle force. Table 3 lays forth the plan to achieve a 355-ship battle force by FY2034 with sustainment of 355 ships through FY2049. The total naval force inventory is an aggregate of the long-range procurement plan, which breaks down the procurement of each ship type by fiscal year; the battle force delivery plan, which breaks down the delivery of each ship type to the Navy by fiscal year; and the battle force retirement plan, which breaks down the retirement (decommissioning) of each ship type by fiscal year.

Table 3. Battle Force Inventory. Source: OPNAV (2019, p. 13).

Fiscal Year	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**
Aircraft Carrier	11	11	11	11	11	10	10	9	10	10	10	10	10	10	10
Large Surface Combatant	94	92	93	95	94	95	96	100	102	104	107	110	112	115	117
Small Surface Combatant	30	33	33	32	35	35	36	38	41	43	45	47	49	50	52
Attack Submarines	52	53	52	51	47	44	44	42	42	44	46	48	49	51	53
SSGNs/Large Payload Submarines	4	4	4	4	4	4	2	1							
Ballistic Missile Submarines	14	14	14	14	14	14	14	13	13	12	11	11	11	11	11
Amphibious Warfare Ships	33	34	34	35	36	37	38	37	38	36	36	36	36	38	36
Combat Logistics Force	29	30	31	31	32	32	31	32	32	32	32	32	32	32	32
Support Vessels	34	34	39	41	41	42	43	44	44	44	44	43	44	44	44
Total Naval Force Inventory	**301**	**305**	**311**	**314**	**314**	**313**	**314**	**316**	**322**	**325**	**331**	**337**	**343**	**351**	**355**

The three driving elements of readiness, capability, and capacity all must be balanced to field a credible naval force. The Navy sponsored three independent studies to determine the future fleet architecture. The results of these studies, along with findings from ongoing war games, all agreed on the need for a larger navy. These results were included in the FY2018 National Defense Authorization Act that established a 355-ship battle force as the minimum requirement (OPNAV, 2019).

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III. LITERATURE REVIEW

The following chapter provides a background on the literature previously published consistent with the topics explored in this research.

A. INDUSTRIAL BASE PRODUCTION CAPACITY

Periodically released defense planning guidance provides the shipbuilding industry with a baseline acquisition profile of forecasted new ship construction requirements. In this context, these planning documents are developed with consideration to the strategic needs of the nation from multiple perspectives. Of the many factors contemplated, the future battle force composition, financial resources able to be committed to the objectives, and the capabilities of the shipbuilding industry to achieve these objectives are considered as critical factors.

The focus of our research is centered on the production capacity of the naval shipbuilding industry. In late 2018, an interagency task force led by the SECDEF published a report titled *Assessing and Strengthening the Manufacturing and Defense Industrial Base and Supply Chain Resiliency of the United States.* In the report, the task force found that the American shipbuilding industry lacked competition and capacity needed to fulfill the strategic goals for both the commercial and defense sectors.

Detailed findings noted in the interagency task force report correlated the contraction and consolidation within the shipbuilding commercial and defense sectors to the demise of the American industries involved in the manufacturing of shipbuilding components. Effectively, the report concluded that the commercial and naval shipbuilding industry could not meet the long-range strategic needs of the nation (Secretary of Defense [SECDEF], 2018).

Echoing the concerns highlighted in the SECDEF's report were the testimonies of the Department of Transportation's maritime administration chair, Mark Buzby. On March 6, 2019, during a Congressional hearing on strategies to improve U.S. shipbuilding industries, Buzby informed Congress that while the defense sector of shipbuilding leads in innovation, there has been a sharp decline in shipbuilding domestic productivity capacity industrywide. His testimony cited the exponential growth and productivity of foreign shipbuilders in China, Korea, and Japan, where ships are built at a lower cost. Between those three countries for the last 30 years, their production outputs account for slightly over 90% of new vessel construction on the global market (Gourdon & Guilhoto, 2019). Buzby further testified that of the roughly 41,000 U.S. flag vessels in operation, only 99 were produced in the U.S. and capable of deep ocean operations (Buzby, 2019). Even though applicable domestic protectionism shipbuilding production policies have been put in place, Buzby determined there was a significant reduction of the domestic maritime industry's capacity to sustain the needs of the nation (Buzby, 2019).

Additional research detailing the issue of production capacity deterioration in the shipbuilding industry, as testified before Congress, is not contemporary. In 2009, a GAO report detailing the best practices in shipbuilding found that the most productive foreign shipbuilders they were able to analyze had several shared commonalities. For example, rather than waiting to begin production until after a contract has been signed, these foreign shipbuilders operate based on forecasted demand—thereby increasing production capacity and efficiency. According to GAO, the shipbuilders, through their actions, signaled to future contracted buyers a commitment to cost savings in production and delivery schedule. In turn, these shipbuilders were able to garner additional orders on the books based on their newly advertised capacities, which increased their global competitiveness long term (Government Accountability Office [GAO], 2009).

First Marine International, an independent shipbuilding consultancy firm, produced the most significant assessment and written report in the last 20 years to graphically represent the issues in the domestic shipbuilding industry (FMI, 2005). The scope and methodology of their report included evaluating each major U.S. shipyard engaged in the production of naval vessels through the application of a standardized benchmarking system and comparing the results against leading international shipyards.

Through the application of an estimated compensated gross tonnage (CGT) complexity factor model, FMI's report concluded that U.S. shipyards often functioned at anywhere from less than 20% of their core productivity levels to only 50% of their core productivity levels (FMI, 2005, p. xii). The primary reasons attributed to the domestic shipyard performance were associated with undeveloped ship designs at the time of production and poor customer relationships (FMI, 2005, p. xii). The FMI report concluded that unless these issues were corrected, U.S. shipyards would continue to lag behind the productivity of their international naval vessel and commercial sector peers.

Regarding the need for an increase in production capacity, Organisation for Economic Co-operation and Development (OECD) economists Karin Gourdon and Joaquim J. M. Guilhoto found that the 1920s-established domestic protectionist policy, the Jones Act, which intended to shield shipbuilders from foreign competition and bolster domestic shipbuilding and repair capacities, failed to achieve its stated objectives (Gourdon & Guilhoto, 2019). According to Gourdon and Guilhoto (2019), policies such as the Jones Act disincentivized domestic shipbuilders over the long run from proactively seeking production and cost efficiencies at the same adoption rate of their global counterparts.

In support of their research, we employed an applied general equilibrium model to estimate the effects of the Jones Act on the U.S. economy in terms of welfare, production, trade, and employment (Gourdon & Guilhoto, 2019). By examining the supply and value-added chains in the shipbuilding industry to model elastic demand, the OECD policy paper concluded that a limiting factor in the American shipbuilding sector, when compared to other shipbuilding economies' production outputs, could be traced to inflated profit margins from a lack of competition (Gourdon & Guilhoto, 2019). Hence, we surmised that if policy changes were enacted, competitive forces would push domestic prices lower and could trigger as much as an 80% increase in the demand for domestically produced commercial and wartime ships (Gourdon & Guilhoto, 2019).

In the same context of the OECD policy paper, a Congressional Research Service report from 2018, which analyzed the Navy's annual long-range plan of 2019, determined that a lack of capital infrastructure investments and managerial attention would result in the Navy falling short of meeting the mandated 355-ship battle force as planned in the 30-year production schedule (O'Rourke, 2018). We found that although the domestic shipbuilding industrial base had some unused capacity for increased production of certain ship designs, a marked overall increase in shipbuilding production rates across the board would require improved efficiencies throughout the supply chains for each naval vessel design (O’Rourke, 2018).

B. QUEUING THEORY AND CAPACITY PLANNING

Queuing models are widely used to estimate capacity. Typically, they are single-plant capacity estimates requiring knowledge of the process network within the plant. The model in this thesis is a rough approximation of an upper bound because it ignores the internal congestion of manpower constraints, scheduling, and machine setup.

James J. Solberg (1981) discussed two capacity models: bottleneck and stochastic. The bottleneck model considers the load distribution of the work contained in the specific product mix. The stochastic model accounts for the flaws in the bottleneck model using random variables. These two models work in parallel to provide a comprehensive understanding of the capacity estimation problem. He used these two models to estimate capacity in an industrial practice (Solberg, 1981). Recently, queuing models have been used for online service systems with proactive serving capability (Zhang et al., 2017). By predicting user arrival, the system can allocate capacity proactively and pre-serve upcoming requests. This approach is applied to reduce the delay between service requests and service completion times.

Queuing models normally require a detailed process model. When detailed process data are not available, simplified, fast approximations have been used to estimate capacity. L. Bain and W. E. Wilhelm (1983) applied “fast” capacity planning techniques to estimate requirements in a critical health care facility. They used four queuing theory models to conclude that utilization factor might be the most critical index when measuring capacity (Bain & Wilhelm, 1983). More recently, Linda Green (2006) used a queuing model to determine how to adjust staffing to meet the time-varying demands of a hospital waiting room. She applied the M/M/s (Markovian) model to determine the probability that an arriving patient will not find a bed available (descriptive) and to find the minimum number of beds needed to attain a target probability of delay (prescriptive; Green, 2006). Both Solberg and Green preferred queuing models for measuring capacity because they require relatively little data and are simple and fast to use.

Nonlinear regressions capturing queuing/congestion effects have been applied to historical data to estimate capacity. Ross Henderson (1981) built upon the aircraft learning curve developed by Wright (1936) and used steel casting setup data to predict the setup duration for machine-intensive plants. His explorations sought better measures to setup procedures until the plant was regularly producing at full capacity (Henderson, 1981).

To the extent of this research, queueing models have not been used to estimate aggregate shipbuilding capacity in the past. There is no reason why the techniques should not be applicable, however. The queuing model applied in this thesis is cross-validated with the industrial base productivity learning curve model in Chapter IV.

C. LOGISTICS PRINCIPLES

In his 2011 Center for a New American Security report titled *Driving in the Dark: Ten Propositions About Prediction and National Security*, former SECNAV Richard Danzig (2011) discusses five descriptive problems that military planners face when making complex acquisition decisions and provides five prescriptive solutions to help military planners better adapt to our increasingly complex and dynamic threat environment.

Danzig (2011) begins his discussion of the descriptive problems by explaining why humans have the propensity to predict the future and plan for it. Since humans lack many of the superior physical characteristics of other species, they have adapted by using reasoning to increase the odds of survival. This deep-seated instinct is what causes humans to fear the unknown and plan for the future. Danzig (2011) goes on to explain that although humans desire to plan for the future, requirements for prediction consistently exceed the ability to predict. Despite this, the Department of Defense (DoD) has a strong propensity for predicting and planning for the future—driven by government bureaucracies that crave predictability and military planners that understand the advantages of knowing future enemy actions. During the last 70 years, the military propensity for predicting the future was made even more powerful by the desire never again to let the United States be unprepared for war as had happened at the start of World War II. The Soviet threat of the Cold War, which was surprisingly predictable, also cemented the importance of predicting the future for the DoD. Danzig (2011) concludes the descriptive portion of his report by explaining how military planners, despite their desire to plan for an uncertain future, failed to predict the end of the Cold War, the attacks of September 11, 2001, and the rise of China. Due to these failures, he provides a framework for improving DoD preparedness going forward.

IV. METHODOLOGY

The following chapter discusses the methods underlying the design productivity complexity model, learning curve model, queuing theory and capacity model, and logistics principles.

A. DESIGN PRODUCTIVITY COMPLEXITY MODEL

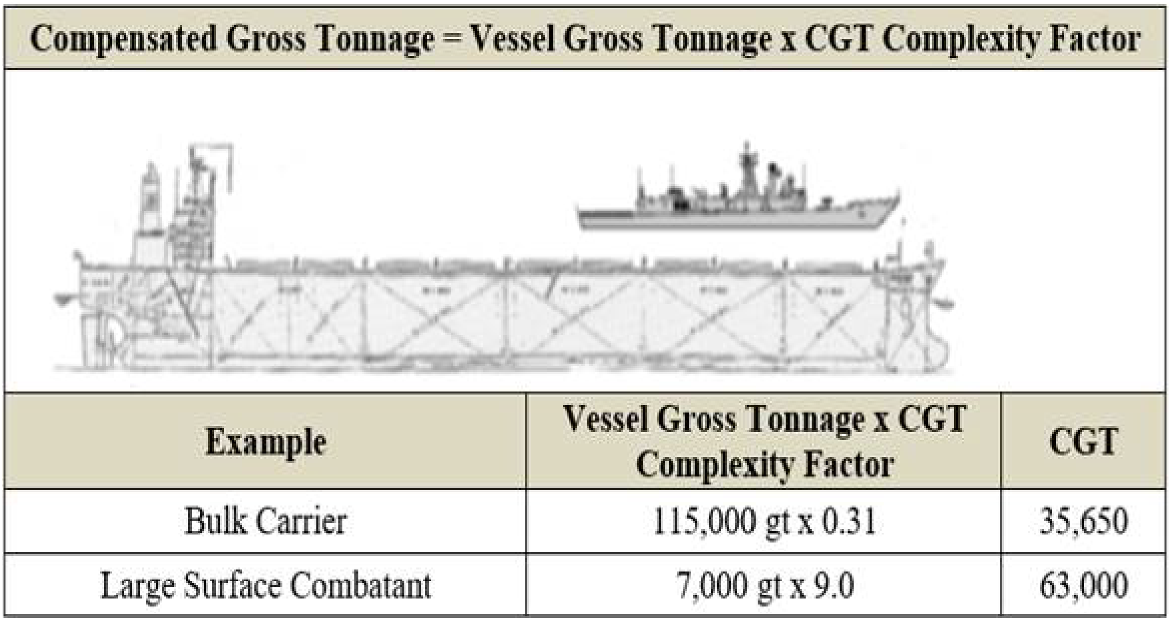
The design productivity model used in this thesis is a modified version of the CGT system developed in 1994 by the OECD. The original intent of the OECD CGT system was to create a uniformed and structured metric to measure productivity across shipyards based on a ship design’s classification. In the commercial shipbuilding sector, the CGT model applies a proprietary complexity unit of measurement as a weighted factor that is correlated to the complexity of a commercial ship design and performance characteristics (Organisation for Economic Co-operation and Development [OECD], 1999).

