Fall 12-2022

# Learning Curve Characterization Within Complex Low-Rate Production Environments

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## Recommended Citation

Gies, Robert J.. "Learning Curve Characterization Within Complex Low-Rate Production Environments" (2022). Doctor of Philosophy (PhD), Dissertation, Engineering Management & Systems Engineering, Old Dominion University, DOI: 10.25777/f6zj-rf78
https://digitalcommons.odu.edu/emse_etds/190

# LEARNING CURVE CHARACTERIZATION WITHIN COMPLEX LOW-RATE PRODUCTION ENVIRONMENTS

by

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A Dissertation Submitted to the Faculty of
Old Dominion University in Partial Fulfillment of the
Requirements for the Degree of

DOCTOR OF PHILOSOPHY

ENGINEERING

OLD DOMINION UNIVERSITY

December 2022

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# ABSTRACT

## LEARNING CURVE CHARACTERIZATION WITHIN COMPLEX LOW-RATE PRODUCTION ENVIRONMENTS

Robert J. Gies
Old Dominion University, 2022
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Traditional and current learning curve approaches, methods, and theories were deficient when addressing complex low-rate production systems. The purpose of this research was to address this problem and develop a learning curve approach that characterizes learning in low-rate production environments such as naval ship construction. This research identified the principal aspects that influence learning within this environment and developed a learning characterization more reflective of this environment.

There obviously exists a large body of knowledge covering learning. However, the research contained herein addresses learning as it relates to learning curves in low-rate production environments, such as naval shipbuilding. The various theories impacting learning curves has been explored in detailed as part of this research. Through the completed literature review, the researcher has confirmed that there is gap in the body of knowledge associated with learning curves specifically addressing the low-rate production of naval ships. The results of this research have addressed this gap in knowledge accordingly.

The research completed has a significant impact not only on the body of knowledge involving learning curves, but also on the expectations associated with the design, production, test, and delivery of complex naval ships. In addition, the results of

the research were also a concise assessment of learning curve theories, their applicability, and the fact that, until now, there has not been published research addressing learning curves associated with the low-rate production environments.

The results of the completed research also identified the principal factors associated with learning curves in low-rate production environments.  These principal aspects formed the basis of the development of a characterization of learning in low-rate production environments, which the researcher has developed the terminology of overall learning curve characterization (OLCC) defined by stability (S), procurement strategy (P), industrial and organizational culture (I), knowledge management (K), and demographic environment (E), which the researcher has also referred to this characterization as SPIKE.  The results developed by this research was also generalizable to other low-rate production complex systems such as one-of-a-kind systems like the space program, oil well platforms, and other low production rate industries.

This dissertation is dedicated to my wife, Louisa, my son, Austin, my Parents, Edward and Beatrice Gies, my Family, my PhD Advisor and Mentor, Dr. Resit Unal, and to every teacher and professor that I have learned from through Concordia Lutheran School, McDonogh School, and Old Dominion University.

# ACKNOWLEDGMENTS

There are many people who have contributed to the successful completion of this dissertation. I would like to express my sincerest thanks for their help, guidance, and support.

First, I would like to thank my wife, Louisa, and my son, Austin, for their love, support, and help. I am truly blessed to have such a wonderful and loving family. Thank you very much for your support as I progressed through this journey. Thank you for being such a wonderful and loving wife and son.

Second, I would like to thank my PhD Advising Committee of Dr. Resit Unal, Dr. Holly Handley, Dr. Chuck Keating, and Dr. Linda Vahala. They have provided guidance throughout and I value their perspectives. I would like to thank them for their support. As a direct result of this PhD Program, my views and approach to engineering, complex problems, and systems has grown exponentially and broaden. This transformation is as a result of the terrific professors that I was fortunate enough to learn from while completing this program, and they were: Dr. T. Steven Cotter, Dr. Holly Handley, Dr. Chuck Keating, Dr. Andres Sousa-Poza, and Dr. Resit Unal. I would also like to thank each of them for their time and support as well as the numerous concepts that I learned from each of them, which I utilized extensively herein to complete my dissertation. I have been and still are using the concepts that I learned from them daily at my job.

I would like to acknowledge and thank Dr. Megan Boeshart for helping to edit my dissertation. I sincerely appreciate her help.

Lastly, I would like to offer my deepest appreciation to my PhD Advisor and Mentor, Dr. Resit Unal. I earned my Master’s degree in Engineering Management from

Old Dominion in 1994, and Dr. Unal was one of my professors. Over the years, I have stayed in contact with Dr. Unal, and had communicated to him that when my son went off to college, that I was then also going to go back to school too focusing on this Program. My son started his first semester at Georgia Tech in the Fall of 2018, and I started my first semester too in this Program in the Fall of 2018 with Dr. Unal, fortunately, as my Advisor. I truly value Dr. Unal's guidance and support, and I have completely enjoyed working with him and learning from him. Dr. Unal truly has been a wonderful advisor and friend, and I would like to express to him my sincerest thanks.

I look forward to the future to pursue various research areas and to have the opportunity to continue to contribute to the body of knowledge.

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# PREFACE

The researcher developed a logical approach to this dissertation, which was rooted in systems engineering and scholarly research principals as well as a purposeful and deliberate research methodology.  The researcher wanted to ensure that the organization of the dissertation was provided to assist with the understanding of this research.

Chapter 1 provided the purpose, details of the complex problem, and the theoretical foundations associated with this research.  Chapter 2 provided the literature review through the initial pieces of literature detailing the body of knowledge through and including the current year (2022).  Chapter 3 covered the research methodology broken into fifteen work breakdown structured (WBS) research areas, and Chapter 3 covered the research approach for each of those respective areas.  Chapter 4 provided the results associated with executing the research methodology, which was outlined via Chapter 3, through and including WBS 8.  Specifically, Chapter 4 provided the results associated with executing WBS 1 through WBS 6 which framed and bounded the complex system and problem, and obtained and analyzed public domain data covering four different ship classes.  Chapter 4 also provided the results associated with executing WBS 7 and WBS 8 which applied five different learning curve theories to the four ship classes, where applicable, to determine if they forecasted actual ship class data.

Chapter 5 contained the remaining WBS areas, which were WBS 9 through 15 because these WBS's were focused on deductions based on this research.  As such, independent of the results of WBS 7 and WBS 8, the researcher, using only Class A Ship data, determined the key factors and associated conclusions involving learning curves in low-rate production environments, but just as indicated, only using Class A Ships. This was the objective of WBS 9.

Utilizing the results of WBS 9, which was the development of a set of conclusions utilizing Class A Ship data only, a low-rate learning curve characterization was developed and presented via WBS 10. In order to validate the learning curve characterization deduced via WBS 10, WBS 11 utilized the conclusions deduced from Class B Ships to validate the conclusions deduced in regards to Class A Ships via WBS 9. Conversely, WBS 12 utilized the conclusions deduced from Class C and Class D Ships to validate through triangulation the conclusions deduced in regards to Class A Ships via WBS 9 as well as the OLCC deduced via WBS 10.

WBS 13 then utilized the results of WBS 7 and WBS 8 to assess the five leading learning curve theories prediction of learning in low-rate production environments versus the overall learning curve characterization (OLCC) that was developed by the researcher via WBS 10. As indicated, WBS 10 utilized Class A Ship conclusions that were deduced from WBS 9 to develop the OLCC which was validated by WBS 11 and WBS 12.

As a result of WBS 13, WBS 14 provided the OLCC for low-rate production environments that was developed using Class A Ship data, validated by Class B Ship data, and triangulated by Class C and D data, which was a more comprehensive characterization as compared to the five leading learning curve theories. Due to system darkness and emergence, WBS 15 iterated back through the research methodology to identify any other areas of research that needed to occur to support this research.

# CHAPTER 1

# INTRODUCTION

## Purpose

The main purpose of this research was to develop an approach and theory to characterize learning in low-rate production environments such as naval ship construction. Currently, the Navy applies a learning curve to each succeeding ship to be built. There are many references that discuss learning and learning curves in production environments, but none that specifically cover this issue in low-rate production environments. As Cooper and Koenig (2020) state, "extrapolation from actuals is the most reliable method. If a system is already being produced, then it becomes increasingly easy to predict the cost of the very next unit of production." Harper (2020) quoted O'Rourke, who stated, "Ships of the same general type and complexity that are built under similar production conditions tend to have similar costs per weight and consequently unit procurement costs that are more or less proportional to their displacements." Lessig (2019) states that the contract [for aircraft carriers] "stipulates an 18% labor cost reduction from ship to ship." NAVSEA 05C Cost Estimating Handbook (2005) states that historical data is to be used in learning curve characterizations by using Wright's (1936) and Crawford's (1944) learning curve theory. As such, these four references, which were just representative samples of a much larger population of literature in the public domain, utilize Wright's (1936) and Crawford's (1944) learning curve theories, which characterize learning in, without specifically specifying, high-rate repetitive production environments. Low-rate production naval shipbuilding cannot be characterized accordingly. Fox, Brancato, and Alkire (2008) state that "out of sample forecasting using early lots to predict later lots has shown that, even under optimal conditions, labor improvement curve analyses have error rates of about +/- 25 percent."

As such, this was the foundation for this research, which was the development of a learning curve characterization that was more indicative and reflective of low-rate production manufacturing utilizing domestic Naval shipbuilding as the complex system to complete this research. There are numerous factors that influence the possibility of attaining the contracted learning curve, and in many cases, the shipbuilder was actually working to overcome reverse learning, which was counteracting the learning curve (Moore (2015) and Lee (2014)). The results of this research also included the identification of the major areas that impact the learning curve associated with building Naval ships.

Ship over ship performance during the design, construction, testing, and delivery of a ship or a block of ships were influenced by various factors, which was researched herein. World events as well as emerging threats and/or perceived future threats has and will challenge and change requirements and needs associated with each ship. Ships were designed to last at least twenty-five years and some ships were designed to last over fifty years, and for low-rate production ships, it takes over four years to build a ship and, for some, can even take more than ten years to build. In addition to a long duration to actually build each ship, low-rate production ships were also characterized by producing only one ship per year to only one ship every seven years or even longer. Due to these factors, the domestic naval low-rate production shipbuilding business is a complex system operating in a complex environment. The principal factors affecting ship over ship learning and thereby ship over ship labor hour performance was also researched as a part of this effort.

In summary, the purpose of this research was to assess learning within low-rate production environments, such as naval shipbuilding. The results associated with this research was based on shipbuilding data and information contained within the public domain.

## Problem

The concept of learning curves was first espoused and documented by Wright (1936). Wright (1936) analyzed the manufacturing of aircraft at the Curtiss-Wright Corporation where Wright was employed. He observed that the average cost of producing airplanes decreased as the number of aircraft produced was increased. Wright then derived a formula to predict the phenomena that he observed, which when plotted logarithmically follows a linear line. This approach has been carried forward in many different documents including the *Inflation and Escalation Best Practices for Costs Analysis: Analyst Handbook* (2017) which states that "experience shows that for every doubling of cumulative production quantity, touch labor hours tends to decrease by a fixed percent." This follows Wright's (1936) observations and associated learning curve characterization that he developed. Katz (2019), through the Congressional Budget Office (CBO), also follows this method by stating that "a standard cost estimate would also adjust the cost of those later ships [new sealift vessels] downward to reflect the effects of rate and learning as more ships of the class were built…".

Johnstone (2017), Moore (2015), Lee (2014), Camm (1987), Asher (1956), and others support the use of Wright's formula for estimating labor hours and cost estimates, but they do not differentiate the application based on high or low-rate production manufacturing. However, for complex products/systems, such as navy ships constructed in small numbers, the common application of Wright's formula can be misleading, which is the point of this research. It has been observed that labor hour estimates of consecutive large ships can be over or understated in terms of the effect of learning. For instance, Capaccio (2020) stated that a given shipbuilder is "falling short of a Navy goal to reduce cumulative labour hours by at least 18% from the first ship." Capaccio (2020), continues to state that the "workforce performed at 91 cents of work for every Navy dollar spent in the last year." This assessment by Capaccio (2020), written in Bloomberg News, was an assessment of one specific domestic shipbuilder, but, as the researcher has shown, this is indicative of the challenges associated with all domestic navy shipbuilders producing ships in a low-rate production environment.

As previously indicated, this was a complex problem within the context of a complex environment, and as such, there were many factors to consider. As written by US Senator Perdue from Georgia (2020) in order for the US "to keep up with our competitors" and those that countries that are major threats to the US, "America must boost shipbuilding." Senator Perdue continues by stating that in order for the Navy to reach a 355 ship Navy, which was mandated by the "2018 National Defense Authorization Act, the US would have to spend $31 billion per year for 30 years." This estimate was obviously based on having reliable cost estimates. However, cost estimates based on traditional learning curves may also be misleading, resulting in large differences in labor hour estimates at contract signing and at delivery. As Barber (2011) states, "ultimately, the only way to know the "true" learning curve for a particular system is to observe it after the fact." Barber (2011) continues by stating that this was not useful since cost estimates were due years in advance of production. Such differences are usually interpreted as cost overruns whereas the problem lies in the inappropriate use of a learning curve. As the researcher has shown through a worldview perspective of this research, the misrepresentation of the characterization of learning curves for low volume complex systems presents many issues and problems, and has not been characterized, until now. As a matter a fact, the NASA Cost Estimating Handbook (2015) states that “how a learning curve applies to the space sector is questionable where fewer items rather than multiple items in a mass-production environment are fabricated.”

It was clear and was discussed herein that Wright’s (1936) learning curve theory is deficient when addressing complex low-rate production systems. The purpose of this research was to address this problem and develop a learning curve theory that better characterizes learning in low-rate production environments such as naval ship construction. The research contained has identified the principal aspects that influence learning within this environment including the development of a learning characterization more appropriate for this environment.

## Theoretical Foundations

This research was focused on learning curves, and specifically, their use to forecast learning within a complex system’s environment defined as low-rate production. There obviously exists a large body of knowledge covering learning and learning techniques. The research did not attempt to address these different learning areas; however, the research contained herein did address learning as it relates to learning curves. Sections throughout this research included theories associated with learning as well as theories that addressed learning curves. The various theories impacting learning curves were primarily addressed via the included Literature Review and the researcher’s assessment of the Literature Review. For this research, the principal theory that was analyzed is Wright’s (1936) work as it relates to learning because Wright is renowned as the “Father of learning curves” as per numerous authors and researchers such as Johnstone (2017), Moore (2015), Lee (2014), Waterworth (2000), Camm

(1987), and Asher (1956), among others. The research addressed the five principal learning curve theories as well. As indicated, this research was based on developing a theory that will address learning in a different context then the context that Wright's (1936) work was utilized as well as the other principal learning curve theories, which were addressed herein too.

Chapter 1 not only includes and discusses theories and methodologies that have influenced this research area, but also those that were currently influencing this research area. Learning curve theories were characterized primarily in the 1930's and 1940's. Since then, subsequent authors have been utilizing those theories as the basis of their research thereby perpetuating those theories forward independent of the context of their utilization, which was discussed in more detail via Chapter 2.

# CHAPTER 2

# LITERATURE REVIEW

## Literature Review Approach

Following a systems approach, a high-level strategy and approach has been developed in regards to the literature review. A strategy was developed in order to not only adjudicate inclusion versus exclusion for each reference, but to be able to triage each reference so that each can be dispositioned and recalled easily and when needed. In order to properly handle each piece of literature, criteria were developed to address each reference. Learning was comprised of several tenants; however, this dissertation focused on learning curves. It is important to note that the other tenants are potential post-doctoral research areas that are directly affiliated with this dissertation, and many have the opportunity for cross discipline or cross college/university collaborations, which is discussed via the Future Research Section. Sousa-Poza, Landaeta, Bedoya, Bozkurt, & Correa (2004) was utilized to help structure some aspects of the literature search contained herein since their article assessed research methods from 368 articles written for three leading engineering journals.

In regard to learning curves, each piece of literature harvested was triaged into several areas so that a complete and comprehensive literature review was completed accordingly. The first four categories associated with the literature review tool that was developed by the researcher was the normal pedigree associated with a bibliography of author, title of the article, book, etc., name of the publication, and year it was published. The researcher was focused on identifying the most recent articles possible; however, learning curve theory was first published in 1936, and it has evolved, in the researcher's opinion, for the past eighty years. As such, it was important to research and identify articles and the prevailing thought in regard to this topic over the years. The next category of the literature search is entitled “Contribution to the Body of Knowledge.” Each piece of literature, for this category, was placed into one of three possible areas of:

- Wright’s Foundational Literature
- Wright’s Era until the 1990’s
- 1990’s to Present (2022).

For this category, each piece of literature can only reside in one area. The foundational literature area defines articles, books, papers, and references that establishes the baseline and foundation for learning curves, and it provides the fundamental theory that, in many cases, was still used today, and were referenced in more recent articles. This was primarily characterized by the work accomplished by T.P. Wright. The Wright’s era until the 1990s category has been grouped in this fashion because the variations in learning curve theory were extensions off of Wright’s work. However, the literature review revealed that most of the research and theories developed in the mid-1990s until 2022 was still rooted in research that was published in 1936 by Wright. The last category was the specific application that the learning curve theory was focused on during this time frame. In some cases, all three of these categories were defined by research completed that was specifically targeted to a given population or area.

The next category associated with the literature review tool created by the researcher addressed the approach associated with each piece of literature. Meaning, was the approach taken within the literature being reviewed a theoretical study, an application-based study, a methodology focused study, or any combination of these.

- Theory, which was defined as a postulate, maxim, or principle.
- Methodology, which was defined as research and efforts describing a process and/or a method to either analyze a specific topic or area of study.
- Application/Practice, which was defined as research and efforts that analyze data and/or assess a real-world application.

Specific work breakdown structure (WBS), which was the next category associated with the tool, specifies the area that the piece of literature was primarily utilizing to articulate the arguments that were in the piece of literature being reviewed. There were seven choices for this, which were:

- Military
- Aircraft
- Commercial ships
- Naval ships
- Manufacturing
- High volume
- Service

This was a very straightforward assessment to pick the area most represented or discussed within the literature being reviewed.

The next column was Primary Themes. Simply put, this was the principal theme associated with each piece of literature. This was a free text field so that the document being reviewed could be summarized accordingly, but in a concise manner.

The next two columns addressed reliability associated with the piece of literature. Reliability grades were assessed via three different ratings. Grade A means that there was strong evidence articulated within the document thereby eliminating all grounds for doubt. Grade B refers to literature that there was no reason to doubt or no reason to accept beyond acceptance. Lastly, Grade C was for literature where there was some particular reason to doubt the literature. The next category addressed the Source of Reliability. Only one was chosen for each piece of literature to address the reliability of the source, and they were:

- Expert testimony,
- Observation,
- Memory,
- Non-expert testimony, or
- Intuition.

The next area that was assessed is the "Type of Literature", defined as:

- Scientific and mathematical,
- Particular fact,
- Observation,
- Intuitive, and
- Supported general (as in the literature was just supported in generalities).

Lastly, the literature review was based on the researcher providing an overarching assessment of the piece of literature to also include agreement, disagreement or agreement for some portions and disagreement for other portions for the piece of literature that was reviewed. The details of the literature review were encapsulated in the next sections.

## Literature Review

### Assessment of Wright's Foundational Work

As has been delineated throughout, Wright is considered to be the "Father" of learning curves. He first published on this topic in 1936 through the *Journal of Aeronautical Sciences* in a paper entitled: "Factors Affecting the Cost of Airplanes." He also presented this paper at the Aircraft Operations Session of the Fourth Annual Meeting of the International Aeronautical Society. At that time, Wright was working for Curtiss-Wright Corporation as the Vice President of Engineering. He was focused on understanding the effect of production quantity on cost (Wright, 1936). His effort was also motivated by the fact that the Bureau of Air Commerce (the precursor to the Federal Aviation Administration (FAA) and National Aeronautics and Space Administration (NASA)) wanted to develop a two-seat airplane that could be marketed for $700 assuming a quantity of ten thousand planes would be built and procured (Wright, 1936). Ironically, Wright, utilizing his own estimating process, estimated that the lowest price of the airplane to be $2,100 after one million were produced.

Wright actually began analyzing cost variation as a function of quantity in 1922, which was a year after he joined Curtiss-Wright as an engineer. Wright started to collect data during the production and construction process of planes that Curtiss-Wright was building from 1922 to the early 1930's. The empirical data that he collected showed variation in costs with differing quantities (Wright, 1936). At first, he focused on labor only to estimate cost, but he adjusted as he collected more data. Later, he focused on the ratio of labor to raw material as a function of quantity. The culmination of these efforts in this area was published by Wright in 1936. The researcher for the efforts contained herein has reviewed and analyzed numerous articles, papers, etc., but has not found a reference that analyzes Wright's own published works. Many authors reference Wright's work, and Waterworth (2000) steps through Wright's analysis through utilizing data that Waterworth (2000) obtained on twenty identical sections of an aircraft fuselage. As such, the researcher has re-created the data from the graphs that Wright provided in his 1936 paper entitled "Factors Affecting the Cost of Airplanes," and then the researcher repeated Wright's process thereby providing additional insights into Wright's theory, which was the recognized foundation for learning curve theory. This effort provided additional insights into Wright's work as delineated below.

As such, Figure 1 was created using data from Wright (1936), and it only contains the labor curve as a function of quantity. Wright (1936) when describing the figure in his paper, states that this curve shows "the variation of the ratio of labor to raw material as quantity varies." It is important to note that Wright was collecting data from Curtiss-Wright's assembly line for aircraft. As such, this fact coupled with Wright's previous statement suggests that Wright's empirical curve was a plot to indicate the percentage of labor required as compared to a fixed amount of raw material to build an aircraft at Curtiss-Wright in the mid to late 1920s, and that as the quantity of aircraft that were built increases, then the ratio of labor required to raw material reduces.

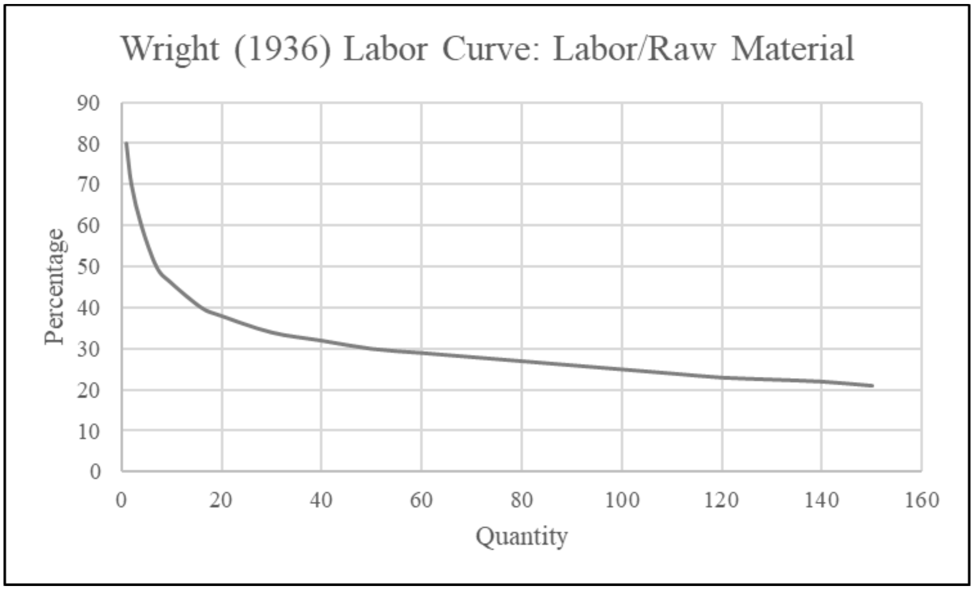

Figure 1: Labor Curve: Ratio of Labor Required to Raw Material – Data Extrapolated from Wright (1936)

Wright (1936) also developed a plot of the cost of each machine as a percent of the total cost as the quantities varied. This is illustrated via Figure 2. Wright (1936) also concluded that this was an approximation due to different "accounting methods". Wright also conveys that there are other factors that could affect the shape of this curve, which was focused on airplane construction, since they also govern cost, such as:

- type of construction,
- design, which could also affect the shape of the curve,
- number of jigs and fixtures that can be used,
- welding, in Wright's (1936) opinion, would only reduce costs down to a certain point.

Wright (1936) also discusses the cost of raw materials and differing materials used during construction. Wright's work was not just focused on learning or learning curves, but rather, he was, as the title of his paper implied, focused on various factors affecting the cost of airplanes.

As a matter a fact, Wright did not address his empirical observations of reduction in cost as quantity increased as related or due to learning or following some sort of a learning curve, but rather, he just made the observation, based on data that he collected, that this phenomenon was occurring.

As of 2022, it should also be noted that Wright was making his observations over ninety years ago and published his 1936 paper eighty-six years ago. At this time, welding was seen as an expensive and slow process, and Wright (1936) states that riveting and other forms of mechanical joining was more efficient than welding. The point is that Wright (1936) explains the reduction in cost to build airplanes as quantity increases due to making the design simpler, reducing parts, tooling changes, and making changes to the manufacturing process as more and more planes are made, but as indicated previously, Wright (1936) does not associate the reduction in the cost to build airplanes as quantities increases as being related to or associated to learning.

Wright (1936) stated that he assumed no design changes during construction. He did recognize that change would occur, but he also stated that as technology matured, the ability to accommodate change should be more cost effective. However, his conclusions and the information contained within Figures 1 and 2 were based on not making any changes to the airplane and/or production line. Wright (1936) also espoused that the larger an airplane was then the cheaper it would be to build. He did not offer any empirical information or rationale for this statement.

Wright (1936) also stated that for assembly operations, there was a labor proficiency improvement as the quantity increases, but he states that this was due to less design changes as the quantity increases, the ability to re-use fixtures, and he also states that as the quantity increases, then more tooling and standard procedures could be utilized thereby allowing the use of less skilled labor. In regard to the curve that shows a reduction in labor cost as production quantity increases, which was illustrated in Figure 2, Wright (1936) represented this curve by the formula of:

$$F = N^X \qquad \text{(Equation 1)}$$

Where F was a factor of cost variation proportional to the quantity of N. When the curve was plotted on log-log paper, the curve becomes a straight line, which is shown in Figure 3. As such,

$$X = \text{Log } F / \text{Log } N \qquad \text{(Equation 2)}$$

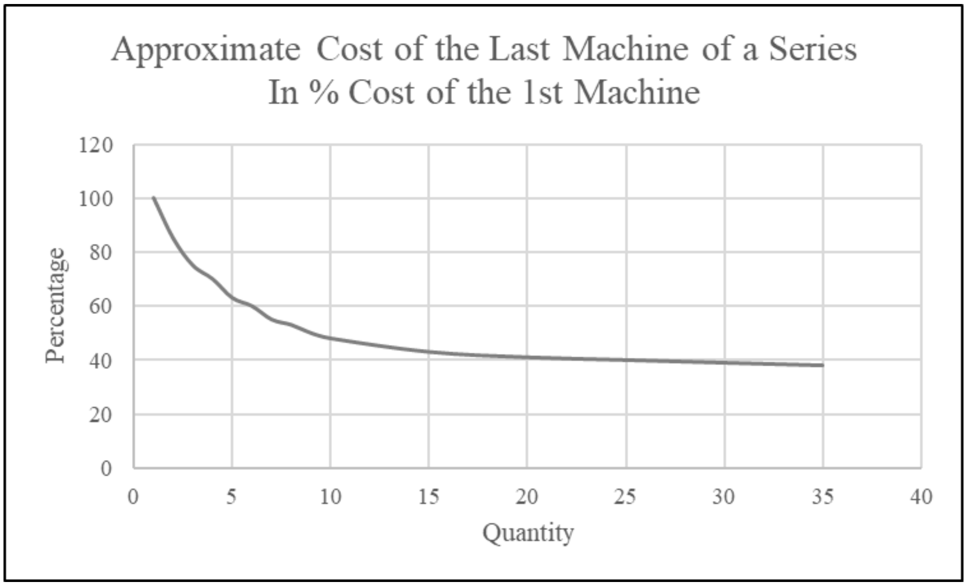

Figure 2: Approximate Cost of the Last Machine of a Series in Percent Cost of the First Machine – Data Extrapolated from Wright (1936)

When Wright (1936) plotted Figure 2 on log-log paper, he obtained the plot shown in Figure 3 for an eighty percent learning curve. Based on the empirical data that Wright collected which showed that every time the quantity doubled, there was a linear reduction in labor to build airplanes.

Figure 3: Eighty Percent Labor Curve – Data Extrapolated from Wright (1936)

As such, an eighty percent learning curve meant that every time the number of units that were built doubled in quantities, then the labor to build those units went down by twenty percent or, in other words, it would take eighty percent of the labor to build accordingly. Table 1 expands this concept using standard labor curves from Wright (1936). Of course, Wright developed these curves based on empirical data from building airplanes.

| **Quantity** | **95% Labor Curve: Time to Complete Work** | **88% Labor Curve: Time to Complete Work** | **80% Labor Curve: Time to Complete Work** |
|---|---|---|---|
| 1 | 100.00 | 100.00 | 100.00 |
| 2 | 95.00 | 88.00 | 80.00 |
| 4 | 90.25 | 77.44 | 64.00 |
| 8 | 85.74 | 68.15 | 51.20 |
| 16 | 81.45 | 59.97 | 40.96 |
| 32 | 77.38 | 52.77 | 32.77 |
| 64 | 73.51 | 46.44 | 26.21 |
| 128 | 69.83 | 40.87 | 20.97 |
| 256 | 66.34 | 35.96 | 16.78 |
| 512 | 63.02 | 31.65 | 13.42 |
| 1024 | 59.87 | 27.85 | 10.74 |

Table 1: Labor Curve Percentages – Extrapolated from Wright (1936)

Wright (1936) did espouse that new orders for the same airplane will have a different starting point in terms of cost as compared to producing the same airplane that were part of a consecutive order.  He states that consideration should be given to:

- the time between the orders,
- the changes to the airplane design between the orders,
- changes in tooling and tool set-ups, and
- labor turnover between orders.

Wright (1936) briefly covers the fact that producing government planes were between “fifteen and thirty-five percent more expensive than commercial planes” due to:

- added complexity of the planes,
- meeting government specifications, and
- delays due to inspections and approvals.

He does not provide empirical evidence to his estimation of the increase in expense of government over commercial aircraft.

Wright also puts forth the concept of utilizing weight as a cost estimating relationship for the total price of airplanes. Since Wright's article in 1936 was written about factors impacting the cost of producing airplanes in the late 1920's and early 1930's, Wright also proceeds with a discussion involving other factors that impact costs. He states that as material quantity increases then the cost of material decreases. Wright states that as more material is purchased, then there is less waste. The researcher surmises that this was more of a function of how material was handled back then and the ability to loft material to minimize waste as well as the fact that manufacturing technology back in the 1920s and 1930s required different tooling and handling then what was required today. Wright does state that economic ordering quantity would affect price, which was still valid today for most commodities. Wright continues to discuss purchased material and he even applies labor curves to purchased material. Wright also has a short discussion on overhead. He states that the more people that a company has, then the less overhead that the company will have, which does not follow at least for modern companies today. This discussion on material and overhead, as previous indicated, was outside the bounds of this research, but the researcher was just mentioning herein for completeness.

Wright (1936) does state that "some conclusions from a study of this comparison are of interest, even though the values are extremely approximate in nature." This sentence was at the end of his article as a summary for the article that he wrote. This was a very important statement because the researcher would suggest that this was very relevant especially given the fact that many authors and researchers have utilized the labor curves produced by Wright at face value and without the consideration of his conclusions as being approximations.

In summary, as already indicated, the foundation upon which most of the learning curve research was based upon was written by Wright in 1936 through an article published in the *Journal of Aeronautical Sciences.* Wright's focus was on airplanes and their serial production thereby developing associated learning curves. His efforts established the foundation associated with learning curves, and his efforts were referenced by numerous articles. Wright collected data on the manufacturing of airplanes that were already completed (and in the researcher's opinion should be characterized as a high-rate production environment), and when he plotted the data on log-log paper, he observed a straight-line comparison. He acknowledges that time between orders and turnover could affect production, but he ignores those factors to support the mathematical assessment that he derives. He also states that military planes will more than likely be more expensive due to government specifications and inspections, which the researcher agrees with. Wright does suggest that a production line that has been leaned out would probably result in a situation where the rate of learning would be reduced; however, he does not reflect this as part of his theory. Wright states throughout his research that his theory was related to assembly operations, and that it can be used for other systems, which the researcher disagrees with since Wright's work was focused specifically on airplane assembly in a controlled environment. It is acknowledged that Wright did lay the foundation for learning curves. Wright's personal and professional background as well as the context of the environment and time frame that he worked provided for him a foundation to analyze the production of aircraft. His empirical assessments supported his efforts to analyze historical assembly production data for a high-rate production environment of manufacturing airplanes on an assembly line. Wright (1936) stated that less skilled labor could be used "as more and more tooling and standardization of procedures are introduced". His world view in 1936 for airplane production may have been accurate, but was not valid today at least for low-rate production. Wright also stated that purchased material should have the exact same learning curve. The researcher disagrees with that statement as well. Purchased material will have its own specific learning curve for a given product line, and could be potential future research. Lastly, Wright stated that “material is more important than labor as quantity increases.” Both labor and material are needed to support production and manufacturing, but was probably valid during Wright’s time. The researcher does want to make one additional assessment, which was that Wright did not reference anyone in his article that he wrote despite the fact that Thurstone (1917) had actually written a paper for his dissertation twenty-four years earlier, which Wright (1936, 1943) may not have had access too given the time frame for both Thurstone (1917) and Wright’s (1936, 1943) work.

It should also be noted that all references to Wright work (1936, 1943), such as Johnstone (2017), Moore (2015), Lee (2014), Camm (1987), Asher (1956), and others, refer to Equation 1 from Wright (1936) as:

$$y = ax^b \qquad \text{(Equation 3)}$$

where

$y$ = prediction of direct labor cost or hours to produce the xth unit

$a$ = initial unit cost or number of direct labor hours required to produce the first unit. Sometimes this is referred to as “K”.

$x$ = cumulative units of production

$b$ = fixed value, for Wright, based on empirical data, equaled -.322 or an 80% learning curve slope graphed on a logarithmic scale. This is referred to as the learning or slope parameter, and is typically between zero and minus one. Yelle (1979) also referred to this as “n” which is the learning index where n = log Φ /log 2, where Φ is the learning rate and 1 – Φ is the progress ratio.

Table 2 below was an example applying Wright’s theory, which was based on a 90% learning curve. As such, every time that the units’ double, then the reduction in hours to manufacture that given product is reduced by 10% consistent with a 90% learning curve. Meaning, according to Wright, the second unit should be able to be manufactured utilizing only 90% of the labor hours that were used to manufacture the first unit. Subsequently, manufacturing the fourth unit should only take 81% of the hours, and so on.

| **Cumulative Number of Units Manufactured** | **Direct Labor Hours Required to Manufacture One Unit with a Learning Curve of 90%** |
|---|---|
| 1 | 1.0 |
| 2 | 0.9 |
| 4 | 0.81 |
| 8 | 0.73 |
| 16 | 0.66 |
| 32 | 0.59 |
| 64 | 0.53 |
| 128 | 0.48 |
| 256 | 0.43 |
| 512 | 0.39 |
| 1024 | 0.35 |

Table 2: 90% Learning Curve Example

In Wright's formulation of his theory in 1936, he referred to this as the "cumulative average curve theory", and as such, "y" is an average direct labor cost per aircraft. Wright (1936) also stated that the purchase of raw material costs had a 95% slope, based on the empirical data that he collected, and that purchased material costs had an 88% slope also based on the empirical data that he collected. These are outside the bounds of this research, but the researcher provided for completeness.

As has been indicated, Wright was acknowledged as the "Father" of learning curves. His 1936 journal article that was published in the *Journal of the Aeronautical Sciences*, as has already been discussed, was adopted across all industries. His 1943 report to the Aircraft Production Board furthered his recognition in regard to learning curves.

However, the researcher wanted to gain additional understanding into Wright as well as his research. As such, the researcher obtained from the Harry S. Truman Library in Independence Missouri the remaining copies of Wright's research and work. During World War II, President Franklin D. Roosevelt, per the New York Times (1970) appointed Wright in 1943 as the Director of the Aircraft Resources Control Office to "spur the country's aircraft production. President Franklin D. Roosevelt called on him to produce 50,000 planes a year. He doubled that goal." When President Truman came into office, Wright continued to serve his country through the Aircraft Resources Control Office until 1948. As such, the researcher obtained all the reports that were still in existence that Wright authored to gain insights into his methodology and world views at that time. Specifically, the researcher read eighteen reports that were authored by Wright or approved and signed by Wright, and they were: Wright (June 1943), Wright (July 1943), Wright (August 1943), Wright (September 1943), Wright (October 1943), Wright (November 1943), Wright (December 1943), Wright (1943), Wright, Lombard, Williams (1943), Wright, Lombard, Williams (1943), Wright (January 1944), Wright (February 1944), Wright (February 1944 Revision), Wright (March 1944), Wright (April 1944), Wright (May 1944), Wright (June 1944), and Wright (1944). It should be noted that since these documents captured the aircraft production efforts during WWII, these documents were classified until December 1973 when they were subsequently declassified and stored at the Truman Presidential Library. These documents were obtained and read by the researcher to try to gain additional insights into Wright's Theory. The researchers' conclusions were addressed via Chapter 5. In summary, Wright's theory was based on empirical data that as the quantity of units' double, then the number of hours it takes to produce the unit decreases at a uniform rate.

## Assessment of Wright's Era until the 1990's

It should be pointed out that different authors refer to learning curves by other names such as progress curves or improvement curves or experience curves. For the purposes of this research, all of these curves are reflective of learning curves. For consistency, the term learning curves was utilized throughout.

Through the literature review completed by the researcher, Ebbinghaus (1885) was the first to publish a theory in regard to learning as Pappas (2014) states the "idea of (a) 'forgetting curve' is credited to Hermann Ebbinghaus." Ebbinghaus (1885) who theorized "that the human brain will forget information it has learned if that information is not out into practice." After Ebbinghaus published his book entitled *Memory – A Contribution to Experimental Psychology*, the first attempt to discuss learning curves was actually put forth by Thurstone (1917) via his dissertation with the University of Chicago. He focused on the experience learning curve, which he claims only recognizes "unconscious learning" defined as "learning accomplished unconsciously through experience, either through imitation, or more formally through reaction to reward and punishment" (Thurstone, 1917). The experience curve learning model "ignores conscious learning which relates to formal education and conscious problem solving" (Thurstone, 1917). This was a good foundational start; however, as the research has shown, there are several additional factors affecting learning curves. Researching the various tenants associated with conscious and unconscious learning are several research projects, and are outside the bounds of this research. Thurstone (1917) does assert that learning curves "are usually very erratic," and that because of this fact, it is necessary to study the "general trend of observations vice individual observations." Thurstone (1917) states that learning curve analyses is not applicable when "learning is as a result of trial and error and generalizations."

Thurstone's (1917) dissertation asserted the fact that it was common knowledge that doing the exact same thing over and over again would yield a reduction in time to complete that task, but he was actually attempting to assess how much more efficiency was actually attainable. His actual research question was:

"Our present problem concerns the relationship between practice and attainment in learning. When an observer notes as an element in common experience that attainment increases as practice increases, he may generalize by verbally asserting a positive relation between the two variables. The verbal generalization is so common that it is embodied in what we call common sense. This we expect without further verification that twenty hours of practice in a complex function will yield higher attainment than ten hours of practice under roughly similar conditions, but uncontrolled observation does not tell us how much higher."

Thurstone (1917) stated that as practice increases, the amount of time to complete something decreases, but that eventually, learning will level off and eventually plateau. He continues by saying that this could then lead to predicting the limit of where practicing levels off. Thurstone (1917) does not offer any references to support these specific claims that he makes within his dissertation, but he does complete an assessment of his assertions via a typewriter test. From a typing test that Thurstone administered to eighty-three students, based on empirical data, he developed four different learning curves, which were the (1) speed-amount curve, (2) time-amount curve, (3) time-time curve, and (4) speed-time curve.

The speed-amount curve is speed of completion, shown on the y-axis versus, and the amount of practice, shown on the x-axis., and it was expressed as

$$Y = L(X+P)/((X+P)+R) \qquad \text{(Equation 4)}$$

where:

$Y$ = “attainment” or the number of times something was successfully completed per a given unit of time.

$X$ = the total number of times that were practiced or something was done.

$P$ = practice

$L$ = the maximum number of units attained as a result of practicing or doing something.

$R$ = rate of learning.

The time-amount curve, per Thurstone (1917), is time per unit amount of work against the total amount of work since the start of the work. The time-amount curves were expressed as:

$$t = X+R/(L*(X+P)) \qquad \text{(Equation 5)}$$

where:

$t$ = time per unit amount of work

$X$ = total amount of work

$P$, $L$, $R$ are the same as was delineated for the speed-amount curve.

The time-time curve (Thurstone, 1917) was the learning curve shown as a plot between time per unit amount of work and the total time, and was expressed as:

$$T = K-t * L*P/(L*t-I)*L + K-P/L \log(K-P/L*t-I) + C_2 \qquad \text{(Equation 6)}$$

where:

$C$ = constant

$K$ = additive constant

The speed-time curve (Thurstone, 1917) was speed in terms of number of successful acts per unit of time versus the total amount of time developed to practice, and was expressed by:

$$T = P-K/Y-L \ + \ K-P/L \log Y - K-P/L \log (L-Y)+C_2 \qquad \text{(Equation 7)}$$

where:

$T$ = total amount of time devoted to practice

These equations are only valid, according to Thurstone (1917), when the learning curve takes on a hyperbolic shape. Thurstone (1917) did not substantiate these assertions other than the typing test that he administered to eighty-three students. Thurstone (1917) did suggest an assessment of learning curve analysis using log-log graphs, but he dismissed the idea in favor of focusing on characterizing learning following a hyperbolic shape.

Crawford (1944), while working for Lockheed Aircraft Corporation, analyzed two hundred units that were in their airframe manufacturing process. Crawford (1944) utilized Wright's (1936) work in regards to formally describing the relationship between the direct hours required to produce each unit (y) and the cumulative units produced (x) shown by the equation:

$$y = ax^b \qquad \text{(Equation 8)}$$

However, Wright (1936) espoused that the learning curve slopes were applicable to all types of aircraft and that the variability of the learning curve slopes was a function of the tooling, skill sets, and equipment that were being used at each factory. However, Crawford (1944), based on his empirical observations, believed that the different learning curve slopes in fact applied to different types of aircraft. Wright's (1936) methodology was called the cumulative average curve whereas Crawford's (1944) was referred to as the unit curve. Obviously, plotting a curve based on cumulative average would reflect a different curve as compared to an individual unit curve. Crawford (1944) also developed a set of tables showing values of x from one to nine-hundred and ninety-nine and for slope values ranging from fifty-one percent to ninety-nine percent for Equation 8. Crawford (1944) was the first researcher to discuss the labor learning factor as it relates to man-hour costs as compared to cumulative effort. He stated that labor learning was not a function of how fast or the speed upon which a person worked but rather the improvement in how a worker approached his or her job “to eliminate lost motion with no additional effort and oftentimes with less effort” (Crawford (1944)). Crawford (1944) also espoused those jobs which require “less mental effort” has an improvement ratio that diminishes as compared to those jobs that require more mental effort. He goes on to say that “jobs requiring the most mental effort improve at the most rapid rate. This was valid whether the mental effort was due to the complexity of the job or to the lack of experience of the workman.” As such, Crawford (1944) espoused that experienced workers require little mental effort to learn a new technique.

Berghell (1944) extends upon Wright (1936) and Crawford’s (1944) work addressing the cumulative average curve, the unit curve and the cumulative total curve. However, he expands on Wright’s (1936) basic equation and develops the formula of:

$$y = a(1+b)(x+B)^b \qquad \text{(Equation 9)}$$

where:

B is based on empirical data to estimate the asymptote of the plotted empirical data as it approaches the given learning curve slope.

Berghell (1944) also tries to address learning curves on aircraft that have not been built yet. He suggests that the direct manhours to build different types of aircraft should be divided by the respective weights to obtain a metric of hours per pound to build a certain type of aircraft.

This assessment could then be used to estimate the hours to build a new type of aircraft by multiplying the weight per pound times the predicted weight of the new aircraft.

Middleton (1945), using WWII aircraft production data suggested that a better way to assess production versus learning was to assess total pounds of airframes that are produced versus the number of airframes produced. The same types of assessments that Wright (1936) and Crawford (1944) espoused could then be applied using Middleton's (1945) methodology but just using total weight vice total hours.