This study adopted OECD’s CGT system as a way of standardizing and measuring naval shipyard productivity in a model. Additionally, in the same context of FMI’s report cited in the literature review, the reproduced complexity factors were based on current naval ship designs and performance characteristics. Reflected in Table 4 are the ship design complexity factors developed for this model. In a similar manner to the OECD CGT system, the complexity factors used in this model corrected for the differences in the level of effort estimated to be required to produce a naval ship based on the design. Although productivity levels may vary from shipyard to shipyard, the application of a ship design specific complexity factor as used in this research provided a uniform metric to compare production output levels of the various major U.S. shipyards.

Table 4. Compensated Gross Tonnage Complexity Factors. Source: FMI (2005).

Type/Class	**Complexity Factor**
Aircraft Carriers	18.0
Large Surface Combatants	9.0
Small Surface Combatants	8.0
Amphibious Warfare Ships	14.0
Attack Submarines	8.5
Guided Missile Submarines	11.0
Ballistic Missile Submarines	11.0
Combat Logistics Force	7.5
Expeditionary Fast Transport/High-Speed Transport	6.5
Expeditionary Support Base	5.0
Command and Support	8.0

While previous research models referenced in this project used the number of labor hours required by each ship design to measure for production efficiency, the modified CGT model incorporated production days from the start of construction to delivery to measure productivity efficiency (FMI, 2005). The outcome of this calculation was the benchmark of production efficiency associated with each ship design analyzed in this project. Reflected in Figure 1 is an example of the methodology for calculating compensated gross tonnage. Figure 1 details a comparative application of CGT complexity factor of 9.0 for a typical large surface combatant of 7,000 gross tons and OECD's CGT complexity factor of 0.31 for a commercial bulk carrier of 115,000 gross tons. Based on these CGT complexity factors, a large surface combatant with only 6% of the volume of a hypothetical commercial bulk carrier that weighs 115,000 gross tons, is calculated to be 77% more complex to produce for a major U.S. naval shipyard. The difference in the CGT between these two ship designs is attributed to the increased complexity of the production of military vessels when compared to the production of commercial vessels for a major U.S. shipyard.



Compensated Gross Tonnage = Vessel Gross Tonnage x CGT Complexity Factor

Example	Vessel Gross Tonnage x CGT Complexity Factor	CGT
Bulk Carrier	115,000 gt x 0.31	35,650
Large Surface Combatant	7,000 gt x 9.0	63,000

Figure 1. Compensated Gross Tonnage Calculation. Source: FMI (2005)

By benchmarking the production efficiency associated with each naval vessel design regardless of shipyard or shipbuilder, the CGT formula allows for the baseline measurement of production capacity from historical production data (OECD, 2011). According to OECD (2011), this approach for quantifying capacity theorizes that actual production data can serve as an indicator of the minimum capacity for any given shipyard.

B. PRODUCTION EFFICIENCY LEARNING CURVE MODEL

In the shipbuilding industry, a learning curve can be used to graphically represent the efficiencies gained in the serial production of a ship design by a producer. Fundamentally, the learning curve in the shipbuilding industry is a large-scale representation of T. P. Wright’s (1936) production efficiency theory. According to Wright (1936), an organization can be expected to learn from their previous experience, and if incentivized, become more efficient in the completion of a task in serial production. Through his research in the aircraft production industry, he proved that if a worker were to perform the same task multiple times, the time to complete that specific task would be reduced at a relatively constant rate.

For this reason, as a shipyard engages in the serial production of a new class of ship, in most cases it is contractually required that the shipbuilder develop production efficiencies that will improve the production time from hull to hull (NAVSEA, 2004). In this research project, we applied the learning curve theory to calculate production efficiencies by shipbuilders over a defined period based on ship design complexity.

The learning curve formula applied is based on guidance as detailed by the Naval Sea Systems Command's (NAVSEA, 2004) *Cost Estimating Handbook*.

Y_x = AX^b where:

Y_x = Cumulative average unit value of the X units - number of days to produce

A = Theoretical first unit value (T$_1$) - days to produce

X = Unit number

b = Slope coefficient where:

$$b = \frac{Ln\ (slope)}{Ln\ (2)}$$

1. Assumptions

The CGT analysis used in this project assumes the combined total productivity effort required per gross ton and the level of complexity associated with the production of a naval vessel. Collectively, this includes the efforts of the primary contractor, subcontractors, and all suppliers whose linked processes form the supply chain. A primary assumption of the OECD CGT model is that naval vessels require a higher level of productivity output per gross ton as compared to a commercial vessel (FMI, 2005).

2. Data Limitations

In contrast to the OECD, FMI, and NAVSEA models referenced in this study, we lacked access to reliable and comprehensive labor hours to accurately assess the total effort required in the production of a naval vessel. Additionally, we developed a modified version of the NAVSEA learning curve equation for use in this project where production days from the start of construction to delivery were applied in this research. The data used are tabulated in Appendix B.

C. QUEUING THEORY AND CAPACITY MODEL

Queueing theory is the mathematical study of waiting lines, or queues. It was developed in 1904 by A. K. Erlang to determine the capacity requirements of the Danish telephone system (Brockmeyer et al., 1948). This methodology applied some of Erlang's framework as it assessed the shipbuilding capacity of the U.S. defense shipbuilding industry. The queuing model in this thesis is a rough approximation of an upper bound because it ignores the real-time internal congestion of manpower constraints, scheduling, machine setup, and other resource contentions. This model assumed the system is performing at a steady state, meaning any variabilities in processing times will produce queuing behavior. There is no constraint on the length of the queue, and ships continue to join and remain in the queue.

1. Definitions

A list of definitions for this queuing model is as follows:

1. *Inter-arrival time:* The average time in days between keel-laying dates converted to years between keel-laying dates.
2. *Arrival Rate (λ):* Frequency of ships to start construction per year.
3. *Service Rate (μ):* The rate at which ships are built per year.
4. *Ships in Service:* The number of ships under construction per year.
5. *Utilization Rate (ρ):* The proportion of time the system is in use.
6. L_q: Average number of ships in the queue.
7. W_q: Average time a ship spends waiting to be built.
8. *s:* The number of service lines in the system.

9. *Surge Capacity:* The extra capacity in the system not being utilized. Defined as 1-ρ.

10. *Coefficient of Variation for Arrival Time:* The measure of variability in the standard deviation about the arrival rate. Defined as the ratio of standard deviation for arrival rate to the mean for arrival rate.

11. *Coefficient of Variation for Service Time:* The measure of variability in the standard deviation about the service rate. Defined as the ratio of standard deviation for service rate to the mean for service rate.

2. Data

This thesis research included data from the NVR, maintained by the NAVSEA Shipbuilding Support Office. The data are tabulated in Appendix C and contains the following:

- Ship Class
- Hull Number
- Ship Name
- Keel Date
- Delivery Date
- Days Between Keel Date
- Days Under Construction
- Light Displacement Weight
- Builder

The data was tabulated for each of the 299 active ships, then narrowed to the focus of two shipbuilders: Bath Iron Works, a division of General Dynamics, located in Bath, Maine; and Ingalls Shipbuilding, a division of Huntington Ingalls Industries, located in

Pascagoula, Mississippi. We focused on one ship class: the Arleigh Burke–class guided missile destroyer (DDG). These two shipbuilders are used for comparison in an effort to determine and cross validate a shipbuilder's capacity within the shipbuilding sector of the defense industrial base.

3. Equations

This model used formulae for a multi-server model with general arrival and general service time distributions (G/G/s). Once the data was tabulated, a series of specific steps were performed. First, the average days between keel-laying dates was calculated then converted into years, assuming a 260 work-day year. This served as the inter-arrival time.

The arrival rate was calculated as:

Equation 1

$$\lambda = \frac{1}{avg\ inter - arrival\ time}$$

Next, the average days under construction was calculated then converted into years. This served as the inter-service time. As already noted, this ignores internal congestion (some of the inter-service time is waiting, not processing) and means this model is an approximation. The service rate was calculated as:

Equation 2

$$\mu = \frac{1}{avg\ inter - service\ time}$$

Then, both the arrival time and service time standard deviations were calculated across ships manufactured at the respective shipyards and converted into years, assuming a 260 work-day year.

The coefficient of variation for arrival time was calculated as:

Equation 3

$$CV_{arrival\ time} = \frac{\sigma_{arrival\ rate}}{\lambda}$$

The coefficient of variation for service time was calculated as:

Equation 4

$$CV_{service\ time} = \frac{\sigma_{service\ rate}}{\mu}$$

The utilization rate was calculated as:

Equation 5

$$\rho = \frac{\lambda}{s * \mu}$$

Surge capacity was calculated as:

Equation 6

$$1 - \rho$$

The average number of ships in the queue L_q (Hopp & Spearman, 2008) was calculated as:

Equation 7

$$L_q = \frac{\rho^{\sqrt{2(s+1)}}}{1-\rho} * \frac{CV_{arrival\ time}{}^2 + CV_{service\ time}{}^2}{2}$$

The average waiting time a ship spends waiting to be built W_q was calculated via Little's (1961) Law as:

Equation 8

$$W_q = \frac{L_q}{\lambda}$$

D. LOGISTICS PRINCIPLES

The logistics principles examined and proposed in this thesis are based on the 2011 Danzig report previously mentioned. Danzig describes five descriptive principles that characterize problems with DoD acquisition processes and proposes five prescriptive principles to solve the DoD’s acquisition processes going forward.

The first prescriptive recommendation that Danzig (2011) makes is to dramatically accelerate acquisition decision-making with the aim of reducing the amount of time between concept and realization. With the rapid advance of technology and rapidly evolving threats faced by the United States today, this strategy could be key to keeping the U.S. military ahead of its adversaries. Current military acquisition timelines often drag on for decades, especially for large programs. Danzig suggests the remedy is to increase the tempo of decision-making in the acquisition process commensurate with the need and delay certain decisions, ultimately resulting in accelerated acquisition times.

The second prescriptive recommendation from Danzig (2011) focuses on increasing the agility of production processes. Ideally, processes in a production line are able to change the quantity or type of product being produced without tremendous effort or retooling. The shift toward open-architecture systems, modularity, and plug-and-play upgrades are examples of this push for increased agility. Standardization in components is also stressed as an important tool for increasing the agility of production processes.

The third prescriptive recommendation from Danzig (2011) calls for the prioritization of the most adaptable equipment. Due to the long development times and long service lives of many military assets, Danzig insists that adaptable equipment will be at a premium as long as the future remains uncertain. Easily reconfigurable equipment and lean equipment (equipment designed for a simple core function) are provided as examples of ways to provide warfighters with more adaptable equipment ensuring the DoD gets the most from its costly investments.

The fourth prescriptive recommendation from Danzig (2011) is to build more for the short term. In this principle, Danzig explains the difference between “high-road” infrastructure and “low-road” infrastructure. High-road infrastructure is usually built to endure and built at high cost but cannot be easily adapted and retrofitted—similar to many DoD major weapons programs. Low-road infrastructure is built for the short term, at less expense, and lends itself to be retrofitted more easily or replaced without regret. By focusing more on short-term (low-road) assets, the DoD would not be locked into outdated equipment and could be less dependent on the predictions of the future.

The fifth prescriptive recommendation focuses on nurturing diversity and creating competition. Danzig (2011) recognizes the waste and inefficiencies that come with market-based systems. He also acknowledges that these systems are still the “least bad” option for most situations. He argues that the DoD should embrace greater competition by starting more programs than necessary and killing off the ones that do not meet expectations. He also argues for redundant systems to increase the options available to the warfighter.

This thesis discusses ways that Danzig’s prescriptive principles and other principles can be applied to the U.S. shipbuilding industry to increase capacity and allow the Navy to reach its 355-ship goal as quickly as possible.

V. ANALYSIS

The following chapter provides an analysis on the results of the data implemented into the models discussed in Chapter IV.

A. DESIGN PRODUCTIVITY COMPLEXITY MODEL AND PRODUCTION EFFICIENCY LEARNING CURVE MODEL

The following section discusses the results of the design productivity complexity model and production efficiency learning curve model.

1. Design Productivity Complexity Model

By using the CGT formula defined in Chapter IV, we were able to calculate the annual CGT output necessary for identifying the maximum annual CGT delivered over the last 10 years for Bath Iron Works (BIW) and Ingalls Shipbuilding. Reflected in Tables 5 and 6 are the results of the calculations.

Table 5. Bath Iron Works 10-Year CGT Production Output

Bath Iron Works			
	Large Surface Combatants		
Delivery Year	**Arleigh Burke CGT**	**Zumwalt CGT**	**Annual CGT Delivered**
2009	64,206	-	64,206
2010	64,206	-	64,206
2011	64,206	-	64,206
2012	64,206	-	64,206
2013	-	-	-
2014	-	-	-
2015	-	-	-
2016	-	121,851	121,851
2017	63,252	-	63,252
2018	63,252	121,851	185,103
2019	-	-	-
Design 10-year CGT	509,832	243,702	753,534

Table 6. Ingalls Shipbuilding 10-Year CGT Production Output

Ingalls Shipbuilding				
Delivery Year	**Amphibious Warfare Ships**	**Large Surface Combatant**	**Small Surface Combatant**	**Annual CGT Delivered**
	Assault Ship CGT	**Arleigh Burke CGT**	**Cutter CGT***	
2009	663,600	64,206	33,600	761,406
2010	-	64,206	-	64,206
2011	268,800	64,206	33,600	366,606
2012	537,600	-	-	537,600
2013	268,800	-	-	268,800
2014	630,000	-	33,600	663,600
2015	-	-	33,600	33,600
2016	268,800	63,252	33,600	365,652
2017	268,800	63,252	-	332,052
2018	-	-	33,600	33,600
2019	-	63,252	33,600	96,852
Design 10-year CGT	2,906,400	255,870	235,200	3,397,470

Note: U.S. Coast Guard vessels do not count towards Navy FSA requirements.

The annual CGT production capacity calculated for BIW was 185,103 CGT, which corresponds to their production output for 2018 and the delivery of the initial Zumwalt-class DDG 1000 and one Arleigh Burke–class DDG 51. To accomplish this observed peak, BIW's core productivity efforts appear to have been diverted from all other production operations.

Based on the data pulled from the NVR for BIW from 2009 to 2012, we found that BIW's maximum production output was the delivery of one Arleigh Burke DDG 51, registering 7,134 tons annually. Through the application of the large surface combatant CGT complexity factor of 9.0, we determined that BIW's CGT output during those four years was 64,206 CGT annually. The analysis found that BIW was able to maintain their one ship per year pace of delivery until the period from 2013 to 2015.

This does not infer that BIW was not engaged in the production of ships during this period of zero ship deliveries. The lapse of ships delivered is representative of the lag time between the start of production and delivery.

Coinciding with this gap in ship deliveries was BIW's shift in core production efforts towards the Zumwalt-class ship design, whose first two keels were laid in 2011 and 2013. In this context, the lapse in the delivery of ships is reflective of the increased complexity and level of effort in ship designs that BIW had been contracted to produce during this period. The analysis found that the two more sophisticated Zumwalt ship designs produced from 2011 to 2018 by BIW averaged 2,000 production days.

Comparatively, the established Arleigh Burke ship design averaged 837 production days, which represents a 239% decreased production time for a similar-class ship design. For these reasons, the CGT delivered in 2018 by BIW appears to reflect their actual maximum CGT production capacity regardless of ship design.

An evaluation of the data for the same 10-year period for Ingalls Shipbuilding found that the scope of their production lines included multiple battle force classes of ships. For this reason, the research applied the complexity factors of large surface combatant (9.0), amphibious warfare ship (14.0), and small surface combatant (8.0) through the CGT model.

Based on the data, Ingalls Shipbuilding was able to meet the core productivity effort requirements for the delivery of two amphibious warfare ships, LHD 8 and LPD 21; one large surface combatant, DDG 105; and one U.S. Coast Guard vessel, WMSL 751. Cumulatively, we found that in 2009 Ingalls Shipbuilding achieved its maximum CGT delivery of 761,406 tons. As a caveat to this delivery figure, Coast Guard vessels produced by Ingalls Shipbuilding are not included in the Navy's battle force count, which is the focal point of our research. The concurrent production of this ship design was included in this model to account for the shipbuilder's distributed core productivity efforts during the periods analyzed.

Given the production totals detailed above, the annual CGT output calculated for Ingalls Shipbuilding suggests that their core productivity effort was capable of concurrently maintaining multiple production lines to deliver a new ship annually regardless of design complexity. The next section analyses the rate of learning associated with ship production through the learning curve model.

The BIW and Ingalls Shipbuilding detailed actual production days, days out of water, days in water, and delivery data points analyzed in this section can be found in Appendix A.

2. Production Efficiency Learning Curve Model

By using the learning curve model defined in Chapter IV, we determined the degree to which learning occurred and to what extent each shipbuilder's core productivity effort was affected during peak CGT output. Using the Arleigh Burke DDG-51 design as a cross-reference point, we were able to compare the actual production days for this ship design for both BIW and Ingalls Shipbuilding relative to their maximum CGT delivered per year.

The learning curve shown in Figure 2 reflects the actual rate of learning by BIW. The data output from the model suggests that during periods in which BIW's core productivity efforts were split between two separate ship designs, specifically the Zumwalt and Arleigh Burke, there was a sharp increase in the production days. In contrast to this increase in production days, the model also suggests that during periods in which BIW's core productivity efforts were assigned to the production of only one ship design, BIW was able to maintain a positive rate of learning.

Previously, through CGT analysis, we calculated that the Zumwalt destroyer design averaged 2,000 production days, which was approximately 239% greater than the 837 average production days for an Arleigh Burke destroyer. The learning curve model in this section provided us with evidence to explain what occurred. In the periods of parallel production, BIW's core productivity effort had reached its maximum output capacity. Additionally, we found that the average production days for the two Arleigh Burke DDG hulls that overlapped the production of each Zumwalt ship increased higher than their forecasted rate of learning by 6% for DDG hull 115 and 21% for DDG hull 116.

An in-depth review of the model's results suggests that the Zumwalt design suffered from a lack of design maturity and definition before production. In a review of the model's outputs, the reduced production efficiencies for the Arleigh Burke design for BIW appears to correspond to our logistics principle 6 in Section C of this chapter. Specifically, BIW's effort to concurrently produce the Zumwalt design negatively impacted its production efficiency of the Arleigh Burke design.

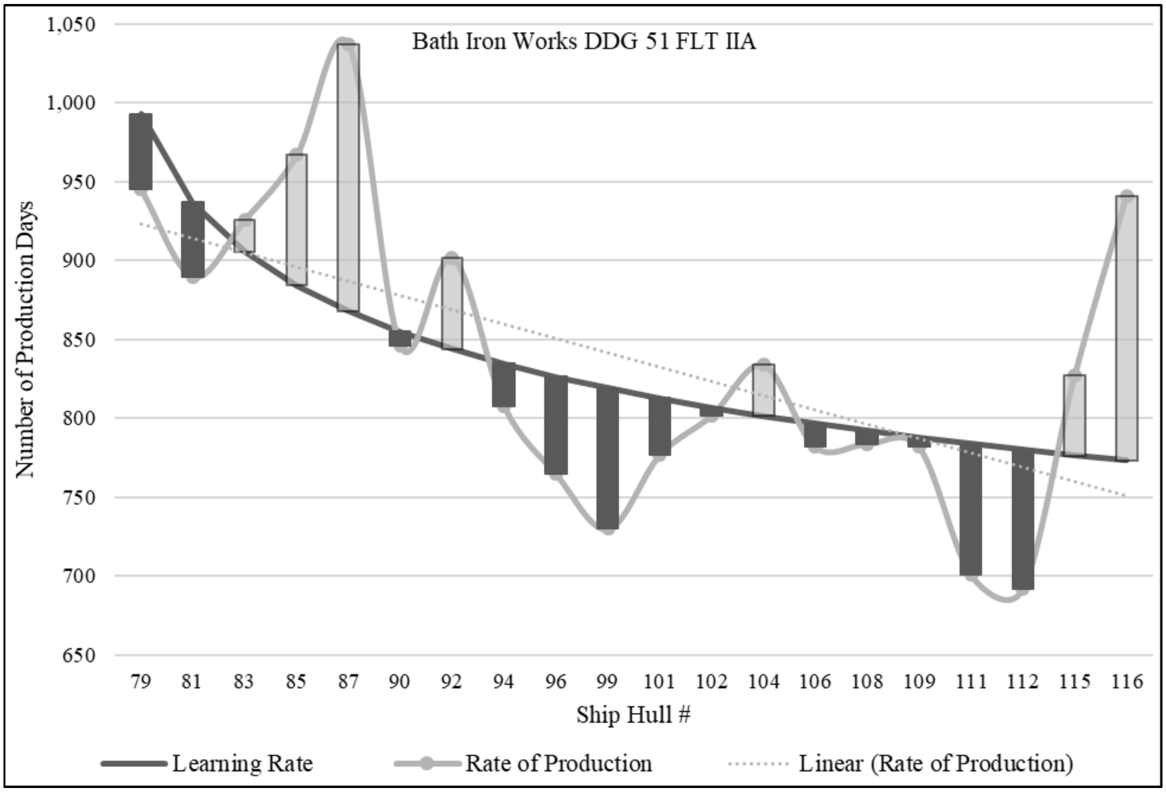


Figure 2. Bath Iron Works DDG 51 FLT IIA Learning Curve

The results of the learning curve model in Figure 3 provide evidence of a negative rate of learning during the production of the Arleigh Burke ship design. This suggests that the shipbuilder's multiple lines of concurrent production undermined the degree to which learning occurred. The learning curve slope from this model suggests that during periods in which the shipbuilder's core productivity effort expanded to complete the production of more complex ship designs, the level of efficiency associated with the production of the less complicated DDG-51 ship design was negatively affected. Based on the model's output, the reduced productivity efficiency of Ingalls Shipbuilding during periods of peak concurrent production appears to correspond to our logistics principle 4, which recommends a reduction in design variations and complexity to increase capacity. By using the total production days for measuring efficiency based on ship design, Ingalls Shipbuilding averaged 1,067 production days for each DDG-51 ship delivered during the period analyzed in this model. Additionally, during the periods in which the production of a DDG-51 overlapped with the production of more complex ship designs, such as LHD-8 and LHA-6, the average production days were 12% higher than expected at 1,190 days.

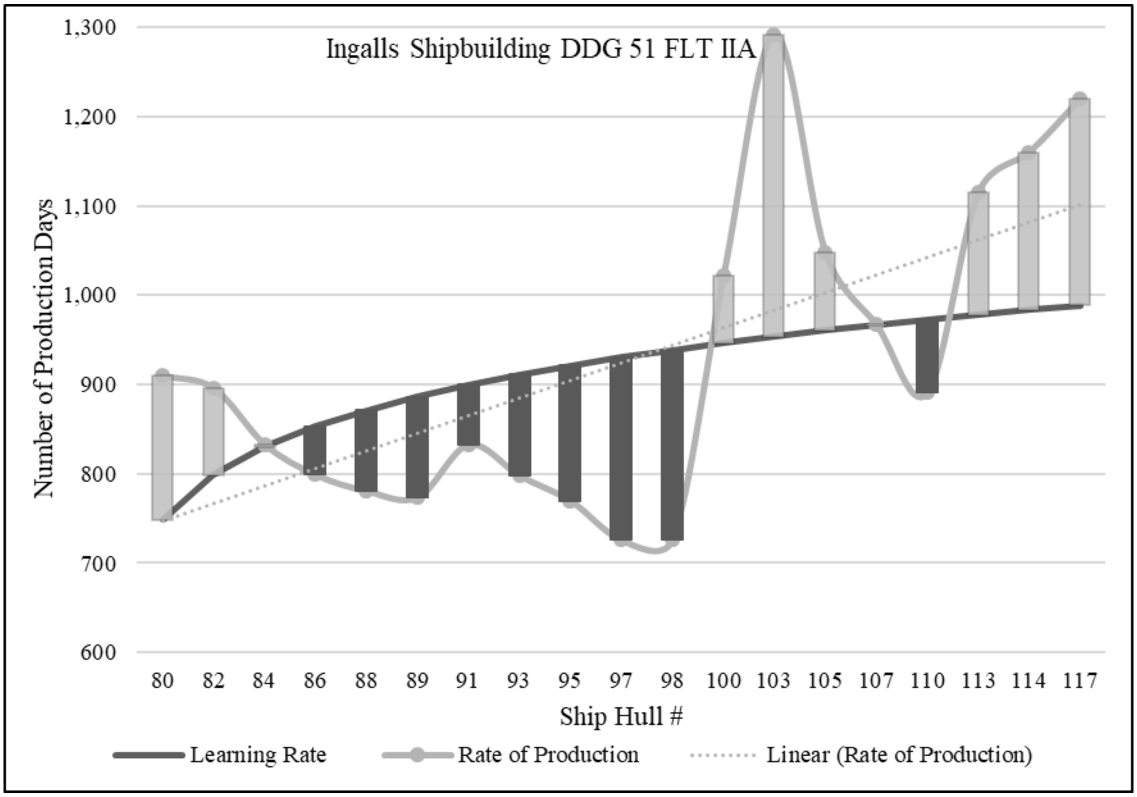


Figure 3. Ingalls Shipbuilding DDG 51 FLT IIA Learning Curve

B. CAPACITY MODEL

Using the equations outlined in Chapter IV, shipbuilding data from BIW and Ingalls Shipbuilding were applied to derive the results in Table 7. This is a side-by-side comparison between BIW and Ingalls Shipbuilding for DDG construction.