Searle in the 1945 *Monthly Labor Review* wrote an article "Productivity Changes in Selected Wartime Shipbuilding Programs." Searle's (1945) article was based on empirical data analyzing the construction of Liberty ships and Victory ships being produced during WWII across multiple shipyards. His assessment of the data showed that there was a ten to twenty percent in reduction in labor hours to produce these ships every time the production doubled, which followed Wright's (1936) assessments. It is important to note that the data collected by Searle (1945) does show a flattening of the learning curve associated with the construction of these vessels, and in some cases, reverse learning occurring in 1944, which Searle attributes to the beginning of contracts being terminated. Searle (1945) observed that the largest variation occurred between the individual yards constructing the ships vice differences in these types of vessels. The researcher contends that this was not a representative sample associated with modern low-rate production naval shipbuilding. These types of vessels built during WWII had very little to no variation between ships of each class. In addition, consistent with a world war environment, the level of inspections and certifications were, understandably, very minimal to non-existent. The ships built during WWII were more consistent with a high-rate production environment, at least in the researcher's opinion. Searle (1945) stated that: "The great improvements in man-hour and time requirements that have occurred [during WWII] should be viewed primarily as contributions to the successful development and completion of a war program."

Carr (1946) builds upon his predecessors, but he states that the cumulative average curve was better represented by an s-type curve. He states that the shape of the "s" is based on the "rate of acceleration" of the production line, meaning how quickly does the production start, and he also states that the shape of the "s" was based on the amount of tooling that was provided to support production. He also suggested that the build strategy would also affect the shape of the s-curve. Carr (1946) assessed production of aircraft, and in the researcher's opinion, high-rate production environments, to also conclude that "there is a definite limit below which operations cannot be performed at reduced man-hours," which was governed by the "speed of machinery and not the individual worker's skill."

Guibert (1945) is the first to try to address the rate of production being a variable impacting unit labor cost. He too espouses that the progress or learning curve will flatten out after a large number of units are produced, and this depends on the rate of production which was driven by production tooling. He, through empirical assessment of aircraft production, developed the following equation, which determines the number of units produced as:

$$A = aCK \qquad \text{(Equation 10)}$$

where:

A = number of units produced at peak production

a = monthly production

C = time from initial start of production to the completion of production

K = is a parameter close to 1 and depends on rate of production and on flow time. Guibert assumed it would be equal to one, but states that more research would be required.

Alchian (1950) utilized Wright's (1936) theory plus the cost estimating relationship of labor per pound of airframe to support cost estimates for the US Air Force. He also utilized WWII data of various airplane manufacturers to support his estimates. Alchian (1950) also observed, from WWII data, that the error of prediction was about twenty-five percent, meaning if specific curves for a given airframe are fitted to the past performance of a particular manufacturing facility in order to predict future requirements, the margin of prediction error was about twenty-five percent (predicted hours versus actual hours). Most airframe manufacturers had assumed an eighty percent learning curve, and this did not take into consideration the margin of error. This was a significant finding, especially given the fact that the data that Alchian (1950) was utilizing was based on over 1000 air frames.

In 1956, Asher, who was working for the RAND Corporation, also wrote about learning curves. He confirms the use of Wright's (1936) work, but he states, contrary to Wright, that the "progress curve is not an accurate description of the relationship between unit cost and cumulative cost." Asher (1956) states that it is more convex based on the empirical data that he observed. Wright (1936) had observed that the relationship was linear in nature when plotted on log-log graph paper. Asher's work (1956) exclusively focused on the airframe industry. Asher (1956) does conclude by saying that "it is a matter of judgement". He does cover that there are factors that account for cost decreases associated with learning such as job familiarization, tooling, shop organization, and parts supply. Asher (1956) starts to suggest alternatives to Wright's work, and that plotting a progress curve on logarithmic paper "is not an accurate description of the relationship between unit cost and cumulative output," which the researcher agrees with. However, Asher's (1956) comment in regard to analyzing the data was a matter of judgement and was too subjective. Asher (1956) does suggest that a linear curve may be acceptable if a large percentage of error is acceptable. Asher (1956) does use the term progress curve interchangeably with the term learning curve.

Asher (1956) briefly mentions the possibility of learning curves being applied to other product lines, but he was focused on products that were produced in a high-rate production environment. Asher (1956) does reference the work of Andress (1954) who, according to Asher (1956), stated that learning curves could be applied to "(1) electronics, (2) home appliances, (3) residential home construction, (4) shipbuilding, and (5) machine shop". Asher (1956) makes reference to a study done by Crawford (1944) and Strauss (1947), who suggested that the following circumstances can impact production and its associated learning curve as: length of production, engineering's involvement in production, design changes, if all tools and tooling were available or not, availability of materials, availability of parts, schedule changes, and plant lay-out.

Farrell (1957), through the *Journal of the Royal Statistical Society*, did not explicitly focus on learning, but he did focus on the measurement of productive efficiency. Farrell (1957) stated that most research into workers productivity was focused on the "average productivity of labour, and to use this as a measure of efficiency." He continues by stating that this was "unsatisfactory" as it "ignores all inputs" to labor. As such, his research was to identify all inputs to labor. He utilizes the agricultural production in the United States as his data source because of the amount of data available in the public domain, per Farrell (1957). In regard to how Farrell (1957) contributed to the research herein, he distinguishes between “price efficiency” versus “technical efficiency.” Farrell (1957) stated that price efficiency was related to the hours required to produce a given product while technical efficiency was related to the number of workers employed to produce the given product. As indicated, he focused on developing factors that affect productivity associated within the agricultural industry within the US. As such, he identifies factors such as “climate, location, and fertility [of the soil]” and not just the actual productivity associated with each farmer as the principal measure of farming output. Farrell’s (1957) journal article was made a part of this literature review because Farrell identifies other environmental factors affecting the productivity of the worker, and in this case farmers, beyond just the number of bushels of corn that they harvested per day as a measure of efficiency. As such, the research methodology for this research assessed shipbuilding in low-rate reduction environments beyond just labor hours to design, build, test, and deliver ships, but the research methodology included efforts to identify other factors affecting ship construction and shipyards.

Hirschmann (1964) argues that learning curves should be applied to other industries because learning was a natural characteristic. The researcher agrees with this statement and conclusion; however, the learning curve must be applicable to the environment that it was addressing. The researcher does not agree with Hirschmann (1964) when he states that progress was based on faith and believing that progress was actually made. Progress and learning were objective measurable actions and efforts, and they cannot be on faith and hope that they will get better as Hirschmann (1964) states.

Abernathy and Wayne (1974) utilize Wright's theory to assess Model T and Model A Fords. They show that Model T Ford's follows Wright's theory; however, due to increasing complexity, Model A Fords did not follow Wright's theory towards the end of their production life. Abernathy and Wayne (1974) analyze different technology changes, percentage of market share, and number of salaried employees to assess impacts to cost associated with the Model A Ford. They also analyze, briefly, airframe manufacturing, computers, and televisions. However, all of these assessments were within the context of high-volume high-rate production, which was not applicable to low-rate production shipbuilding.

Berend (1977), for the US Air Force, extended upon Wright (1936) and Crawford's (1944) work by developing what he called the "unified linear progress curve." It simply merges together the "cumulative average curve and the unit curve" by plotting the unit cost values at the mid-point between each unit, meaning between the previous unit and the current unit. Berend (1977) still utilized the same fundamental equation that Wright (1936) and Crawford (1944) used, but he added to it the mid-point assessment for each unit. This allowed the slope of both of these curves to be the same, and per Berend (1977), he stated that the "cumulative average curve" and the "unit curve" could now be replaced by the "unified linear progress curve."

Yelle (1976) discusses utilizing learning curves to predict future costs of completed products if there was sufficient historical data to determine the learning curve for that given product. Yelle (1976) proceeds to discuss a process to address new products that do not have any historical costing data. He suggests that similar products that do have cost data should be utilized to develop a predictive learning curve model. He also states that new products are usually manufactured on product lines that are "aggregates of existing technology". Yelle (1976) was alluding to the fact that these new products were being made on production lines that contain current technology to perform the manufacturing steps. As such, he concludes from this that using the associated costs and learning curve for these individual manufacturing steps would then provide insights into the learning curve for the new product line. Yelle provides an example of this such as producing semi-conductors.

Yelle (1979) provides a summary of different models that have been developed since Wright's model for learning curves, and they were: the Stanford-B model, the DeJong model, and the S-model, which were addressed herein. As Yelle (1979) states, these other models were developed because Wright's model did not provide the best fit for all situations. However, according to Yelle (1979), Wright's theory is still the most widely used model, which was also confirmed by Bradu and Mundlak (1970).

Like Asher (1956), Camm (1987) confirms Wright's (1936) theory; however, Camm (1987) analyzes different mathematical models, statistics, and calculus to try to find a better way to predict learning. Camm (1987) views the learning curve as really an improvement curve. Camm (1987) also states that Wright's work can also be applied to "production planning, product mix, and economic ordering quantity models," but the actual total cost is needed. Camm (1987) expresses Wright's equation also from a total cost (TC) perspective of:

$$\mathrm{TC(b,K)} = \mathrm{A} \sum_{x=1}^{K} X^{\mathrm{b}} \qquad \text{(Equation 11)}$$

where:

b = learning or slope parameter. Camm (1987) defines this parameter as a positive number between zero and one. Wright (1936) defined this as a negative number between zero and one. As such, to be consistent, the author is using Wright's (1936) sign convention.

K = number of units being produced

A = cost of the first unit

Kopcso and Nemitz (1983), which were also referenced by Camm (1987), estimates the cost of the first K units of production by integrating the unit learning curve from zero to K. The equation that Kopcso and Nemitz (1983) derived was:

$$A1 = \int_0^K Ax^{-b}dx = \frac{AK\,{}^\wedge 1-b}{1-b} \qquad \text{(Equation 12)}$$

Camm (1987) states that a learning curve that has a steep slope defined by Equation 12 does not reflect the actual cost very well because the integral does not address the area under the curve very accurately according to Camm (1987). The researcher agrees that approaching learning curves in a different manner as compared to Wright (1936) is logical, but having the actual total cost to support a learning curve assessment was contrary to trying to forecast the impact of learning on production. Having the actual total cost upfront would then allow an assessment to be done that would enable "backing into" (researcher's quotes) the solution and determining the learning curve after the product line was completed.

Smunt (1986), who shared some similar views of learning with Camm (1987) in regard to other factors affecting learning, took a different approach and espoused an alternative to a learning curve analysis "that considers aggregation of cost data across time." For Smunt (1986), "a moving average analysis" would provide better estimates of cost, including the effects of learning, on “short-term component operations.” This was obviously aimed at high-rate production manufacturing, but Smunt’s (1986) research was part of the progression to address learning curve methodologies.

## Assessment of 1990s to Present

Continuing with the literature review, this section was focused on research that has been done in the last thirty-two years. This body of knowledge, during this time frame, was primarily characterized by learning curves with applicability to a specific area or applicability to production and manufacturing in general.

Cavin (1991) through the international journal entitled, *Defence Economics* (now named *Defence and Peace Economics*), covers the development of a system to assist a program manager in the management of the costs associated with a new weapons system. The model recognizes the effects of learning, through the use of Wright’s and Crawford’s research. Cavin focuses on the development, construction, and procurement of torpedoes, which represent, in the researcher’s opinion, high-rate production manufacturing. Erichsen (1994) researches learning in regard to shipbuilding, and specifically he espouses Wright’s theories through data he collected from Norwegian shipyards during the 1970s, which in the researcher’s opinion, were produced in a high-rate production environment. Erichsen (1994) does state that “a workforce that has a good relationship with management has a greater degree of learning than one that has another kind of relationship,” which the researcher agrees with Erichsen (1994) in regard to this specific statement. Spicknall (1995), via the Society of Naval Architects and Marine Engineers, writing for the Naval Surface Warfare Center Carderock Division, covered learning curves in small and large North American commercial shipbuilding companies. Spicknall (1995) stated that future performance does not depend on past production volume and performance. Following his logic, however, he also continues by saying that organizations that only make incremental improvements based on past performance and experience through competency and units produced in series will not be able to compete with organizations focused on “market driven performance targets, conscious learning, and problem solving to drive innovation” (Spicknall, 1995). He continues by covering that the market will dictate learning and performance improvements, and that price, delivery time, and quality was actually dictated by each company. In a commercial shipbuilding environment, this may be logical; however, in a low-rate production naval shipbuilding environment, other factors are involved, which this research addressed in Chapter 5. Moses (1990) utilizes data from the development of missile weapons systems to analyze learning primarily using Wright and Crawford’s theories. Moses (1990) espouses that “new programs do apparently experience considerably greater cost improvement with increased quantity when compared to follow-on programs.” Moses (1992) continues his research and concludes, from a cost perspective, that “any element [of the cost model] that is not subject to learning then the traditional learning curve model is consistently biased toward underestimation of future cost.” Moses (1996) focuses on learning curves associated with the manufacturing of items. He refers to these items from the perspective of a “repetitive process.” He states that the use of most learning curves was based on focusing on the cumulative quantity produced; however, he also espouses those other variables should be considered similar to Spicknall’s (1995) research.

Waterworth (2000) also covered airplane production leaning curves, but he emphasized that Wright’s learning curves can be useful, and they were based on empirical data. Waterworth (2000) states that most references adopt Wright’s methodology for all fields; however, in his opinion, he states that there will be different learning occurring in different fields. Waterworth (2000) continues by also emphasizing that other factors can affect outcomes associated with learning and learning curves, such as skill level, prototyping, and management buy-in to learning. The researcher does agree with Waterworth (2000) in regard to different learning in different parts of a plant, and that learning curves will eventually level off, but Waterworth (2000) was focused on airplane manufacturing. The author agrees with Waterworth (2000) that Wright's (1936) data is empirically based.

Goldberg (2003) focused on learning curves as a function of high-volume lot productions for tactical missiles and the F-15E Program. Goldberg (2003) is writing from the perspective of the Center for Naval Analysis - Cost Analysis and Research Division. He discussed the uses of various models and cost estimating relationships (CER). He also discussed several statistical techniques to address learning curves and learning curve models all focused on large lots where individual units of each lot are not separately priced. His work did add value to the body of knowledge associated with learning curves; however, naval shipbuilding is focused on individual ship costs even though a set of ships may be contracted together in a lot, block, or flight. Goldberg (2003) was "not considering the source of the unit cost reduction, if it was confined to production workers performing repetitive tasks, or extends to some other economic or technological factors."

Coleman et al (2007) discuss loss of learning due to "stretched-out ship-class acquisitions" due to less demand for ships, and "increasing time between starts" due to "less-steady demand." Coleman et al (2007) based their analysis on a learning curve theory that assumed that "learning is constant and incremental and proceeds from one ship to the next." They state that this "means that as other effects occur, the learning curve factor is still in play."

They continue by stating that the learning curve for ships never stops. Coleman et al (2007) state that the "literature of learning" conveys "that learning continues through all units." Coleman et al (2007) does not consider any other factors affecting learning other than increasing the time between construction starts as well as the impacts as result of instability associated with the demand for ships.

While working for Strategos Corporation, Lee (2014) wrote about learning and learning curves associated with manufacturing and marketing. He stated that math was not necessary to understand learning within a manufacturing environment, which in a shipbuilding environment is not the case. He did espouse that shipbuilding should experience a 15-20% learning curve; however, he did not offer how that was calculated or determined. He also stated that learning was not "pre-ordained" meaning there was nothing requiring learning to even occur. He does espouse using Wright's work within his research. Lee (2014) discussed that learning can get worse if the production of a given product was neglected. Lee (2014), like Spicknall (1995), states that market share was the principal driver for learning and experience curves. Lee's (2014) work was focused on manufacturing large numbers of units, and their associated learning curves which were influenced by management involvement, culture, technology, capital, and engineering. Lee (2014) makes a differentiation between experience curves versus learning curves. Experience curves, in his opinion, were used to "develop marketing and manufacturing strategies, and they relate to entire factors rather than individuals" whereas learning curves were more tactical to evaluate a work group (Lee, 2014). As already alluded, the researcher does not agree with Lee (2014) in regard to not needing math to understand learning curves. His article did not provide any additional insights on this, but he may be alluding to the fact that there was an element of understanding the system to determine the factors affecting learning and that not everything can be derived mathematically. This is supposition on the researcher's part. The lack of data or information in regard to the espoused learning curve data for shipbuilding was a concern for the researcher. The researcher does agree that there is nothing mandating that learning has to occur.

Sokri (2017) at the 3rd International Conference in Technology, Management, and Social Sciences espoused that learning curves in defense projects will eventually remain constant over time and reach steady state called saturation, and they will not approach zero. His paper was focused on using a statistical analysis to estimate the distribution of the steady state value. Sokri (2017) felt that learning was a type of risk defined as a measure of the potential variation in achieving efficiency in production. He does cover negative learning or "forgetting" due to breaks in production or changes in personnel and methods. He states that empirical evidence has shown that learning was a central cost factor in defense projects. He suggests that a method that combines "statistical analysis and stochastic simulation" may be a way to estimate the distribution of the steady state portion of learning. Sokri (2017) states that saturation cannot occur in military shipbuilding due to the low volume of units being built unlike the aircraft business. The researcher disagrees with Sokri's (2017) comments in regard to shipbuilding, which was addressed in Chapter 5.

Sato (2012) through the *Tokyo Annals of Business Administrative Science* states that many organizations focused learning on "things already known," and that they would not pursue new knowledge through "exploration." He uses the term "exploitation" to emphasize his point that "most organizations give precedence to exploitation (use of things already known) over exploration (pursuit of new knowledge)" when it comes to learning. Sato (2012) does not offer any reasons or background for this statement in regard to exploitation over exploration. The researcher does agree that new knowledge should always be pursued when it comes to learning; however, in a production and manufacturing environment, especially involving naval shipbuilding, there was an aspect of learning how to do things already known as best as possible as well as ensuring that the learning is captured and provided to each succeeding ship.

Johnstone (2017) also recognizes Wright's work and contribution to the field. Johnstone (2017) emphasizes two main points, which were (1) production rate impacts are "real, but are not linear, including their impact on learning," and (2) "increased production rates are beneficial to the rate of learning." The researcher agrees with Johnstone (2017). He also provides a good summary of the maturity of the learning curve equation, and so does Boemke and Freels (2017). Prior to that, Johnstone (2015) states that utilizing legacy performance and engineered labor standards (cost estimating relationships) would yield a "basic learning curve slope to which early performance asymptotically recovers over time." Johnstone (2015) also states that learning curve literature offers very little guidance in regard to predicting future learning curve slopes, and that learning curve industry averages are based on empirical data collected from historical programs. However, as Dutton (1984) stated, "predicting future progress rates from past historical patterns has proved unreliable," and Fox, Brancato, and Alkire (2008) continue by stating that "out of sample forecasting using early lots to predict later lots has shown that, even under optimal conditions, labor improvement curve analyses have error rates of about +/- 25 percent." In a related approach, Knecht (1974), while utilizing the production of aircraft, developed a concept that includes technology growth and its' impact on manufacturing labor hours.

Craggs, Bloor, Tanner, and Bullen (2004) completed research on "leading UK and continental European commercial and naval shipbuilders" to "determine compensated gross tonnage (CGT) coefficients for naval vessels" such that "lower compensation coefficients imply lower work content per gross ton.". Craggs, Bloor, Tanner, and Bullen (2004) discuss organizational learning, which they define as learning that was "due to improvements in processes and practices." They also discuss ship learning, which they define as learning that was due to "improvements made on a series, for example, reduction in rework." They then proceed in stating that ship learning was "most significant over the first few ships of a series." This was consistent with most learning curve theories.

Deschamps and Greenwell (2019) wrote a recent article focused on cost drivers, which does include some of the research completed by Craggs, Bloor, Tanner, and Bullen (2004). Deschamps and Greenwell (2019) did not address learning curves, but they did discuss cost drivers for surface ship naval combatants, such as offshore patrol vessels, amphibious ships, and auxiliary ships. Deschamps and Greenwell (2019) cover the major systems associated with these ships and their relative labor and material costs both by system and Ship's Work Breakdown System (SWBS). In addition to discussing these types of "hard cost drivers," Deschamps and Greenwell (2019), also cover "soft cost drivers." According to Descamps and Greenwell (2019), soft cost drivers are just as influential on ship costs as were the costs associated with ship's equipment and costs to install systems. Deschamps and Greenwell (2019) highlight five soft cost drivers, and they were "outfitting density, quality and timeliness of engineering, production and shipyard management performance, cost risk, and change orders." Deschamps and Greenwell (2019) state that labor costs were higher if the outfitting density were higher, which means that the spaces on the ship have a lot of piping, equipment, and systems restricts workers to accessing their work. They conclude that the labor hours for a very dense naval ship can be 70% to 80% higher than a tanker. Deschamps and Greenwell (2019) did not provide any empirical data to substantiate this claim; however, they did offer an equation to calculate a density factor for commercial and naval ships of:

$$\text{Density Factor} = \sum (\text{SWBS 200-700 weight}) / \text{Ship Displacement} \quad \text{(Equation 13)}$$

where:

SWBS 200-700 was a categorization process to capture the weights of all of the systems that comprise a ship.

In terms of quality and timeliness of engineering, Deschamps and Greenwell (2019) state that if the technical information was late or was incomplete, then production will be negatively impacted thereby driving up costs. They espouse the impacts of cost in regard to where the work occurs within the value stream; however, the numbers that they provide are not substantiated, and as such, were not included herein. Using the same logic as quality and timeliness of engineering, Deschamps and Greenwell (2019) state that production and shipyard management performance can also increase costs if the production plan was poorly developed and/or implemented prior to and during construction. This also includes the efficiency by which the value stream responds to and adjudicates problems.

Eden, Williams, and Ackermann (1998) focused on disruptions or factors that affect learning and learning curves. Their research was in support of litigation that they were supporting and was focused on railroad box cars for the Channel Tunnel, which the researcher is assuming is the Chunnel. They also focused their research on the impact of changes on developmental projects or contracts. In addition, their research, as delineated in their article, was applicable to production lots greater than 100. Eden, Williams, and Ackermann (1998) stated that their approach was not relevant to production runs of ten or less. Despite their assessment, the researcher would suggest that some of their observations and assessments were potentially applicable to low-rate production environments including construction of naval ships. Eden, Williams, and Ackermann (1998) substantiate a claim that there has been very little written in regard to the "impact of disruption on the extent of learning and the changing characteristics of the learning curve." Eden, Williams, and Ackermann (1998) assert that Wright's Law assumes that all modifications to a product have been made before production begins with little to no disturbance to the manufacturing environment, which the author agrees. Eden, Williams, and Ackermann (1998) also define learning more from the perspective of a standard time for when learning reaches an asymptote, which for a learning curve would be when the rate of learning levels off. Wright's theory espouses that learning continues in a linear fashion. Eden, Williams, and Ackermann (1998) espouse that learning tapers off to the point where rate of learning eventually ceases. As such, Eden, Williams, and Ackermann (1998) address learning when it becomes an asymptote as:

$$T_n = T_s \left[1 + K\ LCI^{\log 2(n)}\right] \qquad \text{(Equation 14)}$$

where:

$T_s$ = standard time

K = constant for a particular organization and product type

LCI = learning curve index

n = number of units

$T_n$ = function (characteristics of the plant, workforce, product type and organization)

Eden, Williams, and Ackermann (1998) also discussed manufacturing the same product at different plants. They concluded that it is “problematic” to compare efficiencies between plants due to their inherent differences of tooling, machines, and management style such that they may have different LCIs. As such, comparing LCIs between plants or companies does “not necessarily give a measure of relative efficiency” (Eden, Williams, and Ackermann, 1998). Eden, Williams, and Ackermann (1998) did also assume that manufacturing was designed to produce x number of units, and that any deviation from that number would be a distraction from learning. The researcher does agree with this assessment and assumes that it would be valid for large production runs. However, for low-rate production, shipyards are not initially designed for a specific throughput due to the large amount of capital requirements required to build those types of ships. In addition to analyzing learning associated with the production of box cars, Eden, Williams, and Ackermann (1998) also discusses learning associated with developmental projects or contracts. They state that a change in learning due to a new process or procedure change could then translate into an impact on the learning curve for a given product. Eden, Williams, and Ackermann (1998) also reference Kilbridge (1962) who asserts that “the more complex the work the longer it takes a group to reach a given pace.” This was compounded by the fact that developmental projects also translate into disruptions as the new technology was integrated accordingly and can result in wasted learning.

Teplitz (2014) wrote an article for the *Journal of Applied Business and Economics* discussing the forgetting impact on learning curves. Teplitz (2014) states that reverse learning was caused by forgetting, which was caused by three “disruptive events to the learning curve which affect future production costs," and they were "manufacturing interruptions, design changes, and manufacturing changes." Manufacturing interruptions would lead to future increased costs while design and manufacturing changes would either result in an increase or decrease in future costs. Teplitz (2014) uses the term "setback" to allude to the degree of learning that was lost due to a disruption. Manufacturing and design changes could result in a cost savings, but sometimes, according to Teplitz (2014), a re-design could result in a manufacturing process with fewer opportunities for learning which would result in a flatter learning curve. Teplitz (1991) also states that the best time to evaluate the impact of disruptive events was after the event occurs to understand the impact of learning due to the forgetting effect. The researcher agrees that this would be the best time to do this; however, the current contracting process for the construction of navy ships was adjusted by a learning curve employed prior to construction start. Takahashi (2013) took a similar approach when he espoused that the learning curve projection should be based on the mid-point of the production line. This methodology also does not support a low volume rate production environment.

Lolli, Messori, Gamberini, Rimini, & Balugani (2016) attempted to develop a model which addressed both the effects of learning and forgetting. They also state that literature was lacking to address these in a production environment, and they also confirm the fact that the "most adopted learning curve is that proposed by Wright (1936)." Lolli, Messori, Gamberini, Rimini, & Balugani (2016) state that the model that they developed requires a lot of data and that they were not able to obtain enough data to actually validate their model. Boemke and Freels (2017) developed a tool that incorporates Wright's (1936) and Crawford's (1944) research to compute a learning curve. Their tool characterizes learning within the context of high-rate production manufacturing since they utilized the research associated with Wright and Crawford.

Thornton (2001) also tried to assess learning and forgetting effects by analyzing World War II shipbuilding data, and he determined that on the job training was the principal learning tool utilized.

The researcher also reviewed other industries to obtain insights, such as the Society of Petroleum Engineers, and their assessment of learning curves associated with drilling wells. Jablonowski, Ettehad, Ogunyomi, & Srour (2011) wrote an article covering this specific area. They noted that learning curves should not be applied to drilling operations that were short in duration because there would not be enough time to implement learning and lessons learned from previous drilling operations.

There are a few handbooks which address learning curves, and as such, they should also be discussed. The Defense Acquisition University (DAU) developed the Department of Defense (DOD) Manufacturing Management for Program Managers in 2018. Within this very extensive handbook, they quote that the learning curve that should be applied to shipbuilding should be between “80-85%,” which was also espoused by Miroyannia (2006). They did not offer any basis for this assessment, however. The DAU (2018) also states that the “slope of the learning curve is usually an issue in production contract negotiation,” and “the slope of the learning curve is also needed to project follow-on costs.” The DAU (2018) does acknowledge, which is a point that this researcher is also emphasizing, that a learning curve analysis must be done prior to just applying a standard learning curve. They also state that some try to “assign an arbitrary number to a learning curve for the purposes of negotiations or to make the cost match the budget.” The researcher agrees with the DAU on this specific point. The DAU (2018) espouses the use of Wright’s and Crawford’s theories by stating that “the learning curve…technique was first discussed in the journals of the 1930’s and continues as an industry standard today both in commercial and non-commercial (government) applications." The DAU (2021) through the *Defense Acquisition Guidebook* simply states that various "alternatives should [be] consider[ed] to exploit the use of new learning techniques…to promote the goals of enhancing user capabilities, maintaining skill proficiencies, and reducing individual and collective training costs." The DAU (2021) also states that "learning curves that include tested and applied continuous improvements" should be used in the contracting process. As such, the DAU (2021) views the incorporation of learning curves as part of the acquisition process. In a related handbook published by the DOD to support cost analysis for a program entitled cost assessment and program evaluation (CAPE), CAPE (2017) specifies the use of learning curves. CAPE (2017), without explicitly referencing, utilized Wright's and Crawford's theories. CAPE (2017) states that "experience shows that for every doubling of cumulative production quantity, touch labor hours tends to decrease by a fixed percentage." They also state that "learning…occurs on labor hours," and that the learning curve is a contributor to costs coupled with inflation and escalation.

The Society of Cost Estimators and Analysis issued a presentation that covers cost estimation, and Module 7, written by Cobb and Cullis (2010), covers learning curves. Cobb and Cullis (2010) acknowledge Wright and his learning curve theory as well as Crawford. They characterize the past as understanding historical data, the present as developing estimating tools and relationships, and the future as projecting costs for future units based on the learning curve developed utilizing historical data. Cobb and Cullis (2010) do acknowledge, however, that there are competing learning curve theories but they also state that a model should be chosen that "best fits the data available." Anzanello and Fogliatto (2011), via the *International Journal of Industrial Ergonomics*, provides a literature review, but brief in content, in regard to learning curves and their respective applications. Anzanello and Fogliatto (2011) also provides a brief overview of the leading learning curve theories such as Wright's as well as Stanford-B, DeJong, and S-Curve. Anzanello and Fogliatto's (2011) focus was on job scheduling within the manufacturing and in the service industries, and specifically, "learning curves may be used to model the impact of assigning a new model on workers' performance in assembling lines given the model currently under production as well as previous models already produced in the line." Anzanello and Fogliatto (2011) continue by stating that "estimates of job completion times are affected by the LC [learning curve] goodness-of-fit. Imprecise estimates lead to unreliable scheduling results, particularly when the time to complete a batch of jobs in considered."

The *NASA Cost Estimating Handbook* (2015) only briefly addresses learning curves. However, it did state that "how a learning curve applies to the space sector is questionable where fewer items rather than multiple items in a mass-production environment are fabricated." The researcher agrees with this characterization. The *NASA Cost Estimating Handbook* (2015) did not offer any substantiation to that claim other than just making that specific statement.

*NAVSEA 05C Cost Estimating Handbook* (2005) provides guidance associated with learning curves. It acknowledges both Wright's theory and Crawford's theory as methods to calculate learning curves. The *NAVSEA 05C Cost Estimating Handbook* (2005) also states that historical data should be utilized in the learning curve characterization, which is consistent with utilizing Wright's and Crawford's learning curve theories. Lastly, the *NAVSEA 05C Handbook* also provides a learning curve slope for Shipbuilding of 80% to 93% with no provided justification for that learning curve claim. Obviously, the researcher disagrees with this characterization as this is the basis for the research contained herein.

The *GAO Cost Estimating and Assessment Guide* (2009) addresses learning curves, and it recommends that the learning curve should be extrapolated from actual costs. The GAO Guide (2009) does not specifically reference Wright or Crawford, but the guide does follow the same methodology to address learning curves. The guide did mention the loss of learning if a production line was shut down for a given amount of time. The Office of the Parliamentary Budget Officer for Canada presented in 2016 the Canadian Frigate Program learning curve methodology at the International Cost Estimating and Analysis Association (ICEAA). The Office of the Parliamentary Budget Officer for Canada (2016) presented the theories that were espoused by Wright and Crawford. Just as the *GAO Guide* (2009), the Office of the Parliamentary Budget Officer for Canada did not acknowledge Wright and Crawford in their presentation.

The *Parametric Estimating Handbook* (2008) also discusses Wright's unit theory and Crawford's cumulative average theory without referencing them accordingly. The handbook addresses breaks in production and the associated impacts to loss of learning just by stating that they need to be taken into consideration. Miroyannia (2006) also covers the causes for loss of learning or reverse learning, such as "sporadic production, …major upgrades to facilities and processes" until workers become accustomed to the changes, and "significant design changes." Fioretti (2007) infers the use of Wright and Crawford's work, and he states that learning rates "may differ across different plants." He also states that worker strikes or major re-structuring within a company may interrupt learning, and he also states that he espouses Huberman's (2001) views of organizational learning. Huberman (2001) states that learning is impacted by the "interactions and interpersonal relationships between organizational units" that were captured by procedures. Fioretti (2007) states that Huberman's (2001) model of organizational learning "assumes…no constraints on the sequencing of operations." The researcher disagrees with this aspect because sequencing matters in shipbuilding. Huberman's (2001) approach was based on two principal parameters of "the probability to establish a link between two nodes" and the "probability of exploring the right ones," meaning the right nodes, and these nodes may be human, machine, or a combination of both, according to Fioretti (2007) and Huberman (2001). As Fioretti (2007) states, "the bulk of the empirical literature on organizational learning curves [was] focused on macroscopic features such as cumulative production." Ennis, Dougherty, Lamb, Greenwell, & Zimmermann (1997) tried to address learning curves in their development of a cost model called Product-Oriented Design and Construction Cost Model (PODAC). They based their model on a range of commercial and some military ships which were not produced in a low-rate production environment because, as they stated, "there was no (cost) data for Navy ships."

## Learning Curve Theory Literature Review Summary

The foundation upon which most of the learning curve research is based on was written by Wright in 1936 through articles he published in the *Journal of Aeronautical Sciences*. Wright's (1936, 1943) focus was on airplanes and their serial production thereby developing associated learning curves. His efforts established the foundation associated with learning curves. Thurstone (1917) discussed learning curve theory prior to Wright; however, Wright, has already been identified as the recognized expert in learning curve theory as well as being credited as the "Father" of learning curve theories. Crawford's theory compliments Wright's theory by developing the individual unit curve theory whereas Wright developed the cumulative average curve theory that for the doubling of a production quantity made, then there would be a linear reduction in time to produce the given product due to learning. Thurstone (1917) focused on experience gained through learning and that doing the same thing over and over again would yield a reduction in time to do that specific job or task. Crawford theorized that labor learning was not a function of speed of work completed, but how a worker approached the job from a body position standpoint and how quickly they learned that position as well as their ability to repeat that over and over again. Berghell's (1944) theory still utilizes aircraft, but his theory was based on the weight of the aircraft to estimate hours to build as part of a cost estimating relationship. Finally, as was discussed, Middleton's (1945) theory assessed learning through the pounds of aircraft produced versus the number of aircraft produced over time. Waterworth (2000) also covered airplane production leaning curves, but he emphasized that Wright's (1936) learning curves can be useful if applied correctly, and they are based on empirical data. Waterworth (2000) continues by also emphasizing that other factors can affect outcomes associated with learning and learning curves. Moore (2015), through the US Air Force, also discussed learning curves associated with airplane production, specifically for the F-15 C/D & E models. He utilized the learning curve model developed by Wright (1936) along with the DeJong learning formula, and the S-Curve model to analyze the production of the F-15. The results of his study were inconclusive, but he did determine that the percentage of the production processes that were automated does impact learning curves. Goldberg (2003) focused on learning curves as a function of high-volume lot productions for tactical missiles and the F-15E Program. Goldberg (2003) was writing from the perspective of the Center for Naval Analysis - Cost Analysis and Research Division. He discussed the uses of various models and CERs. However, he only covers large lots where individual units of each lot were not separately priced. His work did add value to the body of knowledge associated with learning curves; however, naval shipbuilding was focused on individual ship costs even though a set of ships may be contracted together in a lot, block, or flight. Lee (2014), while working for Strategos Corporation, wrote about learning and learning curves associated with manufacturing and marketing. He stated that math was not necessary to understand learning within a manufacturing environment, which in a shipbuilding environment would not be the case. He did espouse that shipbuilding should experience a 15-20% learning curve; however, he did not offer how that was calculated or determined. He also stated that learning was not “pre-ordained” meaning there was nothing requiring learning to even occur. Spicknall (1995), via the Society of Naval Architects and Martine Engineers, writing for the Naval Surface Warfare Center Carderock Division, covered learning curves in small and large North American commercial shipbuilding companies. Spicknall (1995) stated that future performance did not depend on past production volume and performance, which in the naval shipbuilding environment has not been the case. He continues by covering that the market will dictate learning and performance improvements, and that price, delivery time, and quality was actually dictated by each company. In a commercial shipbuilding environment, this would stand to reason; however, as has been discussed, the naval shipbuilding environment has other factors. Sokri (2017) espoused that learning curves in defense projects will eventually remain constant over time called saturation, and they will not approach zero. His paper was focused on using a statistical analysis to estimate the distribution of the steady state value. Sokri (2017) felt that learning was a type of risk defined as a measure of the potential variation in achieving efficiency in production. He does cover negative learning or “forgetting” due to breaks in production or changes in personnel and methods. Some of these areas also would hold valid for the naval shipbuilding environment too. In 2018, the Congressional Budget Office (CBO) provided a high-level methodology to adjust costs based on the rate of learning and the acquisition strategy from a CBO perspective. The CBO (2018) stated that the slope of the learning curve will vary by ship type based on complexity of the ship, but the slope of the learning curve will continue through each class of ship.

Wright's Theory was still very actively espoused today. As Kell (2021) states, "The first of anything is expensive. Theodore Wright studied this in the 1930s and found a mathematical relationship…. Wright's Law states that for every doubling of production, the cost drops by a certain percentage." Kell (2021) continues by stating that "Wright's Law suggests that by the eighth and final nuclear submarine made in Australia…our production will be about as half as efficient as the Americans who have already produced 19 out of a planned 66 Virginia-class nuclear submarines." Kell (2021) concludes by saying "Theodore Wright's analysis provides us with a clear way forward. Building the submarines in the US won't just save a prodigious sum of money and take precious years off of schedule." As this research has proven, Wright's Theory did not characterize low-rate production environments like low-rate production shipbuilding. Kell's (2021) comments are extrapolating Wright's Theory into areas that it was not meant to be utilized, which is proven throughout this research. Pires, Lamb, and Souza (2009) state that all shipbuilding follows a learning curve with each ship requiring less hours to build. They espouse that the "learning effect beyond the tenth ship in a series is considered negligible." Kell (2021) and Pires, Lamb, and Souza (2009), among other references, highlight the fact that Wright's Theories are still actively utilized today.

Deschamps and Greenwell (2019) did not focus on learning curves; however, their focus was on cost drivers. There focus was on outfitting density and concluded that the denser the ship, then the higher the production costs. Jablonowski, Ettehad, Ogunyomi, and Srour (2011), through the Society of Petroleum Engineers, espoused that learning curves should not be applied to drilling operations that are short in duration.

There are several handbooks that address learning curves. The researcher assessed those handbooks for applicability to this research. The DAU (2018) states that the learning curve for shipbuilding is between “80-85%”, but they do not offer justification for this range. The DAU also acknowledges that the learning curve was usually also an issue during contract negotiation. Cobb and Cullis (2010), through the Society of Cost Estimators and Analysis, recognizes Wright and Crawford, and as such, they espouse using historical data to forecast future costs based on a learning curve. The *NASA Cost Estimating Handbook* (2015), as previously indicated, states that applying learning curves to the space sector are “questionable.” The *NAVSEA 05C Cost Estimating Handbook* (2005) also acknowledges the use of Wright’s and Crawford’s theories, and it states that the learning curve slope for shipbuilding is between 80% to 93%, and similar to the DAU (2018), they do not offer a substantiation to their claim. The *GAO Cost Estimating and Assessment Guide* (2009) states that learning curves should be extrapolated from actual costs. The Office of the Parliamentary Budget Officer for Canada in 2016 stated that they use the theories espoused by Wright and Crawford. Lastly, the *Parametric Estimating Handbook* (2008) also implies the use of Wright and Crawford.