Table 7. BIW versus Ingalls Shipbuilding DDG Building Capacity

	Bath Iron Works	**Ingalls Shipbuilding**
Average Inter-arrival Time (days)	215	220
Average Inter-arrival Time (years)	0.825	0.847
Arrival Rate (λ) Ships/Year	1.21	1.18
Arrival Rate Standard Deviation	0.706	0.831
Average Service Time (days)	867	895
Average Service Time (years)	3.33	3.44
Service Rate (μ)	0.300	0.291
Service Rate Standard Deviation	0.467	0.602
CV Arrival Time	0.583	0.703
CV Service Time	1.56	2.07
Service Lines	5	5
Utilization Rate (ρ)	0.808	0.813
Surge Capacity	0.192	0.187
Number of Ships in Service	4.04	4.06
Lq	3.46	6.22
Wq	2.85	5.27
Number of Tons Under Work	28830	28560
Authorization to Build (days)	741	1370

This model measures ship production as a single event, aggregating the many shipbuilding processes such as design, planning, fabricating, keel laying, launching, and delivery.

The arrival rate represents the number of ships that start construction each year. BIW is slightly higher, with an arrival rate of 1.21, compared to Ingalls Shipbuilding of 1.18. The service rate represents what percentage of a ship that is built each year. Both shipbuilders build just under one-third of a ship each year at 0.30 and 0.29. Service lines are assumed at five, derived from the Huntington Ingalls Industries *2018 Annual Report,* stating the number of ships under construction (Huntington Ingalls Industries, 2018).

Another comparison to highlight is the authorization to build. In other words, this is the number of days it would take each shipbuilder to start the next ship if it were given authorization to build one today. BIW could start in approximately 741 days, compared to 1,370 days for Ingalls Shipbuilding. One suspected reason for this is that Ingalls Shipbuilding also builds the America class (LHA) and San Antonio class (LPD) of amphibious warships, along with cutters for the Coast Guard.

The utilization rate is perhaps the most important. Both BIW and Ingalls Shipbuilding have a similar utilization of 0.808 and 0.813, respectively. This indicates that both shipbuilders are utilizing approximately 81% of their factories. This is important to note if these shipbuilders are asked to surge in the event of increased demand by the Navy as a result of war or other national security crisis. At 81% capacity, this would suggest that both shipbuilders have an additional 19% to grow or surge. But could they really?

The capacity of any given process is quite difficult to analyze. Effective capacity is defined as “the maximum sustainable flow rate through the resource unit” (Anupindi et al., 2012, p. 104). Each individual complex operation associated with shipbuilding can be identified as a resource unit. Each resource unit has its own effective capacity. The sum of the resource unit effective capacities is the effective capacity of the resource pool. The slowest resource pool of the shipbuilding process is the bottleneck. The effective capacity of the shipbuilding process is the effective capacity of the bottleneck (Anupindi et al., 2012). In other words, shipbuilding is only as fast as its slowest process, which means that the capacity of the shipyard is determined by the bottleneck.

Several other factors need to be taken into consideration. Does the fabrication process handle units sequentially or are they loaded in batches? Are all resources available for the same amount of time? What effects do setups and switching between processes have on the overall shipbuilding process? (Anupindi et al., 2012). This analysis also assumes that demand for ships from the Navy is steady and consistent year over year. Given the enormous supply chain complexities of raw materials, the time required to train a skilled labor force, and the degree of a complex manufacturing process, the shipbuilders are believed to be at full effective capacity, which means they lack the necessary capacity to meet the Navy’s long-range shipbuilding goal of 355 battle forces ships.

If utilization were to be increased, it would take a large-scale investment of money, time, and resources to meet demand or achieve desired efficiencies. The following section outlines several logistics principles that might be considered in efforts to improve efficiencies, meet surge demands, or reduce complexities in the defense shipbuilding industrial base.

C. LOGISTICS PRINCIPLES

Due to the lack of required capacity identified by the learning curve and capacity models in Sections A and B above, we discuss several approaches for how the Navy can adapt logistic principles from Danzig (2011) and others to improve shipbuilding capacity in the future. Logistics principles 1 through 4 directly connect with one or more of Danzig's principles, while principles 5 and 6 connect with other commonly held logistics principles.

1. Lack of Redundancy Can Lead to Lack of Capacity (Buffer or Suffer)

The ability of our nation's shipyards to build and maintain our naval forces largely depends upon maintaining a certain shipbuilding capacity based on fleet size and production goals. The capacity of any production facility, be it a factory making widgets or a shipyard constructing aircraft carriers, has the potential to be affected by many events. The availability of input materials, local labor and political concerns, and even weather conditions can affect the production of naval ships at America's shipyards. When input materials for shipyards—such as steel—increase in price or decrease in availability, capacity suffers. If the local labor force goes on strike or a local environmental organization passes legislation negatively affecting shipyards, capacity suffers. If severe weather shuts down or damages production facilities, as happened with the Gulf Coast shipyards during Hurricane Katrina, capacity suffers. All these events can have a significant impact on U.S. naval ship production and capacity.

One of the simplest hedges against these capacity risks is redundancy. If risk can be measured, enough redundant capacity can be made available to ensure capacity goals are still met if the risk event comes to fruition. Danzig's (2011) fifth prescriptive principle discusses the importance of redundancy and the potential benefits to the DoD. Redundancy can take many forms. In some production facilities, simply increasing the available capacity of a single resource generates enough redundant capacity to ensure production goals are met. In other production facilities, where production is more dependent on the risk events, simply expanding capacity in one resource may not be enough. In these cases, it may be beneficial to add additional capacity (redundant capacity) in the form of additional resources in separate locations.

This is a practice that many U.S. companies already employ. For example, General Motors manufactures certain models, such as the Chevrolet Impala, in multiple locations—Oshawa, Ontario, and Detroit, Michigan (General Motors, 2011). Many other companies, from appliance manufacturers to construction material producers, also make the same or similar products in multiple locations. Doing so affords these companies the ability to mitigate capacity shortages from certain risks, but also allows them to take advantage of potential labor discounts in alternate locations, which can reduce variable costs. There can also be savings in shipping costs due to the shorter distances provided by the secondary production facility's location. Other possible advantages include tax incentives and tariff avoidance (Gray, 2020).

Two American shipyards already employ this strategy of using multiple production facilities to produce the same product. The most clear-cut example is the Arleigh Burke–class guided missile destroyer (DDG-51 class). Since production began in 1988, all DDG-51–class ships have been produced by either Bath Iron Works in Bath, Maine, or Ingalls Shipbuilding in Pascagoula, Missouri, with total production being divided roughly evenly between the two production sites. Splitting DDG-51 production between two production sites offers many of the previously mentioned advantages. One of the most important advantages is the strategic redundancy achieved by producing this high-value defense asset in more than one place. During times of war, attacks on a nation's wartime manufacturing facilities, including shipyards, can be expected. In the event that one shipyard is destroyed or taken offline due to enemy attack, having a secondary production facility ensures that ship production can continue. Although production capacity would still be reduced in the event of enemy attack, having a secondary production facility ensures that at least some capacity for ship production remains. During times of war this can mean the difference between victory and defeat.

There are many other advantages to producing ships like the DDG-51 class destroyers in more than one location. Much of the work in naval shipbuilding, including welding and other specialized tasks, requires skilled workers who take a long time to train. Having multiple production facilities helps to keep more of these skilled shipyard workers trained and employed, reducing the chances of a shipyard worker shortage. Operating more than one production facility for the same type of ship class also offers the advantage of competition. Competing shipyards, like many other competitive businesses, are forced to cuts costs and find efficiencies in order to remain competitive and earn future government business. The Navy could also encourage superior performance by offering incentives to competing shipyards based on quality, production schedules, and other metrics between production sites.

Unfortunately, the DDG-51 class is the only class of Navy ships to be produced in its entirety in two separate shipyards. The new Virginia-class submarines (SSN-774 class) are produced by both Electric Boat in Groton, Connecticut, and Huntington Ingalls in Newport News, Virginia. Each location builds only certain sections of the boat, however, and then takes turns at final assembly and reactor compartment production (O'Rourke, 2019). The new Columbia-class SSBNs will also likely be produced in this manner. Since neither Electric Boat nor Huntington Ingalls maintains the ability to build the entire boat from start to finish, the advantages demonstrated in the DDG-51–class production are not fully realized. Similarly, the littoral combat ship (LCS) type is built in two separate locations—Marinette, Wisconsin, and Mobile, Alabama. Each location builds a completely different variant of the LCS. Again, this does not allow for all the advantages of the dual facility production to be realized. All other major ship classes currently under production (CVN, LHA, LPD, CLF, DDG-1000) are only produced in a single shipyard per class. Some of these shipyards produce more than one class of naval ship. In the event one of these shipyards were to be taken offline, the Navy could lose the ability to build multiple classes of ships, which could be devastating.

Due to the many advantages provided by having multiple production facilities for the DDG-51 class, it is recommended that the Navy adopt the policy of having all naval ship classes be produced in at least two shipyards per ship class. As identified from our learning curve model outputs, during the parallel production of more than one ship design at the same production site, there is an increased likelihood of a decline in the production efficiency by the shipyard. In order to ensure this consequence is not created by producing all ship classes in more than one site, it may be necessary to ensure all shipyards only produce one class or one type of ship. This policy, although likely to incur some inefficiencies and additional costs, would significantly strengthen the nation's shipbuilding capacity by increasing the facilities and labor force necessary to build our nation's fleet. It would also provide strategic redundancy to ensure that naval ship production of all ship classes can continue in the event of wartime attack or any other disruption. On page 28 of his report, Danzig (2011) describes this trade-off between efficiency and security in his fifth prescriptive principle when he states, "It should be recognized that what may be inefficient in a predicted world may be life-saving if the unpredicted occurs."

2. The Advantages of a Distributed Construction Process

Many consumer products today are not produced from start to finish in just one factory or even in just one country. Everything from cell phones to cars are now produced by assembling many components provided from a widely distributed supply chain. For instance, an American-made car may source parts from Mexico, China, Europe, and domestically, with final assembly taking place in Detroit. Boeing and Airbus source parts from as far away as Australia (Boeing, n.d.). Danzig (2011) discusses the advantages of this process in his second prescriptive principle, which mentions the push for modularity, and his fifth prescriptive principle, which discusses the advantages of increased competition. The process of using distributed construction processes, made possible by globalization, allows for specialization and greater efficiency in many industries. With this specialization, suppliers can focus on one component or module of the end product, achieving efficiencies and proficiencies that a vertically integrated producer would not.

There are many ways to adapt this model to shipbuilding in the United States, and in some cases, this process is already taking place. As previously mentioned, all current and future classes of Navy nuclear submarines (Virginia, Columbia, and SSN[X]) are planned to be produced by both Electric Boat and Newport News Shipbuilding through an industrial arrangement between the two shipyards. Both shipyards manufacture different sections of the submarine and take turns building the reactor compartments and completing final assembly. This arrangement helps to maintain the shipbuilding industrial base by ensuring that both Electric Boat and Newport News remain partially capable of submarine production. It also allows each shipyard to focus and become more proficient and efficient at constructing their sections of the submarine, as opposed to having to be concerned with constructing the whole submarine on their own. Discussed below are two proposals for how this construction method can be expanded to other ship classes.

The Gulf Coast of the United States has long been a premier location for construction of naval ships. Currently, there are two new construction naval shipyards on the Gulf Coast—Huntington Ingalls in Pascagoula, Mississippi, and Austal in Mobile, Alabama. Huntington Ingalls is the largest shipyard and builds amphibious ships of all classes as well as Arleigh Burke–class destroyers (DDG-51 class). Austal is much smaller and newer and produces the Independence variant LCS. Up until 2014, there was a third new construction naval shipyard on the Gulf Coast—Avondale, which had produced various classes of naval ships for more than half a century until it was closed due to Northrup Grumman’s consolidation of shipbuilding into Pascagoula.

It may be possible to greatly expand the construction of naval ships on the Gulf Coast by implementing the distributed supply chain method of construction. Currently, both Huntington Ingalls and Austal construct their ships in their entirety with most major hull components manufactured on site. An alternative solution could instead reserve Huntington Ingalls, Austal, and possibly a reopened Avondale, for only final assembly of premade sections of ships. These premade sections of ships could then be constructed at various manufacturing sites up the Mississippi River. The Mississippi River is already used for the downstream transportation of many products including grain and iron ore, which likely means the river could support the large, deep draft barges that would be required to transport premade ship sections to the Gulf Coast. Prior to globalization, many cities in the heartland of the United States, along the Mississippi River, were major hubs for manufacturing and heavy industry. There is a strong desire by many in the United States, including the current administration, to bring more manufacturing back to the United States

(Haskins, 2020). Building naval ships in premade sections up the Mississippi River could be a viable and politically popular way to restore the manufacturing and industrial base along the Mississippi River and could also bring efficiencies and proficiencies that could streamline the ship construction process, leading to greater capacity and better quality. This proposal could reduce the delivery time and takt time for naval ship construction on the Gulf Coast and would also be enticing to the many congresspersons who represent these economically diminished areas—something that could make this proposal's palatability and likelihood of passage better than expected.

Another possibility for applying distributed supply chains to the shipbuilding industry could be to develop an international supply chain for naval ship construction. This already exists, but in a limited way—both the Freedom and Independence variant of the LCS import some of their parts from foreign countries. But what if the entire ship was sourced from various countries around the world? Similar to the Mississippi River model described above, various countries around the world could produce different sections of a ship and then transport the pieces via ocean liner to the United States for final assembly. This model could take advantage of more affordable foreign labor and raw materials, which make-up approximately 47% of shipbuilding costs in major shipbuilding powers like Korea and Japan (Jiang, 2011).

Whether using the Mississippi River model or the international model, in both cases modularity and distribution of the supply chain allows for faster construction, greater capacity, built-in redundancy, and greater competition in the form of many shipbuilders competing to build all the pieces of a ship.

As with any distributed supply chain, embedding quality within the design would have to play an important role to ensure that all the ship segments fit together when brought to the final assembly shipyard. Many other industries have already mastered the science behind distributed supply chain systems, resulting in high-end products that are assembled from perfectly fitted components sourced from all over the world. Even modern bridges are often built by starting from both sides and then meeting in the middle. If these feats of human engineering can be accomplished and mastered, adopting distributed supply chains for the shipbuilding industry might be feasible.

3. Choosing between the “Low Road” and “High Road”

U.S. naval ship designers and builders have historically designed and built naval ships to last for many decades. Smaller ships like frigates, destroyers, and cruisers are usually designed to last for 25 to 35 years. Submarines are designed to last for about 40 years, assuming a costly and time-consuming midlife nuclear reactor refueling. Aircraft carriers are the longest-lived, with life spans sometimes surpassing 50 years, assuming a midlife nuclear reactor refueling more complex, costly, and time consuming than those required for submarines. The average age of a Navy ship as of 2018 was 18.2 years (Congressional Budget Office, 2018). Designing ships for lengthy service-lives is not easy. The sea is known to be a harsh environment, and DoD missions can be hard on equipment. In order to operate in this environment for decades, ships must be designed with heavy-duty components and redundant systems designed to last. They must also undergo regular maintenance and upgrades to ensure all of their complex systems are in working order and up-to-date enough to counter current threats—something that dramatically increases the life-cycle cost of a weapon system. In his fourth prescriptive principle on page 26 of his report, Danzig (2011) categorizes these types of systems as “high-road”—“systems that are built to endure, elegantly designed, typically rather rigid” and “nearly always high cost.” Danzig goes on to highlight the biggest disadvantage of “high-road” military assets—that in the long term, “high-road” equipment locks the DoD into outdated equipment and requires massive investments in maintenance and upgrades.

While the shipbuilding industry has maintained its tradition of building mostly “high-road” ships for the Navy, other industries have adopted a different strategy. Take the wrist-watch industry for example. Modern watches fall into two major categories—inexpensive low-end watches that are mass produced like Timex and Fossil (low-road) and expensive high-end watches that are produced in limited numbers like Rolex and Breitling (high-road). Low-road watches have standardized inexpensive parts made from common affordable materials like steel, plastic, and glass. They are assembled by automated machines, typically last a few years, and can cost less than $100. High-road watches often have custom and/or low-production parts made from premium expensive materials like gold, sapphire, and titanium. They are built by hand by experienced trained watch-makers, are designed to last a lifetime or longer (with proper maintenance), and can cost tens of thousands of dollars or more. It is also common for low-road watches to use simple and affordable quartz movements while high-road watches use intricate and complex mechanical designs containing dozens of precise tiny parts. While the high-road watch makers maintain a niche market share, they are not able to compete with the sheer numbers that the low-road watch makers offer due to the complexity, manufacturing techniques, and higher costs associated with their "high-road" watches. If one's goal was to increase the number of watches a company produced, choosing to achieve this goal by producing more high-road watches would not be efficient or sensible. Yet this is the path our Navy have been taking.

Adapting the same "low-road" principles of the affordable watch industry to the shipbuilding industry could reap great benefits. Although ships are much greater in size and complexity compared to wrist-watches, this does not mean that modern-day naval ships need to be as complex and durable as they currently are. Building future naval ships as "low-road" ships may mean these ships have significantly shorter service lives than current "high-road" ships. Future "low-road" naval ships may also have significant capability limitations when compared to their current "high-road" counterparts. These shortcomings may be overcome if future "low-road" ships can be produced in high enough numbers and at cheap enough costs. For example, at a certain point, it can become more advantageous to have a large number of cheap, short-lived military assets as opposed to a small number of expensive long-lived military assets. Many of the United States' adversaries already employ this strategy. For example, Russia (then the Soviet Union) opted during the Cold War to counter the U.S. Navy's aircraft carrier strike groups not with their own expensive "high-road" carrier strike groups, but with massive numbers of "low-road" anti-ship cruise missiles. Producing low-road naval ships in the future could also bring the advantage of a reduced need for ship repair, maintenance, and upgrading. Future "low-road" ships could simply be scrapped or gutted and rebuilt after their short service lives, which would free up ship repair facilities to focus on new construction, increasing shipbuilding capacity. By adopting a model of replacement instead of repair and maintenance, the DoD would not be locked into outdated equipment. Opting for "low-road" ships could also open opportunities to develop new suppliers and expand competition. Lastly, the "low-road" production model offers the opportunity to go from concept to delivery much faster due to the reduced complexity of the design—achieving Danzig's first prescriptive principle.

Examples of how the Navy can make future naval ships "low-road" are many. It is likely possible that future "low-road" naval ships could utilize many cheaper commercial marine components. Future "low-road" naval ships could use a single commercially available marine diesel engine instead of multiple expensive gas-turbine engines with main reduction gears. Less stringent commercial hull standards could also be adopted to reduce costs and increase efficiencies. Some defensive weapons and sensors could also be eliminated, especially on unmanned vessels where losses are acceptable. An analysis of every component and system onboard naval ships should be assessed to see what must be required on future "low-road" ship designs. Keeping some future ships as "high-road" designs would maintain certain capabilities, but establishing a mix of low-road and high-road designs could allow the shipbuilding industry to rapidly increase capacity and surge the Navy to or beyond its 355-ship goal.

4. Reducing Variety and Complexity Increases Production Capacity

Modern warships, including those built and operated by the United States, are some of the most complex machines created by man. Ships are designed to exacting and demanding specifications to meet the requirements of a wide variety of missions assigned to the Navy. The mission of an aircraft carrier is obviously different from the mission of a submarine—resulting in two different ship designs. This idea of designing ships based on the mission to be performed, has heavily influenced the design of naval ships since the beginning of the Navy. Conventional wisdom said that each mission required a different class of warship to accomplish it. Submarines patrolled the depths and pursued enemy submerged and surface threats. Frigates were responsible for littoral operations. Destroyers were responsible for anti-submarine operations. Cruisers were responsible for air defense. And carriers were responsible for launching and recovering aircraft. Within each of these ship classes, there were often multiple subclasses that performed different elements of an assigned mission.

Over the past 30 years, the Navy has shifted somewhat away from designing ships based on a single mission to designing ships that are multi-mission. Arleigh Burke–class destroyers, for example, can perform many mission sets including anti-submarine warfare, air defense, ballistic missile defense, strikes, and many more, making it one of the most capable, prized, and produced modern warships. Despite this, the Navy is still building or intending to build other classes of warships similar to the Arleigh Burke–class destroyers. Already in production are the littoral combat ships (LCSs) that will perform some missions in common with the Arleigh Burkes. There are also plans to design and produce 20 new frigates under the FFG(X) program. These ships will also perform many of the same missions as the Arleigh Burkes and LCSs. Additionally, the Navy also maintains a force of 20 Ticonderoga class cruisers that perform many of the same missions as the Arleigh Burkes. The Navy breaks smaller vessel classes, like LCSs, frigates, destroyers, and cruisers into small surface combatants (SSCs) and large surface combatants (LSCs). Littoral combat ships and frigates are considered SSCs, while destroyers and cruisers are considered LSCs. With the commonality of many of the missions performed by these ship classes, it may not make sense to have more than one SSC or LSC. It may not even make sense to have a separate SSC and LSC.

In Danzig’s (2011) second prescriptive principle, he discusses the benefits of standardization and specifically proposes that the simplest, ideal system would be like a Lego set, where all the pieces are standardized and easily assembled and interchanged. In Danzig’s third prescriptive principle he calls for the prioritization of the most adaptable equipment and specifically highlights the B-52 bomber, which has served in numerous roles and conflicts since the 1950s, as a prime example of a military platform that has proven to be adaptable and valuable. He proposes building more platforms like the B-52 in the future and fewer platforms like the F-22 fighter, since the F-22 is not adaptable and is only useful for a narrow set of missions (Danzig, 2011).

One proposal to bring the Navy more in line with Danzig’s second and third prescriptive principles could involve reducing the number and type of ship classes. Reducing several ship classes to a single, more adaptable ship class could result in greater commonality and standardization among parts and construction processes. For example, instead of designing, building, and maintaining littoral combat ships, frigates, destroyers, and cruisers, the Navy instead could design and build one class of ship capable of performing most of the missions these four current classes of ships perform. From the perspective of the shipbuilding industry, it is easier to mass produce one type of ship year after year than it is to design and build several types of ships that often change in design. With fewer types of ship, it also becomes easier to develop new suppliers. In order to maximize adaptability, there may still be a need for some variation within this single ship class that would replace potentially four current ship classes. Some variants may need a helicopter hangar, while others may not. Some variants may need additional vertical launch system capacity, while others may not. Other weapons systems and sensors can also vary between different variants of the single replacement ship class. All the variants could share a common hull, propulsion system, living quarters, and many other systems. This commonality and standardization between variants could greatly reduce the cost of designing, building, and maintaining future naval ships, making it much easier for the shipbuilding industry to master construction techniques and processes, resulting in faster production timelines, higher-quality ships, and more affordable ships.

This same principle could also be applied to other ship types, including amphibious ships (amphibs). Currently, there are roughly three different types of amphibs in use by the Navy—large deck amphibs, like LHDs and LHAs; medium-sized amphibious transport docks called LPDs; and smaller dock landing ships called LSDs. The large deck LHAs currently under construction are almost as large as a nuclear-powered aircraft carrier (CVN) and perform many of the same tasks as CVNs. It may be possible for future LHAs and CVNs to share a common hull or common propulsion elements, although there would need to be consideration for the difference in propulsion type—gas turbine versus nuclear—and the larger flight deck, catapults, arresting gear, and other above-the-water-line equipment differences between an LHA and a CVN. It may also be possible to replace or succeed the LPD and LSD ship classes with a common platform. Both perform roughly the same missions and are close enough in size that one future successor ship class could suffice instead of having two separate ship classes.

Reducing the variety and complexity of military assets to increase efficiencies is not a novel idea. Similar strategies have already been used with carrier-based aircraft and the proposed Common Hull Auxiliary Multi-Mission Platform (CHAMP) program. During the Vietnam War, carrier-based aircraft were used for a variety of missions. Carriers like the USS ENTERPRISE (CVN-65), which served in the conflict, carried a variety of aircraft to perform these missions. A-1 Skyraiders were used for light bombing and ground attack. A-4 Skyhawks were converted from their nuclear missions to perform conventional bombing raids. A-6 Intruders provided all-weather bombing capabilities. The later years of the war saw the introduction of the A-7 Cosair for light bombing. F-4 Phantoms along with F-8 Crusader's provided fighter support (USNI, 1987). Roughly half a century later, American aircraft carriers only carry one type of aircraft to perform all of these missions – the F/A-18 Super Hornet. Instead of designing and building numerous aircraft to accomplish the many missions required of carrier-based aircraft, the Navy instead opted to consolidate all of these capabilities into one-aircraft, easing the maintenance and logistics requirements for carrier-based aircraft. The F/A-18 has also proven to be exceptionally adaptable since its introduction in the 1980s. Since then it has been expanded into its current larger version (the Super Hornet) and has assumed roles originally not intended for the aircraft to include electronic warfare (with the E/A-18 Growler), reconnaissance, and aerial refueling.

The proposed CHAMP program, currently being considered for the replacement of several auxiliary ship classes nearing retirement, also promises to increase efficiency and reduce costs by reducing variety and complexity. CHAMP is being designed to replace hospital ships, command and control ships, submarine tenders, as well as aviation logistics and sealift ships. While originally intended to be a single ship design, the Navy is leaning towards the conclusion that CHAMP will need to be two separate designs—one for cargo and one for people (Eckstein, 2019). Even as a two-ship design, CHAMP will still likely be more efficient and affordable to design, produce, and maintain than doing the same for five or six new ship classes.