In summary, the researcher has confirmed that there is gap in the body of knowledge associated with learning curves specifically addressing the low-rate production of naval ships, which is reflected in Table 3. The results of this research address this gap accordingly. The literature review has been completed to validate the gap in knowledge.

| Year | Author, Year, & Summary Title | Learning Curve for Airplanes | Learning Curve for Typing | Learning Curves & Methodology for High Volume Production Environments | Learning Curves & Methodology for North American or European Commercial Shipbuilding | Learning Curves & Methodology for Constructing Wells, Space Systems, etc. | Learning Curves & Methodology in High Volume Defense Related Projects | Learning Curves & Methodology in WWII Shipbuilding | Learning and Learning Curves & Methodology (i.e. Mid-Life of Product Line, Rate of Learning, Labor Efficiency, etc.) | Learning Curves within Low-Rate Production Environments such as Large Complex Naval Shipbuilding |
|---|---|---|---|---|---|---|---|---|---|---|
| 1885<br>1913 | Ebbinghaus (1885, 1913) Experimental Psychology | | | | | | | | X | |
| 1917 | Thurstone (1917) Learning Curve Equation | | X | X | | | | | X | |
| 1936<br>1943<br>1944 | Wright (1936, 1943, 1944) Journal of Aeronautical Sciences | X | | X | | | X | | X | |
| 1944<br>1947 | Crawford (1944, 1947) Learning Curve Ratios | X | | X | | | | | X | |
| 1944 | Berghell (1944) Learning Curves in the Aircraft Industry | X | | | | | | | X | |
| 1945 | Middleton (1945) Wartime Productivity Changes in the Airframe Industry | X | | | | | | | | |
| 1945 | Searle (1945) Productivity Changes in Selected Wartime Shipbuilding Programs | | | | | | X | X | | |

Table 3: Learning Curve Body of Knowledge

| Year | Author, Year, & Summary Title | Learning Curve for Airplanes | Learning Curve for Typing | Learning Curves & Methodology for High Volume Production Environments | Learning Curves & Methodology for North American or European Commercial Shipbuilding | Learning Curves & Methodology for Constructing Wells, Space Systems, etc. | Learning Curves & Methodology in High Volume Defense Related Projects | Learning Curves & Methodology in WWII Shipbuilding | Learning and Learning Curves & Methodology (i.e. Mid-Life of Product Line, Rate of Learning, Labor Efficiency, etc.) | Learning Curves within Low-Rate Production Environments such as Large Complex Naval Shipbuilding |
|---|---|---|---|---|---|---|---|---|---|---|
| 1945 | Guilbert (1945) Mathematical Studies of Aircraft Production | | | X | | | | | X | |
| 1946 | Carr (1946) Peacetime Cost Estimating Requires New Learning Curves | X | | X | | | | | X | |
| 1950 | Alchian (1950) Progress Curves in Airframe Production | X | | X | | | | | | |
| 1954 | Andress (1954) The Learning Curve as a Production Tool | | | X | X | | | | | |
| 1956 | Asher (1956) Cost-Quantity Relationships in Airframe Production | X | | X | | | X | | X | |
| 1957 | Farrell (1957) Journal of the Royal Statistical Society | | | | | | | | X | |
| 1962 | Kilbridge (1962) Industrial Learning | | | | | | | | X | |

Table 3 (continued)

| Year | Author, Year, & Summary Title | Learning Curve for Airplanes | Learning Curve for Typing | Learning Curves & Methodology for High Volume Production Environments | Learning Curves & Methodology for North American or European Commercial Shipbuilding | Learning Curves & Methodology for Constructing Wells, Space Systems, etc. | Learning Curves & Methodology in High Volume Defense Related Projects | Learning Curves & Methodology in WWII Shipbuilding | Learning and Learning Curves & Methodology (i.e. Mid-Life of Product Line, Rate of Learning, Labor Efficiency, etc.) | Learning Curves within Low-Rate Production Environments such as Large Complex Naval Shipbuilding |
|---|---|---|---|---|---|---|---|---|---|---|
| 1964 | Hirschmann (1964) Profit from the Learning Curve | X | | X | | | | | | |
| 1974 | Abernathy & Wayne (1974) Limits of the Learning Curve | | | X | | | | | | |
| 1974 | Knecht (1974) Learning Curves | X | | | | | | | X | |
| 1976 | Yelle (1976) Estimating Learning Curves | | | | | | | | X | |
| 1977 | Berend (1977) Linear Progress Curve Formulation | X | | X | | | | | | |
| 1983 | Kopcso & Nemitz (1983) Learning Curves and Lot Sizing | | | | | | | | X | |
| 1984 | Dutton (1984) Treating Progress Functions | | | | | | | | X | |

Table 3 (continued)

| Year | Author, Year, & Summary Title | Learning Curve for Airplanes | Learning Curve for Typing | Learning Curves & Methodology for High Volume Production Environments | Learning Curves & Methodology for North American or European Commercial Shipbuilding | Learning Curves & Methodology for Constructing Wells, Space Systems, etc. | Learning Curves & Methodology in High Volume Defense Related Projects | Learning Curves & Methodology in WWII Shipbuilding | Learning and Learning Curves & Methodology (i.e. Mid-Life of Product Line, Rate of Learning, Labor Efficiency, etc.) | Learning Curves within Low-Rate Production Environments such as Large Complex Naval Shipbuilding |
|---|---|---|---|---|---|---|---|---|---|---|
| 1986 | Smunt (1986) Comparison of Learning Curve Analysis to Moving Average | | | | | | | | X | |
| 1987 | Camm (1987) The Unit Learning Curve Approximation of Total Cost | | | | | | | | X | |
| 1990<br>1992<br>1996 | Moses (1990, 1992, 1996) Learning Curves - Factors Influencing Weapons Systems | | | X | | | X | | X | |
| 1991 | Cavin (1991) Defence Economics | | | | | | X | | | |
| 1994 | Erichsen (1994) Effect of Learning When Building Ships | | | | X | | | | X | |
| 1995 | Spicknall (1995) SNAME Symposium Paper and Lecture | | | | X | | | | | |
| 1997 | Ennis, Dougherty, Lamb, Greenwell, & Zimmermann (1997) Product Cost Model | | | X | X | | X | | | |

Table 3 (continued)

| Year | Author, Year, & Summary Title | Learning Curve for Airplanes | Learning Curve for Typing | Learning Curves & Methodology for High Volume Production Environments | Learning Curves & Methodology for North American or European Commercial Shipbuilding | Learning Curves & Methodology for Constructing Wells, Space Systems, etc. | Learning Curves & Methodology in High Volume Defense Related Projects | Learning Curves & Methodology in WWII Shipbuilding | Learning and Learning Curves & Methodology (i.e. Mid-Life of Product Line, Rate of Learning, Labor Efficiency, etc.) | Learning Curves within Low-Rate Production Environments such as Large Complex Naval Shipbuilding |
|---|---|---|---|---|---|---|---|---|---|---|
| 1998 | Eden, Williams, & Ackermann (1998) Dismantling the Learning Curve | | | X | | | | | X | |
| 2000 | Waterworth (2000) Project Mgmt. Journal | X | | | | | | | | |
| 2001 | Huberman (2001) Organizational Learning | | | | | | | | X | |
| 2001 | Thornton (2001) American Economic Review | | | | | | | X | X | |
| 2003 | Goldberg (2003) Center for Naval Analysis | | | X | | | | | X | |
| 2004 | Craggs, Bloor, Tanner, & Bullen (2004) Gross Tonnage vs Work Content & Improvements due to Learning | | | | X | | X | | X | |
| 2005 | NAVSEA 05C (2005) Cost Estimating Handbook | | | | | | | | X | |

Table 3 (continued)

| **Year** | **Author, Year, & Summary Title** | **Learning Curve for Airplanes** | **Learning Curve for Typing** | **Learning Curves & Methodology for High Volume Production Environments** | **Learning Curves & Methodology for North American or European Commercial Shipbuilding** | **Learning Curves & Methodology for Constructing Wells, Space Systems, etc.** | **Learning Curves & Methodology in High Volume Defense Related Projects** | **Learning Curves & Methodology in WWII Shipbuilding** | **Learning and Learning Curves & Methodology (i.e. Mid-Life of Product Line, Rate of Learning, Labor Efficiency, etc.)** | **Learning Curves within Low-Rate Production Environments such as Large Complex Naval Shipbuilding** |
|---|---|---|---|---|---|---|---|---|---|---|
| 2006 | Miroyannia (2006) Ship Construction Costs | | | | X | | X | | X | |
| 2007 | Coleman (2007) Rising Ship Costs due to Loss of Learning | | | X | | | | | X | |
| 2007 | Fioretti (2007) Organizational Learning | | | | | | | | X | |
| 2008 | Fox, Brancato, & Alkire (2008) Guidelines and Metrics for Assessing Space System Cost Estimates | | | | | X | | | X | |
| 2008 | International Society of Parametric Analysts (2008) Parametric Estimating Handbook | | | X | | | | | X | |
| 2009 | Pires, Lamb, & Souza Shipbuilding Performance Benchmarking | | | | X | | X | | X | |
| 2009 | GAO (2009) Cost Estimating & Assessment Guide | | | | | | | | X | |

Table 3 (continued)

| Year | Author, Year, & Summary Title | Learning Curve for Airplanes | Learning Curve for Typing | Learning Curves & Methodology for High Volume Production Environments | Learning Curves & Methodology for North American or European Commercial Shipbuilding | Learning Curves & Methodology for Constructing Wells, Space Systems, etc. | Learning Curves & Methodology in High Volume Defense Related Projects | Learning Curves & Methodology in WWII Shipbuilding | Learning and Learning Curves & Methodology (i.e. Mid-Life of Product Line, Rate of Learning, Labor Efficiency, etc.) | Learning Curves within Low-Rate Production Environments such as Large Complex Naval Shipbuilding |
|---|---|---|---|---|---|---|---|---|---|---|
| 2010 | Cobb & Cullis (2010) Learning Curve Analysis | | | X | | | | | X | |
| 2011 | Anzanello & Fogliatto (2011) Learning Curves & Applications - Research Directions | | | X | | | | | X | |
| 2011 | Jablonowski, Ettehad, Ogunyomi, & Srour (2011) Integrating Learning Curves into Well Construction | | | | | X | | | X | |
| 2012 | Sato (2012) Routine-Based View of Organizational Learning and Mechanisms of Myopia | | | | | | | | X | |
| 2013 | Takahashi (2013) Annals of Business Administrative Science, Tokyo | | | | | | | | X | |
| 2014 | Lee (2014) Paper from Strategos, Inc. | | | X | | | | | | |
| 2014 | Teplitz (2014) Learning Curve Setbacks: You Don't Always Move Down a Learning Curve | | | | | | | | X | |

Table 3 (continued)

| Year | Author, Year, & Summary Title | Learning Curve for Airplanes | Learning Curve for Typing | Learning Curves & Methodology for High Volume Production Environments | Learning Curves & Methodology for North American or European Commercial Shipbuilding | Learning Curves & Methodology for Constructing Wells, Space Systems, etc. | Learning Curves & Methodology in High Volume Defense Related Projects | Learning Curves & Methodology in WWII Shipbuilding | Learning and Learning Curves & Methodology (i.e. Mid-Life of Product Line, Rate of Learning, Labor Efficiency, etc.) | Learning Curves within Low-Rate Production Environments such as Large Complex Naval Shipbuilding |
|---|---|---|---|---|---|---|---|---|---|---|
| 2015 | Moore (2015) US Air Force Institute of Technology | X | | X | | | | | | |
| 2015 | Johnstone (2015) Improvement Curves | | | | | | | | X | |
| 2015 | NASA (2015) Cost Estimating Handbook | | | | | X | | | X | |
| 2016 | Lolli, Messori, Gamberini, Rimini, & Balugani (2016) Modeling Production Costs with the Effects of Learning & Forgetting | | | X | | | | | X | |
| 2016 | The Office of the Parliamentary Budget Officer for Canada (2016) Learning Curves | | | X | | | | | X | |
| 2017 | Boemke & Freels (2017) Implementing Wright & Crawford | | | X | | | | | X | |
| 2017 | Sokri (2017) 3rd International Congress in Technology, Mgmt., and Social Sciences | | | | | | X | | | |

Table 3 (continued)

| Year | Author, Year, & Summary Title | Learning Curve for Airplanes | Learning Curve for Typing | Learning Curves & Methodology for High Volume Production Environments | Learning Curves & Methodology for North American or European Commercial Shipbuilding | Learning Curves & Methodology for Constructing Wells, Space Systems, etc. | Learning Curves & Methodology in High Volume Defense Related Projects | Learning Curves & Methodology in WWII Shipbuilding | Learning and Learning Curves & Methodology (i.e. Mid-Life of Product Line, Rate of Learning, Labor Efficiency, etc.) | Learning Curves within Low-Rate Production Environments such as Large Complex Naval Shipbuilding |
|---|---|---|---|---|---|---|---|---|---|---|
| 2017 | CAPE (2017) Best Practices for Cost Analysis | | | | | | X | | X | |
| 2017 | Johnstone (2017) Do Production Rates Really Matter | | | | | | | | X | |
| 2018 | DAU (2018) DOD Manufacturing Management for Program Managers | | | X | | | X | | X | |
| 2019 | Deschamps & Greenwell (2019) Looking for Cost Drivers | | | | | | X | | X | |
| 2021 | Kell (2021) Australia's Submarines Should be Built in the US | | | | | | | | X | |
| 2022 | Gies (2022) Learning Curve Characterization within Complex Low-Rate Production Environments | | | | | | | | X | X |

Table 3 (continued)

## Context of Low-Rate Production Shipbuilding

There have been a number of articles written recently that address aspects of learning not from a learning or learning curve theory perspective, but they discuss factors that were within the scope and context of a learning environment, and as such, were addressed herein too. As has been addressed throughout, this research was focused on learning in low-rate production environments. The learning curve imposed via a contract by a customer can be aggressive as was articulated by Lessig (2019) who stated "…but the Yard isn't celebrating. The contract stipulates an 18% labor cost reduction from ship to ship." The other sections of this chapter addressed the body of knowledge as it relates to learning curves, and the fact that there does not exist published literature that discusses learning in low-rate production environments. The objective of this section, associated with the Literature Review, was to delineate and discuss literature that was not specifically published to cover learning and learning curves, but the literature contained within this section addresses the context and environment that low-rate production shipbuilding resides within. The researcher also captured this perspective to develop a more inclusive low-rate production characterization.

As such, the environment associated with low-rate production shipbuilding was very complex. Limas-Villers (2022) provided a summary associated with the changing conditions associated with shipbuilding when he stated that "…the Navy is required by law to have at least 355 ships, though plans are in place for expanding the fleet to between 398 and 512 vessels." He also continued by saying "This objective is largely aspirational as the number of private and public shipyards has significantly declined with gaps in experienced personnel, rising costs, and a boom-bust cycle in naval acquisitions."

The shipbuilding procurement environment was another perspective that was also captured within the literature review.  However, the literature written about this topic does not address learning, but rather, the researcher has included the procurement strategies due to connectivity to this complex system.  As such, per Capaccio (2020), the Navy decided to pursue a “block buy” in an effort to help “rein in costs.”  The Navy’s goal was to reduce the second ship of Class D ships by eighteen percent compared to the first ship and reduce the fourth ship of Class D Ships by twenty-two percent from the second ship of the class.  As Osborn (2022) conveyed in regard to a two-ship buy strategy “to consolidate funding and acquisition practices for two separate carriers with one buy.”  Osborn (2022) continued by stating that this block-buy strategy “helped to consolidate and streamline the purchase and delivery of crucial supplies and…long lead items.”  In the researcher’s opinion, these efforts provided stability and supported knowledge retention and transfer thereby assisting learning.

Lessig (2016) covered the fact that since the 1960s, Class A ships have been between three to seven years apart.  He also stated that twice in the 1980s, the Navy did two – two ship block buys for Class A ships such that there were three years between ships.  Lessig (2016) also stated that according to Forbes, a four-year schedule would bring stability because recent drops in work resulted in lay-offs of shipbuilders.  Burgess (2022) continued by stating that the “two-carrier procurement by the Navy for CVN 80 and CVN 81 allowed HII to lock in prices for materials.”  He continues by stating that this helped to support “developing skilled workers.” The procurement strategy also impacted suppliers as Burgess (2022) stated that when suppliers go out of business “they’re gone forever.”  Katz (2021) stated that the Navy is looking into a multi-year, block buy, or multi-ship procurement strategy for the LPD-17 class to support “cost savings as well as needed stability and predictability for the shipbuilder and its vendor base.”

Eckstein (2022) covers that the "savings in multi-ship contracts come from guaranteeing work." However, changing the procurement strategy can have a negative effect as Eckstein (2022) covers that shipyards were impacted when the Navy cancels ships, delays their construction, and/or "stretches" their construction durations.

In addition to the procurement environment, the culture of the company building the ships was also part of this complex system. Diekmann, Horn, & O'Conner's (1982) article was focused on the construction of houses and turbines. They observed that "interruption in repetitive work causes an increase in time and labor." They also discussed that they observed "unlearning" in both of these industries when some sort of an interruption occurred. Another area that was a part of the corporate culture deals with ensuring sufficient numbers of workers as well as the right skill mix. Abbott (1997) states that this issue became a major challenge given the declining number of government contracts especially in shipbuilding since it was very "labor intensive." They state that "sufficient number of qualified workers" were needed "to handle surges in construction" especially for skills such as "welders, pipe fitters, and marine electricians." Instability impacts culture and environment through shifting the number of shipbuilders needed. This issue was covered by Weisgerber (2021) and highlighted the net effect when the Navy's ship procurement plan changed. The impacted shipbuilder stated that the Navy had specifically requested them to increase capacity to be able to deliver current ships "on or ahead of schedule and maintain a rate of two ships per year for future construction as well." However, in the fiscal year 2022 Navy budget request, the Navy asked Congress to approve only one destroyer, which was "one fewer than planned a year earlier," per Weisgerber (2021). While all of this was occurring, this same shipyard was "on a hiring spree" to be able to "meet the Navy's [original] ship demand." The net effect, per Weisgerber (2021), was that without that destroyer added back in, then the impacted shipyard would have to turn-around and “cut its workforce”. Arena, Blickstein, Younossi, & Grammich (2006) stated that a major US shipyard had a workforce that was either “less than 35 years of age and has less than five years of experience or more than 45 years of age with more than 20 years of experience.” As such, the industry faces “issues related to both an aging workforce and green labor.” The industry was experiencing a wave of retirements being replaced by relatively inexperienced workers. Arena, Blickstein, Younossi, & Grammich (2006) continued by stating that in terms of recruitment, “shipbuilding is tough work, and the requirements for labor are driven by unstable demand” due to “fluctuations in ship production and alterations in the Navy’s acquisition strategy.” Clark (2021) stated that shipbuilders could produce more ships from a facilities capital perspective but they did not have a “strong signal” from the Navy to invest in hiring additional workforce and training them so that they can “maximize their capacity.” He continued by saying that “there simply isn’t a strong enough signal from the government that the government is serious about growing. Predictability was key to increasing and stabilizing the shipbuilding industry.” More recently, Ferrari (2022) stated that Congress “starved the Navy of steady funding it needed to purchase capital assets that take years to build.” He continues by stating that this also creates a “constantly shifting resource profile”. Thompson (2022) affirms this as well, in regard to shipbuilding, when she conveyed that “predictability minimizes risks.” She continued by stating that “it takes years of planning to construct such warships. Unless the Navy’s future needs are laid out well in advance and funded at predictable intervals, time and money will inevitably be wasted.”

Capturing lessons learned and applying them supports creating a learning environment. Eckstein (2022) acknowledge this fact in her article when she stated, “the company had a plan going into the construction on the *Gerald R. Ford*, but lessons learned were driving down cost and schedule as the company worked through the *John F. Kennedy* and now the *Enterprise*."

Walpert (2001), via his assessment of the state of the US Shipbuilding Industry for the National Shipbuilding Research Program, suggested that companies can have five "levels" of training. Miller (2017) addressed training in terms of "time to adjust" based on the training content and the "magnitude of technological change sought". She mapped these two parameters as to what an organization needed to do and change to obtain a small to large change. She stated that small changes to be learned would focus on skills or procedures while larger changes to be learned might impact the structure or strategy of the program. The largest changes requiring learning affects the culture of the organization. Utilizing Miller (2017) and Walpert (2001) yields the following in regard to characterizing training within the context of learning.

| Level | Training Plan | Training Strategy |
|---|---|---|
| **1** | Formal Training Plan Does Not Exist | Is Only in Response to Regulations or Legislation |
| **2** | Focused on New Employees Only | On The Job Training |
| **3** | Small Training Budget | Apprentice Program or Other Similar Type of Training. Some shop and supervisor training. |
| **4** | Training Needs Analysis Completed | Training Materials and Library On-Site. Appraisals Lead to Specific Training Needs and Personal Action Plan. |
| **5** | More than 5% of Each Employees Time Devoted to Training. | Continuous Personal Development is Company Policy. High Proportion of Learning is Self Directed. |

Table 4: Self-Directed Learning

Mishra, Henriksen, & Fahnoe (2013) covered self-directed learning, which was the fifth level that Miller (2017) and Walpert (2001) covered in Table 4. They performed research in regards to what motivates self-directed learning. Mishra, Henriksen, & Fahnoe (2013) concluded that there was an internal element, but there were also "external factors" that also have an impact too. They stated that learning environments that use technology will have a positive impact to self-directed learning. They also stated that using "real world learning applications or problem-based learning environments" were effective at supporting self-directed learning as well as creating "flexible opportunities for learning structures." However, as has been discussed, this culture was impacted by funding. Katz (2022) states that "shipbuilders are particularly vulnerable to spikes and dips in the labor market because the work, even at the best of times, often fluctuates year over year." He continues by saying that "when budgets drop, so do the payrolls. Shipbuilders reap the benefits" when budgets were high, which "translates to the freedom to hire and train new workers en masse."

Eckstein (2022) stated that one major shipbuilder delineated that "the company has not done a great job inserting lessons learned into build plans" and there "has been significant workforce turnover." Eckstein (2022) also reported that the pandemic has been "a drag on the system" and that it has also slowed down shipbuilders. The Chief of Naval Operations stated, via Abott (2022), that the "performance gap" in shipbuilding was due to "an outdated approach to institutional learning and problem solving."

Shipyards have been trying to increase training to reduce "time to talent" so that shipbuilders can become proficient faster, which was discussed by Eckstein (2019). According to Eckstein (2019), some shipbuilders were developing training cells to accelerate this time to talent objective for newly hired employees. She also continued by stating that the inexperienced labor that was being hired now will be, in fifteen to twenty years, the “veteran talent.”

As indicated, this section did not specifically capture learning and/or learning curves, but rather, this section provided context in regard to the environment that low-rate production shipbuilding resides within, and as such, the literature review provided that context accordingly. As such, Di Stefano, Gino, Pisano, & Staats (2016) suggested that companies and organizations should emphasize “the role of individuals in creating and storing knowledge” over the “concept of organizational knowledge.” They state that “learning by doing” should be analyzed along with “articulating and codification of knowledge.” They also stated that “organizational learning is not the sum total of individual learning,” which was primarily focused on learning through an “accumulation of experience[s].” Di Stefano, Gino, Pisano, & Staats (2016) also referenced that learning occurs “along the learning curve.” They state that deliberate learning has a direct relationship to "performance outcomes.” Poleacovschi, Javernick-Will, Smith, & Pohl (2020) stated that a “critical step to organizational knowledge sharing involves expertise visibility, or knowing who knows what.” They concluded, similar to Poleacovschi, Javernick-Will, Smith, & Pohl (2020), that providing visibility across an organization of who the experts were or where the expertise resides within an organization actually increases a group’s and/or “organizational performance.” As such, the more employers can encourage that their employees “become more visible outside of their immediate groups” then they will be able “to increase their performance.” Bloor et al. (2016) confirms this as well, and stated “maintaining experience and knowledge is critical to having…and achieving high levels of productivity.” Equally important was capturing lessons learned and continuous improvement for design and production as Ennis, Dougherty, Lamb, Greenwell, & Zimmermann (1997) suggested. They continued by stating that "understanding what the cost drivers are and how they affect the manufacturability and eventual cost of a ship or its products will help…to design more producible ships."

Obviously, the objective of knowledge management was to capture and retain knowledge. However, as Pappas (2014) stated the "idea of (a) 'forgetting curve' is credited to Hermann Ebbinghaus." Ebbinghaus (1885) theorized "that the human brain will forget information it has learned if that information is not out into practice." Kohn (2014) addressed this issue too, and he puts forth, along with Meacham (2016) and Teichert (2010), that "booster events" and "microlearning" can lead to increased retention and retention times.

Through the literature review, the researcher assessed other aspects of the environment associated with shipbuilding. Limas-Villers (2022) touched on the demographic issue in shipbuilding too by stating that since "the 1990's, the workforce has aged, leaving yards with an incredible fragile workforce with a dearth of skilled younger workers in the pipeline…This lack of skilled technicians causes delays in construction and maintenance, compromising the Navy in a possible future engagement." Ress (2021) summarizes the demographic issue associated with naval shipbuilding when he said "the problem is that shipbuilding is highly skilled, there aren't a lot of people who can do it." Lundquist (2021) gets more specific on this issue stating that "US Shipyards are busy building the next generation of Navy ships and Coast Guard cutters. As the current workforce is retiring, and taking their skills and knowledge with them, the next generation of naval architects, naval engineers, tradesmen, and technicians are needed." Lundquist (2021) also conveys that these senior workers also have a "wealth of practical experience," and that the shipyard used to be able to train the "young mechanics…under a few experienced master mechanics, but those senior people have or are retiring," As the researcher conveyed in Chapter 5, this impacted how efficiently shipbuilders can move up the learning curve.  Eckstein (2021) stated in her article that “nearly 60% of” one major shipyard “have been on the job fewer than five years.”  According to Eckstein (2021), this inexperience also translated into management such that “green managers” were “giving less-than-precise orders to inexperienced shipbuilders, the amount of re-work needed on ships grew and the pace of deliveries fell behind.”   As such, as Lundquist (2021) points out, other ways to improve performance must be assessed like “new simulation capabilities and online tools.”  He continues by stating that “formal apprenticeships and internship programs are delivering long lasting results.”  Gagosz (2021) quantified the magnitude of the number of experienced shipbuilders that were at retirement age at one shipyard.  She conveyed that “one in every five shipbuilders” are at retirement age.  Gagosz (2021) also affirmed, similar to Lundquist (2021), apprentice programs, and states that the shipyard apprenticeship takes three to five years, and the design apprentice takes four years.  Lundquist’s (2021) observations in regard to apprenticeships support Walpert’s (2001) article that the researcher used to create Table 4.

Reed & Inhofe (2021), who were both US Senators, wrote an article for *Proceedings*. Within the article, they stated that large warships were unique because they take longer to build, “have higher unit costs, have more suppliers, and are more technologically complex when compared with other US weapons systems.”  The also covered the contextual environment associated with shipbuilding today.  According to Reed & Inhofe (2021), in the 1960s, there were fourteen US shipyards that built large warships and now there are four.  They also emphasized “predictability and stability” from the Navy and Congress as well as the importance of future planning to eliminate production breaks.

O’Brien (2020) stated that gaining experience for new shipyard workers “is lengthy and it takes about five years on average for mechanics to reach peak proficiency because for many of our new employees, there is an extended period of company-provided training and mentoring required before a new mechanic fully contributes to production." According to Bloor et al. (2016), it took between two years for a painter to become experienced, five years for an electrician or machinist to become experienced, and ten years for an engineer to become experienced in the shipbuilding environment. Bloor et al. (2016) also states that there are "major shortages of expertise" in all production trades, such as sheet metal workers, welders, steel workers, machinists, pipe fitters, electricians, and so on. When there was instability, as Eckstein (2020) covered, then the "workforce across the yards dropped after sequestration and budget controls wracked the Navy's budget." According to Eckstein (2020), many experienced workers left the shipyards thereby leaving the shipyard less experienced. This dynamic, as McLeary (2020) covers, shows that shipyards are currently trying to replace older tradesmen who recently retired "during the last shipbuilding [hiring] binge in the 1980's…Training the new group has taken time, and slowed some projects down." This issue is compounded, as Ress (2022) states, when Congress keeps passing "continuing resolutions to temporarily fund the government or opts for a yearlong one instead of simply passing the 2022 appropriations bill." When this occurs, the shipbuilding industry cannot be as efficient, according to Ress (2022).

As indicated, this review complements the learning curve theories related literature review by addressing key contextual and related environmental areas, which influenced learning especially in low-rate production environments. A key area that the researcher identified through extensive reviews dealt with stability. The shipbuilding industry tried to operate within an environment that was continually changing. Larter (2020) provided facts that highlights this issue in particular. According to Larter (2020), in December 2016, the Navy's "force structure assessment" set a goal of a "355-ship fleet." However, in March 2015, the goal was 308 ships.

As of the time that this article was written, the Navy had 296 ships. This instability also occurred on a ship-by-ship basis too. Connors (2020) covered the fact that the "President has taken $261 million out of Austal [US Shipyard] …and moving that $261 million over to help build 17 miles of new wall and refortifying about 160 miles of wall." This same type of issue was also covered by Bergman (2020) who covered that a US Congressional delegation was meeting with "top Navy officials to … advocate restoring the attack submarine cut under President Donald Trump's latest budget proposal." The Navy continually conveys instability through their actions as represented by Eckstein (2022), who stated "The Navy bought 13 Flights I LPDs and had planned to buy another 13 to replace the aging Whidbey Island-class dock landing ships." She continues by saying, "Under the Navy's proposal, it would buy just 3 of the 13 Flights II and then end the program, shrinking the amphibious fleet dramatically." Eckstein (2022) concludes that "this could leave Ingalls in a pinch." Just a month prior as Katz (2022) covered that the "force assessments the service has undertaken almost always point to needing a Navy larger than the 355-ship minimum." He continued by stating that "this would require a significant expansion of our [US] shipbuilding industrial base and repair facilities." Even the title of Katz's (2022) article referred to a 500 ship Navy. These extreme contradictions were impossible for the Shipbuilding Industry to respond and adjust. This fact is highlighted by Eaglen (2022), who stated that "a recent Pentagon report called for more arms manufacturers to bolster competition in the shipbuilding-aerospace-and defense-industrial base." Senator Perdue (2020) summarized the funding instability associated with shipbuilding very plainly by stating that "Washington politicians have failed to provide consistent funding to our shipbuilding enterprise over the years." He continues by saying that "since 1975, Congress has only funded the government on time on four occasions due to our broken budget process. As a result, Congress forces the military in most years to operate under continuing resolutions, which further restricts the Navy's efforts to rebuild." Smith (1981) covered this same issue in regard to the impacts of production rates. As Talent (2021) points out, the defense budget was reduced by over a third in the 1990s "forcing the Navy to cut 200 ships." The first "fifteen years of this century" resulted in the Navy losing "another 100 ships." Instability has occurred through all of the ship classes as Axe (2021) states that in December 2019, the Navy proposed to reduce construction of Arleigh Burke class destroyers "between 2021 and 2025 from thirteen ships to just nine." Three months after the December 2019 Navy statement in regard to destroyers, Sharp (2020) covered the fact that the "Trump budget proposal would cut destroyer production from 13 ships to eight ships over five years." The same day as the article written by Sharp (2020), Radelat (2020) wrote an article stating that the President's "budget request cuts from two to one the number of Virginia-class submarines that would be funded in next year's budget." This issue of continuing to change the baseline number of ships was also highlighted by Larter (2019) when he stated that the Department of Defense moved "one Virginia Class Submarine out of the 2021 budget dropping down to one submarine instead of the plan of two." It also slowed the procurement of the next generation frigate program from ordering only one in 2021 and 2022 instead of the two that had been articulated to industry. Fabey (2020) conveyed that the Pentagon is "calling into question the current USN carrier force, with preliminary findings and recommendations pointing towards a smaller large-deck fleet in the next decade." This constant and continual instability "highlights the U.S. shipbuilding-industrial base's increasing fragility", per Clark and Walton (2020). Also, per Clark and Walton (2020), shipbuilding suppliers have spent decades "being whipsawed by changes to shipbuilding plans and budget uncertainty." Larter (2019) continued by stating that these "cuts would be disastrous for the building programs and would cause layoffs." He continued that "we need stability in the shipbuilding industrial base, and such cutbacks are going the opposite direction of the strategic goals laid out by DOD, the Department of the Navy, and the White House over the past three years." Just a few months prior, McLeary (2019) reported that the Navy is reconsidering the "long-stated goal of a 355-ship fleet" and moving to a goal of 310 ships. Harkins (2020) expanded on the impacts of this instability. In 2020, the Navy had laid out plans to buy a total of 44 ships over the next five years." However, the previous year [2019], the Navy stated that they were buying a total of "55 ships by 2024," per Harkins (2020). The Navy and Congress continually change the number of ships that they were going to procure which has profound impacts on individual ship classes. For instance, as Shelbourne (2022) covered, "the funding profile in the President's budget submission essentially cancels the LPD program following the procurement of LPD-32 in FY 23." This then gives the shipbuilder one year's notice of this change. Her articles also state that "the program originally planned to procure through LPD-42." This is a reduction of "ten ships in this one class alone with only one year's notice to the shipbuilder creating uncertainty and instability." More recently, Thompson (2022) covered the fact that the "U.S. Navy's 30-year shipbuilding plan calls for reducing the number of manned warships in the fleet to 280 later in the decade." Thompson (2022) stated this was not good news for the shipbuilding industrial base, and that there were only a "handful of [US] shipyards capable of building complex naval warships." Thompson (2022) conveyed that the few remaining US shipyards are having difficulty "finding skilled workers and sustaining a dwindling supply chain." Thompson (2022) continued by saying that the "Navy's constantly shifting plans provide little incentive to invest in what seems to be a low-margin, unpredictable business" and even compares the predictability of shipbuilding to that of "trading cryptocurrencies." The 2023 Navy plan of record proposes to "wipe out a program for a dozen LPD amphibious warships," per Thompson (2022). The current plan of record for Naval shipbuilding shows other shipbuilding programs at risk, and as a matter of fact per Thompson (2022), "the back and forth over naval ship construction goals has done little to sustain the industrial base." As Thompson (2022) indicated, hiring skilled workers was a challenge to the US Naval industrial base.

Tiron & Capaccio (2020) covered that the shipbuilding budget was to grow in 2022 through 2026; however, the Hudson Institute conveyed in their article that this plan was "a terrible idea" because the Navy would not have the money to pay for sustainment and/or staffing new ships. However, on the same day that Tiron & Capaccio (2020) published their article, Weisgerber & Williams (2020) stated that the 30-year shipbuilding plan now was calling for "one less big-deck carrier." Two days after this article, Ress (2020) covered that the shipbuilding plan was being reduced "from 91 to 74" large surface ships. This instability rippled through the industrial base. A good example of this was covered by Eckstein (2020) when she quoted a Navy Admiral who stated that "they hadn't done submarine work in 10 years, and…we underestimated how they had atrophied in that skill set."

Stability was also a factor from a ship design standpoint as well. As Abbott (1997) covered that a primary driver of high costs was the "uncontrolled generating of thousands of change orders during construction." He continued by saying that the "Navy Program Offices must make every effort to minimize changes if they are serious about controlling costs." Even though Abbott (1997) did not mention learning in his article, a lack of a stable technical baseline increased costs through additional labor hours expended because every change order was a change that had not been done so learning has to start over in that area. Grazier (2021) also addressed the same issue by stating "With the Ford, Littoral Combat Ship, and Zumwalt programs, the Navy attempted to cram its ships with as many new technologies as possible. Construction on each began before engineers completed the development process on the new systems, which inevitability resulted in skyrocketing costs and schedule delays." He continues by stating that "on the new *USS Gerald R. Ford*…new and risky major technologies…numbering nearly a dozen" were installed on the lead ship of this ship class. Francis (2013) conveyed similar concerns to Congress in regard to the Littoral Combat Ship. Brimelow (2022) actually expanded the number of new technologies aboard the *Ford* to twenty-three. Lessig (2019) summarized the comments put forth by the late Senator John McCain who stated that "putting so many new, untested components on a single ship increased the risk. Lessig (2019) also referenced that the contract for Ford Class ships "stipulates an 18% labor cost reduction from ship to ship." Foggo (2022) complements the statements made by Lessig (2019) and Brimelow (2022) by stating that the Navy "embraced the idea of transformation…even if it came with huge risks." The "Ford class aircraft carrier, DDG-1000 Zumwalt class destroyer, and the littoral combat ship (LCS)" tried to "put to many new and immature technologies and concepts into just one new class of ship." Foggo (2022) continues by stating that the "Ford, Zumwalt, and LCS all introduced dozens of new systems and concepts," and it was "just too much for the acquisition, test, and evaluation system to digest." Again, as this section of the research methodology has conveyed, the topics in this section do not directly address learning in low-rate production environments, but rather, the issues and facts that reside within the context of low-rate production shipbuilding all have had an indirect impact on learning in this environment and, in the opinion of this researcher, these factors were accentuated due to the long durations associated with the ships that were designed and built within this context.

Limas-Villers (2022) just recently wrote about stability in the National Defense Magazine. He stated that the main issue inhibiting private shipbuilding "is the inconsistency in demand from the Navy." The Navy's and Congress's actions has created "decades of boom-and-bust cycles in procurements reducing the industrial base." Limas-Villers (2022) continues by stating that Shipyards were "harmed as each program requires significant investment to properly construct and maintain new ships, only for it to be squandered when the Navy cancels orders and moves to develop other systems." This then created an environment that "encourages consolidation" which then limits competition needed for a robust naval acquisition strategy," per Limas-Villers (2022). Limas-Villers (2022) stated that to stop the deterioration, the Navy and Congress must provide a "consistent procurement of ships and a clear commitment toward new systems as needed." Limas-Villers (2022) concluded by stating that to meet the demands of the "larger Navy," "significant changes to training and acquisitions need to take place to ensure sustainability for the longer term." Eckstein (2022) stated that the 2022 spending request by the Navy, which was released in March, reduced the number of San Antonio Class Ships from a "planned 26 ships" to "16 ships." This creates instability across the shipbuilding environment. This was why the researcher was providing this context because these issues have had a direct effect on learning and training. Capaccio (2020) also covered this same issue prior by stating that the "cost report's figures stem in part from changes such as improvements…and Congressional direction requiring increased capabilities" for the second ship of the Ford Class of Ships. The researcher was providing this additional context because even though Capaccio (2020) did not specifically reference learning, these types of changes are the effect of reversing learning in areas that have changed because engineers have to re-design these areas and production personnel have to learn how to install these new systems for the first time despite the learning challenges associated with the second ship of the Ford Class.

The Navy and Congress realized that stability was important as Marine Link (2022) captures at a Congressional Hearing of Erik Raven, nominee for Under Secretary of the Navy, and William LaPlante, nominee for Under Secretary of Defense for Acquisition and Sustainment. Raven is quoted by Marine Link (2022) saying "The 30-year shipbuilding plan…is the signal to industry of what to expect for future years." Abott (2022) affirms the same fact in regard to the "30-year shipbuilding plan" by stating that this is the signal to industry of what to expect for future years and so that industry "can prepare to build those ships in the most effective manner possible." This signal, as Grady (2022) states was "what to expect from the Navy in the way of contracts and mix of ships." Eckstein (2019) also covered the fact that the Navy realizes that they need to make changes. She covered a quote from James Geurts, the Navy's Chief Acquisition Officer, "One of the best ways to take cost out could be to take cost risk out. And so, getting the design mature much earlier, prototyping critical areas which we knew were going to be hard to rebuild…".

Stability was also defined by the degree of changes associated with each ship. As Eckstein (2020) covered in USNI News, "One example…of cost-cutting gone wrong was a decision more than a decade ago to not build a prototype and land-based testing facility." This would have enabled a better understanding of the system to not only refine the design but to gain information in regard to building the system and the ship.

Stability, or lack of stability, can also be influenced by world events, as discussed by Zengerle and Cowan (2022), such as Russia invading Ukraine. As Zengerle and Cowan (2022) states, this issue can increase defense spending in some areas at the expense of other areas and vice versa. This can lead to an increase or decrease in ships. Hooper (2022) covered that the FY 2023 budget proposal showed a "grim budget season for the Navy." The proposed budget was "set upon cutting the Navy to the bone, targeting both legacy Navy force structure and uneconomical vessels for termination." Burgess (2022) suggested a viable approach to support stability in shipbuilding. He pointed to the Navy's procurement of two Ford Class Carriers in a single block buy which created stability and "enabled the aircraft carrier industrial base to control costs and enact savings." This was also espoused two months before by Burgess (2022) and by Decker (2022) that block buying was the most cost-efficient means of procuring ships.

The US was not the only country dealing with instability and its' impacts. The Australians were dealing with similar issues as they determined their strategy for the construction of nuclear-powered submarines. As Turner (2021) stated, "the repercussions of these actions will have long-lasting implications for the new program." He continued by saying that the "absence of a commitment to 12 submarines under the AUKUS pact (the statement that there will be 'at least eight' is suitably vague) further reduces the market." Turner (2021) also conveyed that the government leadership in Australia was changing with different views in regard to Australia's construction of nuclear-powered submarines. As such, he stated "how much confidence can industry maintain for investment when the new program has now apparently by-passed the strategic and political discussions about the requirement for nuclear powered vessels?"

The bottom line, per Thompson (2019), was that problems in shipbuilding are "largely traceable to how Washington's political culture operates, and the inefficiencies that result." The culture was "unstable, unpredictable demand," as delineated by Thompson (2019), which created uncertainty across the shipbuilding enterprise by delaying the start of construction on different ship classes. This, in turn, per Thompson (2019), caused companies to not invest in the future due to uncertainty in the viability of each ship class. This then created a workforce lacking in skills because, as Thompson (2019) pointed out, the pool of workers to draw upon decreased as "welders, pipe fitters, and other specialties essential to naval shipbuilding" move to other industries.

Learning can also be impacted by the complexity of the ship that was being produced. Given the fact that this research was based on low-rate production of ships, the classes of ships that were in this category are those that were very complex, and by their very nature were extremely complicated and have numerous systems. Even though Terwilliger (2015) or Grant (2008) do not cover learning, they both focused on the "outfitting density" associated with submarines. Submarines, by design, were very "dense", which was the terminology that they both use. This connectivity that the researcher was making between Terwilliger (2015), Grant (2008), and learning was covered in further detail in Chapter 5. Gaspar, Ross, Rhodes, & Erickstad (2012) also discussed the complexity associated with ship design and ship construction. Arena, Blickstein, Younossi, & Grammich (2006) covered complexity associated with the operation of the ship, crew size, different missions, and so on. The point was that shipbuilding was complex in design, construction, and end use. In an effort to "counter" [researcher's quotes], the various complexity aspects associated with shipbuilding, Schank et al (2016) discussed modularity and flexibility in ship designs. The approach that Schank et al (2016) take was to have more flexible and modular ship designs to decrease costs through making the ships more producible. As a side note, Gaspar, Ross, Rhodes, & Erickstad (2012) alluded to Ashby's Law of Requisite Variety. Lastly, Fabey (2022) summarized stability, or lack of stability, in regard to US Navy Shipbuilding when he discussed the impacts of delays, government bureaucracy, technology challenges, change orders, funding variability due to Congress and the media, and challenges associated with dealing with the Navy. Fabey (2022) also stated that the COVID-19 pandemic created instability within shipbuilding. Fabey's (2022) book provided the context of the challenges each shipbuilder faces, and in regard to this research, these challenges, as well as the context that they reside in, affects learning. These studies and various published articles clearly indicated the need for research into low-rate production naval shipbuilding and supports the gap identified in the literature review. These published articles also provided contextual information which was used to support the development of the overall learning curve characterization.

# CHAPTER 3

# METHODOLOGY

## Philosophical Approach

The research contained herein utilized deductive reasoning.  Deduction, deductive arguments, or deductive reasoning is a methodology of reasoning which starts with a general statement and works to specifics.  With this foundation, this research was based on a positivistic mind independent deductive reasoning methodology (Van Brewer and Sousa-Poza (2019), Creswell (2018), Gliner, Morgan, and Leech (2017), Siangchokyoo and Sousa-Poza (2012), Trochim and Donnelly (2007), and Bozkurt and Sousa-Poza (2005)) to characterize learning curves in low-rate production environments.  The researcher also assessed the four types of failures to ensure that the research methodology and subsequent implementation of the research methodology would not be compromised by committing one of these errors.  As such, a brief assessment of each of these failures was captured within the next section.

## Failure Assessment

As indicated, the researcher addressed the four types of failures (Keating, 2018) so that the development of the research methodology and subsequent implementation would result in a research product that would not fail due to one of these types of failures.  The first was a Type I error, which was solving a problem that does not exist.  The literature review herein contained numerous documents that substantiates the fact that a problem exists, and the problem impacted learning curves in low-rate production ships.  This problem presented itself via the cost of naval ships as well as the labor hours to produce them.  The Navy assumes a learning curve for each ship of a class based on Wright's (1936) work, which the Navy then utilized to determine the cost of each subsequent ship. This methodology then yields a disparity between the predicted hours to build a ship versus the actual hours. The point was that the problem exists and the focus of this research is addressing the learning curve associated with low-rate production ships. In terms of a Type II error, a problem does exist and it has been identified that the learning curve characterization utilized by the Navy does not reflect low-rate production. Type III errors, which occur when the wrong problem is solved very efficiently, has been mitigated by the fact that even though the learning curve assumptions that were made by the Navy for low-rate production ships were not reflective of the environment that these ships reside in, the fact that this research was addressing this environment utilizing data and information from this environment mitigates this risk. Previous researchers utilize Wright's (1936) theory as the fundamental theory to perform their analysis, which was in error because, as the researcher details, Wright's theory was rooted in high-rate production manufacturing. The Navy and the Shipbuilder have different world views, so the possibility of creating a Type IV error does exist; however, this was mitigated via framing and bounding the complex problem, which was outlined via the research methodology. It is also mitigated by focusing on the development of a learning curve characterization for low-rate production ships based on using data from low-rate production ships.

## Assumptions

This research was focused on new construction and not on the overhaul or repair of naval ships. It was also focused on naval ship construction at non-government owned and operated shipyards. Life cycle costs were not included including overhaul and repair of naval ships.

Overhaul and repair of naval ships has different inputs and different world views, but many of the concepts contained herein may be transferable and would be the subject of future research. Some of the learning concepts could be applicable or could be made applicable to government shipyards, but they have different inputs and a different world view. This too may be the subject of future research. Some naval ships were built by more than one shipbuilder meaning the construction of different sections of each ship were built by more than one shipbuilder and then assembled at one of the shipbuilder's facilities. Ships such as these were not included as a part of this research because they would have different inputs and a different world view. In addition, the research contained herein does not address material, material costs, overhead, or work completed by leased employees, contractors, sub-contracted labor, Tiger Teams, etc. The focus of this research was principally focused on labor hours only because

- of the connectivity to learning curves,
- labor hours constitute a majority of the total cost, and
- Wright's (1936) principal focus was on factors affecting the cost of airplanes, and he focused on labor hours.

The research herein was focused on low-rate production systems, and specifically naval ships. Due to the fact that there does not exist any research on low-rate production environments until now, the researcher defined low-rate production as:

- the production of a system, equipment, component, product, or ship characterized by design and construction taking more than forty-eight months,
- the time between succeeding construction starts was longer than four months,
- the ship would also be highly dense and complex,
- there were a large number of hours to design, build, test, and deliver each ship, and

- successive ship deliveries were greater than four months.

The only references in the public domain to low-rate production was by Abbott (1997), and he only mentioned “low productivity rates” at it relates to the competitiveness of US shipyards as compared to other shipyards throughout the world. Abbott (1997) was not addressing low-rate production from a manufacturing and learning curve perspective. It was also defined from the perspective of “low-rate initial production,” as delineated by Reed et al. (1993), Defense Acquisition University (2021), and DoD INST 5000.02 (2020), simply meaning the initial production of a given commodity, which would include various milestones throughout the design and construction of the commodity, as delineated by Misra (2015) and Corporate-Tech Planning, Inc. (1978). The data and associated assessments were based on data that exists within the public domain. No proprietary data was utilized during the completion of the research.