It is recommended that all naval ship classes be assessed to determine if consolidation with other ship classes is possible. Future naval ships should also be designed to be as adaptable as possible, with a focus on establishing commonality in hull structure, propulsion, and other major systems, while leaving room for variation in weapons, sensors, and other equipment.

5. Subsidies Can Be a Valuable Strategic Tool

After the end of the Second World War, the United States was the global leader in shipbuilding. With the U.S. homeland largely protected from the destruction of the war that so badly damaged Europe and Asia, and U.S. industry primed from its wartime buildup, no other nation could keep up. At that time, U.S. shipbuilders benefited from many forms of government subsidies, such as construction differential subsidies. Even three decades after the war, during the 1970s, the United States still built most of the world's fleets (Klein, 2015). Then in 1981, the U.S. government ended most of the subsidies that benefited U.S. shipbuilders, except for a few loan guarantees that the Department of Transportation still offered. This removal of subsidies, combined with the industrial rise of Asian nations that subsidized their shipbuilding industries, precipitated the quick decline of the U.S. shipbuilding industry. In the course of a decade, the United States went from producing over 45 commercial vessels a year in 1980 to almost none in 1990 (Klein, 2015). Today the United States produces less than one-third of 1% of all the ships produced in the world, despite being the world's largest economy (Thompson, 2019). For comparison, South Korea, the world's largest ship producer, produces 100 times as many ships as the U.S. The remaining U.S. shipyards remained viable by largely ditching the production of commercial vessels in favor of pursuing government contracts for military shipbuilding (Thompson, 2019). The only commercial vessels still built in the United States are built specially for domestic waterway transportation due to the 1920 Jones Act, which mandates that vessels of this purpose be built in the United States. Without the Jones Act, it is unlikely the United States would still produce any commercial ships at all.

Meanwhile, many countries in Asia and Europe continue to heavily subsidize their shipbuilding industries. Fifteen years after the United States cut most of its subsidies to its shipbuilders, European nations were subsidizing their shipbuilding industry at more than $1 billion annually, more than 20 times the remaining subsidies the United States still provided to its shipbuilding industry (Sanger, 1996). Put another way, European governments were paying about 9% of the cost of every ship their countries produced (Sanger, 1996). At this rate, U.S. shipbuilders could not be competitive. To make matters worse, some countries were using state-subsidized or state-owned entities to “dump” ships, which refers to the temporary selling of ships below their manufacturing cost with the goal of putting other nation’s shipbuilding industries out of business (OECD, n.d.).

In 1996, U.S. trade negotiators were almost successful in pushing a trade deal between the United States, Europe, and Asia that would have eliminated most shipbuilding subsidies worldwide (Sanger, 1996). The proposed deal would have also ended the dumping of ships and led to a fairer trading environment for the shipbuilding industry. There was bipartisan support in Congress for the proposal, and many within the U.S. shipbuilding industry were in favor of its passing. Unfortunately, not all in the shipbuilding industry were in favor, and several of the large shipbuilders remaining in the United States used their lobbying power to oppose the trade proposal when they realized that the United States would also have to relinquish its own remaining subsidies. With that, the trade proposal unraveled and has since not been readdressed. With the state of the U.S. shipbuilding industry even worse today than it was in 1996, and the growth of competitor nations like China, it may be time again for the Navy and the U.S. shipbuilding industry to consider pushing for another trade deal to eliminate subsidies across the board or push for the reinstatement of domestic shipbuilding subsides to allow the U.S. shipbuilding industry to compete on a global scale.

Recent efforts by the Trump administration to extend cargo preference rules to reserve more of America’s trade for domestically built and manned shipping could also be a step in the right direction (Thompson, 2019), although the legality and long-term consequences of this action are unknown. While this effort would likely not be as beneficial as an equal playing field where no country used subsidies to give its shipbuilders an unfair advantage, it could help to keep the remaining U.S. shipbuilders operating by providing them with additional business. There are also efforts currently underway between the Navy and Congress to build and replace the aging organic sealift assets that the military depends upon for transportation to and from conflict zones. The CHAMP project is being proposed that could provide much-needed business for U.S. shipbuilders, although there is consternation as to whether the U.S. shipbuilding industry has enough capacity to build CHAMP while also building the dozens of Navy warships required by the 2016 FSA.

6. Demand Variability Leads to Higher Costs, More Risk, and Reduced Capacity

Supply chain managers understand the importance and advantages of reducing demand variability. Demand variability complicates the production planning process by introducing unpredictability. Production planners need to understand the demand for the end products they are producing in order to properly plan for the processing of raw materials, the scheduling of labor hours, and many other aspects of production. The more variability there is in demand, the more difficult this process gets. With the additional difficulty comes additional risk. If demand cannot be predicted, the risk of overproducing or underproducing (overage or underage) goes up. In order to account for this increased risk, many manufacturers generate safety stock (often at large additional expense) to ensure demand spikes can be accommodated. Other manufacturers and producers may take different actions, like delaying large capital investments. Large manufacturers, like shipyards, need to make large investments in new infrastructure and manning in order to meet the Navy's long-range shipbuilding plan. The constant changes in Navy priorities, shipbuilding plans, and funding, presents naval shipbuilders with a constantly changing demand environment with little predictability. In this environment, shipbuilders may delay or cease to consider the large capital investments necessary to increase shipbuilding capacity. Shipbuilders may also delay the hiring of new employees, or worse yet, lay off current employees due to the unpredictability of future demand for ships.

The Navy has contributed to this unpredictability in future ship construction for many decades. This unpredictability in demand has also increased over the past 20 years. While many ship classes, like the DDG-51 class, have been consistently ordered and built for many years, others—like the DDG-1000 class and LCS variants—have not. Originally, the Navy intended to build up to 32 DDG-1000s when early planning for the ship class began in the late 1990s. In the subsequent years, the Navy revised its number for planned construction of the class from 32 to 16 to 24 to 7, then finally just three (O'Rourke, 2020).

This kind of wild variation in demand presents a major challenge to our nation’s shipbuilders. As mentioned before, without relatively consistent demand, producers cannot efficiently manage things like raw materials purchases and new employee hires. Additionally, ship manufacturers likely delayed necessary investment in new facilities, equipment, and personnel due to the large demand uncertainty presented by the DDG-1000 class.

The LCS ship variants are another case of unpredictable demand negatively affecting the shipbuilding base in the United States. Envisioned as two separate variants (Freedom and Independence), each was to be produced in separate shipyards. Although this separation of production facilities can be a positive endeavor that could potentially expand the shipbuilding capabilities of the country, the LCS program also hindered this process by not providing a consistent demand to both shipyards involved. Similar to the DDG-1000 class, the Navy frequently entertained altering the final production number and even delayed the award of production contracts due to uncertainty about the ship class. Again, this has a large impact on the ability of shipbuilders to meet the Navy’s demand.

There are solutions to this problem, and many are already being implemented. The use of multi-year procurement (MYP) and block buy contracting (BBC) have shown great promise in other ship classes and comes with the added benefit of significant savings to the Navy. Most programs in the Navy and military in general are funded based on annual contracting, which uses one or more contracts for each year’s worth of procurement for any given item (O’Rourke, 2017). Under MYP and BBC, a contract can use multiple years’ worth of procurement, thereby providing a contractor, or shipbuilder in this case, a longer time frame of predictability and greater demand certainty. With this greater demand certainty, shipbuilders would be more likely to make the long-term investments in infrastructure and manning necessary to increase our nation’s shipbuilding capacity to reach the 355-ship goal. With the increased demand certainty, shipbuilders can also make more efficient production decisions, leading to costs savings that could be passed to the Navy. Compared to conventional annual contracting programs, MYP and BBC programs have shown cost reductions as high as 15% (O’Rourke, 2017).

Another solution is to focus on building and/or modifying existing mature designs. The new Flight III version of the Arleigh Burke DDG-51 class is a good example. The DDG-51 class, having been around since the late 1980s, has been tried and tested for over three decades and is one of the Navy’s most adaptable ship designs, having gone through four different versions or “flights.” With continuous construction during this entire time, both shipbuilders (BIW and Huntington Ingalls) have had a long time to hone the manufacturing process to be efficient and effective. This long stability has also allowed both BIW and Huntington Ingalls to make the investments in infrastructure and manning necessary to sustain relatively large-scale ship production. When the Navy decided to base the next LSC on the DDG-51 design, it allowed both BIW and Huntington Ingalls to build on the success they already established with the DDG-51 class. Although some had advocated for a completely new design, doing so would have necessitated massive retooling efforts, greater personnel training requirements, and other costly and burdensome endeavors. It is almost always easier to continue an existing design or modify an existing design than it is to start from scratch with a new design. This mantra should be applied to all naval ship classes.

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VI. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The following is a synopsis of the purpose of this project along with our conclusions and recommendations.

A. SUMMARY

The purpose of this thesis was to investigate and determine the learning curves achieved from historical shipbuilding data. Then, by applying queueing theory, a capacity risk model using a multi-server model was developed to determine a utilization rate. Finally, several commonly held logistics principles—including the value of redundancy, the advantages of distributed construction processes, and the usefulness of building for the short-term, among others — were applied to propose potential improvements in the defense shipbuilding industrial base. We analyzed historical shipbuilding data for the Arleigh Burke–class of DDGs from BIW and Ingalls Shipbuilding in order to generate a utilization model for current shipbuilding production.

In Chapter II, we discussed the Navy's background and current composition of the fleet battle force given permission by 10 U.S.C. § 8062. The FSA assists in determining the required number of vessels and ultimately how many of each ship class or type. We also gave an overview of the Navy's 30-year shipbuilding plan and how it plans to achieve the goal of a 355-ship battle force by FY2034.

Chapter III examined the previous literature that applied to the United States shipbuilding industrial sector. Most notably, the interagency task force identified the lack of capacity needed to fulfill the strategic goals for both the commercial and defense sectors. Also of note is former SECNAV Richard Danzig's (2011) prescriptive and descriptive logistics principles for complex acquisition decisions. Finally, we discussed how Solberg (1981) used bottleneck and stochastic models to estimate capacity in an industrial practice.

Chapter IV detailed the methodology used to collect and prepare the data to generate learning curves and utilization rate models. We described the process by which the data was input into T. P. Wright's (1936) learning curve rate formula. We also described the process by which the data was input into the multi-server model. In this chapter, we also discussed how commonly held logistics principles were applied to the learning curve rate and multi-server model results.

Chapter V examined the results provided by the learning curve rate theory and multi-server model. Once applied, the multi-server model revealed a comparison between DDGs built at BIW and Ingalls Shipbuilding. This provided a similar platform construction approach in order to validate the accuracy of the results. Further analysis included average inter-arrival time, average service time, the number of ships under construction, and the number of ships waiting in the queue. Additional research is needed to determine how the individual shipbuilding processes affect the results of the multi-server model. The learning curve model was applied to identify the productivity efficiencies by different shipbuilders based on the complexity of the Arleigh Burke ship design. This revealed that the completeness and maturity of any ship design are vital to a successful production process. For optimality in a shipbuilding learning curve to occur, serial production across multiple hulls is required. We found that as a shipbuilder begins to build a new ship design, not only does learning occur from hull to hull, the development of more efficient production methods occurs.

In the case of BIW, optimality in their learning occurred only when they were able to focus on the production of a single design. During those periods they proved to be overwhelmingly efficient in the production of the Arleigh Burke ship design. Once BIW expanded its production operation to include the more complex and unfamiliar Zumwalt ship design, it resulted in the loss of learning and gained efficiencies in the overlapping production of an Arleigh Burke DDG-51. Perhaps had the Zumwalt ship design been a closer derivative of the Arleigh Burke, the outcome would have been different. Lastly, it was determined that the two shipbuilders were not reaching optimal utilization. Six logistics principles were explored in detail to give the industrial shipbuilding base a path forward to assist the Navy in reaching its goal of 355 ships.

B. CONCLUSIONS

Our research posed three questions. First, what does the Navy need to do to expand the nation's shipbuilding capabilities to fulfill the Navy's 30-year shipbuilding plan?

Second, what are some of the ways the Navy's acquisition process has influenced the defense sector of the American shipbuilding industry? Third, how have contraction and consolidation trends within the American shipbuilding industry impacted production capacity?

By analyzing the independent data from two existing DDG shipbuilders, we discovered shipbuilding learning curves and utilization are similar within this ship type. One key assumption underlying the capacity model is that it underestimates the weight of other factors in the production process. It is trying to look at overall capacity as if processes and functions did not change during a specified time period. This model measures ship production as a single event, aggregating the many shipbuilding processes such as design, planning, fabricating, keel laying, launching, and delivery.

The data in Table 7 noted key differences between Lq and Wq for the two shipbuilders. These differences might be attributable to single ship-type construction (BIW) versus multiple ship-type construction (Ingalls). Comparatively, the variance between Lq and Wq in Table 7 appears consistent with our congestion effect findings from the learning curve model outputs reflected in Figures 2 and 3. Furthermore, the data outputs support our theory that during the periods in which these two shipbuilders were engaged in the concurrent production of more than one ship type, a managerial shifting of productivity effort occurred for the prioritization of production as a consequence of increased design complexities. For this reason, it can be inferred that the maximum annual production CGT determined in Tables 5 and 6 is a realistic reflection of each shipbuilder's actual practical annual capacity rather than an annual theoretical capacity.

In the case of both Ingalls Shipbuilding and BIW, concurrency in their production lines resulted in increased days of production for the completion of the same ship design. Based on our analysis of the production data, BIW's construction of DDG-1000 provided evidence to demonstrate how parallel production practices can reduce actual capacity through congestion. Additionally, the production data from Ingalls Shipbuilding', suggested that their broad spectrum of production lines resulted in the throttling back of their overall production capacity. Given the fact that the majority of U.S. Navy shipbuilders engage in the concurrent production of multiple ship designs, it is unlikely that the Navy will be able to achieve its 355-ship goal unless changes to acquisition and shipbuilding process occur.

C. RECOMMENDATIONS

Sections A and B of Chapter V in this report identify a lack of required shipbuilding capacity to meet the Navy's long-range shipbuilding goal of 355 battle forces ships. Due to this lack of capacity, Section C of Chapter V provides six possible recommendations for the Navy to pursue to increase shipbuilding capacity in order to reach its shipbuilding goals. Provided below is a summary of the recommendations.

Recommendation one proposes building all classes of naval ships in at least two separate shipyards in order to increase capacity through buffering and to establish strategic redundancy. The DDG-51 class destroyer is already produced in this manner. It is recommended that this model be applied to all other ship classes.

Recommendation two proposes the establishment of a shipbuilding final assembly hub on the Gulf Coast, with most raw materials and component assembly moved to various industrial production sites located up the Mississippi River. Such a shipbuilding model would allow for greater specialization, faster construction, and increased capacity. The importation of sections of ships from foreign nations to be assembled in the United States is also explored.

Recommendation three proposes a move towards manufacturing "low-road" naval ships—ships that are less sophisticated, short-lived, and less expensive to make compared to current "high-road" naval ship designs. This proposal could dramatically reduce the time and expense involved in naval ship design and construction, thereby allowing for significant increases in shipbuilding capacity.

Recommendation four proposes the consolidation of similar ship classes to reduce the variety and complexity of future naval ship designs. The establishment of common-hull designs is also discussed as a way to simplify future naval ship designs. Simplifying future designs eases the burden on shipbuilders and could lead to increases in capacity.

Recommendation five discusses the decline of the U.S. shipbuilding industry due to the government's elimination of subsidies for domestic shipbuilders. It is recommended that the Navy advocate for either the reinstitution of domestic shipbuilding subsidies or the elimination of all shipbuilding subsidies (international and domestic), creating an even playing field that will allow the U.S. shipbuilding industry to compete with its international rivals.

Recommendation six proposes minimizing the demand variability experienced by the nation's shipbuilders by emphasizing the production of mature designs in favor of radically different designs. Such measures could ease the burdens experienced by the nation's shipbuilders, resulting in reduced retooling efforts, fewer design expenses, faster production timelines, and greater capacity.

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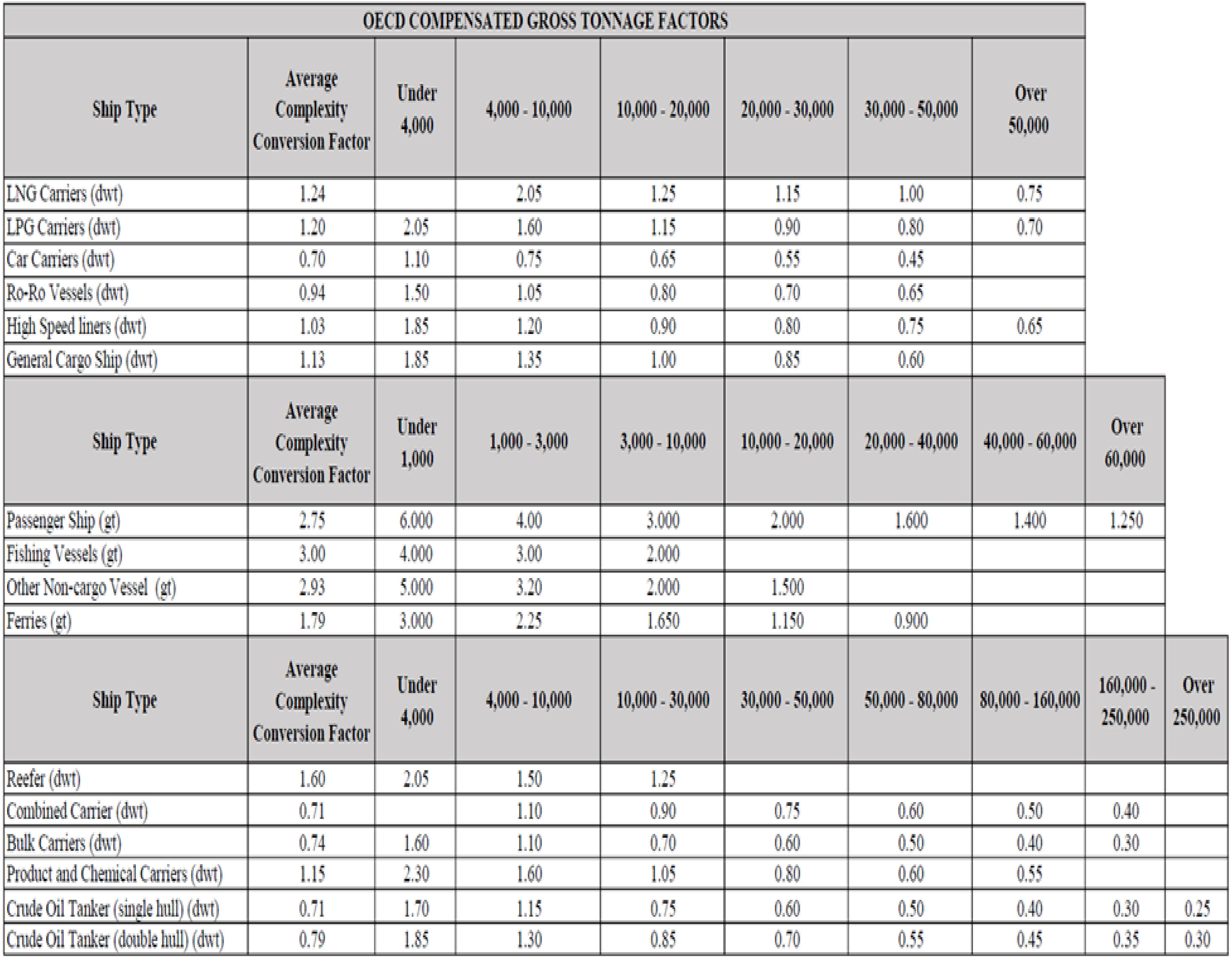
APPENDIX A.
OECD COMPENSATED GROSS TONNAGE FACTORS



OECD COMPENSATED GROSS TONNAGE FACTORS

Ship Type	Average Complexity Conversion Factor	Under 4,000	4,000 - 10,000	10,000 - 20,000	20,000 - 30,000	30,000 - 50,000	Over 50,000
LNG Carriers (dwt)	1.24		2.05	1.25	1.15	1.00	0.75
LPG Carriers (dwt)	1.20	2.05	1.60	1.15	0.90	0.80	0.70
Car Carriers (dwt)	0.70	1.10	0.75	0.65	0.55	0.45	
Ro-Ro Vessels (dwt)	0.94	1.50	1.05	0.80	0.70	0.65	
High Speed liners (dwt)	1.03	1.85	1.20	0.90	0.80	0.75	0.65
General Cargo Ship (dwt)	1.13	1.85	1.35	1.00	0.85	0.60	

Ship Type	Average Complexity Conversion Factor	Under 1,000	1,000 - 3,000	3,000 - 10,000	10,000 - 20,000	20,000 - 40,000	40,000 - 60,000	Over 60,000
Passenger Ship (gt)	2.75	6.000	4.00	3.000	2.000	1.600	1.400	1.250
Fishing Vessels (gt)	3.00	4.000	3.00	2.000				
Other Non-cargo Vessel (gt)	2.93	5.000	3.20	2.000	1.500			
Ferries (gt)	1.79	3.000	2.25	1.650	1.150	0.900		

Ship Type	Average Complexity Conversion Factor	Under 4,000	4,000 - 10,000	10,000 - 30,000	30,000 - 50,000	50,000 - 80,000	80,000 - 160,000	160,000 - 250,000	Over 250,000
Reefer (dwt)	1.60	2.05	1.50	1.25					
Combined Carrier (dwt)	0.71		1.10	0.90	0.75	0.60	0.50	0.40	
Bulk Carriers (dwt)	0.74	1.60	1.10	0.70	0.60	0.50	0.40	0.30	
Product and Chemical Carriers (dwt)	1.15	2.30	1.60	1.05	0.80	0.60	0.55		
Crude Oil Tanker (single hull) (dwt)	0.71	1.70	1.15	0.75	0.60	0.50	0.40	0.30	0.25
Crude Oil Tanker (double hull) (dwt)	0.79	1.85	1.30	0.85	0.70	0.55	0.45	0.35	0.30

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APPENDIX B.
LEARNING CURVE DATA