Table 5 summarizes the assumptions made to support this research.

| # | Section within Dissertation | Assumption: Category | Assumption | Comments |
|---|---|---|---|---|
| 1 | Class B Ships | Class B Ship Data | Only the cost to build each Class B Ship was in the public domain. Actual labor hours to build Class B Ships was not in the public domain. For all ship classes, the researcher normalized the labor hour data or cost data (as was the case for Class B data). Only the relative values were of a concern to support the analysis and not the actual values. This then also mitigated the impact of not having actual labor hours for the Class B Ships. As an additional note, the researcher did escalate the costs of the Class B Ships so that the dollar values would all be associated with the same calendar year. | - |
| 2 | Chapter 4: WBS 5 and WBS 6 | Class B Ship Data | Total construction and production as well as construction and production support hours to design and build each Class B Ship does not exist in the public domain. However, the funding to support each Class B Ship is in the public domain. As such, the researcher assumed that the funding profile for each Class B Ship would also characterize the labor profile for each Class B Ship. This assumption is reasonable, and it still provides an understanding of the effort required to build each Class B Ship. | - |
| 3 | Class C Ship Data | Class C Ships | The researcher utilized Flight I data only for the Class C Ships. Other flights were not used just simply in an effort to bound the complex system. | A flight of ships is a set of ships that have similar features which are contracted together as an over-arching group with specific contracts for groupings of ships within that specific flight of ships. |
| 4 | Throughout | Definition of low-rate Production | Low-rate production shipbuilding was defined by:<br>(1) ship design and construction was greater than 48 months,<br>(2) time between starts of succeeding products was longer than 4 months,<br>(3) highly dense and complex ships,<br>(4) large number of hours to design, build, test, and deliver each ship,<br>(5) successive ship deliveries greater than 4 months. | - |

Table 5: Assumptions Made to Support and Bound this Research

| # | Section within Dissertation | Assumption: Category | Assumption | Comments |
|---|---|---|---|---|
| 5 | Conclusion #10-2 | Demographic Data | The demographic data utilized was representative of the United States. Class B Ships were built in England. The researcher utilized the same demographic profile for England as the United States. | Given the similarities of the two countries, this was a reasonable assumption. |
| 6 | Conclusion #11-1<br>Conclusion #12-1 | Factors Affecting Work Output | In addition to the organizational culture and demographic environment, there were other factors that influence work output; however, these were outside the scope of this research. Obviously, work output was affected by mechanization, automation, work processes, and other factors, but the data that exists in the public domain was not at this level of detail to be able to deduce these types of conclusions. The researcher did assume that the employee work output was applicable to Ship Classes A, B, and C. Class D Ships occurred after the time frame associated with this data. | - |
| 7 | Chapter 4: WBS 5 and WBS 6<br>Conclusion #7-2 | Impact of Changes | Utilizing information contained in the public domain, the researcher identified the most significant changes impacting each ship of this class. As each were identified using the references herein, the researcher simply counted each change. The researcher also assumed that the impact of each change was the same meaning that the researcher did not quantify the difference in the impacts associated with each change. This was an assumption and limitation with respect to this research; however, due to the limited information contained within the public domain in regards to the number of systems impacted by each change, this assumption was a logical conclusion to pursue accordingly. | This was both an assumption and a limitation. Analyzing the degree of impact of each change would require proprietary information, which was beyond the scope of this research. |

Table 5 (continued)

| # | Section within Dissertation | Assumption: Category | Assumption | Comments |
|---|---|---|---|---|
| 8 | Chapter 4: WBS 5 and WBS 6 | Labor Elements and Profiles | For Class A Ships, the data to support the development of labor elements and profiles does not reside in the public domain. However, based on the fact that this research was focused on low-rate production of ships, data and subsequent information identified in the public domain associated with Class B, Class C, and Class D Ships was applicable to Class A Ships. The researcher assumed that engineering, management, planners, and production support were some of the key non-production elements associated with low-rate production shipbuilding. The data for these three ship classes provides insights into Class A Ships, which was discussed via Chapter 5 herein. | - |
| 9 | Chapters 3, 4, and 5 | Learning Curve Percentages | Per Lessig (2019), Capaccio (2020), and O'Rourke (2022), an 82% learning curve was applied to Class D Ships during the contracting process for those ships. The information within the public domain did not provide the contracted learning curves applied to Class A, B, or C Ships. However, since these four classes of ships were all low-rate production ships and since the DAU (2018) and Teplitz (1991) states that the learning curve associated with shipbuilding was between "80% to 85%", then for the purposes of the research contained herein, the researcher utilized an 82% learning curve to support this research. However, the OLCC developed was not dependent on an 82% learning curve or any specific learning curve number because the OLCC developed was based on a low-rate production environment and not a high-rate production environment. | - |

Table 5 (continued)

| # | Section within Dissertation | Assumption: Category | Assumption | Comments |
|---|---|---|---|---|
| 10 | Chapter 2: Literature Assessment of Wright's Era until the 1990's | Learning Curve Terminology | Different researchers have used various terms to define learning curves, such as: progress curves, improvement curves, experience curves, and so on. Some researchers define these differently and some define these as the same. For the purposes of the research and to bound the terminology accordingly, the researcher utilized the term learning or learning curves throughout. | - |
| 11 | Chapter 3 | Life Cycle Costs | Life cycle costs were not included including overhaul and repair of naval ships. Overhaul and repair of naval ships has different inputs and a different world view, but many of the concepts may be transferable and would be the subject of future research. | - |
| 12 | Chapter 3 | New Construction Shipbuilding | This research was focused on new construction shipbuilding at non-government owned or operated shipyards. | - |
| 13 | Throughout | Public Domain Data | The data and associated assessments made were based on data that exists within the public domain. No proprietary data was utilized during the completion of the research. | - |
| 14 | Chapter 3 | Ship Construction | Some naval ships were built by more than one shipbuilder meaning the construction of different sections of each ship was built by more than one shipbuilder. Ships such as these were not included as a part of this research because they would have different inputs and a different world view. | - |

Table 5 (continued)

| # | Section within Dissertation | Assumption: Category | Assumption | Comments |
|---|---|---|---|---|
| 15 | Chapter 4: WBS 5 and WBS 6 | Ship Delivery | Sometimes in low-rate production of ships, some amount of work was completed after delivery, but for the purposes of this research, the researcher assumed that this volume of work was negligible. As such, the researcher assumed that the delivery date for each ship meant that all work was completed for that specific ship on that specific day. | - |
| 16 | Chapter 4: WBS 5 and WBS 6 | Shipbuilder Efficiency versus Experience | Birkler et al (1994) completed research to support the development of shipbuilder efficiency versus experience for Class C Ships. However, extending its' applicability to other ship classes was a logical deduction realizing that different ship complexities and funding strategies will alter the shape of the curve; however, the researcher was assuming that the general shape of the curve can be extended to other ship classes. The slope of this curve may vary some based-on ship complexity and funding; however, the researcher was assuming that this was a reasonable assumption to make to apply this curve to Class A, B, and D Ships since they were all low-rate production ships. | - |
| 17 | Chapter 3 | Shipyard Labor | The research did not address material, material costs, overhead, or work completed by leased employees, suppliers, contractors, sub-contracted labor, Tiger Teams, etc. This was outside the scope of the research, and this data did not exist in the public domain. In addition, the basis for Wrights (1936) research was labor hours. As such, the principal focus of the research was based on labor hours. | - |

Table 5 (continued)

## Overview of Research Methodology

There was no universal approach to developing a unique research systems methodology, and it was rooted in philosophy through world views, principles, laws, and concepts (Keating (2018), Gliner, Morgan, and Leech (2017), Siangchokyoo and Sousa-Poza (2012), Trochim and Donnelly (2007)). The methodology delineated herein was developed so that it could accommodate emergence within the context of the problem domain; otherwise, the solutions developed would be myopic and not robust. The research methodology was also based on the research and information that could be obtained and/or developed within the public domain. In addition, the research methodology includes framing the problem within its contextual domain so that the research methodology was a "generalized" framework that guides "applications for the field" (Keating, 2018). From a philosophy of research perspective, the approach to the methodology will differ depending on the researcher's personal philosophical foundation. As Trochim & Donnelly (2007) succinctly state, methodology "is concerned with how you come to know." As Keating (2018) indicated, a methodology was a "generalized" framework that guides "inquiry and is informed by philosophical and theoretical underpinnings specific to a particular discipline." It provides the "road map" that the research followed and provided the foundation for the methods to be built upon which were, per Keating (2018), "specific approaches that are performed in a systematic manner to accomplish something." Gliner & Morgan (2017) conveyed that the methods portion of an article or study "instructs the reader as to exactly what was done in the study and so allows the reader to replicate the study under identical conditions." As Keating (2018) and Gliner & Morgan (2017) implied, methods were tools and techniques to analyze and evolve complex problems and/or research areas.

The unique research method that was developed was based on thirteen key elements which are further defined and captured via fifteen work breakdown structure (WBS) areas. These are reflected and articulated via Figure 4. Figure 4 is a concise visual highlighting the research methodology that was core to the research contained herein. It is important to note that the unique research methodology was not a prescriptive approach, but rather, it was an iterative approach with the flexibility to adapt and adjust as the research progressed.

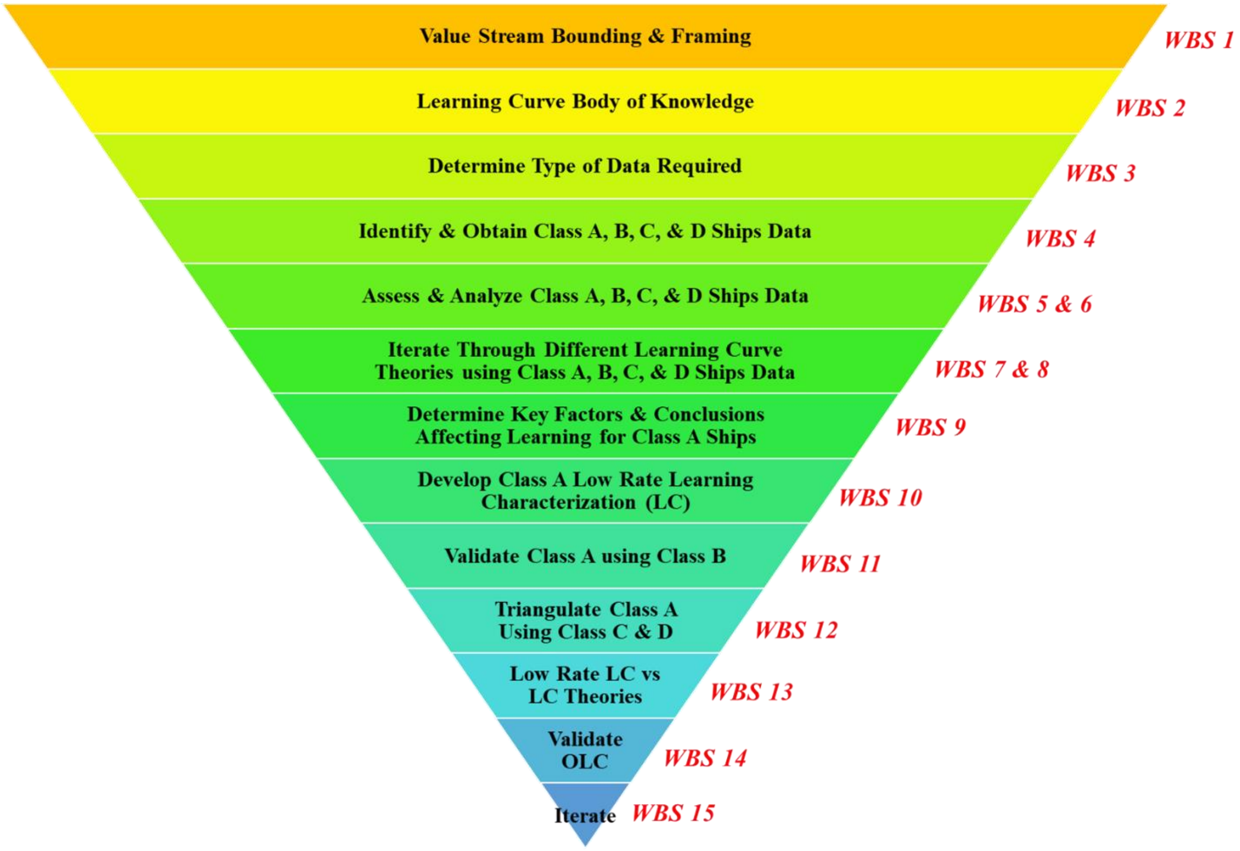

Figure 4: Low-Rate Production Learning Curve Characterization Research Methodology

As Figure 4 showed and consistent with a deductive mode of reasoning, the research methodology began with bounding and framing of this complex problem. This effort helped to identify the key entities associated with the value stream. It was also important to bound and frame the complex system prior to proceeding as this helped to ensure that a Type I, II, III, or IV error did not occur, as was covered previously. This was not to imply that bounding and framing this very complex problem was viewed as an over-arching activity, but rather, the bounding and framing focused the complex problem and system towards the intended research area. A more detailed understanding of the value stream entities as well as their associated connectivity was also a product of this effort. The source of the information that supported the bounding and framing was developed utilizing the various references herein.

After bounding and framing, a complete and thorough understanding of the learning curve body of knowledge was completed which validated that the current body of knowledge associated with learning curves did not address low-rate production environments. This effort has been validated, via the included literature review; however, to ensure a consistent and accurate literature assessment, the researcher developed a review methodology. It was important to emphasize that this was accomplished to not only triage and adjudicate each piece of literature, but to ensure a consistent and repeatable literature review assessment. In order to complete this knowledge assessment, a capture tool was created to ensure that there was a logical and consistent approach to adjudicate, index, and categorize each piece of literature reviewed. The literature review addressed the foundational learning curve theories, the theories that were developed after World War II through the 1990's, and those that were developed in the last thirty-two years.

As Figure 4 shows, the research then moved into the data phase. Only data and information that exists in the public domain was utilized to support this research. No proprietary data or information was utilized in the assessment or completion of this research. Due to this fact, the researcher captured public domain data associated with naval shipbuilding especially focusing on low-rate production ships. The details of this process are delineated in more detail in the succeeding sections. The data was then analyzed to determine the pertinent data that could be utilized to ultimately determine the key factors affecting learning in low-rate production environments.

After which, the researcher iterated through the different prominent learning curve theories, which included Wright's theory. Then, the researcher developed a learning characterization which was then assessed versus a different ship class and then triangulated versus two different ship classes. Lastly, the researcher iterated through the entire research methodology again to increase the robustness of the research realizing that emergence and system darkness were systems principles that reveal themselves as research progress, as discussed in Keating (2018) and Whitney, Bradley, Baugh and Chesterman (2015). Detailed below was a more in-depth discussion to delineate the research methodology.

## WBS 1 - Bounding and Framing and WBS 2 - Body of Knowledge

Value stream bounding and framing as well as addressing the learning curve body of knowledge was included with the research methodology because these two steps are crucial to the development of a shipbuilding learning curve characterization in a low-rate production environment. Naval shipbuilding is a very complex system with numerous complex problems. In order to ensure that the right problem was addressed, there must be an understanding of the context of the problem, and there must be an understanding of the current body of knowledge that addressed learning curves.  These two areas, which are captured via WBS 1 and WBS 2, provided the overarching understanding of the environment of this complex system as well as the who and what makes up the value stream, and what impacts and affects this value stream.  A strong foundation and understanding of the body of knowledge associated with this topic was also imperative as this establishes the baseline and foundation to support development of a unique learning characterization.

### WBS 3 - Determine Type of Data Required and WBS 4 - Identify and Obtain Class A, B, C, and D Ship Data

Next, the research methodology progressed into the data phase by determining the type of data required to support this research and assessing the available ship production data that resided in the public domain.  All of the research to date associated with learning curves utilizes Wright's (1936) data collection strategy, and then develops a learning curve based on Wright's work or utilizes elements of Wright's (1936) research to develop a learning curve for a given industry.  Using Wright's methodology inherently brings in the context of his empirical work and theories into the applications that were being analyzed.  As such, due to this fact, it was imperative to develop a collection and analysis methodology that anyone can follow and was also rooted in a low-rate production environment.  The development of a learning curve characterization of a low-rate production environment must be able to trace its origins to low-rate production data, which this research accomplished.

As such, the very first step was to ensure that the data collected was accurate.  As was just indicated, it was imperative that low-rate production data be obtained and utilized to develop a low-rate production learning curve. The low-rate production data collected by the researcher was secondary data because all of the data obtained to support this research was identified within the public domain, and most of the data was reported by various Government organizations. Due to this fact, the researcher accepted the data in the public domain as accurate. By definition, low-rate production has extremely long durations from a schedule and time frame perspective. The research was based on ship classes that have already been delivered or as was the case for one class of ships utilized, was in process of being produced. In either case, the same types of data outlined below was collected.

- Total Hours to Design and Build Each Ship
- Major Milestone Dates
  - Contract Dates
  - Keel Dates
  - Launch Dates
  - Delivery Dates
- Significant Changes
- Procurement Strategy
  - Number of Ships being Procured with each Contract
- Labor Profiles
- Workforce Demographics
- Customer Funding Profiles

The researcher did not include quality or safety type data because this type of data does not have a direct implication to learning in low-rate production environments. The researcher was not concerned by an inherent bias associated with dismissing this type of data because it was outside the scope of this research. Quality mistakes usually results in a number of different issues that must be resolved. Many of them result in increased production hours. The data obtained to support this research would then contain the hours spent recovering from quality issues through additional labor hours spent. However, as indicated, analyzing the impacts of quality and safety issues to learning curves was beyond the scope of this research.

In order to identify the data within the public domain for the four ship classes that were a part of this research, the researcher went through an exhaustive and very thorough review of literature in the public domain through numerous different sources that are referenced. All four of these ship classes were different in terms of their mission profiles; however, they all share a common fact that they were characterized as being produced in a low-rate production environment. As such, per the research methodology, different ship classes facilitated the characterization of learning in low-rate production environments. The data associated with Class A Ships was utilized to develop the learning characterization for low-rate production environments. Class B Ships was used to validate the characterization while Class C and D Ships was used to triangulate the characterization.

## WBS 5 - Assess and Analyze Class A Ship Data and WBS 6 - Assess and Analyze Class B, Class C, and Class D Ship Data

The research methodology then moved into WBS 5 and WBS 6, which focused on analyzing and assessing data that defines Ship Classes A, B, C, and D. The data that was assessed and analyzed was the data captured via WBS 4. The public domain data associated with these four ship classes provided information in regard to three categories of parameters associated with shipbuilding of: parameters supporting ship design and construction, parameters specific to shipbuilding but not to a specific class, and parameters not specific to shipbuilding, but were applicable to shipbuilding. The researcher indexed these parameters accordingly based on the data that was in the public domain. Within each of these categories, specific data associated with each ship class was assessed and analyzed, and is discussed via Chapters 4 and 5.

The ship classes were labeled as Class A, B, C, and D Ships because the actual ship class and its' associated mission was irrelevant to the research because each ship class is characterized as a low-rate production as defined within the Assumptions Section. In addition, the data within each ship class was also normalized so that relative relationships within each data set could be compared and analyzed accordingly. As per SCEA (2010), it states that "in order to develop a learning curve, we normalize this data" because "this data may be noisy." It also helps to simplify the assessment and helps to evaluate each graph within the same perspective.

### WBS 7 - Iterate through Different Learning Curve Theories using Class A Ship Data and WBS 8 - Iterate through Different Learning Curve Theories using Class B, Class C, and Class D Ship Data

Entering WBS 7, the researcher had framed the complex problem and bounded the problem accordingly. The researcher has now also understood the current body of knowledge, identified the type of data required, obtained it via the public domain for the given four ship classes, and analyzed the data accordingly per ship class. With this foundation, the researcher then applied the five leading learning curve theories (Wright (1936), Crawford (1944), DeJong (1957), Stanford-B (1949), and the Sigmoid S Curve (1973)) to this data so that a learning characterization of Class A, Class B, Class C, and Class D Ships could then be subsequently developed. Wright's Theory and Crawford's Theory, per Martin (2019) and Teplitz (1991) were the most common learning curve theories, and they have the largest use across all industries. As such, the researcher included Wright's theory and Crawford's theory to each of the associated graphs for comparison purposes. The remaining three learning curve theories, per Teplitz (1991), are primarily used to support cost estimating, but they can provide additional insights into learning, and they were DeJong, Stanford-B, and the Sigmond (S) Curves.

Per Lessig (2019), Capaccio (2020), and O'Rourke (2022), an eighty-two percent learning curve was applied to Class D Ships during the contracting process for those ships. The information within the public domain did not provide the contracted learning curves applied to Class A, B, or C Ships. However, since these four classes of ships are all low-rate production ships and since the DAU (2018) and Teplitz (1991) states that the learning curve associated with shipbuilding is between "80% to 85%", then for the purposes of the research, the researcher utilized an eighty-two percent learning curve to support all of the assessments herein. However, the overall learning curve characterization (OLCC) developed herein was not dependent on an eighty-two percent learning curve or any specific learning curve number because the OLCC developed was based on a low-rate production environment and not a high-rate production environment. The five fundamental learning curve theories presented were all based upon, as well as the learning curve theories that are extensions of these five theories, high-rate production environments.

### WBS 9 - Determine Key Factors and Conclusions Affecting Learning Utilizing Results from the Class A Ship Analysis

The researcher analyzed the Class A Ship data that was identified in the public domain to determine factors that affect low-rate production environments focusing on learning curves. The

Class A Ship data and information was utilized by the researcher as the baseline for this research and was utilized to ultimately developed the conclusions to support this research including the development of the learning curve characterization for low-rate production ships. Class B, C, and D Ship data was then utilized, which is captured via WBS 11 and WBS 12, to validate the conclusions derived from the Class A data. The researcher also utilized the results associated with bounding the complex system to also help to adjudicate the data. In order to organize the data, the researcher developed a table with the following information:

- Factors Affecting Learning
    - These were the various influences impacting learning.
- Source of the Parameters
    - Provides the reference(s) that identified the specific factor(s) affecting learning.
    - The Source of the Parameters was further broken into three principal groupings of:
        - Literature mentions learning and mentions shipbuilding,
        - Literature mentions learning but does not mention shipbuilding, and
        - Literature does not mention learning but does mention shipbuilding.
    - If there does not exist a literature source for the given factor, then the researcher identified that factor accordingly.
- Parameters
    - The parameters portion of the table provides additional information in regards to the factors affecting learning:
        - Provides the figure(s) that characterizes those specific factors affecting learning utilizing Class A Ship data, and

        - Provides the figure(s) that characterizes that specific factor affecting learning that is specific to Class B, C, and/or D Ships.
- High Level Grouping
    - The high-level grouping was a summary of factors affecting learning.

The net effect of this was a consolidated table developed by the researcher to assist the researcher in the adjudication of the many factors affecting learning curves so that the key parameters could be identified and analyzed.  This information then supported the development of another table which focused on those key parameters to then determine the conclusions that were associated with learning.  These conclusions were then used to assist with the development of the low-rate production overall learning characterization.  After both tables were presented, which were the Factors Affecting Learning Associated with Class A Ships and Conclusions in regard to Learning Associated with Class A Ships, the researcher then presented each parameter that affects learning associated with Class A Ships as well as the associated conclusions impacting learning curves.

### WBS 10 - Develop Class A Low-Rate Production Learning Curve Characterization

Using the conclusions associated with WBS 9, the researcher developed an overall learning curve characterization (OLCC) based on Class A Ship data.  The OLCC is comprised of five learning curve parameters defined by learning enablers and learning disruptors.  The five learning curve parameters were those that have been shown to be the most influential with respect to learning in low-rate production environments using Class A Ship data.  They were also the five that summarize and/or define a larger population of sub-parameters.  The learning enablers were defined in regards to elements of learning for an organization that supports efficient learning while learning disruptors were defined in regards to elements of learning for an organization that were experiencing a loss of learning.

The research methodology continues for this area by:

- defining the learning enabler(s),
- defining the learning disruptor(s),
- describing each OLCC learning parameter, and
- detailing the impacts to learning for each OLCC parameter.

As a side note, it was important to note that the researcher did not utilize the results of WBS 7 and WBS 8, which iterated through the five principal learning curve theories using Class A, B, C, and D Ships, when the researcher developed the OLCC. This was because the researcher did not want those assessments to impact the development of the low-rate production learning curve characterization, which was captured via the OLCC, based on Class A Ship data.

### WBS 11 - Validation of Class A Ship Data and Conclusions Using Class B Ship Data and Conclusions

In order to assess the conclusions derived from Class A Ships, Class B data and information gained from Class B Ships was assessed against Class A Ships. As such, to support this validation, conclusions derived from Class A Ships was shown with Class B Ship assessments to assist with the comparison and analysis. The researcher also developed a table which captures the figures that reflect the learning factors and their associated groupings. Just as was the case with the Class A Ships via WBS 9, the same two tables were developed, which were:

- Factors Affecting Learning Associated with Class B Ships and
- Conclusions in Regards to Learning Associated with Class B Ships

The same types of details were developed for these two tables as they were in WBS 9; however, the only difference was that these two tables for this WBS were for Class B Ships being compared to Class A Ships while the two tables captured in WBS 9 were only capturing the learning parameters for Class A Ships.

Utilizing the Class B Ship assessment, the researcher developed conclusions based on Class B Ships, and then compared the Class B Ship's conclusions to Class A Ship's conclusions to validate Ship Class A, which this was captured via a table in the same manner as WBS 9. The researcher then discussed in detail each conclusion that was derived from Class B Ship data and compares these conclusions to the Class A Ship data so that ultimately for each conclusion, the researcher determined if the Class A Ship conclusion was validated or not using Class B Ship conclusions derived from Class B Ship data.

### WBS 12 - Validation via Triangulation of Class A Ship Data and Conclusions by Using Class C and Class D Ship Data and Conclusions

In order to assess the conclusions derived from Class A Ships, Class C and Class D data and information gained from Class C and D Ships was assessed against Class A Ships. As such, to support this triangulation, conclusions derived from Class A Ships was shown with Class C and Class D Ship conclusions to assist with the comparison and analysis. The researcher also developed a table which captures the figures that reflect the learning factors and their associated groupings. Just as was the case with the Class A Ships via WBS 9 and Class B Ships via WBS 11, the same two tables were developed, which were:

- Factors Affecting Learning Associated with Class C and D Ships and
- Conclusions in Regards to Learning Associated with Class C and D Ships

Utilizing the Class C and D Ship assessments, the researcher developed conclusions based on Ship Class C and D, and then compared those conclusions to Ship Class A's conclusions to validate Ship Class A, which this was captured via a table in the same manner as WBS 9 and WBS 11. The researcher then discusses in detail each conclusion that was derived from Class C and D Ship data and compares those conclusions to the Class A Ship data so that ultimately for each conclusion, the researcher determined if the Class A Ship conclusions were validated or not by using Class C and/or Class D Ship conclusions which were derived from Class C and/or D Ship data.

### WBS 13 - Low-Rate Production Overall Learning Curve Characterization versus Learning Curve Theories

The research methodology for WBS 13 was to analyze the five leading learning curve theories to determine if they accurately predicted learning in low-rate production environments. As has been articulated, there were five leading learning curve theories, and they were:

- Wright (1936),
- Crawford (1944),
- DeJong (1957),
- Stanford-B (1949), and the
- Sigmoid S Curve (1973)

These theories are discussed in detail via WBS 7 and WBS 8. As such, the objective of WBS 13 was to simply determine if these learning curve theories characterize learning in low-rate production environments. This assessment then supported WBS 14, which was to validate the OLCC.

### WBS 14 - Summary Validation of the OLCC

The purpose of this WBS was to confirm the OLCC as the characterization of learning curves in low-rate production environments. In order to support this conclusion, the research methodology has been purposefully developed and executed as summarized below:

- As a result of the research executed via WBS 1 through WBS 6, the researcher
    - framed and bounded the complex system and problem and
    - obtained and analyzed public domain data covering four ship classes.
- WBS 7 and WBS 8 then applied five different learning curve theories to all four ship classes.
- Independently of the results of WBS 7 and WBS 8, the researcher, using only Class A Ship data, determined the key factors and associated conclusions involving learning in low-rate production environments, but just as indicated, only using Class A Ships. These conclusions became the baseline upon which Class B, C, and D Ships would be compared too so that these ship classes would be utilized to validate the conclusions developed from the Class A Ship data. This was the objective of WBS 9.
- Utilizing the results of WBS 9, which was the development of a set of conclusions utilizing Class A Ship data, a low-rate learning curve characterization was developed and presented via WBS 10.
- In order to validate the learning characterization derived via WBS 10, WBS 11 utilized Class B Ship data to validate the conclusions and characterization of the Class A Ship data.

- WBS 12’s purpose was to accomplish the same validation that WBS 11 completed, but to utilize Class C and Class D Ship data to validate through triangulation Class A Ship data.
- WBS 13 then utilized the results of WBS 7 and WBS 8 to assess the five leading learning curve theories prediction of learning in low-rate production environments versus the OLCC that was developed by the researcher via WBS 10 and validated by WBS 11 and WBS 12.
- As a result of WBS 13, WBS 14 was simply providing the OLCC that was developed using Class A Ship data, validated by Class B, C, and D data, and shown to characterize learning curves in low-rate production environments in a more comprehensive characterization as compared to the five leading learning curve theories.

This summary was provided herein to help convey the logic employed as well as to provide context to the purpose of WBS 14.

### WBS 15 - Iteration

WBS 15 was focused strictly on the researcher iterating back through the research methodology, as needed, to utilize what was learned while progressing through the research methodology to determine if additional areas and/or different areas need to be additionally investigated, researched, and/or analyzed. The researcher employed several different strategies to execute this including many systems engineering principles, and utilized the research completed by DeBono (1999) to support analyzing the research from different perspectives and viewpoints. The researcher also employed creativity and analyzed the complex system and problem from a paradoxical standpoint that the “system is not the system,” per Keating (2018) and Keating, Pyne, and Bradley (2015). The results of the iteration efforts by the researcher are delineated in Chapter 5.

# CHAPTER 4

# DATA COLLECTION, ANALYSIS, RESULTS, AND FINDINGS

This chapter focused on the results associated with implementing the Research Methodology outlined in Chapter 3. Chapter 5 addressed the conclusions associated with the results from this chapter. This Chapter was structured in a similar fashion as Chapter 3 in regards to progressing through each WBS area providing the results associated with implementing the specific research methodology associated with each WBS area.

## WBS 1 – Bounding and Framing

As was delineated via the Research Methodology, the execution of bounding and framing was imperative to ensure that the right problem was being solved to avoid a Type I, II, III, or IV error, per Keating, Pyne, and Bradley (2015). One of the fundamental goals of systems analysis was to be able to understand the control of the output(s) and outcome(s) associated with a system. As such, in order to be able to control the output(s) and outcomes(s) associated with each system, some sort of a control mechanism, which Ashby (1991) calls a regulator, must influence the system, and its' influence must at least match the influences and variety posed by the environmental disturbances impacting the system. Engineers, and others, design the control mechanism (regulator) to be able to influence the system to offset and/or counter the environmental or other disturbances impacting the system.

The implications of Ashby's Law were that the engineers and analysts performing systems analysis must be aware that variety can overwhelm the best designed system(s) even though the desire of the system was to maintain an equilibrium. Environmental perturbations can approach infinity and easily overwhelm the system. As such, the implication was that the feedback control (regulator) for that system must have a design strategy to deal with the almost infinite variety of internal and external perturbations. As such, the regulator has to be designed to handle broad bands of environmental perturbations, or the regulator has to be designed to disposition the inputs into similar groups thereby reducing the number of perturbations that the system has to contend with through the regulator. This in turn reduces the inputs to the system to reach equilibrium and to be able to achieve the desired outputs and outcomes.

All systems deal with variety, and as such, engineers can approach this variety in a number of different ways, Keating, Calida, Jaradat, and Katina (2018). Systems can self-organize, or they can be purposefully designed. The implication was that the engineer and/or analyst can purposefully design the regulator to get the desired outcomes and outputs and deal with the variety via internal organization. It must also be realized that a system that was allowed to self-organize will always organize to the state that requires the least amount of energy, which for a man-made system was usually not optimal or desired, Keating, Calida, Jaradat, and Katina (2018). These are crucial concepts because these will be key to understanding and embracing the context of learning curves in low-rate production environments such as shipbuilding. With this understanding of Ashby’s Law of Requisite Variety, it was applied to this research to support learning in low-rate production shipyards, as shown in Figure 5.

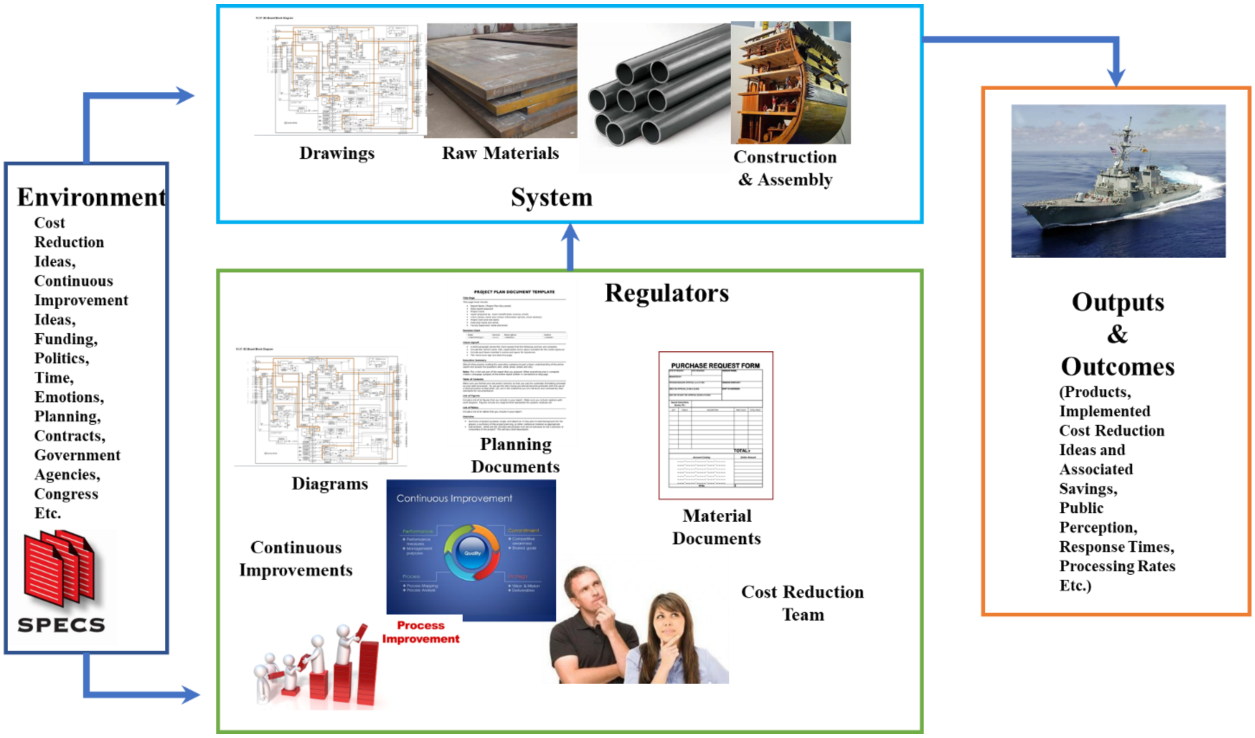

Figure 5: Ashby’s Law of Requisite Variety Applied to Learning in Low-Rate Production Shipyards.

## Ashby’s Law of Requisite Variety - The Environment

The environment impacting learning curves, within the shipbuilding environment, was varied and was constantly changing due to many factors. Due to the long durations associated with low-rate production ships, the customer infuses changes into each ship so that each ship delivered was as modern as possible. This obviously creates challenges in construction, and it created challenges associated with having a consistent baseline to develop and measure learning, meaning the baseline was also shifting. There was a limited number of methods, materials, manpower, minutes, money, and information, (M5I) that was available to support ship construction and to support improvement and learning efforts. A learning and improvement strategy must take this into consideration. The environment that was pressing on the system and the regulators were also defined by internal politics, external politics, shareholders, and actually the political process through Congress, the Department of Defense, and the other branches of the military.

### Ashby's Law of Requisite Variety - The System

The actual system that learning was trying to influence was the sub-systems and processes that support ship construction as well as the documents and efforts to put the ship into full production, which was then utilized by people to build the ship. In addition to the drawings and other documents needed to support ship construction, the system was also defined by the raw materials, manufacturing, production, construction, assembly, and testing processes. As Ashby's Law very astutely shows, the environment was acting on and pressing on the system. Specifically, in regard to learning, the environment was pressing on the system through schedule, budget, Congressional pressures, Navy mandates, Government laws and regulations, etc.

There were numerous regulations and standards that shipyards have to comply with. Those too presses upon and shapes the system directly. The environment was also impacting assembly and construction based on the fact that the shipyard's facilities were limited by funding which then affects production rates.

### Ashby's Law of Requisite Variety – Regulators

As discussed earlier, the role of the regulators was to match the changes and disturbances of the environment. A corollary to this was the fact that the regulators should be purposefully designed to handle and deal with the changes in the environment and associated disturbances, Ashby (1991). The drawings and ship construction related documents were impacted by the specifications that were developed by the Navy, which also has competing priorities between the Navy operators/war fighters, the technical community within Navy, the Program Offices within the Navy, Navy Contracts, and Navy regulations. The first step towards ship construction was to translate the specifications for the ship into a set of system diagrams that conveys what the final ship should be. This then leads to the development of planning documents which then dovetails into material documents to order material. Regulators have challenges adjusting to the environmental disturbances which subsequently impacts learning curves and learning efforts. A good example of this was the Government shifting funding year over year to fund various emergent needs, new funding priorities, or shifts to pay for other competing priorities. The point is that the shipyard's value stream that was working together to prepare for construction and to support construction has to constantly shift as the environment continually changes. All of this was occurring while ships were being put into production.

### Ashby's Law of Requisite Variety – Outputs and Outcomes

The system, which has been influenced by the environment and by the regulators, then produces a set of outcomes and outputs. The outputs range from a delivered ship to a set of lessons learned that were implemented on that particular ship. In terms of outcomes, these range from a very satisfied crew and Navy customer to a poor public opinion because the delivered ship did not meet certain parameters.

Figure 6 is a system diagram that was developed by the researcher to convey the problem and the domain that the system resides within. Figure 6 is representative of the naval ship construction environment.

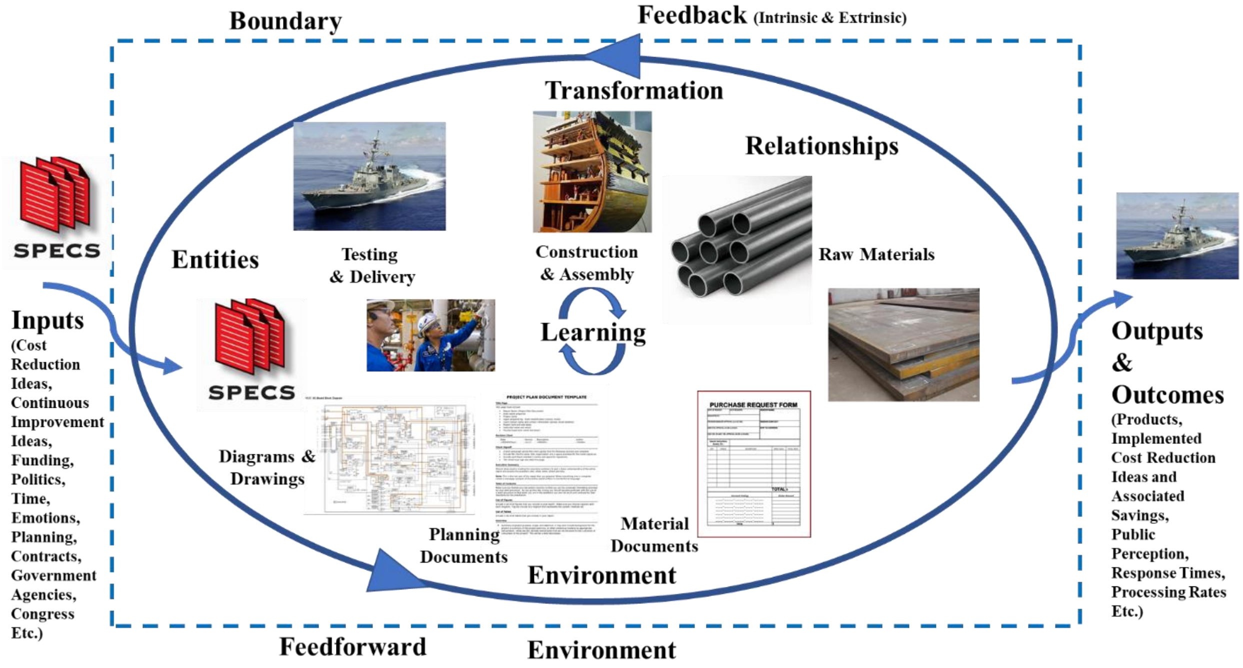

Figure 6: System Diagram of the Naval Ship Construction Environment

In order to explain the system diagram of the learning culture associated with naval shipyards, the requirements associated with a system are discussed herein, which are: boundaries, entities, inputs, outputs, outcomes, environment, transformation, feedback, and relationships.

Boundaries

The assessment of boundaries was very challenging, especially given that this systems analysis was a complex problem and considered a wicked problem.  While trying to select the appropriate boundary, consideration was also given to the fact that there was not a single best solution to a complex problem.  The only reason that this was being mentioned now was simply due to the fact that a poor choice in boundary selection can and will directly influence the outcomes and outputs and influence the systems analysis.

It was very important not to just arbitrary select a boundary.  Defining boundary conditions, and specifically determining the criteria for inclusion and exclusion facilitated a more robust systems analysis describing the learning environment at low-rate production shipyards. As such, it was important to establish the criteria to select and establish the boundary of this complex system as well as what was included and not included.

- The boundary included:
    - The principal documents supporting ship construction.
    - The departments that directly or indirectly build the ship called production trades and service and support departments.
    - The various shops, lay down areas, construction and production areas, and manufacturing areas.
    - The waterfront location that supports construction, assembly, test, and delivery.
    - The associated policies and procedures.
    - The technologies and strategies that are employed to support ship construction as well as to support learning.
- The boundary will not include:

  - It did not include the Navy organization that was outside the physical boundaries of each shipyard as well as the various Navy entities.
  - Public shipyards involved in repair and refurbishment.
  - Vendors that provide products to support ship completion.
  - All sub-contractors that were involved with ship production and/or delivering products that were used to complete ship construction.

The challenge was that the boundary set for this analysis was large; however, the more that was excluded then the greater the error will be associated with the analysis. It should also be stated that over time, systems will become more complex and/or evolve meaning the systems analysis will have to evolve over time, which was why the research methodology employs an interactive step at the very end to go back through each of the WBS steps to verify that new knowledge gained may reveal additional factors to consider. As such, lastly, it is important to point out that a perfect boundary can never be established for a complex system, especially for a highly complex system such as this.

## Entities

Entities were the components and/or units that makes up the system. They were the individual piece parts that defines the system within the boundary to support the systems analysis. There were numerous entities associated with this system, which by definition, was another characteristic of a complex system and one that was dynamically complex as well. It was also important to point out that the interactions between the entities of the system will reveal behavioral and structural patterns that make and define the system. From a system view perspective, entities, which were inter-related will organize in some form or another to transform resources into outputs and outcomes. This does not mean that they were desired outputs and/or outcomes, but rather that the entities will consume resources to do something.

Internal entities associated with learning at shipyards was based on the boundary that has been established for this assessment, and they were:

- The Shipbuilders
    - The people who design, plan, manufacture, assemble, test, and deliver ships.
- Training Organization
    - The core group of folks who were charged with training and skill development.
- Principal Departments
    - The departments, associated people, policies, and procedures that make up those Departments.
    - There were eight main trades identified that construct ships at shipyards
        - Fitters
        - Welders
        - Electricians
        - Sheet Metal
        - Painters and Insulators
        - Piping
        - Machinery
        - Riggers
    - There were numerous departments that support Ship Construction called Service and Support Departments, such as
        - Test

        - Engineering
        - Quality
        - Safety
        - Inspection
        - And so on.
- Technologies
    - The new technologies and technology insertions that were installed on the ship during construction.
- The Ship Design
    - Not every ship design that was built by a shipyard was actually “owned” by that shipyard in terms of making changes to the design to support ship construction including the incorporation of lessons learned.
- The Build Plan
    - The build plan was the strategy to support ship construction, and it was a conduit to support and transfer learning.
- The Procurement Strategy
- Processes
    - This was aimed at all processes that were employed to support construction, and can be a source of not only learning but the capture of lessons learned.
- Tooling
    - The tools used to construct and build ships at shipyards, and was also a source of lessons learned.

External entities associated with this system was based on the boundary that has been established for this assessment by the researcher

- The Navy that exists outside of each shipyard.
- The Ship Specifications that were determined by the Navy.
- The Public who has their own perceptions in regards to the products that each shipyard delivers.
- Congress and the Department of Defense who has their own perceptions in regards to the products that each shipyard delivers.
- The sailors who were the crew for each newly delivered ship.

Input(s)

As a complex system, there were several inputs to the system, such as

- Cost Reduction and continuous improvement ideas which originate from learning.
- Funding
    - Funding always influences a system, and was an inflow to the system.
    - The funding that was being referenced here was the funding to support all aspects associated with construction of ships at low-rate production shipyards.
- Training
    - Training was provided to the shipbuilders to support the principal aspects associated with their jobs.
- Time
    - Schedule and meeting schedule was always a key performance parameter.
- Politics/Politicians

    - Shipyards have a number of political influences at the local, state, and federal levels.
    - There were also political influences within the Navy, Pentagon, Department of Defense, and other branches of the service. Some have competing priorities, and all of them are pushing their perspective(s) on their constituents.
- Various Government Departments
    - There are a number of Government Departments, inspectors, auditors, and contractual representatives who were reviewing shipyard activities.

<u>Outputs</u>

Outputs associated with this complex system include

- Data
    - Similar to all complex system problems, there were numerous amounts of data.
- Products:
    - The ships that were built and delivered.

<u>Outcomes</u>

Outputs were tangible, like those listed above, and they were meeting specific requirements. Outcomes were not tangible and were not verifiable, and they were about meeting expectations. Outcomes can also influence the problem, and they can directly influence perceptions. Outcomes associated with learning at low-rate production shipyards:

- Public Perception
    - Public perception was shaped by the actions of each shipyard plus the perceived actions of each shipyard. Learning curves impacts the successful delivery of each

    ship, and it affects the final costs associated with each ship, which in turns influences what was reported to the public through various media outlets.

- Navy Perception
    - Navy perception was influenced by not only how a shipyard performs, but also the politics and perceptions associated with the programs for each class of ships and the perception of the success associated with each ship built at a given shipyard.

<u>Environment</u>

Environment was crucial to this system.

- The low-rate production shipbuilding environment was very tough and challenging.
- Most shipyards have a long history, and they have evolved overtime, and as such, they were not necessarily based on a serial flow path to support production, which has the potential to impact learning.
- The environment associated with shipbuilding was very challenging and tough, and it can also be hot, cold, dirty, and very physical.

The areas listed above were tangible environmental elements associated with this system. There were also some intangible environmental elements too, such as:

- Despite the fact that the environment associated with shipbuilding was very physically demanding, it was also very rewarding by knowing that each shipbuilder is contributing to the construction of each ship.
- The environment surrounding ship construction, testing, learning, and making improvements was very tense.

## Transformation

The entities within the boundary of the system were all interacting to transform the inputs into outputs and outcomes. The core of system of systems engineering was establishing a systemic understanding of the problem to be assessed and resolved. Transformation was the process that an integrated complex system takes inputs, adds resources, and produces desirable results.

The transformation that occurs was one that was desired in terms of delivering a completed ship to the Navy; however, other tangible factors associated with the ship may not be obtained such as the desired cost or desired delivery date. Learning and incorporating lessons were key enablers to alleviate these issues, and as such, were addressed in Chapter 5. It should also be pointed out that there were also some very straightforward transformations that were occurring as raw materials were being worked, machined, cut, adjusted, and so forth to convert raw materials into a finished product. This was a form of transformation that should not be overlooked because learning was at the core of these efforts.

Complex systems can only produce what they were going to produce, which is called the law of consequent production (Keating, 2018). As such, it would be unrealistic to expect a given shipyard and associated learning program to produce outputs and outcomes different than what it was producing without altering the transformation that was occurring. The processes and procedures that support the transformation of the inputs to outputs were also not fully integrated such that they become competing priorities, especially within low-rate production shipbuilding. Meaning, trying to support and meet schedule was often times contradictory to meeting budget, and in the same manner, may also be contradictory to implementing lessons learned as well as a robust learning culture.

## Feedback and Feedforward

Feedback was crucial to the successful operation of the system so that behaviors can be adjusted to ensure that the intended mission and game plan were being met. Feedforward was also crucial especially in an environment that was rooted in ship production. At most shipyards, feedback associated with learning was usually provided verbally, which different organizations try to capture. The feedback was usually based on if the particular lessons learned was in fact implemented on the forecasted ship to receive the change or if a different ship was able to capture the change accordingly.

In terms of feedforward, this process was more formalized from a learning perspective as lessons learned were “pushed forward” to ships that were built in the future. The biggest challenge was making these changes to the various planning and engineering documents that exist to support ship construction within the funding strategy associated with each ship.

It was important to also put forth that a unique research methodology was required to be able to solve this complex systems problem, and not to try to solve the symptoms or complaints or the politics associated with it, which was captured via the Research Methodology contained within Chapter 3.

## Relationships

Like most things in life, relationships were key to success. For this system, there are many relationships such as:

- Department to Department
- Shipbuilder to Shipbuilder
- Craft Trade to Foreman

- Craft Trade to Construction Supervisor
- Program Office to Departments
- Program Office to Navy

In terms of covering the framing and bounding of the system, the learning environment within low-rate production shipbuilding was truly complex. Bounding the problem was crucial to prevent a Type III error, solving the wrong problem very efficiently. This complex system has the potential to also be considered as a Type IV error, from the perspective of the number of philosophical differences between the various customers associated with naval shipbuilding and the shipyards that build those naval ships.

### WBS 2 – Body of Knowledge (Summary)

As discussed as a part of the research methodology, a strong foundation and understanding of the body of knowledge associated with this topic was imperative as this establishes the baseline and foundation to develop a unique learning curve characterization. The literature review was based on a complex problem including bounding and framing the system and system of systems. A summary of the learning curve body of knowledge was delineated below, which spans over one hundred years. The more detailed literature review was located within Chapter 2.

The foundation upon which most of the learning curve research was based on was written by Wright in 1936 through articles published in the *Journal of Aeronautical Sciences*. Wright's (1936, 1943) focus was on airplanes and their serial production thereby developing the associated learning curves for these planes. His efforts established the foundation associated with learning curves. Thurstone (1917) discussed learning curve theory prior to Wright; however, Wright, as already delineated herein, is the recognized expert in learning curve theory as well as being credited as the “Father” of learning curve theories. Crawford’s (1944) theory compliments Wright’s theory by developing the individual unit curve theory whereas Wright (1936) developed the cumulative average curve theory and the theory that for every doubling of a production quantity made, then there will be a linear reduction in time to produce the given product due to learning. Thurstone (1917) focused on experience gained through learning and that doing the same thing over and over again would yield a reduction in time to do that specific job or task. Crawford and Strauss (1947) also theorized that labor learning was not a function of speed of work completed, but how a worker approached the job from a body position standpoint and how quickly they learned that position as well as their ability to repeat that over and over again. Berghell’s (1944) theory still utilizes aircraft, but his theory was based on the weight of the aircraft to estimate hours to build as part of a cost estimating relationship. As was discussed, Middleton’s (1945) theory assess learning through the pounds of aircraft produced versus the number of aircraft produced over time. Waterworth (2000) also covered airplane production leaning curves, but he emphasized that Wright’s (1936) learning curves were based on empirical data. Moore (2015), through the US Air Force, also discussed learning curves associated with airplane production, specifically for the F-15 C/D & E models. He utilized the learning curve model developed by Wright (1936) along with the DeJong learning formula, and the S-Curve model to analyze the production of the F-15. The results of his study were inconclusive, but he did determine that the percentage of the production processes that were automated does impact learning curves. Goldberg (2003) focused on learning curves as a function of high-volume lot productions for tactical missiles and the F-15E Program. Goldberg (2003) was writing from the perspective of the Center for Naval Analysis - Cost Analysis and Research Division. He discussed the uses of various models and cost estimating relationships (CER). However, he only covered large lots where individual units of each lot were not separately priced. His work does add value to the body of knowledge associated with learning curves; however, naval shipbuilding was focused on individual ship costs even though a set of ships may be contracted together in a lot, block, or flight. Lee (2014), while working for Strategos Corporation, wrote about learning and learning curves associated with manufacturing and marketing. He stated that math was not necessary to understand learning within a manufacturing environment, which in a shipbuilding environment was not the case. He did espouse that shipbuilding should experience a 15-20% learning curve; however, he did not offer how that was calculated or determined. He also stated that learning was not "pre-ordained" meaning there is nothing requiring learning to even occur. Spicknall (1995), via the Society of Naval Architects and Martine Engineers, writing for the Naval Surface Warfare Center Carderock Division, covered learning curves in small and large North American commercial shipbuilding companies. Spicknall (1995) stated that future performance does not depend on past production volume and performance, which in the naval shipbuilding environment has not been the case. He continues by covering that the market will dictate learning and performance improvements, and that price, delivery time, and quality was actually dictated by each company. In a commercial shipbuilding environment, this may stand to reason; however, the naval shipbuilding environment has other factors involved, which this research has discussed. Sokri and Ghanmi (2017) espoused that learning curves in defense projects will eventually remain constant over time called saturation, and they will not approach zero. His paper was focused on using a statistical analysis to estimate the distribution of the steady state value. Sokri and Ghanmi (2017) felt that learning was a type of risk defined as a measure of the potential variation in achieving efficiency in production. He does cover negative learning or "forgetting" due to breaks in production or changes in personnel and methods. This was applicable for naval shipbuilding, and was covered herein. In 2018, the Congressional Budget Office (CBO) provided a high-level methodology to adjust costs based on the rate of learning and the acquisition strategy from a CBO perspective. The CBO (2018) stated that the slope of the learning curve will vary by ship type based on complexity of the ship, but the slope of the learning curve will continue through each class of ship.

Deschamps and Greenwell (2019) did not focus on learning curves; however, they did cover cost drivers. There focus was on outfitting density and concluded that the denser a ship was then the higher the production costs. Jablonowski, Ettehad, Ogunyomi, and Srour (2011), through the Society of Petroleum Engineers, questioned the use of learning curves. Obviously, drilling a well was very different than building a naval ship.

There were some handbooks that address learning curves too. The DAU (2018) states that the learning curve for shipbuilding was between “80-85%”, but they do not offer justification for this range. The DAU also acknowledged that the learning curve was usually an issue during contract negotiations. Cobb and Cullis (2010), through the Society of Cost Estimators and Analysis, recognizes Wright and Crawford, and as such, they espoused using historical data to forecast future costs based on Wright’s and Crawford’s learning curve theories. The *NASA Cost Estimating Handbook* (2015), stated that applying learning curves to the space sector were “questionable”, and they did not offer any other explanation. The *NAVSEA 05C Cost Estimating Handbook* (2005) also acknowledged the use of Wright’s and Crawford’s theories, and it stated that the learning curve slope for shipbuilding is between 80% to 93%, and similar to the DAU (2018), they did not offer a substantiation to their claim. The *GAO Cost Estimating and Assessment Guide* (2009) also stated that learning curves should be extrapolated from actual costs. The Office of the Parliamentary Budget Officer for Canada in 2016 stated that they use the theories espoused by Wright and Crawford.  Lastly, the Parametric Estimating Handbook (2008) also implied the use of Wright and Crawford.

In summary, the researcher has confirmed that there was gap in the body of knowledge associated with learning curves specifically addressing the low-rate production of naval ships, which was reflected in Table 3.  The literature review has been completed to validate the gap in knowledge.

## WBS 3 – Determine Type of Data Required

As has been previously covered, the data to support this research was obtained from the public domain.  One of the contributions to the body of knowledge associated with this research was the development of a research methodology that was based on low-rate production, and specifically, public domain data involving the construction of low-rate production ships.  Low-rate production was defined within the Assumptions Section of this research.  Low-rate production was not defined in the public domain.  However, it was only defined from the perspective of “low-rate initial production”, as delineated by Reed et al. (1993), Defense Acquisition University (2021), and DoD INST 5000.02 (2020), simply meaning the initial production of a given commodity, which would include various milestones throughout the design and construction of the commodity, as delineated by Misra (2015) and Corporate-Tech Planning, Inc. (1978).  It was also mentioned by Abbott (1997), and he only mentions “low productivity rates” at it relates to the competitiveness of US shipyards as compared to other shipyards throughout the world.  He was not addressing low-rate production from a manufacturing and learning curve perspective.  The data and associated assessments made were based on data that exists within the public domain.  No proprietary data was utilized during the completion of this research.

The researcher has completed numerous searches to identify applicable data that was in the public domain and has used this information to support this research.  As was indicated, it was imperative that low-rate production data be obtained and utilized to develop a low-rate production learning characterization, which this was another contribution to the body of knowledge associated with this research.

Table 6 provides the principal data to support research in low-rate production environments.  Table 6 also provides a description and details for each principal data element; however, most importantly, it provides the relationship that each parameter has with this research.  In order to identify the parameters delineated in Table 6, the researcher utilized Trochim & Donnelly (2007) and Gliner, Morgan, & Leech (2017) to help guide the data that was collected in the public domain.  Specifically, after analyzing the system boundaries, the complex system itself, and the data, Table 6 was developed to guide the type of data required to support the objective of this research.

| Parameter | Description | Details | Relationship to Research |
|---|---|---|---|
| Labor Hours | Total Hours to Design and Build each Product | Consists of Production Hours; Engineering and Planning Hours; All Hours Associated with the Delivery of the Final Product | This research was focused on learning in low rate production environments with emphasis on labor hours. |
| Dates | Major Milestone Dates | Contract Dates, Manufacturing and Production Dates, Delivery Dates, and Other Key Acquisition Dates | These dates provided insights in terms of durations to achieve key acquisition milestones associated with each product. In addition, the key dates provided a context for the labor hours. |
| Changes | Significant Changes | Principal Changes Impacting the Product Itself | Significant changes alter the baseline which could increase the challenges associated with learning. |
| Procurement Strategy | Number of Completed Products that are Procured with each Contract | Procurement Strategy coupled with the Duration of Key Milestones | This defined the quantities associated with each low rate production of a specific product. This was the essence of this research especially given the fact that research into low rate production environments did not exist until now. |
| Labor Profiles | Defines the Principal Labor Elements associated with Production | Principal Labor Elements equates to, for example: Welders, Engineers, Pipe Fitters, and Other Manufacturing, Production, and Construction Trades | The focus of this research was on labor hours; as such, an understanding of the labor skills mix provided insights into the learning dynamics across the various labor skills to support low rate production environments. |
| Workforce Demographics | Provides the Age Profiles across a Given Workforce | Age Profiles were Grouped in Increments of 5 or 10 years | Certain profiles were more conducive to transferring knowledge then other profiles thereby directly impacting learning. |
| Learning | Knowledge Management and Retention | Will Provide Insights into Learning Retention and Durations | This provided insights into the affects of long durations between the use of skills. |

Table 6: Types of Data Required to Support This Research

Table 6 provided the high-level parameters and associated descriptions of each parameter. Table 7 expands Table 6 to also reflect the specific parameters that were obtained through various sources that were available via the public domain.

## WBS 4 – Identify and Obtain Class A, B, C, and D Ship Data

Table 6 provided the key parameters and their relationship to this research so that data associated with learning in low-rate production environments can be identified, obtained, and analyzed to obtain new knowledge in this area of research. As was also indicated, one contribution associated with this research was to implement a research methodology that has as its' core using data from low-rate production environments to then characterize learning accordingly. As has been delineated, research, until now, utilized data that was based on high-rate production environments to then characterize various complex systems. The focus of WBS 4 was to obtain the data, which was in the public domain, and provide it herein. Due to the fact that the researcher focused only on data that was in the public domain and due to the fact that this research was also focused on low-rate production environments, specifically naval ships, then the researcher identified and obtained data from four different ships classes that was in the public domain. The types of data were delineated by Table 6 and expanded further into Table 7. As indicated, Table 6 provided the principal parameters to guide researching the information contained within the public domain. This effort then led to identifying data that were subsets of the parameters delineated by Table 6. The further decomposition of these parameters led to the development of Table 7.

The data associated with four different ship classes was researched and identified accordingly. All four of these ship classes were different in terms of their mission profiles; however, they all share a common fact that they were characterized as being produced in a low-rate production environment. As such, per the research methodology, different ship classes will help to facilitate the characterization of learning in low-rate production environments. The data associated with Ship Class A was utilized to develop the learning characterization for low-rate production environments. Ship Class B was used to validate the characterization while Ship Classes C and D was used to triangulate the characterization.

| Type of Parameter | Parameter | Description | Details | Relationship to Research |
|---|---|---|---|---|
| Ship Design and Construction | Labor Hours | Total Hours to Design and Build each Product | Consists of Production Hours; Engineering and Planning Hours; All Hours Associated with the Delivery of the Final Product | This research was on learning in low rate production environments with a focus on labor hours. |
| Ship Design and Construction | Construction Schedule Milestones | Major Milestone Dates | Contract Dates, Manufacturing and Production Dates, Delivery Dates, and Other Key Acquisition Dates | These dates provided insights in terms of durations to achieve key acquisition milestones associated with each product. In addition, the key dates provided a context for the labor hours. |
| Ship Design and Construction | Changes | Significant Changes | Principal Changes Impacting the Product Itself | Significant changes alter the baseline which could increase the challenges associated with learning. |
| Ship Design and Construction | Procurement Strategy | Number of Completed Products that are Procured with each Contract | Procurement Strategy coupled with the Duration of Key Milestones is the Focus of this Research | This defined the quantities associated with each low rate production of a specific product. This was the essence of this research especially given the fact that research into low rate production environments did not exist until now. |
| Ship Design and Construction | Labor Elements and Profiles: Production | Defines the Principal Labor Elements and Profiles Associated with Production | Principal Labor Elements equates to, for example: Welders, Electricians, Pipe Fitters, and Other Manufacturing, Production, and Construction Trades | The focus of this research was on labor hours; as such, an understanding of the labor skills mix provided insights into the learning dynamics across the various labor skills to support low rate production environments. |
| Ship Design and Construction | Labor Workforce by Major Systems | Defines the Principal Labor Workforce by Major Systems | Principal Major Systems: Hull, Machinery, Electrical, Communications, Auxiliary Systems, Outfitting | The focus of this research was on labor hours; however, an understanding of the major systems provided insights into areas of focus. The distribution across different low rate production ship classes were similar. |

Table 7: Description and Details of Parameters Providing Insights into Learning in Low-Rate Production Environments

| Type of Parameter | Parameter | Description | Details | Relationship to Research |
|---|---|---|---|---|
| Ship Design and Construction | Labor Elements and Profiles: Non-Production | Defines the Principal Labor Elements associated with Non-Production oriented Areas | Non-Production Areas: Engineering, Administration, Designers, Management, Construction Support, Production Support | All ships require support from non-production areas; as such, these areas would have a direct relationship to learning in low rate production environments. |
| Ship Design and Construction | Funding Profiles | Provides the Timing of the Funding in relationship to the construction cycle | Relative funding as a function of timeframe for low rate production | The focus of this research was on labor hours and not funding. However, funding was the conduit to labor hours, which would provide insights into the potential opportunities associated with learning. |
| Specific to Shipbuilding but Not to a Specific Class | Workforce Labor Demographics: Shipbuilding | Provides the Age Profiles across a Given Workforce | Age Profiles were Grouped in Increments of 5 or 10 years | Certain profiles may be more conducive to transferring knowledge than other profiles thereby directly impacting learning. |
| Specific to Shipbuilding but Not to a Specific Class | Output per Employee: Shipbuilding | Provides Output per Shipbuilder | The average output per shipbuilder is over a twenty year span | This research focused on learning, and a shipbuilders output was related to learning. |
| Not Specific to Shipbuilding, But are Applicable | Output per Employee: Aircraft and Automotive Industries | Provides Output per Two Other Large Industries | The average output per employee associated with the automotive and aircraft industries over a twenty year span | Automotive and aircraft manufacturing were high rate production environments. These industries provided a basis to compare and contrast to low rate production shipbuilding. |
| Not Specific to Shipbuilding, But are Applicable | Learning Retention | Provides Insights into Learning Retention | Retention of information learned declines dramatically over time | In order to put into practice information that has been learned, retention has to occur and/or strategies must be put in place to increase retention. |
| Not Specific to Shipbuilding, But are Applicable | Learning Efficiencies | Shows Work Efficiency Related to Years of Work Experience | Offers insights into the number of years of experience that must be gained to become proficient | It takes years of experience to gain proficiency; as such, gaining experience in a low rate production environment would extend the time frame to garner that experience due to long cycle times. |

Table 7 (continued)

Table 7 provided the details associated with each parameter that provided insights into learning in low-rate production environments as they relate to four different ships classes. The data and subsequent information developed was obtained through an extensive research process, and the result of that process was delineated below in more detail.

## Parameters

Table 6 provided a high-level summary of the types of the types of data required to support this research. Before presenting the data that was harvested from the public domain by ship class, an understanding of each major parameter that defines each ship class was also summarized via Table 7. Three principal parameters were identified, and they were:

- Parameters Supporting Ship Design and Construction,
- Paraments Specific to Shipbuilding but Not to a Specific Class, and
- Parameters Not Specific to Shipbuilding, but were Applicable to Shipbuilding

## Parameters Supporting Ship Design and Construction

The parameters, and associated data, for ship design and construction that were identified and obtained, as shown in Table 7, were:

- *Labor Hours*
    - Description: Hours to design and build each ship for each ship class. This includes production hours, engineering hours, planning hours, and all non-production hours.

  - Relationship to Research: This research was focused on learning in low-rate production environments with a focus on labor hours. As such, this information was core to this research effort.
- *Construction Schedule Milestones*
  - Description: These were key milestones related to the construction of ships such as the contract award date, the keel and launch dates, and the delivery date for each ship.
  - Relationship to Research: These dates provided insights into the durations between major milestones. This information, within the context of the labor hours expended to produce each ship of the four ship classes, provided insights into learning in low-rate production environments.
- *Principal Labor Elements and Profiles associated with Production*
  - Description: The principal labor elements were those core trades or construction and production skills required to build ships. These include skills such as: welders, pipe fitters, electricians, and other skilled trades. The profile aspects of this parameter provided the labor needs for given skills over time as well as the variance of that specific labor skill over time.
  - Relationship to Research: An understanding of the labor skills mix and variety provided insights into the learning dynamics across various labor skills. This also revealed trade skill areas of focus.
- *Principal Labor Elements and Profiles associated with Non-Production and Construction*
  - Description: These were principal labor elements associated with non-production and/or non-construction labor activities. These included skilled positions such as:

  engineers, designers, planners, construction support, and other skills that were required to support ship construction, but they were not directly involved with ship construction or production.
  - Relationship to Research: The construction of all ships required support from non-production and/or non-construction areas. These areas also directly impacted learning in low-rate production environments, and since many of these skills occur early in the value stream, they can more directly impact production and construction which was later in the value stream.
- *Labor Workforce by Major Systems*
  - Description: This parameter defined the principal labor workforce as a function of major systems associated with ships.  Principal major systems associated with ships and subsequently shipbuilding was hull, machinery, electrical, communications, outfitting, and other major systems.
  - Relationship to Research: An understanding of the major systems associated with ships provided insights into areas of focus as related to various production related skills.
- *Funding Profiles*
  - Description: This parameter showed the funding and timing of funding for each ship of a given ship class.
  - Relationship to Research: As has been indicated, the focus of this research was on labor hours and not funding.  However, funding is the conduit to labor hours.  As such, a basic understanding of the funding and timing of the funding provided

    visibility into the opportunities associated with learning and/or the associated challenges.

- *Procurement Strategy*
    - Description: Procurement strategy was an understanding of how many products (ships) were purchased with each contract. The procurement strategy was determined by the customer and associated contracting strategy.
    - Relationship to Research: This parameter defined the quantities associated with each product produced, which by definition were very low and as such, were reflective of a low-rate production environment. This parameter also highlighted if more than one ship was procured at a time, which also provided insights into the research area of interest.
- *Changes to the Ship Baseline*
    - Description: Changes to the ship baseline were significant technical changes or significant construction changes to a given ship as compared to the preceding ship and/or the first ship of the class.
    - Relationship to Research: These changes alter the baseline of the ship class thereby directly impacting learning from one ship to the next ship of the same ship class. Changes increased the challenges associated with learning from ship to ship or even product to product.

### Parameters Specific to Shipbuilding but Not to a Specific Ship Class

Other parameters that were identified and obtained, but were not specific to a ship class but do provide insights into the field of shipbuilding were, as shown in Table 7:

- *Shipbuilding Workforce Labor Demographics*
    - Description: This parameter provided the age profiles across the shipbuilding workforce. The age profiles were usually grouped in increments of five to ten years.
    - Relationship to Research: Certain labor profiles were more conducive to transferring knowledge as compared to other profiles thereby directly impacting learning from a certain age demographic to the next age demographic as defined by a given profile.
- *Output per Employee - Shipbuilding*
    - Description: This parameter provides a notional assessment of output per shipbuilding employee over a twenty-year time frame.
    - Relationship to Research: A shipbuilder's output was related to learning and learning retention. As such, a basic understanding of output per employee provided insights into low-rate production learning especially coupled with other parameters.

### Parameters Not Specific to Shipbuilding, but are Applicable to Shipbuilding

Given the complex system of systems associated with shipbuilding, the researcher identified and obtained other parameters that were not specific to shipbuilding, but were applicable to shipbuilding, as shown in Table 7:

- *Learning Retention*
    - Description: Learning retention provided insights into information that was forgotten over time.

  - Relationship to Research: In order to increase learning in low-rate production environments, retention has to occur and/or strategies must be developed and put into place to increase retention.
- *Learning Efficiencies*
  - Description: This parameter highlights work efficiencies as a function of years of work experience.
  - Relationship to Research: Gaining an understanding of work proficiency versus years of experience provided insights into learning especially in low-rate production environments. These longer cycle times would increase the duration to obtain proficiency. This analysis also provided strategies to facilitate learning.
- *Output per Employee – Aircraft and Automotive Industries (Non-Shipbuilding)*
  - Description: This provided the average output per employee for these two industries over a twenty-year time frame.
  - Relationship to Research: Aircraft and automotive industries were high-rate production environments. However, they provided a basis to compare and contrast to low-rate production shipbuilding.

### WBS 5 - Assess and Analyze Class A Ship Data and WBS 6 – Assess and Analyze Class B, Class C, and Class D Data

In this WBS area, the researcher presented the data that was in the public domain for each ship class. Table 9 also provided the associated figures that characterize each parameter captured as they relate to each ship class. In order to distinguish each ship class, the figures that were developed to supported this research utilized different colors to designate different ship classes, which was captured in Table 8.

| **Class of Ship** | **Designated Color** |
|---|---|
| A | Blue |
| B | Orange |
| C | Black |
| D | Green |

Table 8: Colors Designated to Each Ship Class

To assist with the execution of the research methodology and in particular the relationships between the four ship classes, Table 9 was developed to associate the learning parameters versus the subsequent figures by ship class. This provided a cross reference to support this research.

| Type of Parameter | Parameter | Description | Details | Ship Class | | | |
|---|---|---|---|---|---|---|---|
| | | | | Class A | Class B | Class C | Class D |
| Ship Design and Construction | Labor Hours | Total Hours to Design and Build each Product | Consists of Production Hours; Engineering and Planning Hours; All Hours Associated with the Delivery of the Final Product | Figure 7 | Figure 14<br>Figure 15 | N/A<br>Data does not Exist in the Public Domain | Figure 39<br>Figure 40<br>Figure 41<br>Figure 42 |
| Ship Design and Construction | Construction Schedule Milestones | Major Milestone Dates | Contract Dates, Manufacturing and Production Dates, Delivery Dates, and Other Key Acquisition Dates | Figure 8 | Figure 16 | Figure 31<br>Figure 32 | Figure 43 |
| Ship Design and Construction | Changes | Significant Changes | Principal Changes Impacting the Product Itself | Figure 9<br>Figure 10 | Figure 17<br>Figure 18<br>Figure 19<br>Figure 20 | N/A<br>Data does not Exist in the Public Domain | Figure 44<br>Figure 45 |
| Ship Design and Construction | Procurement Strategy | Number of Completed Products that are Procured with each Contract | Procurement Strategy coupled with the Duration of Key Milestones is the Focus of this Research | Figure 11 | Figure 21<br>Figure 22<br>Figure 23<br>Figure 24 | Figure 33<br>Figure 34 | Figure 46 |
| Ship Design and Construction | Labor Elements and Profiles: Production | Defines the Principal Labor Elements and Profiles Associated with Production | Principal Labor Elements equates to, for example: Welders, Electricians, Pipe Fitters, and Other Manufacturing, Production, and Construction Trades | Figure 12 | Figure 25 | Figure 35 | Figure 47<br>Figure 48<br>Figure 49<br>Figure 50<br>Figure 51 |
| Ship Design and Construction | Labor Workforce by Major Systems | Defines the Principal Labor Workforce by Major Systems | Principal Major Systems: Hull, Machinery, Electrical, Communications, Auxiliary Systems, Outfitting | Applicable to Figure 30 | Figure 30 | Applicable to Figure 30 | Applicable to Figure 30 |

Table 9: Relationship between Learning Parameters to Ship Class Figures

| **Type of Parameter** | **Parameter** | **Description** | **Details** | **Ship Class** | | | |
|---|---|---|---|---|---|---|---|
| | | | | **Class A** | **Class B** | **Class C** | **Class D** |
| Ship Design and Construction | Labor Elements and Profiles: Non-Production | Defines the Principal Labor Elements associated with Non-Production oriented Areas | Non-Production Areas: Engineering, Administration, Designers, Management, Construction Support, Production Support | Applicable to Figures 25, 36, 52, 53 | Figure 25 | Figure 36 | Figure 52<br>Figure 53 |
| Ship Design and Construction | Funding Profiles | Provides the Timing of the Funding in relationship to the construction cycle | Relative funding as a function of timeframe for low rate production | Figure 13 | Figure 26<br>Figure 27<br>Figure 28<br>Figure 29 | Figure 37<br>Figure 38 | Figure 54<br>Figure 55<br>Figure 56<br>Figure 57 |
| Specific to Shipbuilding but Not to a Specific Class | Workforce Labor Demographics: Shipbuilding | Provides the Age Profiles across a Given Workforce | Age Profiles were Grouped in Increments of 5 or 10 years | Figure 59<br>Figure 60<br>Figure 61 | Figure 59<br>Figure 60<br>Figure 61 | Figure 59<br>Figure 60<br>Figure 61<br>Figure 62 | Figure 59<br>Figure 60<br>Figure 61 |
| Specific to Shipbuilding but Not to a Specific Class | Output per Employee: Shipbuilding | Provides Output per Shipbuilder | The average output per shipbuilder is over a twenty year span | Figure 63 | Figure 63 | Figure 63 | Figure 63 |
| Not Specific to Shipbuilding, But are Applicable | Output per Employee: Aircraft and Automotive Industries | Provides Output per Two Other Large Industries | The average output per employee associated with the automotive and aircraft industries over a twenty year span | Applicable to Figure 64 | Applicable to Figure 64 | Applicable to Figure 64 | Applicable to Figure 64 |
| Not Specific to Shipbuilding, But are Applicable | Learning Retention | Provides Insights into Learning Retention | Retention of information learned declines dramatically over time | Figure 65<br>Figure 66 | Figure 65<br>Figure 66 | Figure 65<br>Figure 66 | Figure 65<br>Figure 66 |
| Not Specific to Shipbuilding, But are Applicable | Learning Efficiencies | Shows Work Efficiency Related to Years of Work Experience | Offers insights into the number of years of experience that must be gained to become proficient | Applicable to Figure 67 | Applicable to Figure 67 | Applicable to Figure 67 | Applicable to Figure 67 |

Table 9 (continued)

### Class A Ships

Labor Hours

- *Figure:* 7
- *References:* Figure 7 was developed utilizing information from Schank et al. (2005), Navy Ship Acquisition (2006), and O'Rourke (1996).
- *Description:* Total construction and production as well as construction and production support hours to design and build each ship of Class A. The hours were normalized to the first ship because the actual value of the hours was not important since the focus was on the increase or decrease of the hours to complete each ship of the class in relationship to the first ship of the class, which was the lead or baseline ship of the class.
- *Analysis of this Figure:* Despite the fact that there were ten ships of this class, Figure 7 shows an increasing trend of hours required to deliver each ship of the same class. The second ship shows a decrease followed by an increase in the number of hours to build the third and fourth ships of the class. The fifth through eighth ships of the class showed a decrease in the number of hours to build each ship with the eighth ship of the class requiring almost the same number of hours to build as the first ship of the class. The last two ships of the class, ships nine and ten, showed a dramatic increase in the number of hours to build them as compared to the first ship of the class.

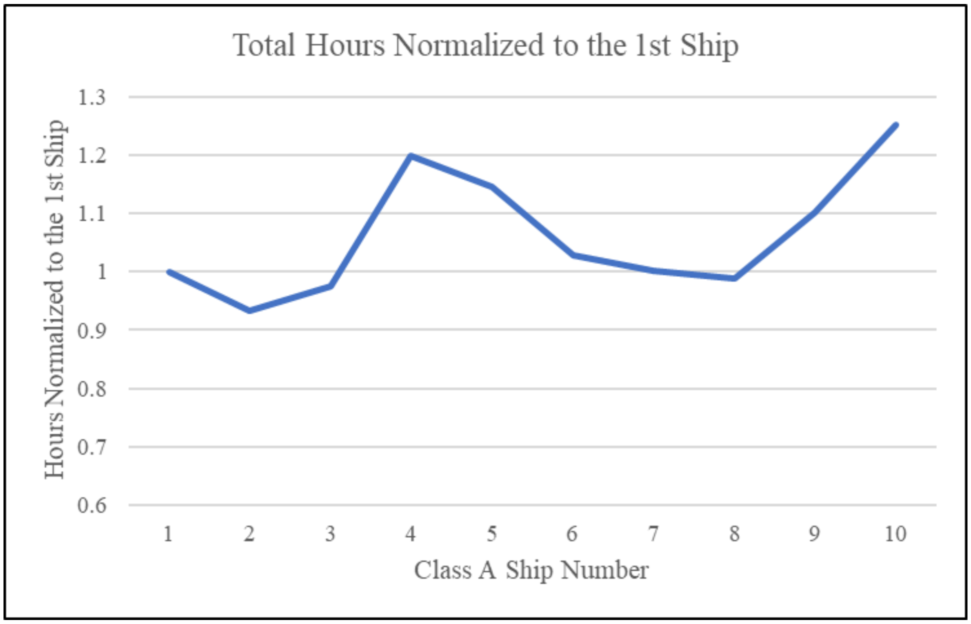

Figure 7: Total Class A Labor Hours Normalized to the First Ship

<u>Construction Schedule Milestones</u>

- *Figure:* 8
- *Reference:* Figure 8 was developed from information contained within Schank et al. (2005) and Navy League (2009).
- *Description:* Four major milestones were depicted in Figure 8, which were:
    - months between delivery dates of successive Class A ships,
    - months from contract award to keel,
    - months from contract award to launch, and
    - months from contract award to delivery.

Also, per Moldafsky et al. (2013) and Schank et al (2005), these were the principal dates associated with naval ship construction. The researcher also had to assume that delivery meant that all work was completed for a given ship. However, sometimes in low-rate production of ships, some amount of work was completed after delivery, but for the purposes of this research, the researcher assumed that this volume of work was negligible.

- *Analysis of this Figure:* Obviously for the first ship of the class, there were no months between delivery dates since it was the first ship of the class. The months between delivery dates increased from ships two through four. The delivery dates for ships five through eight were fairly consistent, but ships nine and ten increased by a large percentage for Class A ships. In terms of contract award to keel, the number of months associated with that specific major milestone remained fairly consistent except for ship number six and ship number eight. Ships nine and ten were fairly consistent as compared to ships one through five and ship number seven. The months from contract award to launch showed a large decrease from ship three to ship four followed by a large increase for ship number six. Ship number eight also showed an increase; however, ship numbers nine and ten actually showed a decrease in the number of months from contract award to launch. In regard to the number of months from contract award to delivery, ship numbers four and five showed a large decrease in the number of months as compared to the first three ships of the class. Ship numbers six and eight also showed large increases in the number of months from contract award to delivery. Ship number ten also showed a large increase in the number of hours from contract award to delivery.

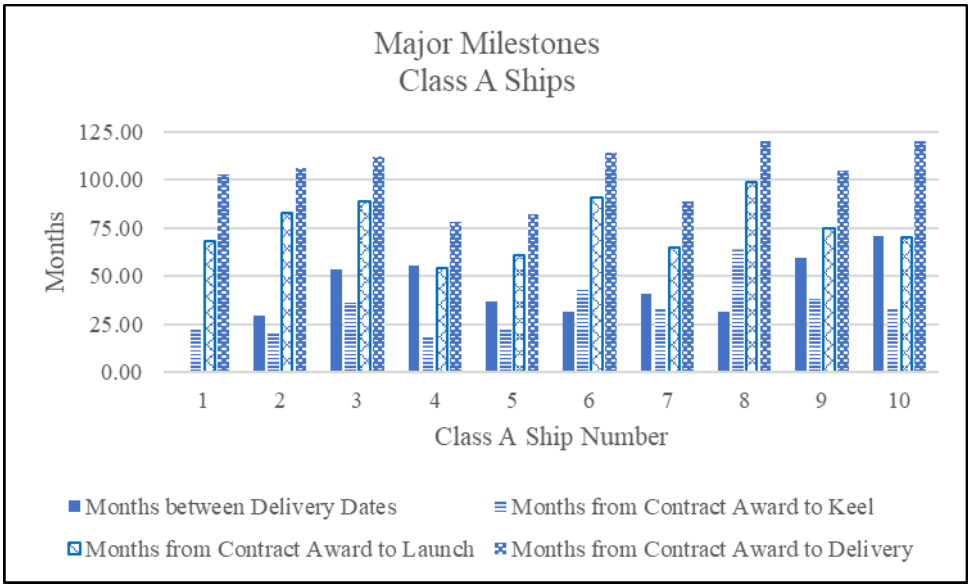

Figure 8: Class A Major Ship Construction Milestones

<u>Significant Changes</u>

- *Figures:* 9 and 10
- *References:* Figures 9 and 10 were developed using the following references: Chesneau (1992), Clancy (1999), Elward (2010), Fox (1986), Green (2021), Lucey (2021), McNab (2020), Polmar (2008), Polmar (2006), and Reilly (2022).
- *Description:* A characteristic that all low-rate production ships have in common was that they all were impacted by changes that occur after contract award and were incorporated prior to ship delivery. Utilizing information contained in the public domain, the researcher identified the most significant changes impacting each ship of this class, if available. As each were identified using the included references, the researcher simply counted each change. The researcher also assumed that the impact of each change was

the same meaning that the researcher did not quantify the difference in the impacts associated with each change. This was an assumption and limitation with respect to this research; however, due to the limited information contained within the public domain in regard to the number of systems impacted by each change, this assumption was a logical conclusion to pursue accordingly. Two figures were developed for this parameter. The first figure, which was Figure 9 analyzed the cumulative number of changes across the ship class by normalizing to the first ship of the class that actually experienced significant changes, at least for what was captured in the public domain. The second figure, which was Figure 10, displays the number of changes as compared to the previous ship. This provides an assessment of the degree of changes from ship to ship while Figure 9 provided visibility into the total number of changes for the ship class utilizing the first ship that experienced changes to normalize too. Both of these figures provide these assessments over the life of the ship class.

- *Analysis of these Figures:* Figure 9 showed that the cumulation of changes over the ship class increased at a constant rate throughout the duration of the class. The trend line associated with Figure 10 also shows an increase in changes over the Class A Ships. The relative number of changes from ship three to ship four showed a reduction in the number of changes as well as the number of changes from ship five to ship six and ship eight as compared to ship seven.

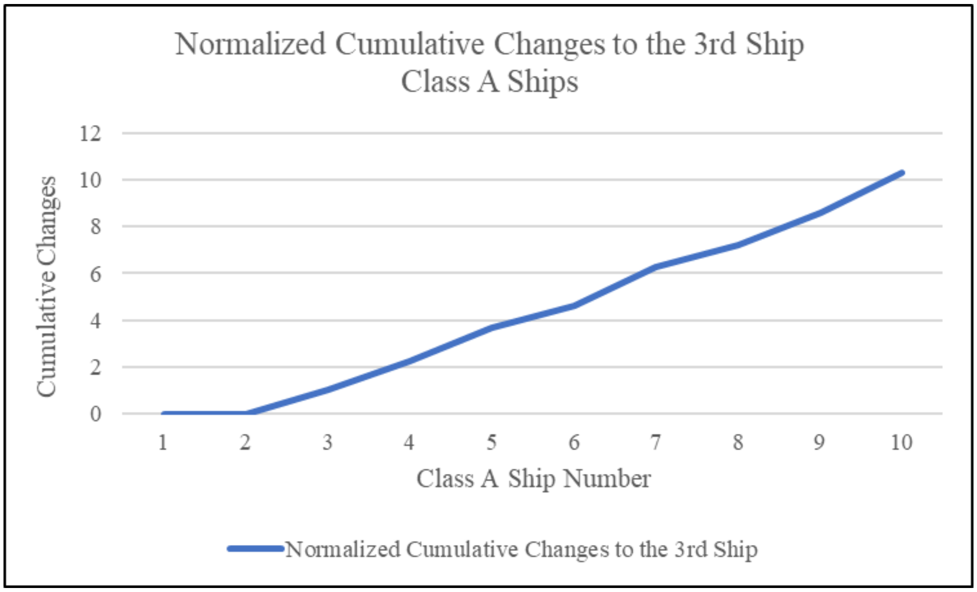

Figure 9: Class A Ships Normalized Cumulative Changes to the Third Ship

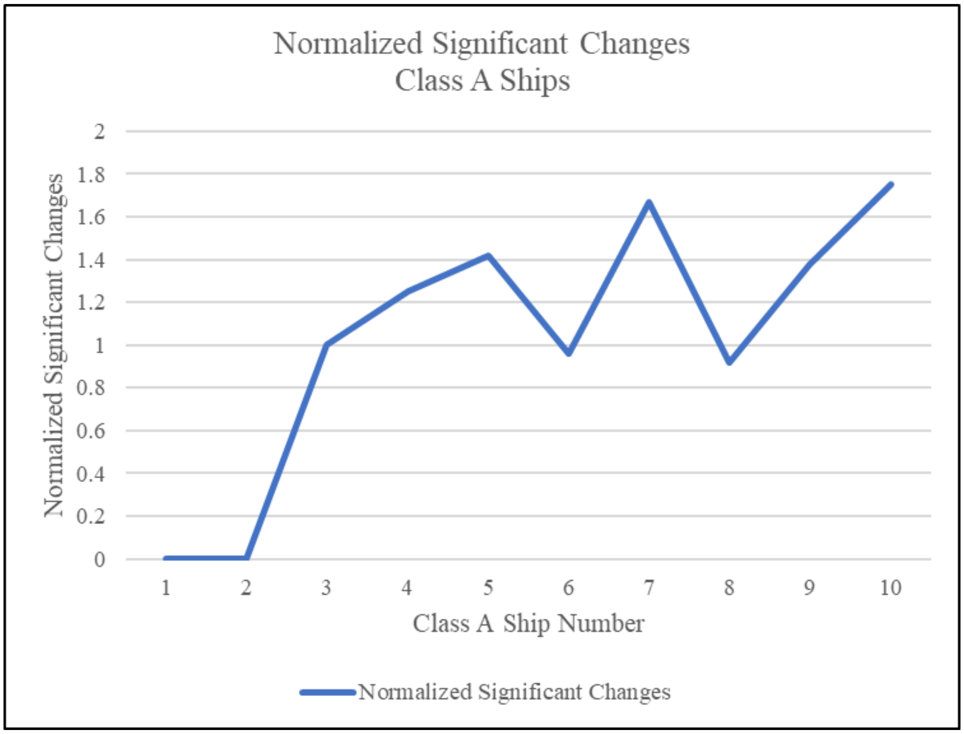

Figure 10: Class A Ships Normalized Significant Changes Compared to the Previous Ship

Procurement Strategy

- *Figure:* 11
- *References:* Figure 11 was developed from information provided by GAO (1974), Herley et al (1998), Birkler et al (2002), and Peeks (2020).
- *Description:* Figure 11 provided the procurement strategy associated with Class A Ships. This defined the quantities that were procured for this class of ship, and by definition, which were commensurate with a low production environment.
- *Analysis of this Figure:* As per the references associated with this figure, ships one and two were contracted together, but they had different construction start dates. Ships five

and six were contracted together, and ships seven and eight were also contracted together. The remaining ships of the class, which are ship three, ship four, ship nine, and ship ten were all single ship procurements.

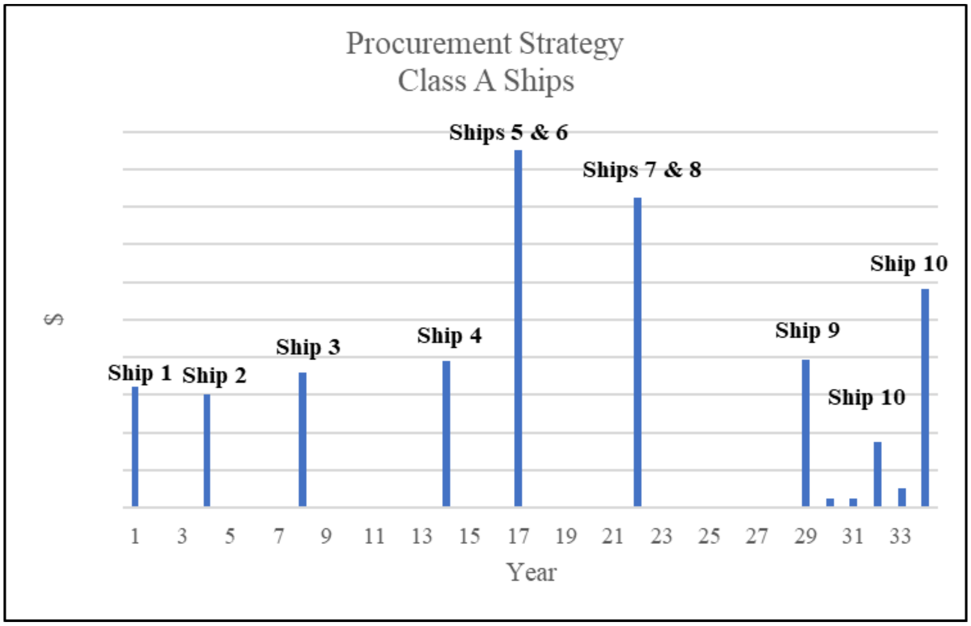

Figure 11: Procurement Strategy for Class A Ships

Labor Elements and Profiles – Production

- *Figure:* 12
- *Reference:* Figure 12 was developed from Birkler et al (1994).
- *Description:* Birkler et al (1994) provided Class A information associated with the principal labor elements to support production activities, as reflected in Figure 12.