Builder	Hull #	Original Name	Original Owner	Battle Force Class	Ship Type	GT	Keel Laid	Launched	Delivered	Production Days Out of the Water	Prodcution Days in Water	Total Production Days	Disposition	Complexity Conversion Factor	Compensated Gross Tonnage
Ingalls Shipbuilding	LHD 8	Makin Island	U.S. Navy	Amphibious Warfare Ships	Assault Ship	28,200	14-Feb-04	22-Sep-06	16-Apr-09	951	937	1,888	Active	14.0	394,800
Ingalls Shipbuilding	LPD 21	New York	U.S. Navy	Amphibious Warfare Ships	Assault Ship	19,200	10-Sep-04	19-Dec-07	21-Aug-09	1,195	611	1,806	Built in New Orleans, active	14.0	268,800
Ingalls Shipbuilding	WMSL 751	Waesche	U.S. Coast Guard	Small Surface Combatant	Cutter	4,200	11-Sep-06	12-Jul-08	6-Nov-09	670	482	1,152	Active	8.0	33,600
Ingalls Shipbuilding	DDG 105	Dewey	U.S. Navy	Large Surface Combatant	Destroyer	7,134	4-Oct-06	18-Jan-08	17-Aug-09	471	577	1,048	Active	9.0	64,206
Bath Iron Works	DDG 108	Wayne E. Meyer	U.S. Navy	Large Surface Combatant	Destroyer	7,134	18-May-07	19-Oct-08	10-Jul-09	520	264	784	Active	9.0	64,206
Ingalls Shipbuilding	LPD 22	San Diego	U.S. Navy	Amphibious Warfare Ships	Assault Ship	19,200	23-May-07	7-May-10	19-Dec-11	1,080	591	1,671	Active	14.0	268,800
Ingalls Shipbuilding	LPD 23	Anchorage	U.S. Navy	Amphibious Warfare Ships	Assault Ship	19,200	24-Sep-07	12-Feb-11	17-Sep-12	1,237	583	1,820	Built in New Orleans, active	14.0	268,800
Ingalls Shipbuilding	DDG 107	Gravely	U.S. Navy	Large Surface Combatant	Destroyer	7,134	26-Nov-07	30-Mar-09	20-Jul-10	490	477	967	Active	9.0	64,206
Bath Iron Works	DDG 109	Jason Dunham	U.S. Navy	Large Surface Combatant	Destroyer	7,134	11-Apr-08	2-Aug-09	2-Jun-10	478	304	782	Active	9.0	64,206
Ingalls Shipbuilding	DDG 110	William P. Lawrence	U.S. Navy	Large Surface Combatant	Destroyer	7,134	16-Sep-08	15-Dec-09	24-Feb-11	455	436	891	Active	9.0	64,206
Ingalls Shipbuilding	LPD 24	Arlington	U.S. Navy	Amphibious Warfare Ships	Assault Ship	19,200	18-Dec-08	23-Nov-10	7-Dec-12	705	745	1,450	Active	14.0	268,800
Ingalls Shipbuilding	LHA 6	America	U.S. Navy	Amphibious Warfare Ships	Assault Ship	45,000	27-Apr-09	4-Jun-12	10-Apr-14	1,134	675	1,809	Active	14.0	630,000
Bath Iron Works	DDG 111	Spruance	U.S. Navy	Large Surface Combatant	Destroyer	7,134	14-May-09	6-Jun-10	15-Apr-11	388	313	701	Active	9.0	64,206
Ingalls Shipbuilding	WMSL 752	Stratton	U.S. Coast Guard	Small Surface Combatant	Cutter	4,200	20-Jul-09	16-Jul-10	2-Sep-11	361	413	774	Active	8.0	33,600
Ingalls Shipbuilding	LPD 25	Somerset	U.S. Navy	Amphibious Warfare Ships	Assault Ship	19,200	11-Dec-09	14-Apr-12	18-Oct-13	855	552	1,407	Built in New Orleans, active	14.0	268,800
Bath Iron Works	DDG 112	Michael Murphy	U.S. Navy	Large Surface Combatant	Destroyer	7,134	12-Jun-10	8-May-11	4-May-12	330	362	692	Active	9.0	64,206
Bath Iron Works	DDG 1000	Zumwalt	U.S. Navy	Large Surface Combatant	Zumwalt	13,539	17-Nov-11	28-Oct-13	20-May-16	711	935	1,646	Active	9.0	121,851
Ingalls Shipbuilding	LPD 26	John P. Murtha	U.S. Navy	Amphibious Warfare Ships	Assault Ship	19,200	6-Feb-12	30-Oct-14	13-May-16	997	561	1,558	Active	14.0	268,800
Ingalls Shipbuilding	WMSL 753	Hamilton	U.S. Coast Guard	Small Surface Combatant	Cutter	4,200	6-Sep-12	10-Aug-13	25-Nov-14	338	472	810	Active	8.0	33,600
Ingalls Shipbuilding	WMSL 754	James	U.S. Coast Guard	Small Surface Combatant	Cutter	4,200	17-May-13	3-May-14	5-Jun-15	351	398	749	Active	8.0	33,600
Ingalls Shipbuilding	LPD 27	Portland	U.S. Navy	Amphibious Warfare Ships	Assault Ship	19,200	20-May-13	15-Feb-16	18-Sep-17	1,001	581	1,582	Active	14.0	268,800
Bath Iron Works	DDG 1001	Michael Monsoor	U.S. Navy	Large Surface Combatant	Zumwalt	13,539	23-May-13	21-Jun-16	24-Apr-18	1,125	672	1,797	Active	9.0	121,851
Ingalls Shipbuilding	DDG 113	John Finn	U.S. Navy	Large Surface Combatant	Destroyer	7,028	18-Nov-13	28-Mar-15	7-Dec-16	495	620	1,115	Active	9.0	63,252
Ingalls Shipbuilding	LHA 7	Tripoli	U.S. Navy	Amphibious Warfare Ships	Assault Ship	45,000	5-Mar-14	1-May-17	28-Feb-20	1,153	1,033	2,186	Active	14.0	630,000
Ingalls Shipbuilding	DDG 114	Ralph Johnson	U.S. Navy	Large Surface Combatant	Destroyer	7,028	12-Sep-14	2-Apr-16	15-Nov-17	568	592	1,160	Active	9.0	63,252
Bath Iron Works	DDG 115	Rafael Peralta	U.S. Navy	Large Surface Combatant	Destroyer	7,028	30-Oct-14	1-Nov-15	3-Feb-17	367	460	827	Active	9.0	63,252
Ingalls Shipbuilding	WMSL 755	Munro	U.S. Coast Guard	Small Surface Combatant	Cutter	4,200	5-Nov-14	14-Sep-15	18-Dec-16	313	461	774	Active	8.0	33,600
Ingalls Shipbuilding	DDG 117	Paul Ignatius	U.S. Navy	Large Surface Combatant	Destroyer	7,028	20-Oct-15	12-Nov-16	22-Feb-19	389	832	1,221	Active	9.0	63,252
Bath Iron Works	DDG 116	Thomas Hudner	U.S. Navy	Large Surface Combatant	Destroyer	7,028	16-Nov-15	23-Apr-17	15-Jun-18	524	418	942	Active	9.0	63,252
Ingalls Shipbuilding	WMSL 756	Kimball	U.S. Coast Guard	Small Surface Combatant	Cutter	4,200	20-Jan-16	18-Dec-16	19-Sep-18	333	640	973	Delivery delayed by Govt. shutdown, active	8.0	33,600
Ingalls Shipbuilding	WMSL 757	Midgett	U.S. Coast Guard	Small Surface Combatant	Cutter	4,200	30-Jan-17	22-Nov-17	1-May-19	296	525	821	Active	8.0	33,600

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APPENDIX C. HISTORICAL SHIPBUILDING DATA

Tables 8 and 9 illustrate the historical production data of Arleigh Burke–class destroyers (DDG-51). As of late, even-numbered hulls are constructed at Bath Iron Works, located in Bath, Maine, and odd-numbered hulls are constructed at Ingalls Shipbuilding, located in Pascagoula, Mississippi. Historically, that has not always been the case. The data collected contained the hull number, ship name, ship status, keel laying date, and delivery date to the Navy. Days between keel date represents the number of whole working days between keel dates. This represents the arrival time. Days under construction represents the number of days between the keel laying date and delivery date to the Navy. This represents the service time. Finally, "light displacement," measured in long tons, is defined as being "complete and ready for service in every respect, including permanent ballast (solid and liquid), and liquids in machinery at operating levels but is without officers, crew, their effects, ammunition, or any items of consumable or variable load" (NAVSEA, 2020). Light displacement was chosen, as it best represents the weight of the ship prior to delivery to the Navy.

Table 8. Bath Iron Works DDG-51 Historical Production. Source: NAVSEA (2020).

Class	Hull	Name	Status	Keel Date	Delivery Date	Days Between Keel Date (Arrival Time)	Days Under Construction (Service Time)	Light Displacement (tons)
DDG 51	51	ARLEIGH BURKE	Active	12/6/1988	4/29/1991		874	6691
DDG 51	53	JOHN PAUL JONES	Active	8/8/1990	8/20/1993	437	1108	6782
DDG 51	54	CURTIS WILBUR	Active	3/12/1991	12/10/1993	155	1004	6740
DDG 51	56	JOHN S MCCAIN	Active	9/3/1991	5/27/1994	126	997	6732
DDG 51	58	LABOON	Active	3/23/1992	12/2/1994	145	984	6742
DDG 51	60	PAUL HAMILTON	Active	8/24/1992	3/10/1995	111	928	6740
DDG 51	62	FITZGERALD	Active	2/9/1993	7/28/1995	122	899	6800
DDG 51	64	CARNEY	Active	8/3/1993	12/8/1995	126	857	6759
DDG 51	66	GONZALEZ	Active	2/3/1994	6/14/1996	133	862	6759
DDG 51	68	THE SULLIVANS	Active	7/27/1994	11/22/1996	125	849	6778
DDG 51	70	HOPPER	Active	2/23/1995	4/11/1997	152	778	6750
DDG 51	72	MAHAN	Active	8/17/1995	8/22/1997	126	736	6805
DDG 51	73	DECATUR	Active	1/11/1996	3/13/1998	106	792	6752
DDG 51	75	DONAL COOK	Active	7/9/1996	8/21/1998	129	773	6765
DDG 51	76	HIGGINS	Active	11/4/1996	1/14/1999	85	801	6664
DDG 51	77	O'KANE	Active	5/8/1997	5/19/1999	134	741	6648
DDG 51	79	OSCAR AUSTIN	Active	10/9/1997	5/11/2000	111	945	7101
DDG 51	81	WINSTON S CHURCHILL	Active	5/7/1998	10/13/2000	151	890	7134
DDG 51	83	HOWARD	Active	12/9/1998	6/22/2001	155	926	7134
DDG 51	85	MCCAMPBELL	Active	7/15/1999	3/8/2002	157	967	7134
DDG 51	87	MASON	Active	1/20/2000	11/22/2002	136	1037	7134
DDG 51	90	CHAFEE	Active	4/12/2001	8/6/2003	321	846	7134
DDG 51	92	MOMSEN	Active	11/16/2001	5/6/2004	157	902	7134
DDG 51	94	NITZE	Active	9/17/2002	12/3/2004	218	808	7134
DDG 51	96	BAINBRIDGE	Active	5/7/2003	6/10/2005	167	765	7134
DDG 51	99	FARRAGUT	Active	1/7/2004	1/6/2006	176	730	7134
DDG 51	101	GRIDLEY	Active	7/30/2004	9/15/2006	148	777	7134
DDG 51	102	SAMPSON	Active	3/14/2005	5/25/2007	162	802	7134
DDG 51	104	STERETT	Active	11/17/2005	2/29/2008	179	834	7134
DDG 51	106	STOCKDALE	Active	8/10/2006	9/30/2008	191	782	7134
DDG 51	108	WAYNE E MEYER	Active	5/17/2007	7/10/2009	201	785	7134
DDG 51	109	JASON DUNHAM	Active	4/11/2008	6/4/2010	237	784	7134
DDG 51	111	SPRUANCE	Active	5/14/2009	4/15/2011	285	701	7134
DDG 51	112	MICHAEL MURPHY	Active	6/12/2010	5/4/2012	282	692	7134
DDG 51	115	RAFAEL PERALTA	Active	10/22/2014	2/3/2017	1138	835	7028
DDG 51	116	THOMAS HUDNER	Active	11/6/2015	6/15/2018	273	952	7028
DDG 51	118	DANIEL INOUYE	Under Construction	3/20/2018		618		
DDG 51	120	CARL M LEVIN	Under Construction	2/1/2019		229		
DDG 51	122	JOHN BASILONE	Under Construction	1/10/2020		246		
DDG 51	124	HARVEY C BARNUM JR	Under Construction					
DDG 51	126	LOUIS H WILSON	Authorized for Construction					
DDG 51	127	PATRICK GALLAGHER	Under Construction					

Table 9. Ingalls Shipbuilding DDG-51 Historical Production. Source: NAVSEA (2020).

Class	Hull	Name	Status	Keel Date	Delivery Date	Days Between Keel Date (Arrival Time)	Days Under Construction (Service Time)	Light Displacement (tons)
DDG 51	52	BARRY	Active	2/26/1990	10/19/1992		966	6830
DDG 51	55	STOUT	Active	8/8/1991	5/16/1994	379	1012	6810
DDG 51	57	MITSCHER	Active	2/12/1992	10/3/1994	135	964	6837
DDG 51	59	RUSSELL	Active	7/24/1992	3/20/1995	118	969	6912
DDG 51	61	RAMAGE	Active	1/4/1993	5/8/1995	117	854	6817
DDG 51	63	STETHEM	Active	5/11/1993	7/24/1995	92	804	6870
DDG 51	65	BENFOLD	Active	9/27/1993	12/4/1995	100	798	6884
DDG 51	67	COLE	Active	2/28/1994	3/11/1996	111	742	6767
DDG 51	69	MILIUS	Active	8/8/1994	8/19/1996	116	742	6855
DDG 51	71	ROSS	Active	4/10/1995	4/21/1997	176	742	6827
DDG 51	74	MCFAUL	Active	1/26/1996	2/23/1998	210	759	6783
DDG 51	78	PORTER	Active	12/2/1996	1/11/1999	222	770	6824
DDG 51	80	ROOSEVELT	Active	12/15/1997	6/12/2000	271	910	7134
DDG 51	82	LASSEN	Active	8/24/1998	2/5/2001	181	896	7134
DDG 51	84	BULKELEY	Active	5/10/1999	8/20/2001	186	833	7134
DDG 51	86	SHOUP	Active	12/13/1999	2/19/2002	156	799	7134
DDG 51	88	PREBLE	Active	6/22/2000	8/12/2002	139	781	7134
DDG 51	89	MUSTIN	Active	1/15/2001	2/28/2003	148	774	7134
DDG 51	91	PINCKNEY	Active	7/16/2001	10/27/2003	131	833	7134
DDG 51	93	CHUNG-HOON	Active	1/14/2002	3/22/2004	131	798	7134
DDG 51	95	JAMES E WILLIAMS	Active	7/15/2002	8/23/2004	131	770	7134
DDG 51	97	HALSEY	Active	2/5/2003	1/31/2005	148	726	7134
DDG 51	98	FORREST SHERMAN	Active	8/12/2003	8/8/2005	135	727	7134
DDG 51	100	KIDD	Active	3/1/2004	12/18/2006	145	1022	7134
DDG 51	103	TRUXTUN	Active	4/11/2005	10/24/2008	291	1292	7134
DDG 51	105	DEWEY	Active	10/4/2006	8/17/2009	388	1048	7134
DDG 51	107	GRAVELY	Active	11/26/2007	7/26/2010	299	973	7134
DDG 51	110	WILLLIAM P LAWRENCE	Active	9/16/2008	2/23/2011	212	890	7134
DDG 51	113	JOHN FINN	Active	11/18/2013	12/7/2016	1350	1115	7028
DDG 51	114	RALPH JOHNSON	Active	9/12/2014	11/15/2017	215	1160	7028
DDG 51	117	PAUL IGNATIUS	Active	9/11/2015	2/22/2019	261	1260	7028
DDG 51	119	DELBERT D BLACK	Under Construction	5/23/2016		182		
DDG 51	121	FRANK E PETERSEN JR	Under Construction	2/21/2017		197		
DDG 51	123	LENAH H SUTCLIFFE HIGBEE	Under Construction	11/14/2017		191		
DDG 51	125	JACK H LUCAS	Under Construction	11/7/2019		518		
DDG 51	128	TED STEVENS	Authorized for Construction					
DDG 51	129	JEREMIAH DENTON	Authorized for Construction					
DDG 51	131	GEORGE M NEAL	Authorized for Construction					
DDG 51	133	SAM NUMM	Authorized for Construction					

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