- *Analysis of this Figure:* Birkler et al (1994) did not show values on the y-axis; however, the researcher was able to estimate the y-axis as a percentage of each individual labor element as compared to the whole. It was also important to note that Figure 12 was reflective of all Class A Ships in regard to the percentage of hours to design, plan, build, test, and deliver each ship. The labor elements were simply displayed alphabetically to be able to identify each more efficiently. The labor elements that constitute more than five percent of the total for Class A Ships were: Electrical, Machinery, Painters, Pipefitters, Riggers, Sheet Metal, Shipfitters, and Welders.

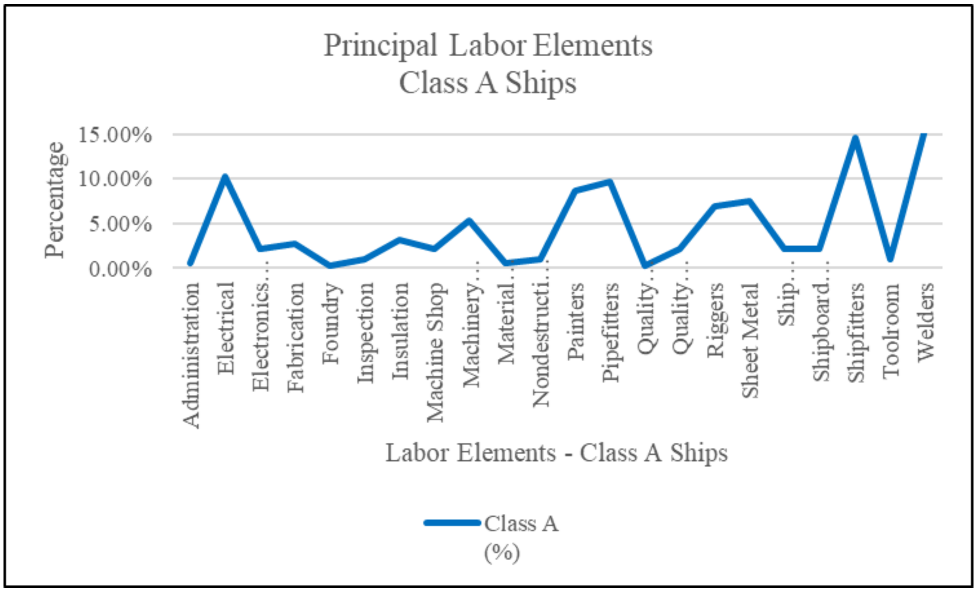

Figure 12: Principal Labor Elements associated with Class A Ships

## Labor Elements and Profiles – Non-Production

*Description:* For Class A Ships, the data to support the development of labor elements and profiles did not reside in the public domain. However, based on the fact that this research was focused on low-rate production of ships, data and subsequent information identified in the public domain associated with Class B, Class C, and Class D Ships is applicable to Class A Ships. However, the researcher safely assumed that engineering, management, planners, and production support are some of the key non-production elements associated with low-rate production shipbuilding. The data for these three ship classes provided insights into Class A Ships, which was discussed via Chapter 5.

## Funding Profiles

- *Figure:* 13
- *References:* Figure 13 was developed from information provided by GAO (1974), Herley et al (1998), Birkler et al (2002), and Peeks (2020).
- *Description:* Figure 13 provided the funding profile for Class A Ships. As a side note, the funding profiles have been adjusted to reflect dollars in year thirty-three.
- *Analysis of this Figure:* The funding for the first two ships was fairly consistent while ships three and four reflect a slight increase. Ships five and six, as indicated, and ships seven and eight were two ship buys, respectfully, thereby reflecting a large spike in funding. Ship nine and ship ten were both single procurements, but ship ten was funded over multiple years.

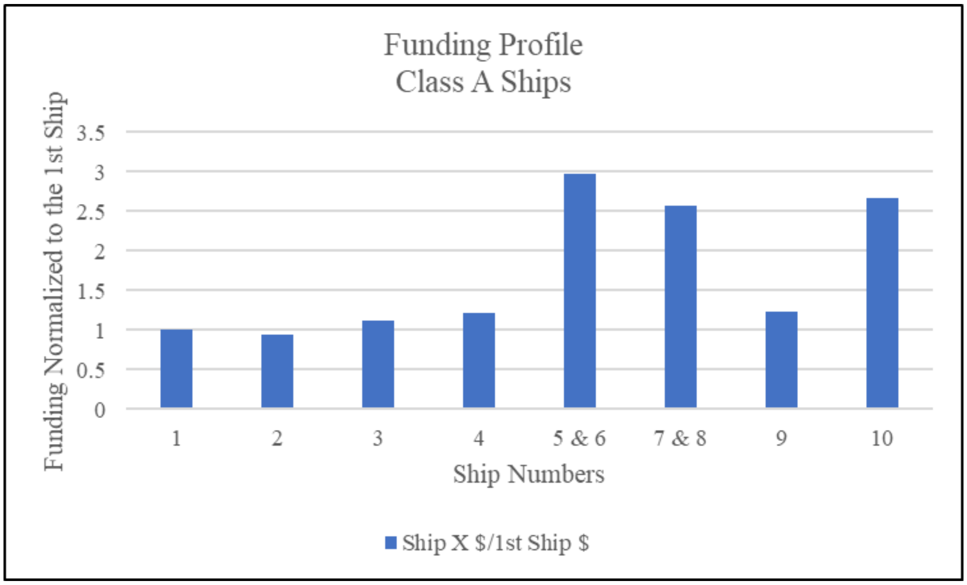

Figure 13: Funding Profiles for Class A Ships

## Class B Ships

### Labor Hours

- *Figures:* 14 and 15
- *References:* Figures 14 and 15 were developed utilizing information from Marriott (1985) and King (1989).
- *Description:* Total construction and production as well as construction and production support hours to design and build each Class B Ship did not exist in the public domain. However, the funding to support each Class B Ship was in the public domain. As such, the researcher assumed that the funding profile for each Class B Ship would also characterize the labor profile for each Class B Ship. This

assumption was reasonable, and it provided an understanding of the effort required to build each Class B Ship. As such, the funding, which as the researcher just indicated, hours, to build each Class B Ship was normalized to the first ship of the class, which is shown via Figure 14. Class B Ships were built by four different shipyards. As such, Figure 15 normalizes the hours (utilizing the funding) to build each Class B Ship for each shipyard to the first ship built by each shipyard. In Figure 14 and Figure 15, the hours were normalized to the first ship because the actual value of the hours was not important since the focus was on the increase or decrease of the hours to complete each ship of the class in relationship to the first ship of the class, which was Figure 14, or to the first ship built by each shipbuilder, which was Figure 15. The ship numbers identified in Figure 14 were reflective of the delivery sequence of each Class B Ship. The x-axis associated with Figure 15 reflected each shipyard, designated as Alpha Yard, Beta Yard, Gamma Yard, and Delta Yard, followed by the ship construction sequence number for Class B Ships.

- *Analysis of these Figures:* Figure 14 shows that the first five sequential Class B Ships were all built and delivered for about the same number of hours. However, starting with ship number six, there was an increase in the number of hours to build each Class B Ship until the ninth ship. Ships ten and twelve showed decreases in the number of hours to build and deliver, but the remaining ships all show increases. In terms of Figure 15 which highlighted the Class B Ships built by each shipyard, Alpha Yard and Delta Yard showed an increase in hours to build each consecutive ship that they constructed at each shipyard respectfully.

However, the Beta Yard and the Gamma Yard both showed that the second ship was built for fewer hours than the first ship. The remaining two Class B Ships built by the Beta Yard and the Gamma Yard had a large increase in the number of hours to build and deliver.

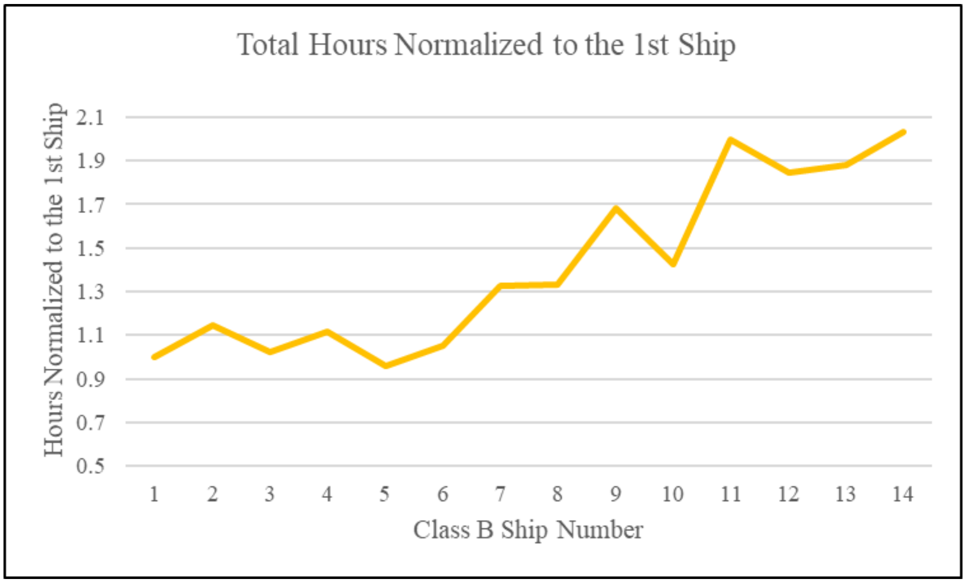

Figure 14: Total Class B Hours Normalized to the First Ship

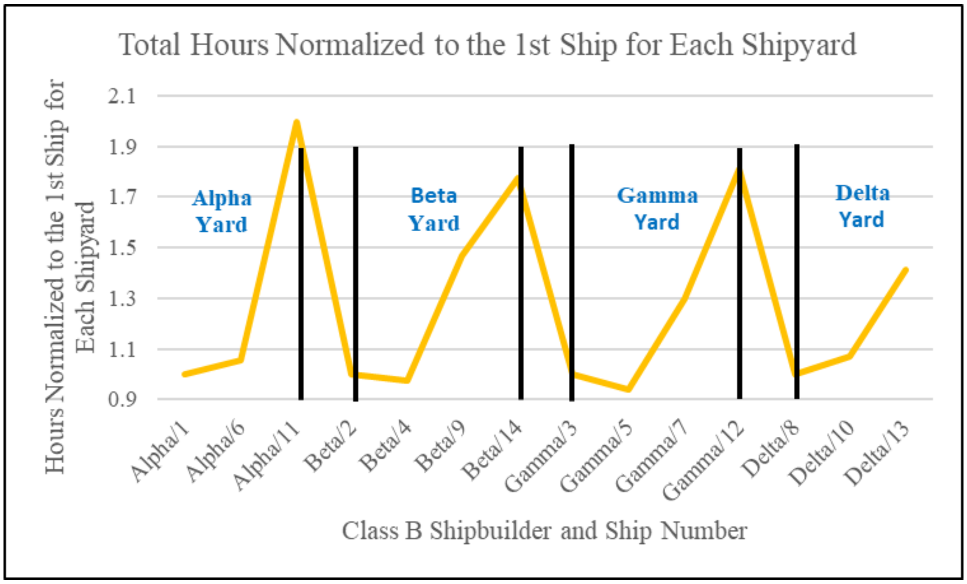

Figure 15: Total Class B Hours Normalized to the First Ship for Each Shipbuilder

Construction Schedule Milestones

- *Figure:* 16
- *Reference:* Figure 16 was developed from information written by Marriott (1985) and King (1989).
- *Description:* Four major milestones were depicted in Figure 16, which were:
    - months between delivery dates of successive Class B ships for each shipyard,
    - months from contract award to keel for each shipyard,
    - months from contract award to launch for each shipyard, and
    - months from contract award to delivery for each shipyard.

As already indicated, per Schank et al (2005) and Moldafsky et al. (2013), these were the principal dates associated with naval ship construction. The researcher also had to assume that delivery meant that all work was completed for a given ship. However, sometimes in low-rate production of ships, some amount of work was completed after delivery, but for the purposes of this research, the researcher assumed that this volume of work was negligible. For Class B Ships, four shipyards were involved in the production of this class of ships. As such, Figure 16 showed the four major milestones for each shipyard on this figure.

- *Analysis of this Figure:* Obviously for the first ship of the class for each shipyard, there were no months between delivery dates since it was the first ship of the class. The months between delivery dates decreased only for the Alpha Shipyard, and they increased for the other shipyards. In terms of contract award to keel, the number of months also decreased for Alpha Shipyard while the Beta and Delta Shipyards remains relatively consistent. The Gamma Shipyard has a large increase in the number of months from contract award to keel. Months from contract award to keel was fairly consistent for Alpha and Delta Shipyards while Beta Shipyard showed an increase. Delta Shipyard for months from contract award to launch had a slight increase. From contract award to delivery, Alpha, Beta, and Gamma Shipyards exhibited an increase in the number of months from the first ship to the second ship for each of these three shipbuilders. This is then followed with the third ship requiring less hours from contract award to delivery. The fourth ship for the Beta and Gamma Shipyards reflected an increase in the number of months from contract award to delivery compared to the third ship. The Delta Shipyard showed just a slight increase in the number of months from contact award to delivery.

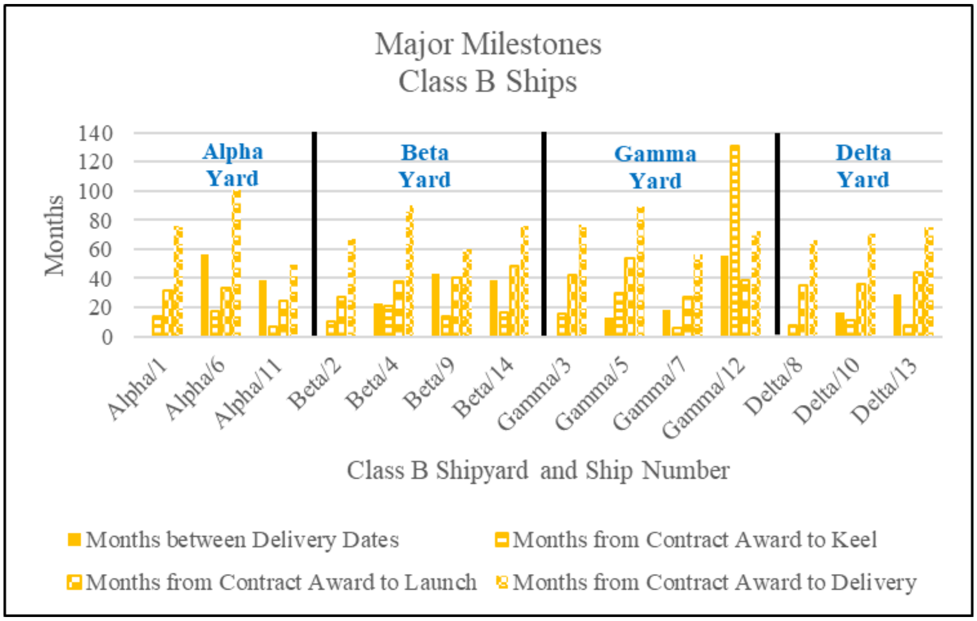

Figure 16: Class B Major Ship Construction Milestones

Significant Changes

- *Figures:* 17, 18, 19, 20
- *References:* Figures 17, 18, 19, and 20 were developed using Marriott (1985) and King (1989).
- *Description:* A characteristic that all low-rate production ships have in common was that they all were impacted by changes that occurred after contract award and were to be incorporated prior to ship delivery. Utilizing information contained in the public domain via Marriott (1985) and King (1989), the researcher identified the most significant changes impacting each ship of this class. As each was identified using the required

references, the researcher simply counted each change. The researcher also assumed that the impact of each change was the same meaning that the researcher did not quantify the difference in the impacts associated with each change. This was an assumption and limitation with respect to this research; however, due to the limited information contained within the public domain in regard to the number of systems impacted by each change, this assumption was a logical conclusion to pursue accordingly. Two types of figures were developed for this parameter along with displaying this information for the consecutive delivery of each ship regardless of shipbuilder and displaying this information for each shipbuilder. As such, the researcher then created four figures, and specifically Figures 17, 18, 19, and 20. The first type of figure analyzed the cumulative number of changes across the ship class by normalizing to the first ship of the class that actually experienced significant changes. The second type of figure displayed the number of changes as compared to the previous ship. This provided an assessment of the degree of changes from ship to ship while the first type of figure provided visibility into the total number of changes for the ship class utilizing the first ship that experienced changes to normalize too. Both of these figures provided these assessments over the life of the ship class. These two types of figures were developed for the Class B Ships in consecutive delivery order as well as for the Class B Ships delivered in consecutive order by shipbuilder.

- *Analysis of these Figures:* Figure 17 showed that the cumulation of changes over the ship class increased at a relative constant rate throughout the duration of the class. The first three ships of the class experienced no changes. Changes associated with this ship class started with the fourth ship and progressed at a constant rate. Like Figure 17, Figure 18 presented Class B Ships in ship delivery order; however, unlike Figure 17, Figure 18 was reflective of changes as compared to the previous ship.  Figure 18 shows that ship numbers four, seven, nine, eleven, and fourteen had a large increase in the number of changes as compared to the previous ship.  For Figure 18, the researcher had to assume that the changes made for each ship were specifically for that ship since the contracting methodology does not exist in the public domain.  The only difference between Figures 19 and 20, as compared to Figures 17 and 18 was that the ships were grouped by each shipbuilder.  Figure 19 showed that the Alpha Shipyard did not have very many changes to incorporate when they were building their three ships.  However, Beta, Gamma, Delta Shipyards had a large number of changes to incorporate.  Figure 20 displayed the number of changes as compared to the previous ship.  Beta Shipyard had to address the most amount of change as compared to the other three shipyards.  Gamma and Delta Shipyards both had two ships with the same number of changes for each ship.

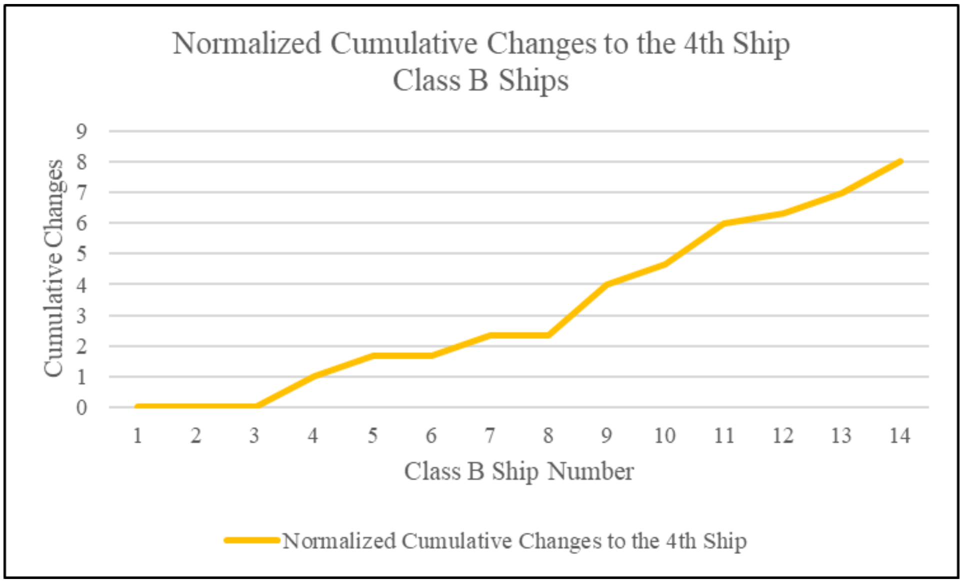

Figure 17: Class B Ships Normalized Cumulative Changes to the Fourth Ship with Ships in Consecutive Delivery Order

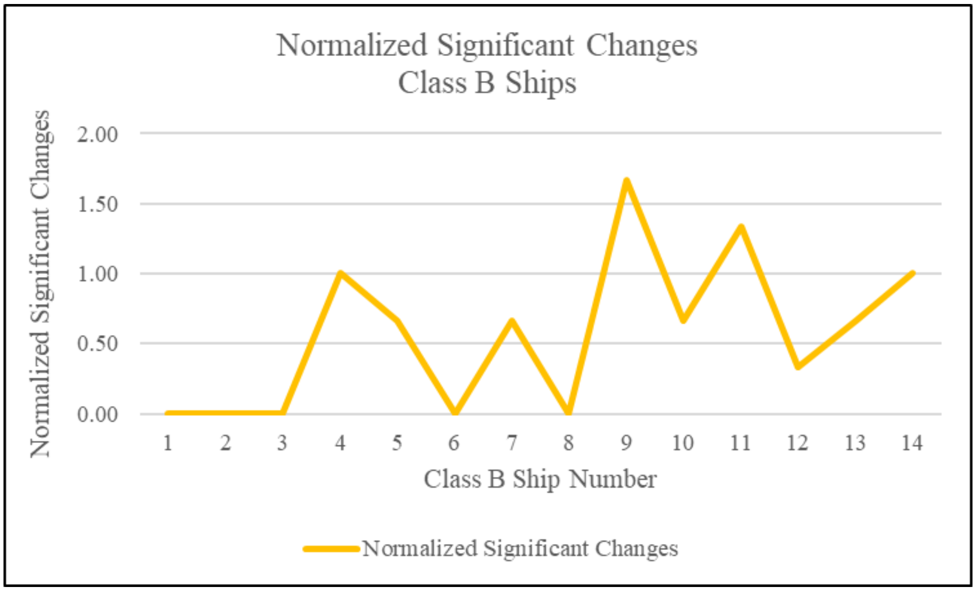

Figure 18: Class B Ships Normalized Significant Changes to the Fourth Ship with Ships in Consecutive Delivery Order

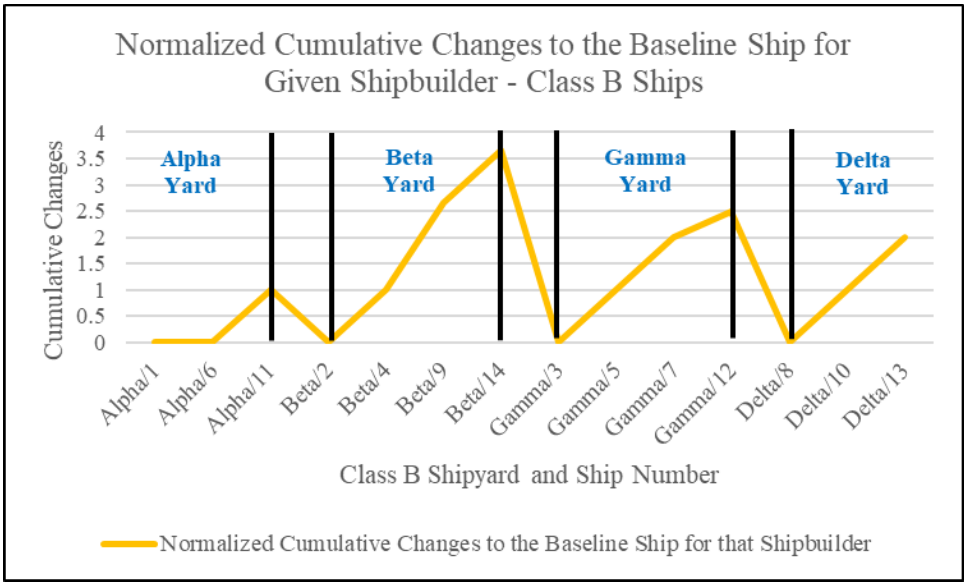

Figure 19: Class B Ships Normalized Cumulative Changes by Shipbuilder

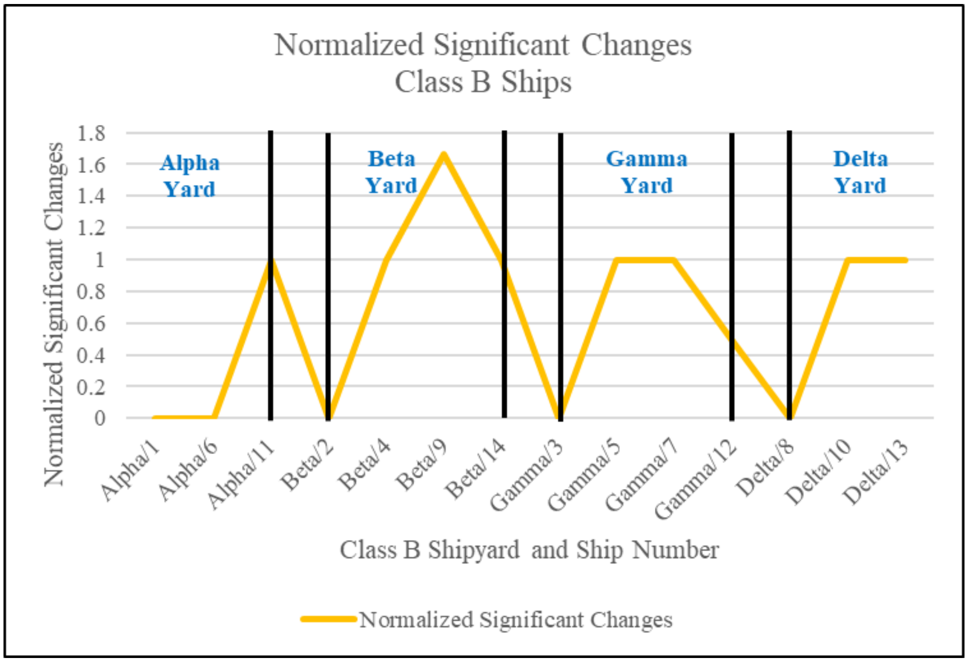

Figure 20: Class B Ships Normalized Significant Changes by Shipbuilder

Procurement Strategy

- *Figure:* 21, 22, 23, and 24
- *References:* Figures 21, 22, 23, and 24 were developed from Marriott (1985) and King (1989).
- *Description:* Figures 21, 22, 23, and 24 provided the procurement strategy associated with Class B Ships. These Figures defined the quantities that were procured for this class of ship, and in this case, for each of the four shipyards that built Class B ships. The quantities built by each shipyard, which were either three or four ships, was commensurate with a low-rate production environment.
- *Analysis of these Figures:* As per the references associated with these figures, Figure 21 was reflective of the procurement strategy for Alpha Shipbuilder, which was a single ship procurement of three Class B ships contracted over eleven years. The Beta Shipbuilder was contracted for four ships over eight years with ship numbers two and four contracted together, which was illustrated by Figure 22. The Gamma Shipbuilder, Figure 23, followed the same procurement strategy as the Beta Shipbuilder with the only differences being that ship numbers three and five were contracted together and the time frame between the last two ships was a year longer for the Gamma Shipbuilder compared to the Beta Shipbuilder. Figure 24 showed the procurement strategy for the Delta Shipbuilder. Like the Alpha Shipbuilder, the Delta Shipbuilder was contracted for three single ship procurements, but the timeframe was only over four years while the Alpha Shipbuilder was over eleven years. It should be noted that the ship numbers listed in Figures 21, 22, 23, and 24 were listed in the order that they were procured and delivered and not by the ship number for that specific shipbuilder. Also, it should be noted that the delivery years

will obviously exceed the years associated with contracting. Figure 16 addressed this parameter accordingly.

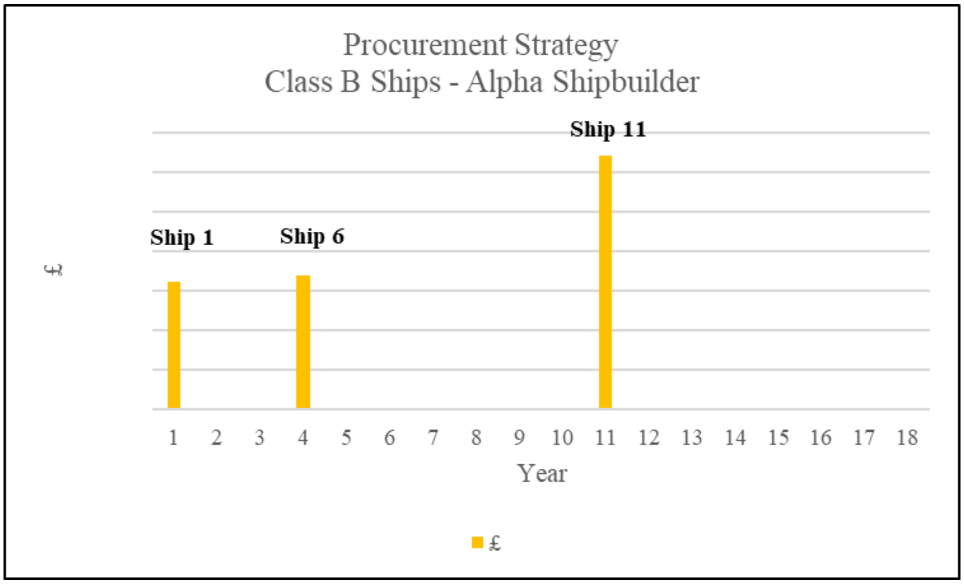

Figure 21: Procurement Strategy for Class B Ships Built by Alpha Shipbuilder

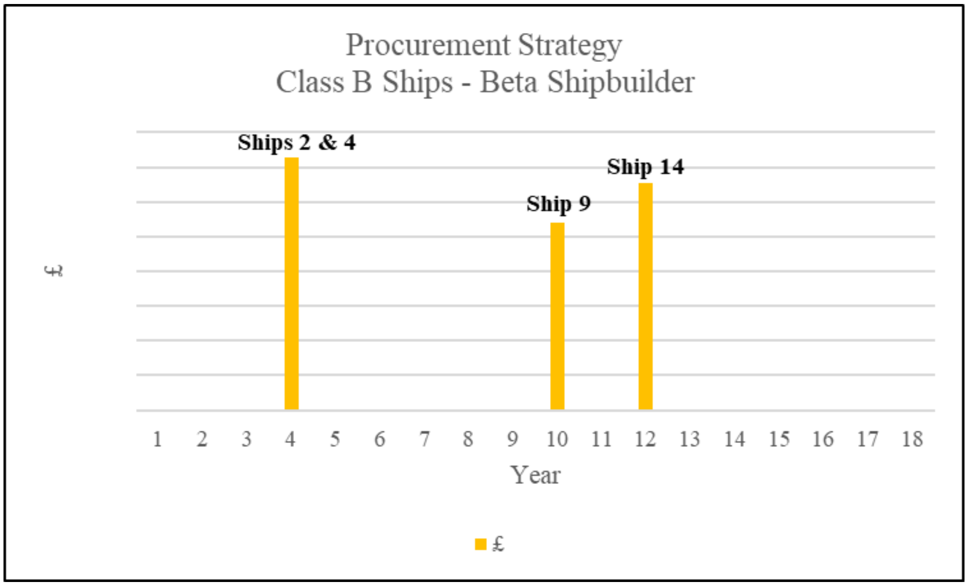

Figure 22: Procurement Strategy for Class B Ships Built by Beta Shipbuilder

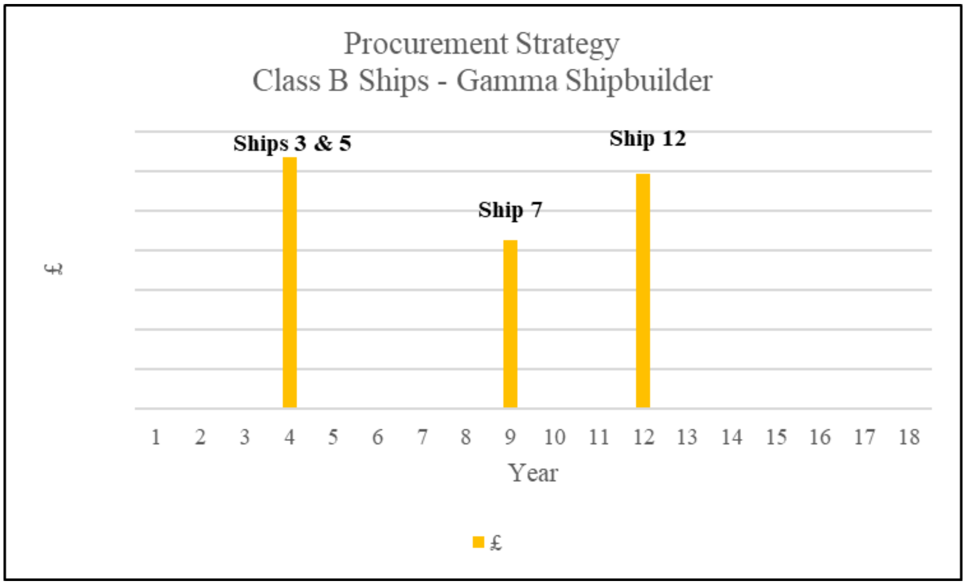

Figure 23: Procurement Strategy for Class B Ships Built by Gamma Shipbuilder

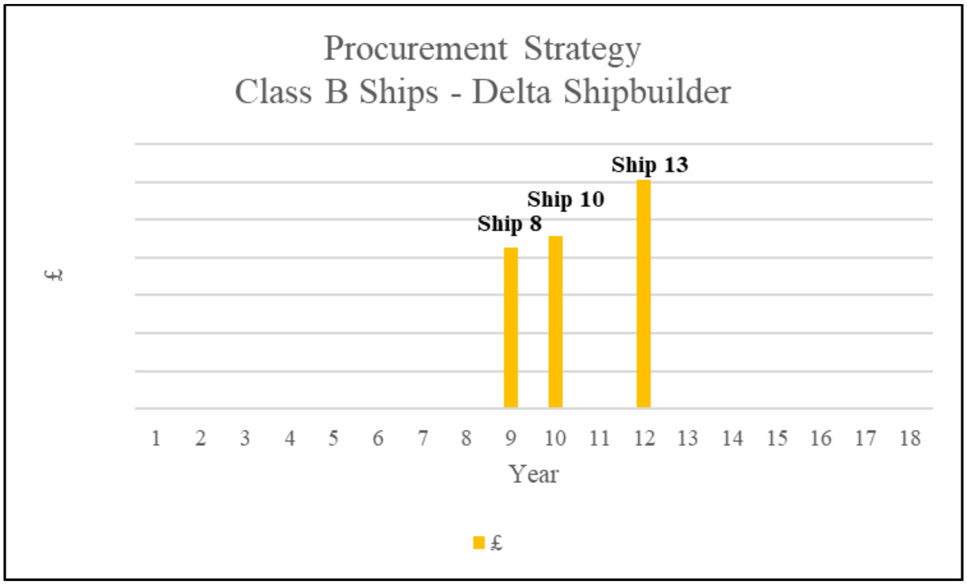

Figure 24: Procurement Strategy for Class B Ships Built by Delta Shipbuilder

Labor Elements and Profiles – Production and Non-Production

- *Figure:* 25
- *Reference:* Figure 25 was developed from information contained within Birkler et al (2005).
- *Description:* Figure 25 not only conveyed a labor profile, but it also conveyed insights into labor hours for Class B Ships. The information captured via Figure 25 provided principal labor elements for both production and non-production as a percentage of the total. Even though the actual labor hours were not presented, the percentages still provided valuable insights into this class of ship.
- *Analysis of this Figure:* Thirty-five percent of the labor associated with Class B ships was in support of non-production efforts while the remaining sixty-five percent was in support of production efforts with welding representing the largest percentage of the production labor elements followed by steel work. Foreman represents eleven percent of the total with electrical and mechanical representing eleven and ten percent respectfully.

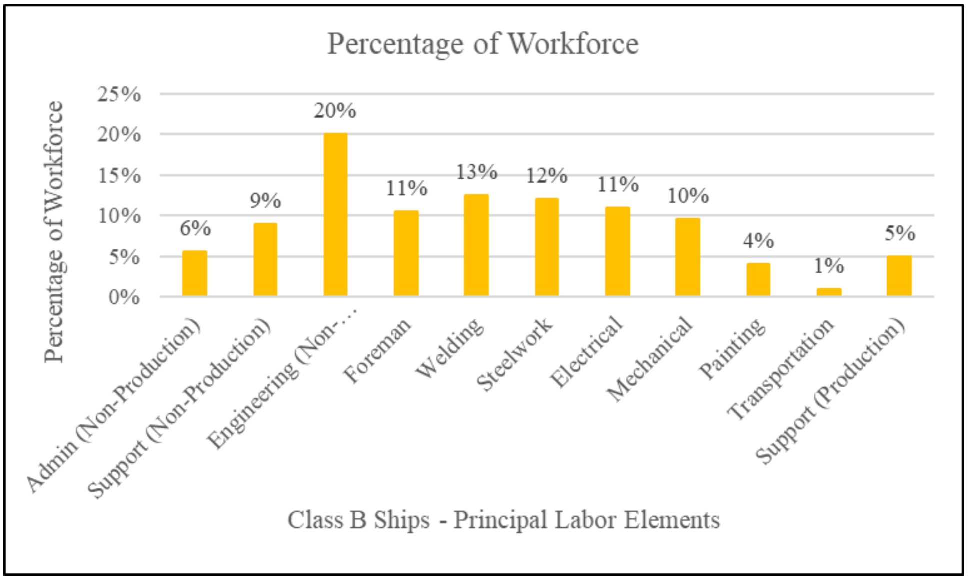

Figure 25: Principal Labor Elements Associated with Class B Ships

Funding Profiles

- *Figures:* 26, 27, 28, and 29
- *References:* Figures 26, 27, 28, and 29 were developed from Marriott (1985), King (1989), and Birkler et al (2005).
- *Description:* Figures 26, 27, 28, and 29 provided the funding profiles associated with Class B Ships for each shipyard involved in their construction.
- *Analysis of these Figures:* As per the references associated with these figures, Figure 26 was reflective of the funding profile for Alpha Shipbuilder. The funding profile for the first two ships that the Alpha Shipbuilder produced was fairly consistent; however, the third ship that the Alpha Shipbuilder built, which was the eleventh ship of the class, was almost double as compared to the first two ships for this shipbuilder. For Beta and Gamma Shipbuilders, its' first two ships were fairly consistent while the last two ships,

ship numbers nine and fourteen, had substantial funding increases to support construction of those last two ships for both the Beta Shipbuilder and the Gamma Shipbuilder. Delta Shipbuilder also had fairly consistent performance over the first two ships, ship numbers eight and ten. However, the last ship that Delta Shipbuilder constructed, ship number thirteen, increased by approximately forty percent over the first two ships that the Delta Shipbuilder produced. This percent increase was less than the other three shipbuilders.

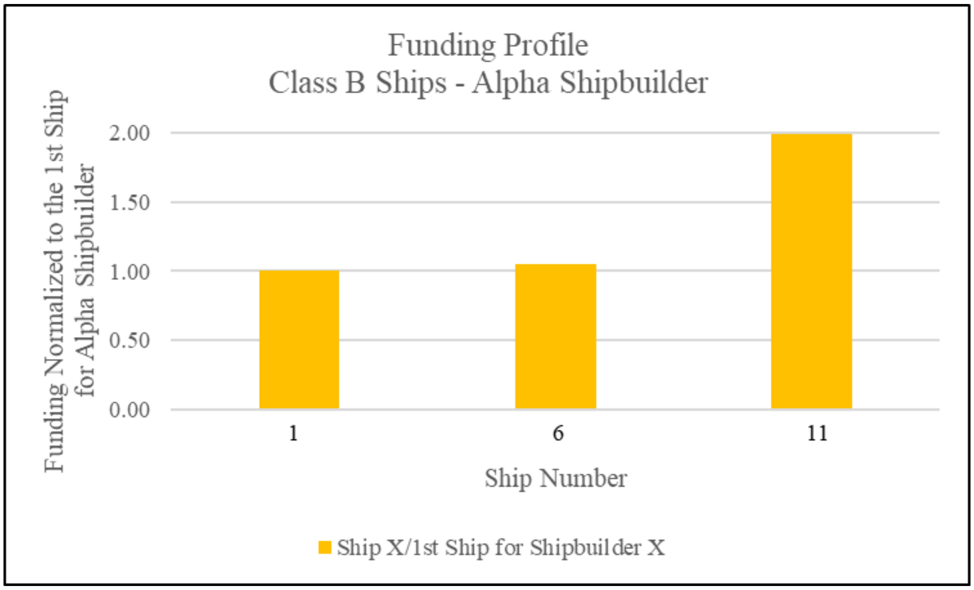

Figure 26: Funding Profile Class B Ships Alpha Shipbuilder

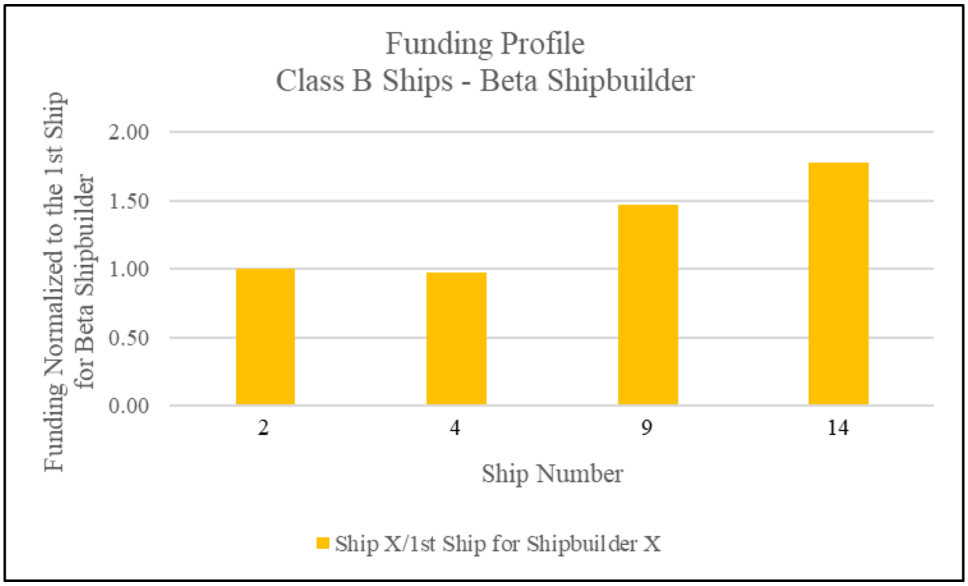

Figure 27: Funding Profile for Class B Ships Beta Shipbuilder

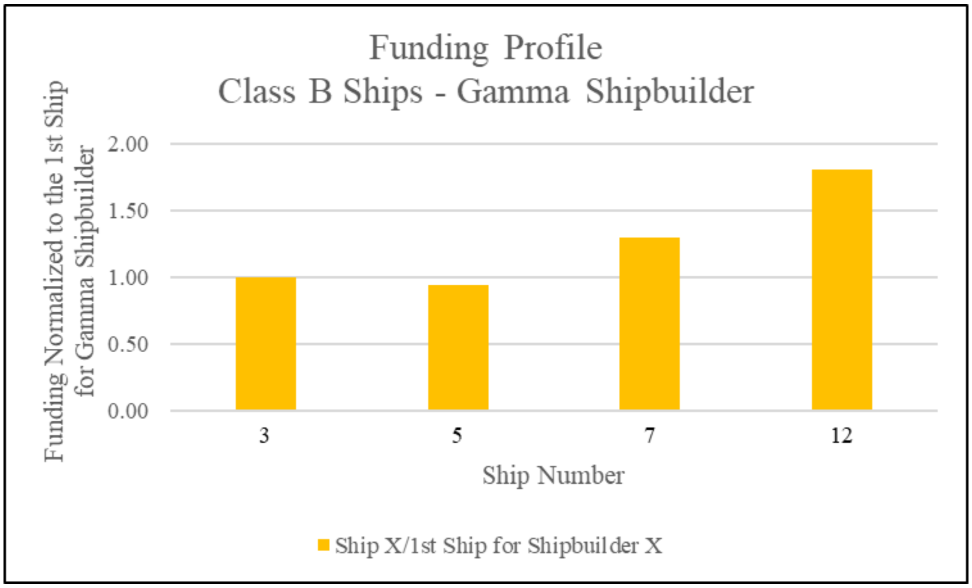

Figure 28: Funding Profile for Class B Ships Gamma Shipbuilder

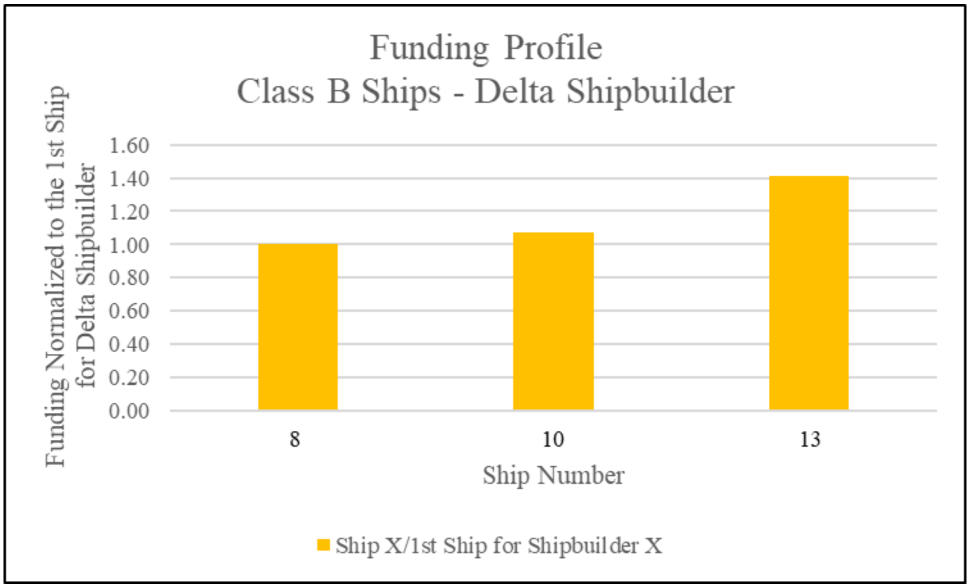

Figure 29: Funding Profile for Class B Ships Delta Shipbuilder

Workforce by Major Systems

- *Figure:* 30
- *References:* Figure 30 was developed from Birkler et al (2005).
- *Description:* Figure 30 provided the percentage of the workforce supporting Class B Ship construction by major systems.
- *Analysis of these Figures:* Birkler et al (2005) also provided, for Class B ships, the production labor workforce for major ship systems as shown by Figure 30. Labor activities associated with the hull supports all aspects of ship construction from plate cutting, forming, shaping, and welding together to make modules to support ship erection. The auxiliary systems were distributed throughout the ship thereby making them the next largest percentage of work to be accomplished.

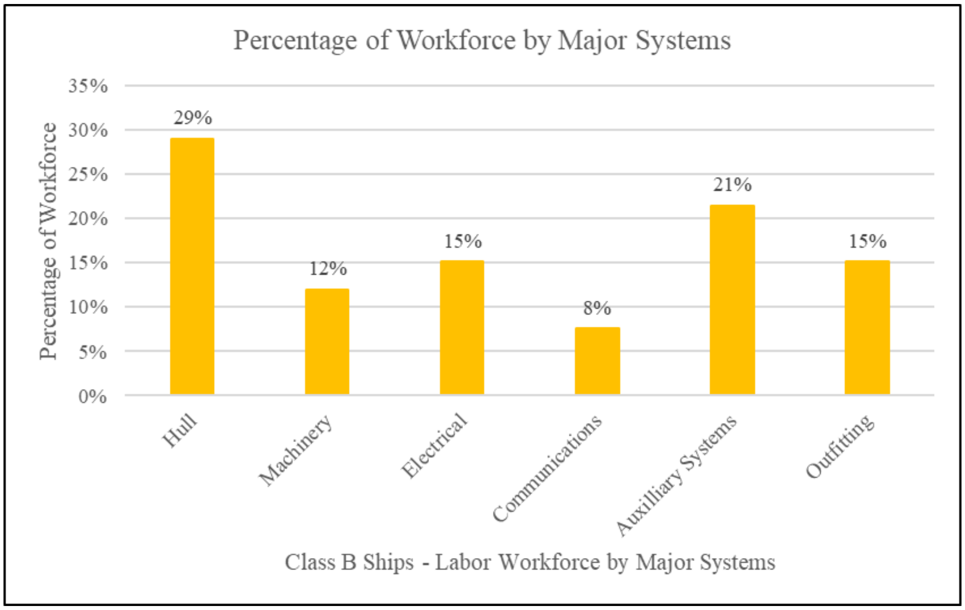

Figure 30: Labor Workforce by Major Systems for Class B Ships

## Class C

### Labor Hours

As Table 9 shows, data does not exist in the public domain that supports Class C Ships.

### Construction Schedule Milestones

- *Figures:* 31 and 32
- *Reference:* Figures 31 and 32 were developed from Birkler et al (1994), Fox (1986), Pike (2022), and US Navy (2022).
- *Description:* There were two different shipbuilders associated with Class C Ships. As such, Figure 31 was reflective of Class C Ships built by Epsilon Shipbuilder while Zeta

Shipbuilder, shown in Figure 32, was the other shipbuilder for Class C Ships. For both figures, there were four major milestones depicted, which were:

- months between delivery dates of successive Class C ships for each shipyard,
- months from contract award to keel for each shipyard,
- months from contract award to launch for each shipyard, and
- months from contract award to delivery for each shipyard.

As already indicated, per Schank et al (2005) and Moldafsky et al (2013), these were the principal dates associated with naval ship construction. The researcher also had to assume that delivery meant that all work was completed for a given ship. However, sometimes in low-rate production of ships, some amount of work was completed after delivery, but for the purposes of this research, the researcher assumed that this volume of work was negligible. The ship numbers associated with each shipbuilder were reflective of each ship's delivery in relationship to the ship class.

- *Analysis of these Figures:* As Figures 31 and 32 show, obviously for the first ship of the class for each shipyard, there were no months between delivery dates since it is the first ship of the class. For the Epsilon Shipbuilder, represented by Figure 31, months between deliveries was very consistent except for the twenty-fourth ship of the class, which was the sixth ship delivered for this shipbuilder and tripled in the number of months between deliveries. The Zeta Shipbuilder, via Figure 32, was fairly consistent between deliveries over the life of the class. In terms of contract award to keel, Figure 31 for the Epsilon Shipbuilder showed an increase to forty months and then oscillates to the mid-forty's and gets as high as fifty-one months with an average of approximately thirty-six months. For the Zeta Shipbuilder, per Figure 32, the months from contract award to keel continues to increase over the ships that they constructed. For the Epsilon Shipbuilder, contract award to launch increased to seventy-four months, and then settles out at approximately mid-sixty months while the Zeta Shipbuilder was on an increasing trend throughout their ship deliveries. For contract award to delivery, after the first ship, all ships associated with the Epsilon Shipbuilder were delivered, on average, eighty-five months with their tenth and thirteen ship delivering in ninety-four and ninety-five months respectfully. The thirteenth ship for this shipbuilder (thirty-first for the class) was the last ship delivered by this shipbuilder for this class. The Zeta Shipbuilder had longer times between contract award to delivery as compared to the Epsilon Shipbuilder. The last five ships that the Zeta Shipbuilder produced had the longest durations from contract award to delivery. Also, the number of months from contract award to delivery for the Zeta Shipbuilder continued to grow after the first ship that they built to the seventh ship that they built before the number of months decreased for the next four ships, and then increased for the rest of the class by this shipbuilder.

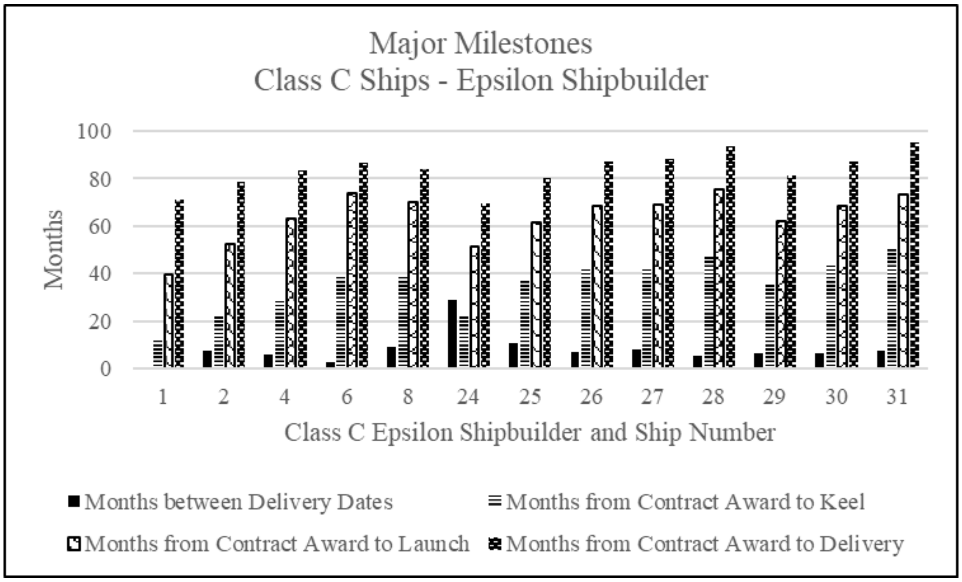

Figure 31: Class C Major Ship Construction Milestones Epsilon Shipbuilder

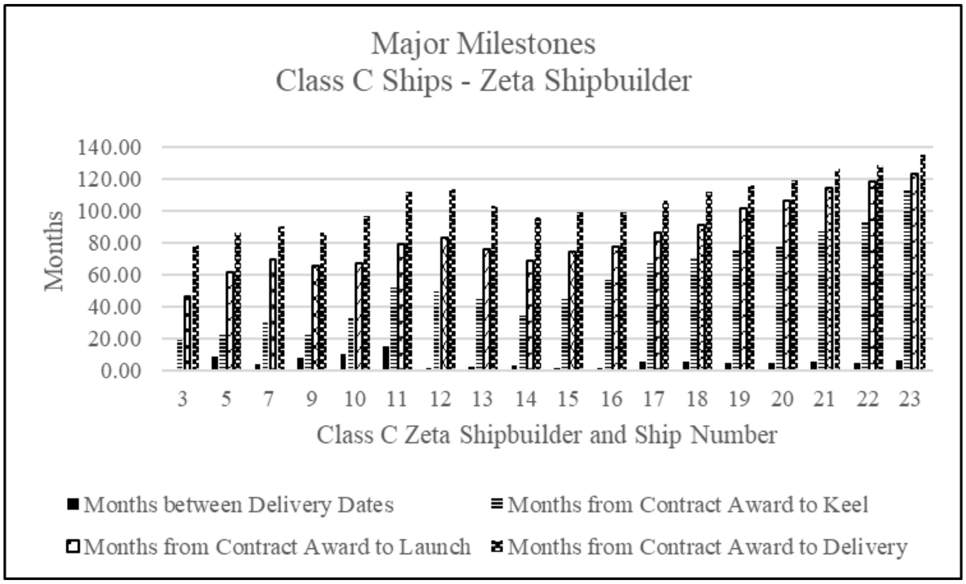

Figure 32: Class C Major Ship Construction Milestones Zeta Shipbuilder

## Significant Changes

As Table 9 shows, data does not exist in the public domain that supports Class C Ships.

## Procurement Strategy

- *Figures:* 33 and 34
- *References:* Figures 33 and 34 were developed from Birkler et al (1994) and Pike (2022).
- *Description:* Figures 33 and 34 provided the procurement strategy associated with Class C Ships. This defined the quantities that were procured for this class of ship, and by definition, this was commensurate with a low-rate production environment. As has already been discussed, there were two shipbuilders associated with Class C Ships; as such, Figure 33 was reflective of Epsilon Shipbuilder while Figure 34 was reflective of Zeta Shipbuilder.
- *Analysis of these Figures:* As per the references associated with these figures, the first four ships for Epsilon Shipbuilder were procured together, followed by a one ship procurement the following year. Three years later, three ships were procured followed by two additional ships one year later, then in the seventh year, three additional ships were procured for the Epsilon Shipbuilder, Figure 33. For the Zeta Shipbuilder, three ships were procured together followed by four ships the next year, and then eleven ships the following year for the Zeta Shipbuilder to build Class C Ships. As has already been indicated for Class B Ships, even though Class C ships were procured together, they were individually delivered over a period of over sixteen years, which is indicative of a low-rate production environment.

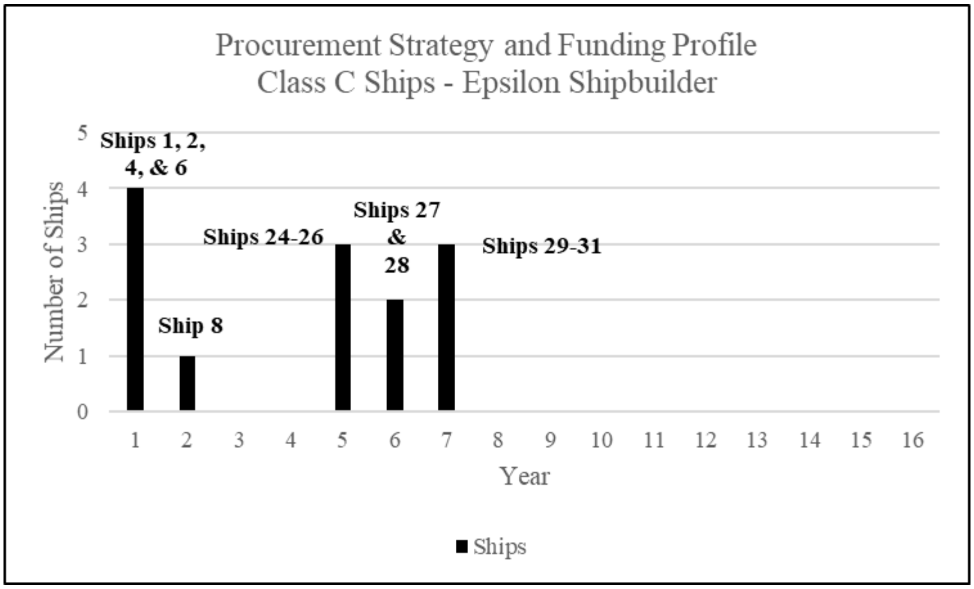

Figure 33: Procurement Strategy for Class C Ships Epsilon Shipbuilder

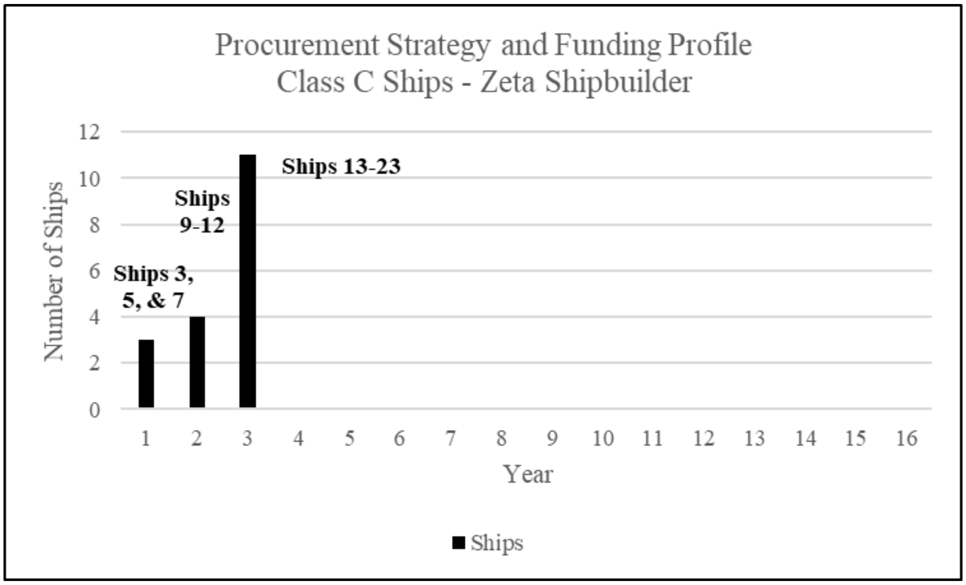

Figure 34: Procurement Strategy for Class C Ships Zeta Shipbuilder

<u>Labor Elements and Profiles – Production</u>

- *Figure:* 35
- *Reference:* Figure 35 was developed from Birkler et al (1994).
- *Description:* Birkler et al (1994) provided Class C information associated with the principal labor elements to support production activities, as reflected in Figure 35.
- *Analysis of this Figure:* Birkler et al (1994) did not show values on the y-axis; however, the researcher was able to develop the y-axis as a percentage of each individual labor element as compared to the whole. It was also important to note that Figure 35 was reflective of the percentage of the total hours to design, plan, build, test, and deliver each ship. The labor elements were simply displayed alphabetically to be able to identify each more efficiently. The labor elements that constitute more than five percent of the total for Class C Ships were: Electrical, Machinery, Painters, Pipefitters, Shipfitters, and Welders.

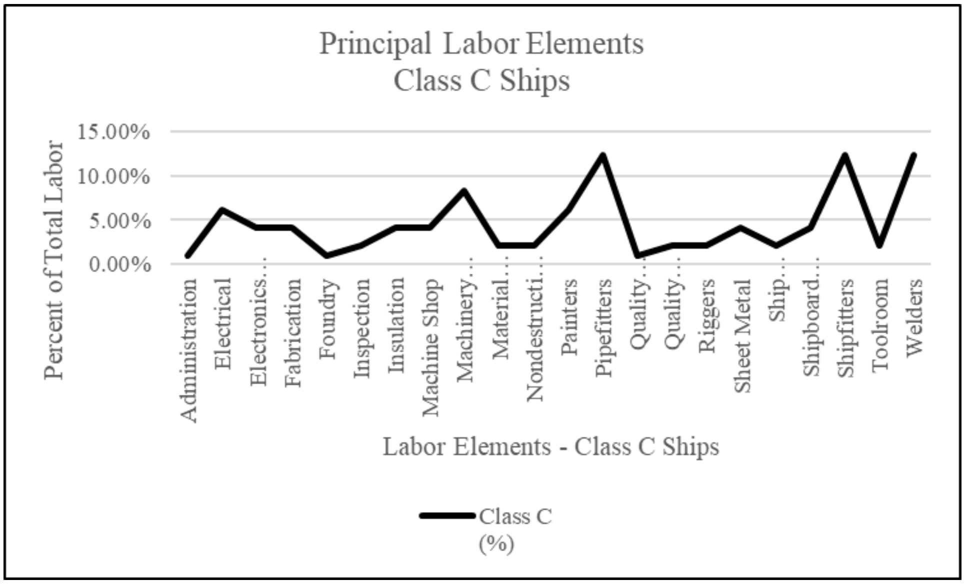

Figure 35: Principal Labor Elements Associated with Class C Ships

Labor Elements and Profiles – Non-Production

- *Figure:* 36
- *Reference:* Figure 36 was developed from Schank et al (2007).
- *Description:* Schank et al (2007) provided Class C information associated with the principal labor elements to support non-production activities, as reflected in Figure 36.
- *Analysis of this Figure:* Schank et al (2007) focused on the labor hours for engineers and designers supporting Class C ships, which was represented by Figure 36. Naval architects and marine engineers were the largest constituent group associated with engineers and designers followed by general designers and management. The remaining designers and engineers were discipline specific.

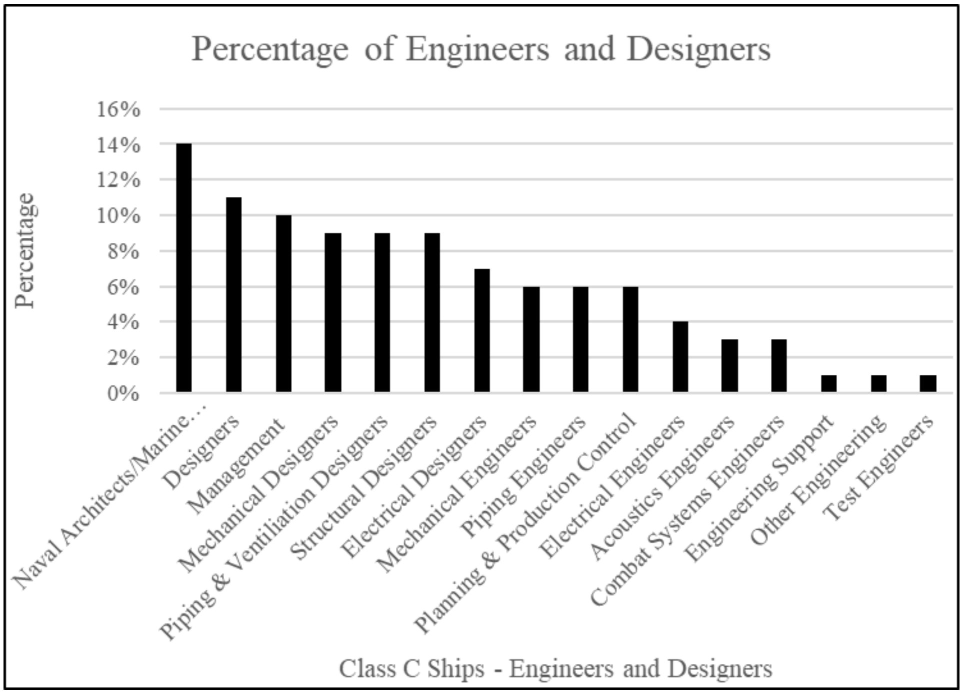

Figure 36: Percentage of Engineers and Designers Supporting Class C Ships

Funding Strategy

- *Figures:* 37 and 38
- *References:* Figures 37 and 38 were developed from Birkler et al (1994) and Pike (2022).
- *Description:* Figures 37 and 38 provided the procurement strategy associated with Class C Ships. Data does not exist in the public domain that provided the cost of each Class C Ship. However, based on each ship's procurement strategy, the funding to build each ship for the Epsilon Shipbuilder and the Zeta Shipbuilder would be commensurate with the procurement strategy.
- *Analysis of these Figures:* As per the references associated with these figures, the first four ships for the Epsilon Shipbuilder were procured together, followed by a one ship procurement the following year. Three years later, three ships were procured followed by two additional ships one year later, then in the seventh year, three additional ships were procured for the Epsilon Shipbuilder, Figure 37. For the Zeta Shipbuilder, three ships were procured together followed by four ships the next year, and then eleven ships the following year for the Zeta Shipbuilder to build Class C Ships. As such, the funding profiles for the Epsilon Shipbuilder and the Zeta Shipbuilder would follow the same profiles accordingly. As has already been indicated for Class B Ships, even though Class C ships were procured together, they were individually delivered over a period of over sixteen years, which was indicative of a low-rate production environment.

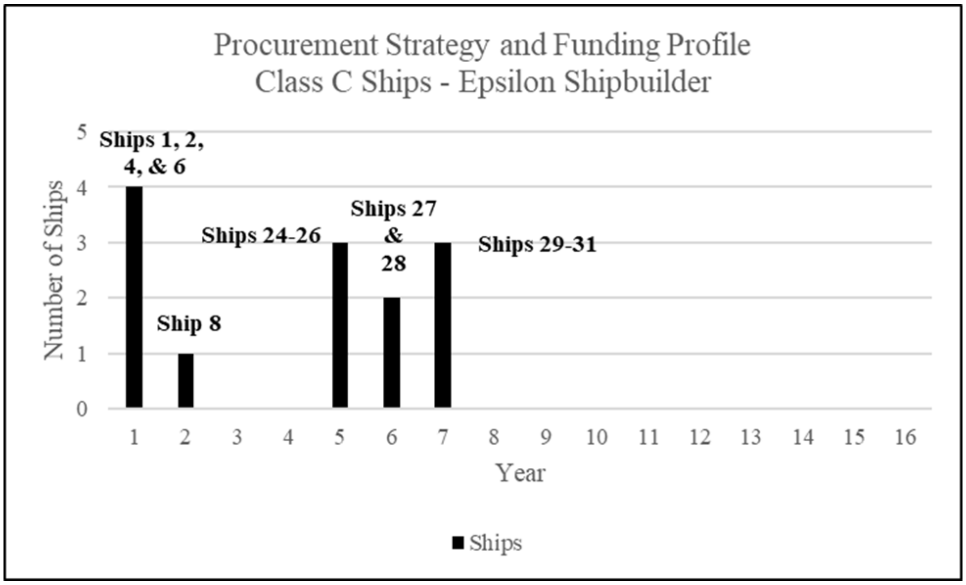

Figure 37: Funding Profile for Class C Ships Epsilon Shipbuilder

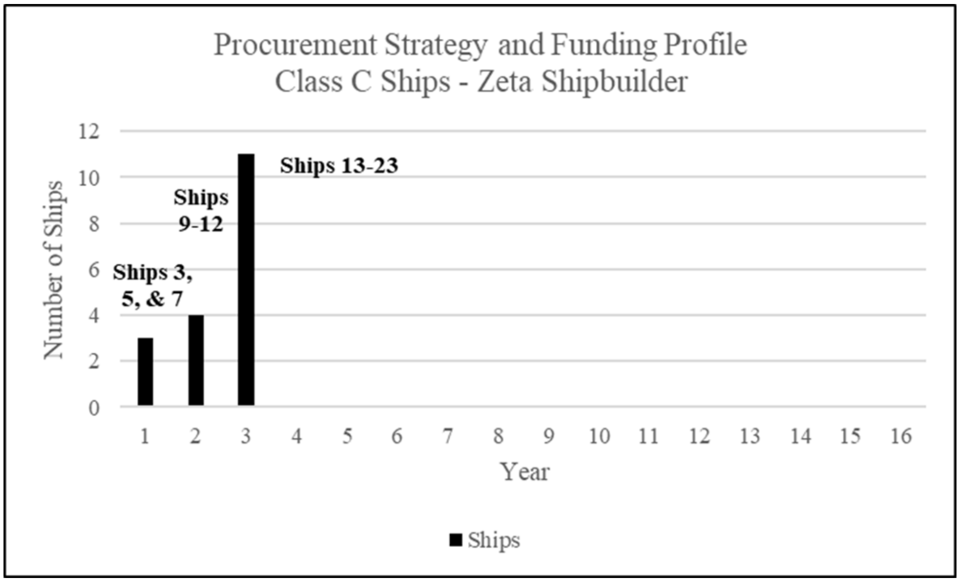

Figure 38: Funding Profile for Class C Ships Zeta Shipbuilder

## Class D Ships

### Labor Hours

- *Figures:* 39, 40, 41, and 42
- *References:* Figures 39, 40, and 41 were developed utilizing information from Mackin (2014) and O’Rourke (2022). Figure 42 was developed using Fabey (2019) and O’Rourke (2022).
- *Description:* The labor hours per year per ship associated with Class D Ships was not available in the public domain; however, the funding per year was available. The funding per year for each of the four ships that comprised Class D Ships was made up of labor costs, material costs, and overhead costs. The labor costs were made up of labor hours. As such, the actual costs were not relevant, but rather, the relative funding profiles per year was relevant. As such, Figures 39, 40, and 41 were funding profiles, but since they were displayed as relative profiles, these same figures can be utilized as labor hour profiles. Figures 39, 40, and 41 were reflective of the funding (labor) profiles for the first four Class D Ships with ship one shown on Figure 39, ship two on Figure 40, and ships three and four on Figure 41. Very similar to the assessments for the Class B Ships, total construction and production as well as construction and production support hours to design and construct each Class D Ship did not exist in the public domain. However, the funding to support each Class D Ship was in the public domain. As such, the researcher assumed that the funding profile for each Class D Ship would also characterize the labor profile for each Class D Ship. This assumption was reasonable, and it still provided an understanding of the effort required to build

each Class D Ship. Per O'Rourke (2022), AP, as shown in these three figures, was defined as Advanced Procurement which supports efforts prior to the award of the construction contract. Figure 42, which was derived from Fabey (2019) and O'Rourke (2022), provided insights into customer requirements to reduce the labor hours for ship numbers two, three, and four normalized to ship number one.

- *Analysis of these Figures:* Figures 39, 40, and 41 showed the labor (funding) profiles spanning several years. The funding has significant variability with funding for Class D Ships one and two occurring over fifteen years. As Figure 41 showed, ships three and four are funded over thirteen years with less variability as compared to the first two ships on this class. Figure 42, based on the information from Fabey (2019) and O'Rourke (2022), showed a customer requirement of an eighteen percent reduction in labor hours, due to the application of the learning curve, for Ship two as compared to ship one. An additional eighteen percent, per customer requirements, reduction over ships three and four.

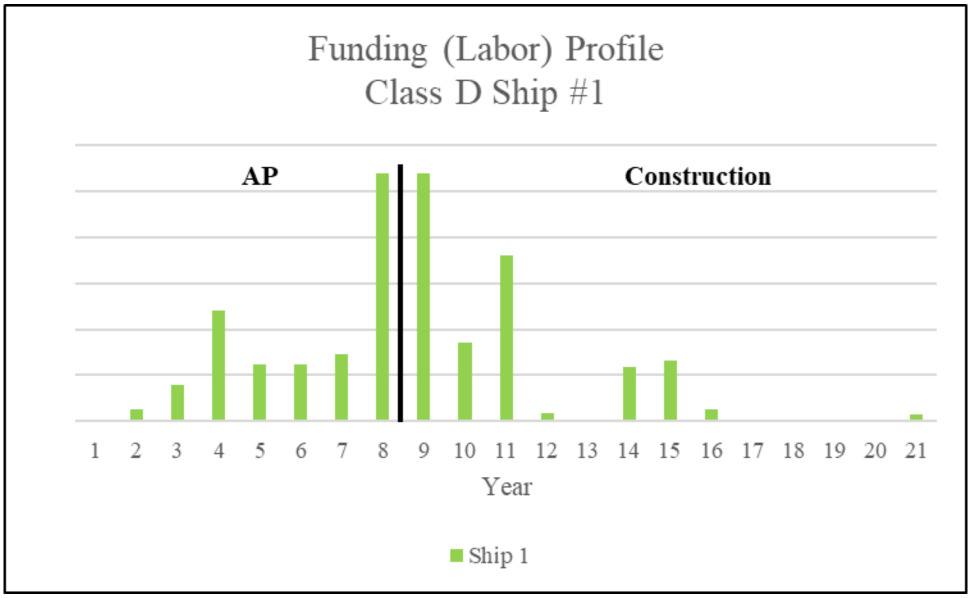

Figure 39: Ship Number 1 Class D Labor Profile

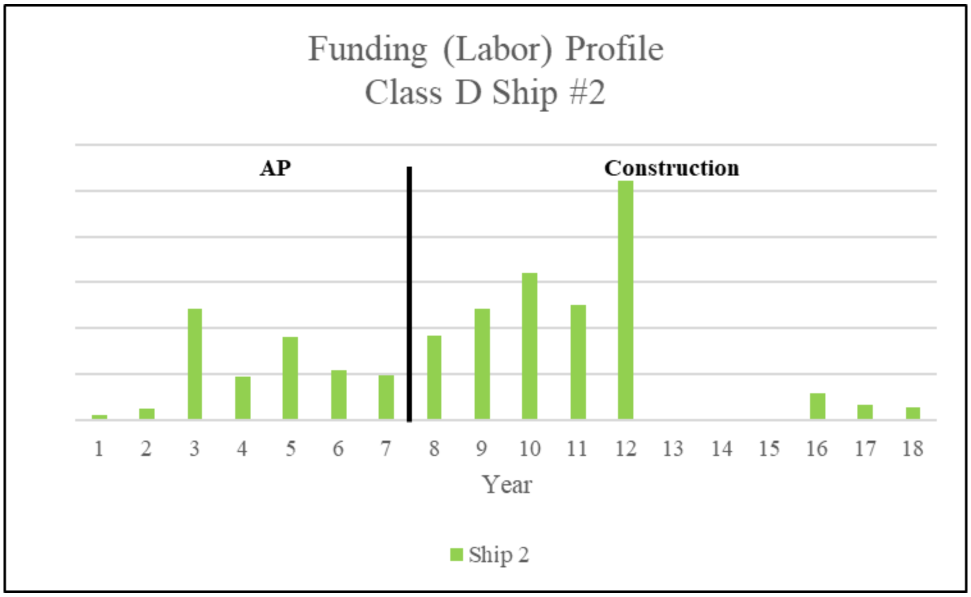

Figure 40: Ship Number 2 Class D Labor Profile

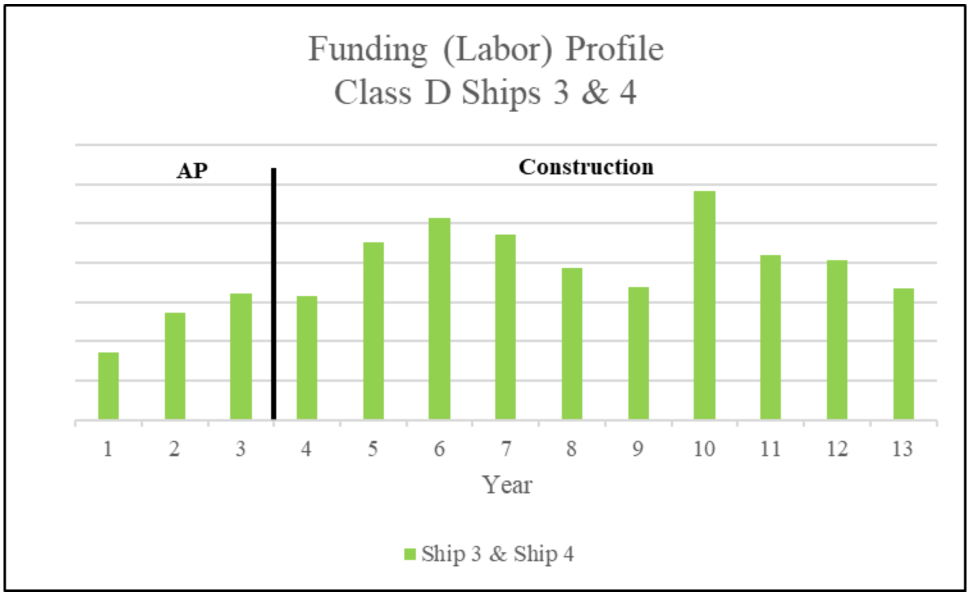

Figure 41: Ship Numbers 3 and 4 Class D Labor Profile

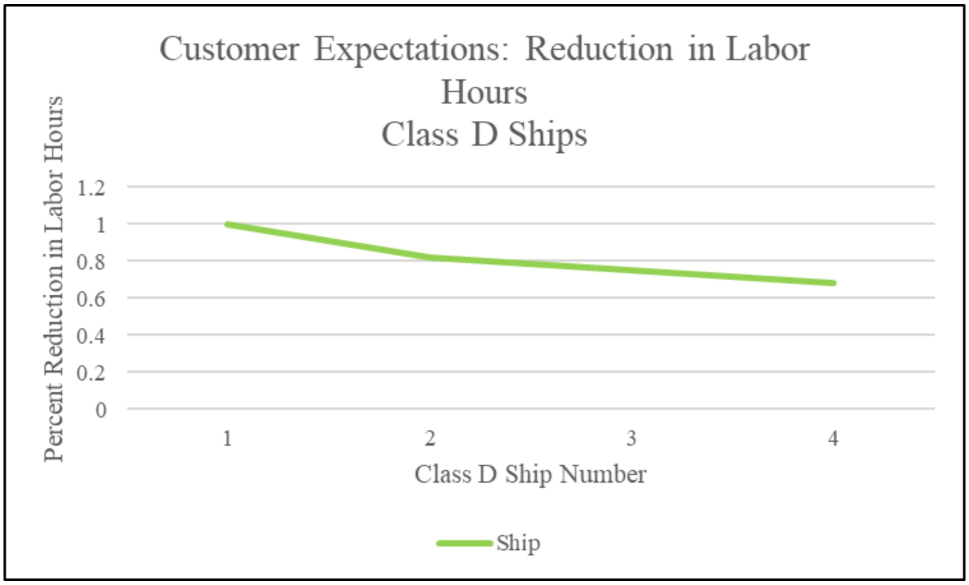

Figure 42: Class D Ships Reduction in Labor Hours Customer Requirements

Construction Schedule Milestones

- *Figure:* 43
- *Reference:* Figure 43 was developed with information from the following sources: Moldafsky et al (2013), Jones (2017), Eckstein (2019), Malone (2019), CVN 79 NVR (2022), Fabey (2022), Navy League (2017), O'Rourke (2022), Pike (2022), and Shelbourne (2022).
- *Description:* There were four major milestones depicted by Figure 43, and they are:
    - months between delivery dates of successive Class D Ships,
    - months from contract award to keel,
    - months from contract award to launch, and
    - months from contract award to delivery.

  As already indicated, per Schank et al (2005) and Moldafsky et al (2013), these were the principal dates associated with naval ship construction. The researcher also had to assume that delivery meant that all work was completed for a given ship. However, sometimes in low-rate production of ships, some amount of work was completed after delivery, but for the purposes of this research, the researcher assumed that this volume of work was negligible.
- *Analysis of this Figure:* As Figure 43 shows, there was approximately seven years between deliveries associated with the first two ships of this ship class. The last two ships of this class have about four years between deliveries. In terms of contract award to keel, there was approximately three and a half years of variability between the first three ships of this class with the last ship of this class over eighty months as compared to the third ship of the class. Contract award to launch varied over the first three ships by about

two years with again the last ship of the class having the largest number of months for this milestone. Contract award to delivery was fairly steady for the first three ships of the class while the last ship had the greatest number of months at almost 160 months. It should also be noted that some of these dates are projected dates since some of the ships associated with Class D Ships were still under construction.

Figure 43: Class D Major Ship Construction Milestones

Significant Changes

- *Figures:* 44 and 45
- *References:* Figures 44 and 45 were developed using Moldafsky et al (2013), Jones (2017), Eckstein (2019), Malone (2019), CVN 79 NVR (2022), Fabey (2022), O'Rourke (2022), Pike (2022), and Shelbourne (2022).

- *Description:* A characteristic that all low-rate production ships have in common was that they all were impacted by changes that occur after contract award and were incorporated prior to ship delivery. Utilizing information contained in the public domain, the researcher identified the most significant changes impacting each ship of this class. As each change was identified the researcher simply counted each change. The researcher also assumed that the impact of each change was the same meaning that the researcher did not quantify the difference in the impacts associated with each change. This was an assumption and limitation with respect to this research; however, due to the limited information contained within the public domain in regard to the number of systems impacted by each change, this assumption was a logical conclusion to pursue accordingly. Two types of figures were developed for this parameter along with displaying this information for the consecutive delivery of each ship. As such, this then created two figures, and specifically Figures 44 and 45. The first type of figure analyzes the cumulative number of changes across the ship class by normalizing to the first ship of the class that actually experienced significant changes. The second type of figure displayed the number of changes as compared to the previous ship. This provided an assessment of the degree of changes from ship to ship while the first type of figure provided visibility into the total number of changes for the ship class utilizing the first ship that experienced changes to normalize too. Both of these figures provided these assessments for Class D Ships. Unlike other ship classes being analyzed to support this research, not only were changes accepted after contract award, but the first ship of the class had a substantial number of systems that were not designed yet. As such, for this parameter for Class D Ships, Figures 44 and 45 not only showed ship numbers one, two, three, and four, but they also showed ship number one after contract award to capture the fact that substantial systems were not designed prior to contract award. Ship numbers two, three, and four were still being built by the shipbuilder, and as such, changes were still forthcoming associated with these ships, and for that matter, there were no changes in the public domain that have been identified with ship number four of Class D Ships.

- *Analysis of these Figures:* In regard to Figure 44, the number of changes between ship number one and ship number two represents a large increase. The changes between the second and third ships was minimal; however, as indicated, these ships were still in production. Ship number four in Figure 44 shows no changes because there were no changes discussed in the public domain, but this will eventually change as the maturity of the ship evolves. In terms of Figure 45, which was a cumulative assessment of the changes over the life of the class, the same trend occurs as Figure 44 with ship numbers three and four showing a decrease in the number of changes primarily due to the relatively immaturity of those two ships.

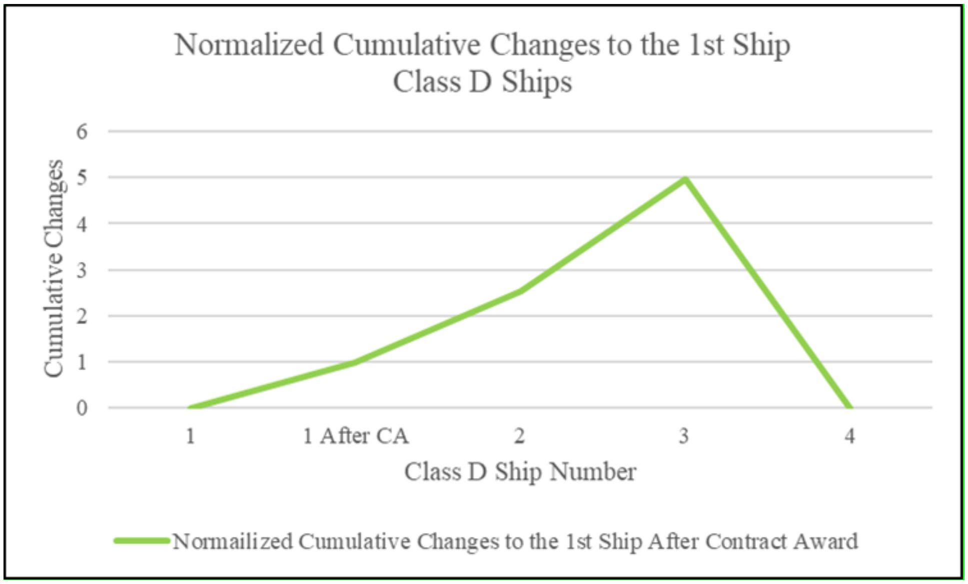

Figure 44: Class D Ships Normalized Cumulative Changes to the First Ship

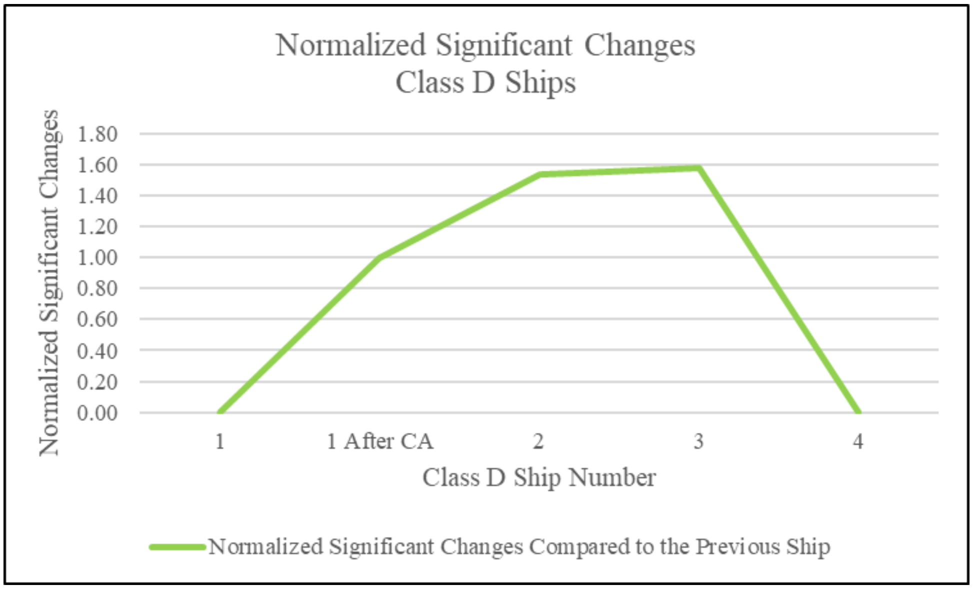

Figure 45: Class D Ships Normalized Significant Changes Compared to the Previous Ships

Procurement Strategy

- *Figure:* 46
- *Reference:* Figure 46 was developed from CRS (2021) and O'Rourke (2022).
- *Description:* Figure 46 provided the procurement strategy associated with Class D Ships. This figure defined the quantities that were procured for this class of ship. Per O'Rourke (2022), ship numbers one and two were procured separately while ships three and four were procured together.
- *Analysis of these Figures:* These ships were procured over multiple years, and the funding for the first two ships were funded separately for different aspects associated with ship construction depending on ship maturity at that time. Only ship three and ship four were procured together other than year eighteen of Figure 46 where some of Ship 3 was procured too. The procurement strategy has large swings year over year.

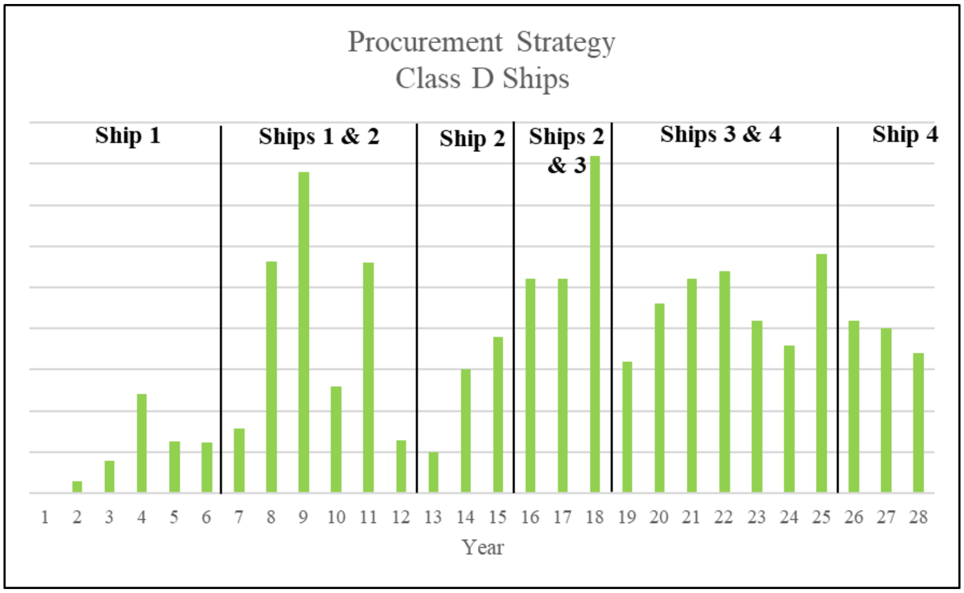

Figure 46: Funding Profile for Class D Ships

<u>Labor Elements and Profiles – Production</u>

- *Figures:* 47, 48, 49, 50, and 51
- *References:* Figures 47, 48, 49, 50, and 51 were developed from Schank et al (2011).
- *Description:* Figures 47 through 51, which were derived from Schank et al (2011), were reflective of projected future workloads associated with various shipbuilding skills associated with Class D ships. They were also reflective of projected workload demands. The projected future workload demands are a function of a projected delivery of a Class D Ship every five years, per Schank et al (2011). Utilizing a delivery of one Class D ship every five years, Schank et al (2011) then developed a projected future workload, by skill, to support Class D ships. Schank et al (2011) does not specifically reference Wright other than stating that efficiencies would result meaning less hours required per

skill over time. As the researcher has proven, the prevailing learning efficiency estimation was Wright, until now, and as such, the researcher was assuming that Schank et al (2011) was also referring to Wright's theories as well.

Schank et al (2011) did not provide values or percentages for the y-axis. However, for the purposes of this research, the relative profiles and shape of the curves was the principal focus. The shapes and profiles of Figures 47 through 49 are proportionally relative to one another because Schank et al (2011) provided Figures 47 through 49 all on one graph, and the researcher split them out accordingly. As such, Figures 47 through 49 have been developed utilizing the information contained within Schank et al (2011).

- *Analysis of these Figures:* Figures 47 through 51 was developed from Schank et al (2011), and it represented the future workload associated with fitters and welders, outfitting production, electrical, machinery, and piping for Class D ships. As indicated, the future for all of these profiles was based on the workload associated with these skills including efficiencies gained through learning.

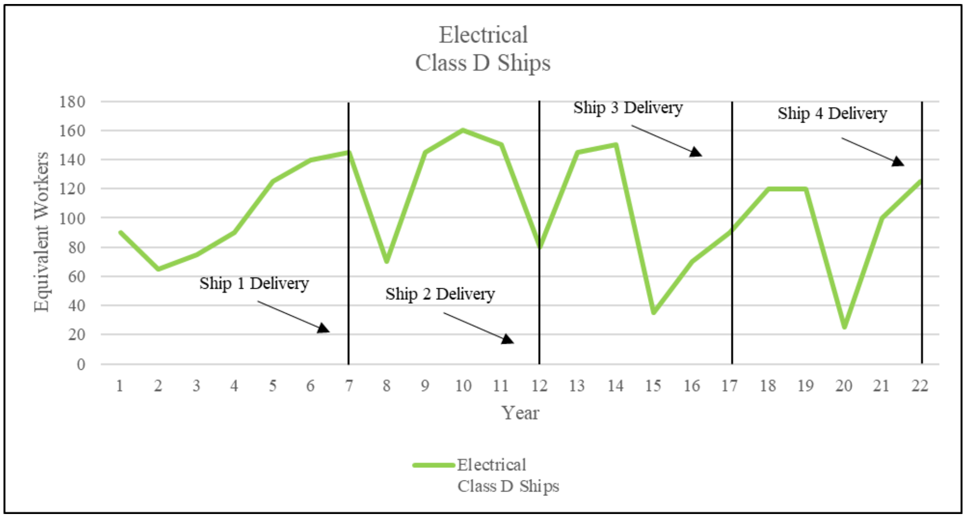

Figure 47: Fitters and Welders Supporting Class D Ships

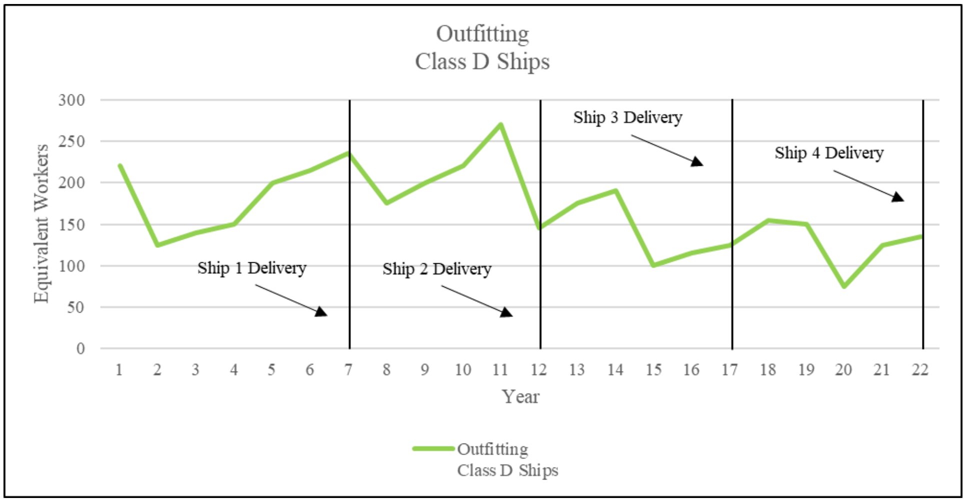

Figure 48: Outfitting Production Supporting Class D Ships

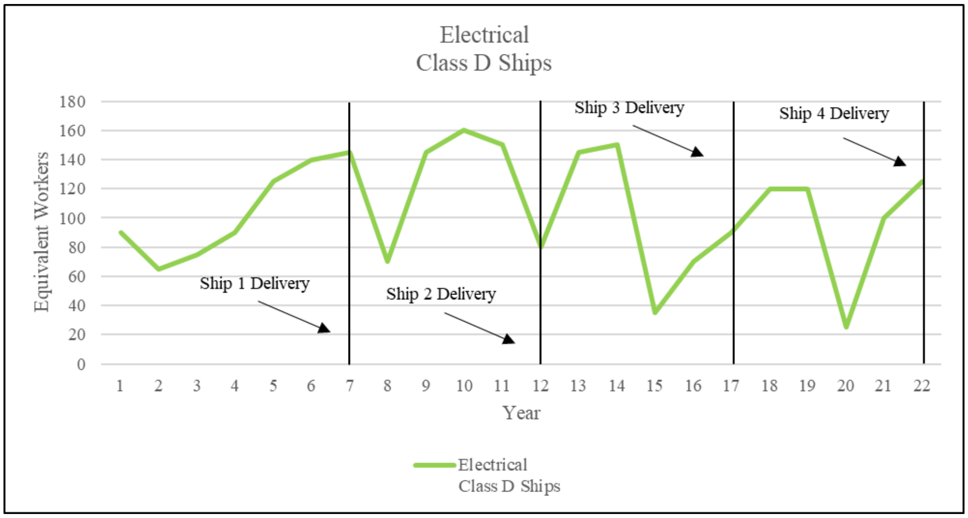

Figure 49: Electricians Supporting Class D Ships

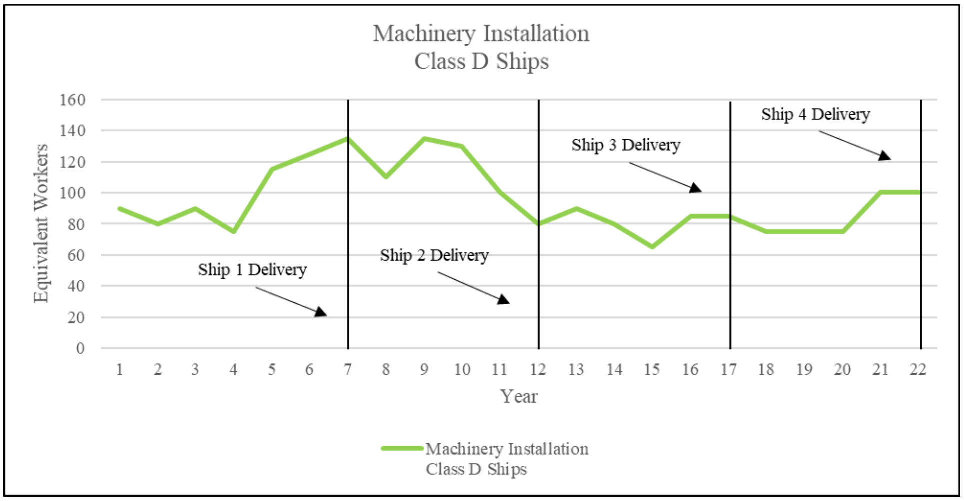

Figure 50: Machinery Installation Supporting Class D Ships

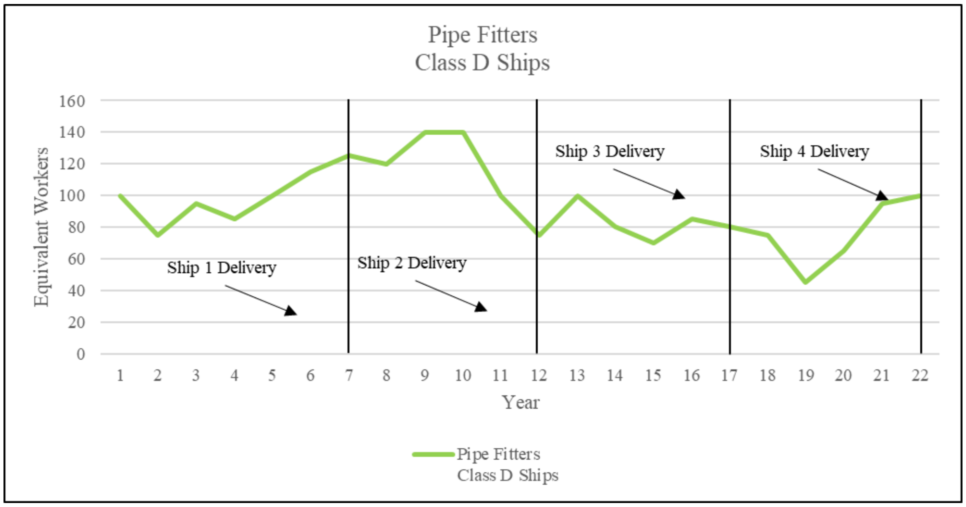

Figure 51: Pipe Fitters Supporting Class D Ships

<u>Labor Elements and Profiles – Non-Production</u>

- *Figures:* 52 and 53
- *Reference:* Figures 52 and 53 were developed from Schank et al (2011).
- *Description:* Figures 52 and 53, which were derived from Schank et al (2011), were reflective of projected future workloads associated with various non-production related shipbuilding skills associated with Class D ships. They were also reflective of projected workload demands with labor efficiencies as a result of projected learning. The projected future workload demands were a function of the overlap in construction activities while delivering a ship every five years. The overlap in construction activities relates to the fact that it takes longer than five years to build a Class D ship; however, Schank et al (2011) based their assessment on Class D ships that were projected to be delivered every five years. Utilizing a delivery of one Class D ship every five years, Schank et al (2011)

then developed a projected future workload, by non-production skill, to support Class D ships which also included efficiencies due to learning. Schank et al (2011) does not specifically reference Wright other than stating that efficiencies would result meaning less hours required per non-production skill over time. As the researcher has proven, the prevailing learning efficiency estimation was Wright, until now, and as such, the researcher was assuming that Schank et al (2011) was also referring to Wright's theories as well.

Schank et al (2011) did not provide values or percentages for the y-axis. However, for the purposes of this research, the relative profiles and shape of the curves was the principal focus. The shapes and profiles of Figures 52 and 53 are proportionally relative to one another because Schank et al (2011) provided Figures 47 through 53 all on one graph, and the researcher split them out accordingly. As such, Figures 52 and 53 have been developed utilizing the information contained within Schank et al (2011).

- *Analysis of these Figures:* Figure 52 was developed from Schank et al (2011), and it represented the future workload associated with construction and production support for Class D ships. Figure 53 was developed from Schank et al (2011), and it represented the future workload associated with engineering for Class D ships. As indicated, these figures were based on the workload associated with these skills including efficiencies gained through learning.

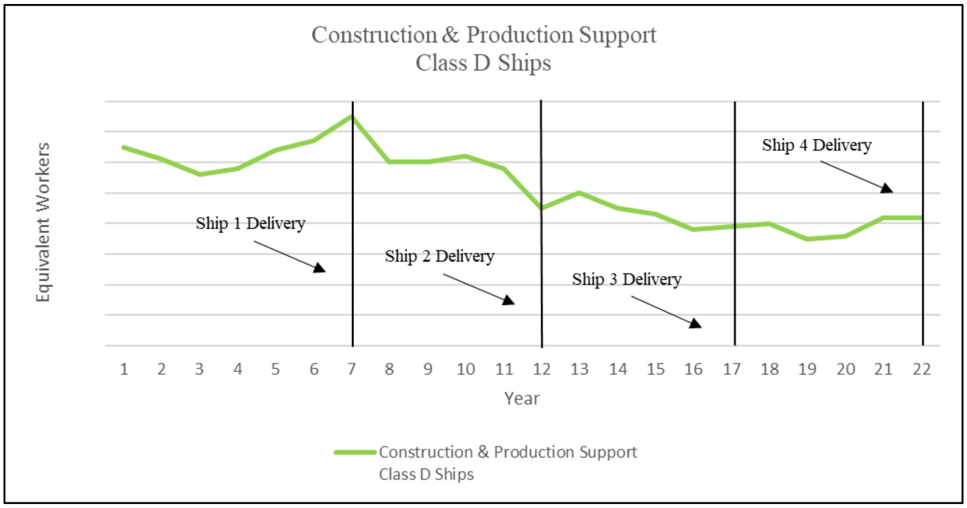

Figure 52: Construction and Production Support for Class D Ships

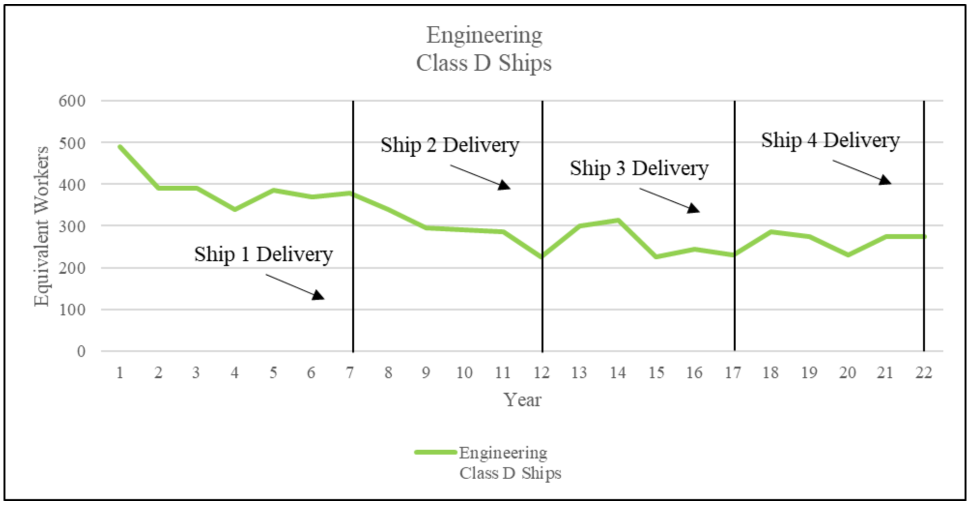

Figure 53: Engineering Supporting Class D Ships

Funding Profiles

- *Figures:* 54, 55, 56, and 57
- *References:* Figures 54, 55, 56, and 57 were developed using Fabey (2019), CRS (2021), and O'Rourke (2022).
- *Description:* Figures 54, 55, 56, and 57 provide the funding profiles and/or strategy for Class D Ships.
- *Analysis of these Figures:* Figures 54, 55, and 56 were reflective of the first four Class D Ships with Figures 54 and 55 displaying the first two ships, which were single procurements with their own unique funding profile. Figure 56 provided the funding profiles for the third and fourth ships of this class. All three figures, per O'Rourke (2022), showed an AP timeframe and a Construction time frame. The AP timeframe was referencing advanced planning, which were pre-construction and early construction efforts while construction refers to construction of the ship through completion. For the single sourced procurements and associated funding profiles, the funding levels varies dramatically with the bulk of the funding occurring over an eight-to-ten-year time frame. Figure 56 showed a funding profile for ships three and four because, per Fabey (2019) and O'Rourke (2022), the third and fourth ships of this class were a combined procurement, and as such, the funding profiles associated with these ships were reflective of the procurement of two ships. In regard to Figure 57, Fabey (2019) and O'Rourke (2022) discussed the fact that the ships contracted to be built included a learning curve associated with each progressive ship. The second ship of this class had applied to it, by the customer, an eighteen percent learning curve while the third and fourth ships of this class had an additional eighteen percent learning curve also applied to both ships collectively. This is discussed in more detail within the Conclusions Section; however,

using Wright's (1936) terminology, the second ship of this class was contracted with an eighty-two percent learning curve. Since Ship Numbers 3 and 4 were procured together, and they have a combined eighteen percent reduction in hours due to learning, which is reflected in Figure 57.

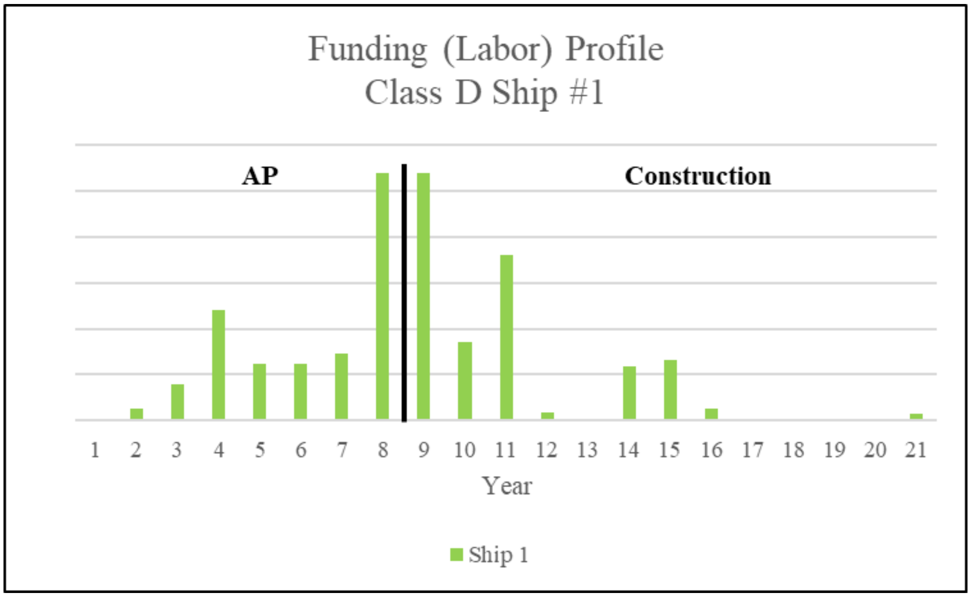

Figure 54: Funding Profile for Class D Ship Number 1

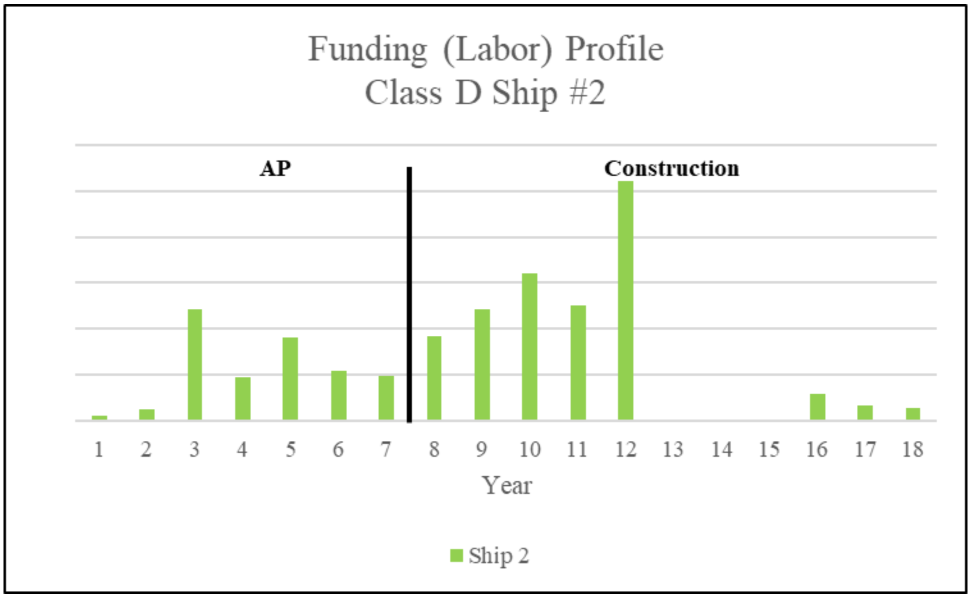

Figure 55: Funding Profile for Class D Ship Number 2

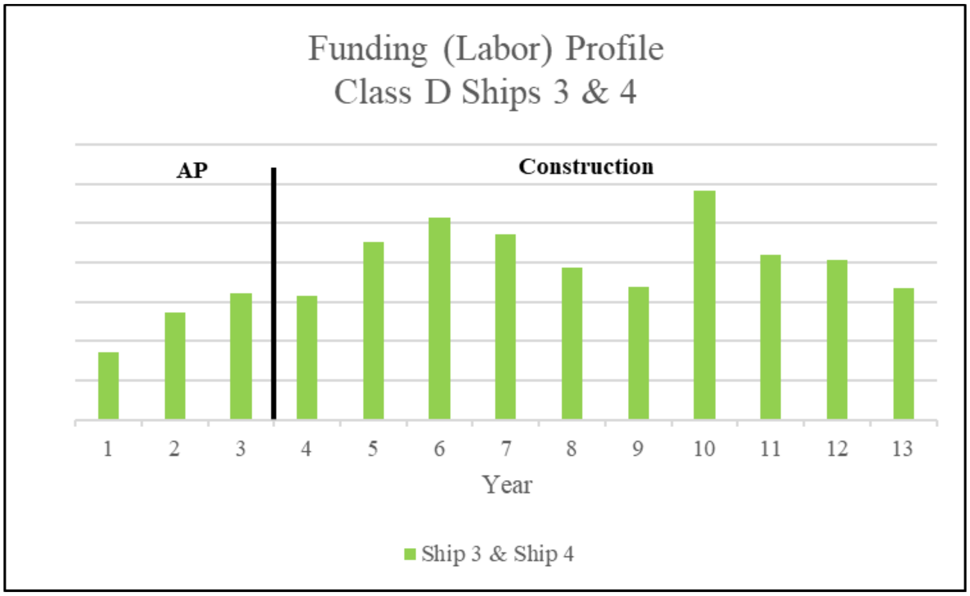

Figure 56: Funding Profile for Class D Ship Numbers 3 and 4

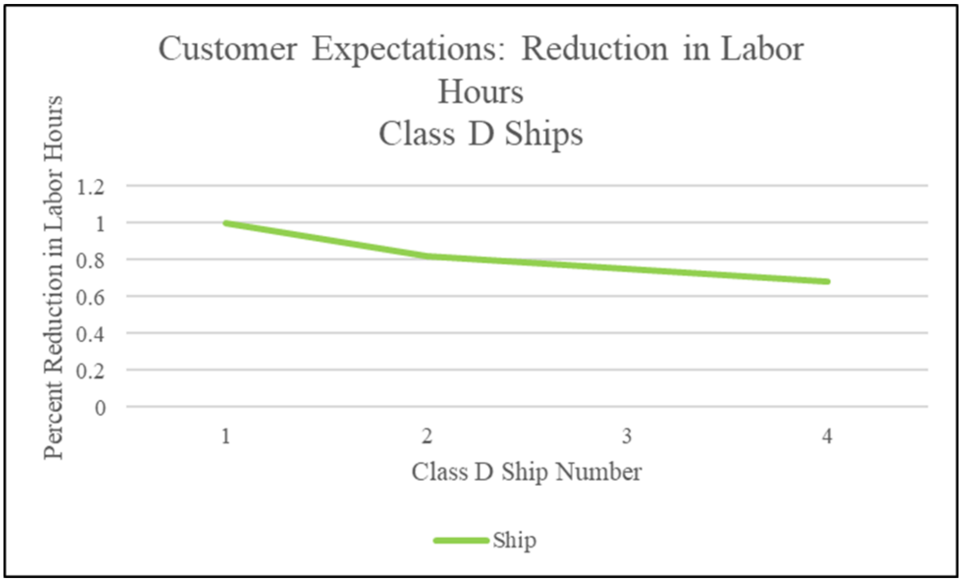

Figure 57: Reduction in Labor Hours for Class D Ships as a Result of the Contracted Learning Curve

## Other Parameters

Table 9 highlights thirteen parameters related to learning across four different ship classes. Seven of these parameters have already been defined and detailed for each of the four ships classes captured herein. The remaining six parameters were delineated in this section. However, these six parameters were applicable to all four ship classes, and were pertinent to assist with characterizing learning in low-rate production environments. The same format was used to articulate these next six parameters as the first seven parameters with the only difference being that these six parameters were applicable to all four ship classes, except if noted otherwise. Of these six remaining parameters, one parameter shown in Table 9, Labor Workforce by Major Systems, was developed for Class B Ships, but was applicable to the other three classes of ships.

Two of the parameters, delineated via Table 9, were specific to shipbuilding but not to a specific class, and they were:

- Workforce Labor Demographics and
- Output Per Employee for Shipbuilding.

The remaining three parameters of Table 9 were not specific to shipbuilding but were applicable to learning, and they were:

- Output per Employee for Aircraft and Automotive Industries,
- Learning Retention, and
- Learning Efficiencies

As such, these six parameters were detailed within the next section.

### Labor Workforce by Major Systems

- *Figure:* 58
- *Ship Class Applicability:* Figure 30 was developed based on Ship Class B, but was appliable to Ship Classes A, C, and D too because Figure 30 conveyed the required labor workforce by major systems. The parameter entitled Labor Elements and Profiles – Production utilized terminology to describe labor elements of electricians, welders, and so on which were labor elements that would be commensurate with working on systems delineated via Figure 30. Also, Lewis (1989) and Molland (2008) delineated that the systems articulated via Figure 30 were representative of systems that were common to all ship platforms and classes of ships. As such, even though Figure 30 was developed for Ship Class B, it was relevant and applicable to Ship Classes A, C, and D too at least in terms of the major systems associated with various ship classes. The actual percentage

for each major system will obviously vary with each class of ship, but for the purpose of this research, the relative percentages were not as important as just identifying the major systems to focus on across various ship classes. As such, since the applicability of Figure 30 was extended to Class A, B, and D Ships, then Figure 30 was shown within this Section as Figure 58.

- *References:* Specifically for Ship Class B, Figure 30 was developed based on information provided by Birkler et al (2005). However, due to Lewis (1989) and Molland (2008), Figure 30 extends applicability to Ship Classes A, C, and D, and was now shown as Figure 58. Also as was just covered, the relative percentages will vary across different ship classes, but for the purposes of this research, the element that was more important was simply the principal systems associated with each ship class which helped to support the characterizations that was developed via Chapter 5.
- *Description:* Due to Lewis (1989), Birkler et al (2005), and Molland (2008), Figure 58 provided the labor workforce required for shipbuilding by major systems across various ships.
- *Analysis of this Figure:* As Figure 58 shows, systems associated with the hull require the most labor workforce. Labor activities associated with the hull supports all aspects of ship construction from plate cutting, forming, shaping, and welding together to make modules to support ship erection per Molland (2008). The auxiliary systems were distributed throughout the ship thereby making them the next largest percentage of work to be accomplished. Outfitting and electrical were approximately equal in terms of percentages needed to support major systems. As already discussed, the actual percentages across different ship platforms were not specifically relevant for this

research. The important aspect was simply the affected systems which was utilized to support the development of the learning curve characterization.

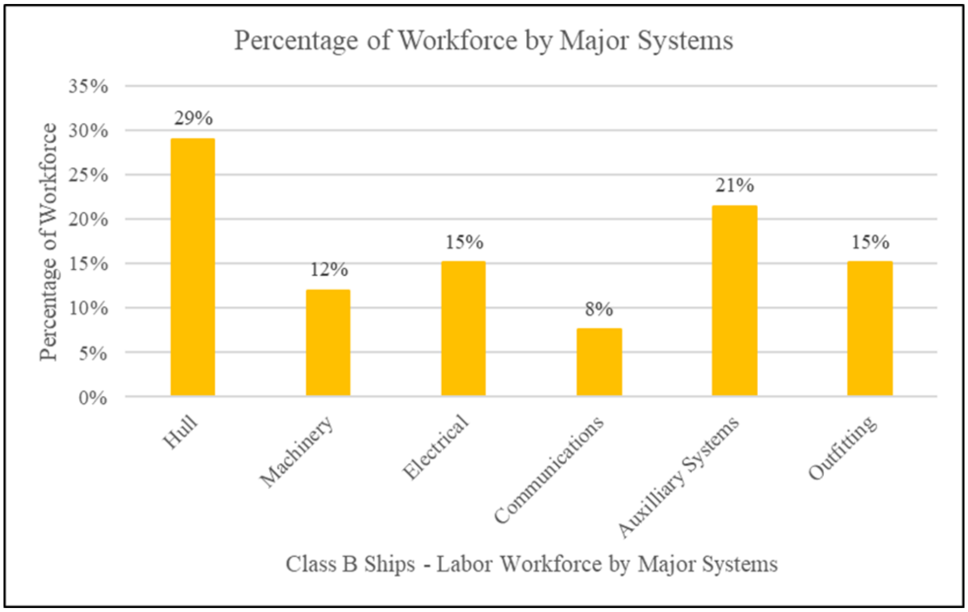

Figure 58: Labor Workforce by Major Systems for Class B Ships with Applicability Extended to Class A, C, and D Ships

## Workforce Demographics - Shipbuilding

As Table 9 indicates, workforce demographics was another parameter to understand as it relates to learning in low-rate production environments.

- *Figures:* 59, 60, 61, and 62

- *Ship Class Applicability:* Figures 59, 60 and 61 are applicable to all four ship classes. Figure 62 was developed from Schank et al (2007), and provides insights into the age demographics associated with Class C Ships.
- *References:* Figure 59 was developed from information provided by the Bureau of Labor Statistics (2020) while Figure 61 was developed using information provided by McClelland and Walton (1980) for the US Maritime Transportation Research Board. Figure 60 was developed for the US Department of Commerce by Baker, Degnan, Gabriel, and Tucker (2001). Lastly, for this parameter, Figure 62 was developed from Schank et al (2007).
- *Description:* All four of these figures were addressing the labor demographics and specifically the age profiles associated with shipbuilding. This does impact ship building and a learning environment, which was addressed in Chapter 5.
- *Analysis of the Figures:* As indicated, Figure 59 was developed by the Bureau of Labor Statistics (2020) to provide age profiles for shipbuilders. The age profiles showed a very high number of shipbuilders over the age of fifty-five with the smallest demographic being the shipbuilders that were in their early twenty's. Twenty years prior, Baker, Degnan, Gabriel, and Tucker (2001) developed, for the US Department of Commerce, a shipbuilder age demographic, which was shown via Figure 60. Figure 60 also showed the production and non-production shipbuilder age distributions too. Figure 60 shows a bell curve for all three categories of production shipbuilders, non-production shipbuilders, and total of all shipbuilders with the bell curve skewed to the right. Forty years prior compared to Figure 59, McClelland and Walton (1980) developed, for the US Maritime Transportation Research Board, a similar assessment reflected via Figure 61.

As can be seen in Figure 61, a bi-modal age distribution was prevalent for those shipbuilders who are age twenty-five to thirty-four and forty-five and older.

Figure 62, which was derived from Schank et al (2007), provides insights into a specific area of support for Class C Ships, production planning. Obviously, there are numerous other job functions associated with ship production; however, Schank et al (2007) provides this one job function as an indicator of demographic challenges that were associated with shipbuilding. Figure 62 was a very specialized area; however, if this age demographic occurred in other shipbuilding areas, then this could have a substantial impact on learning curves. The contribution of demographics to learning in this environment was covered via Chapter 5.

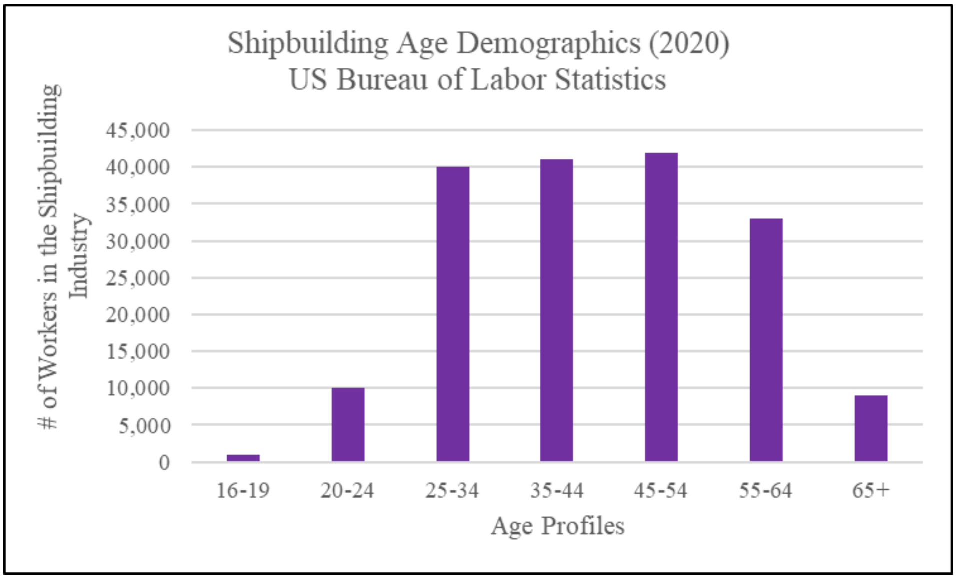

Figure 59: 2020 US Bureau of Labor Statistics Shipbuilding Age Demographics

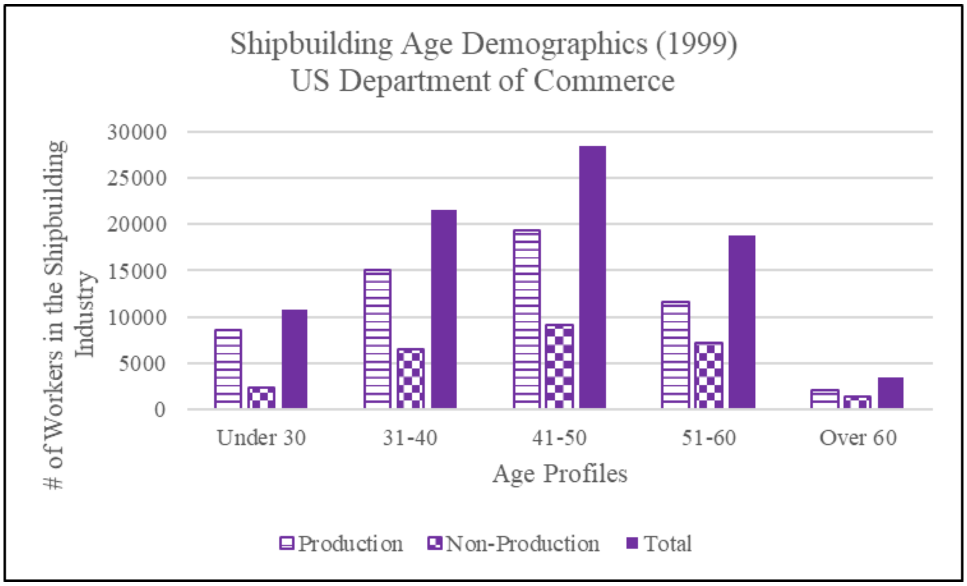

Figure 60: 1999 US Department of Commerce Shipbuilding Age Demographics

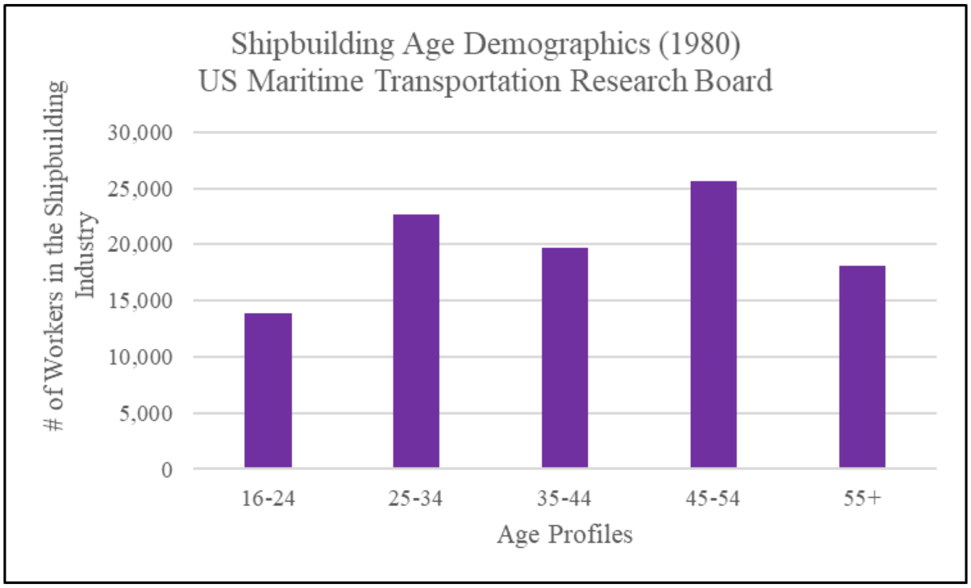

Figure 61: 1980 US Maritime Transportation Research Board Shipbuilding Age Demographics

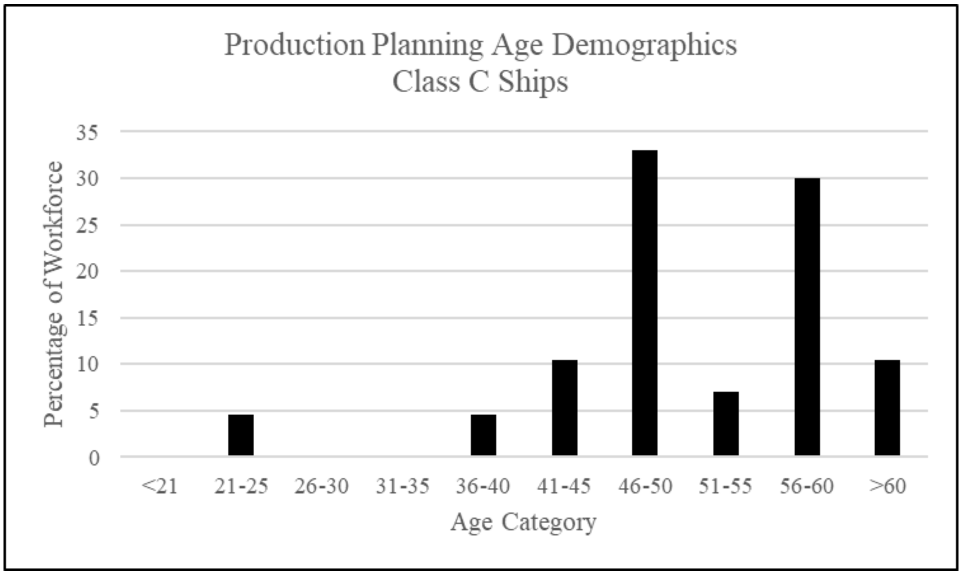

Figure 62: Production Planning Age Demographics – Class C Ships

Output Per Employee - Shipbuilding

- *Figure:* 63
- *Ship Class Applicability:* Class A, B, C, and D Ships because Figure 63 is for shipbuilding.
- *References:* Figure 63 was developed from Baker, Degnan, Gabriel, and Tucker (2001).
- *Description:* Figure 63 shows the output per employee for shipbuilding and repair over a twenty-year time frame. Baker, Degnan, Gabriel, and Tucker (2001) shows Figure 63 combined with Figure 64; however, for the purposes of this research, two figures were created to clearly show work output for shipbuilding separated from the automotive and aircraft industries, which is shown via Figure 64.

- *Analysis of the Figure:* Figure 63 clearly shows that the output per shipbuilder over a twenty-year time frame only shows a slight increase. Figure 63 shows a slight rise in 1982, 1984, 1990, and in 1998. It shows a low point in 1987 and in 1993.

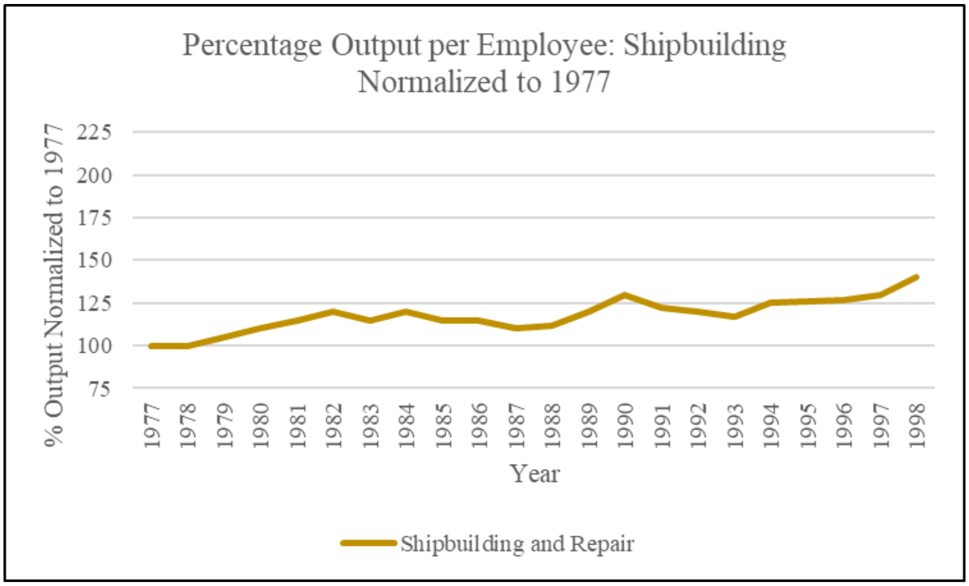

Figure 63: Employee Work Output for Shipbuilding and Repair

<u>Output Per Employee – Automotive Industry and Aircraft Industry</u>

- *Figure:* 64
- *Ship Class Applicability:* Not applicable since Figure 64 is focused on automotive and aircraft industries.
- *References:* Figure 64 was developed from Baker, Degnan, Gabriel, and Tucker (2001).

- *Description:* Figure 63 showed the output per employee for aircraft and automotive industries over a twenty-year time frame. Baker, Degnan, Gabriel, and Tucker (2001) shows Figure 64 combined with Figure 63; however, for the purposes of this research, two figures were created to clearly show work output for shipbuilding separated from the automotive and aircraft industries, which was shown via Figure 64.
- *Analysis of the Figure:* Figure 64 shows both the automotive and aircraft industries with a steady incline in work output over a twenty-year time frame. In terms of the automotive industry, 1980, 1987, and 1995 showed a drop in output per automotive employee while 1983, 1989, 1994, and 1998 showed increases. In terms of the aircraft industry, 1982, 1984, 1989, and 1996 showed declines in output; however, 1980, 1985, 1992, and 1998 shows increases in output per employee for the aircraft industry.

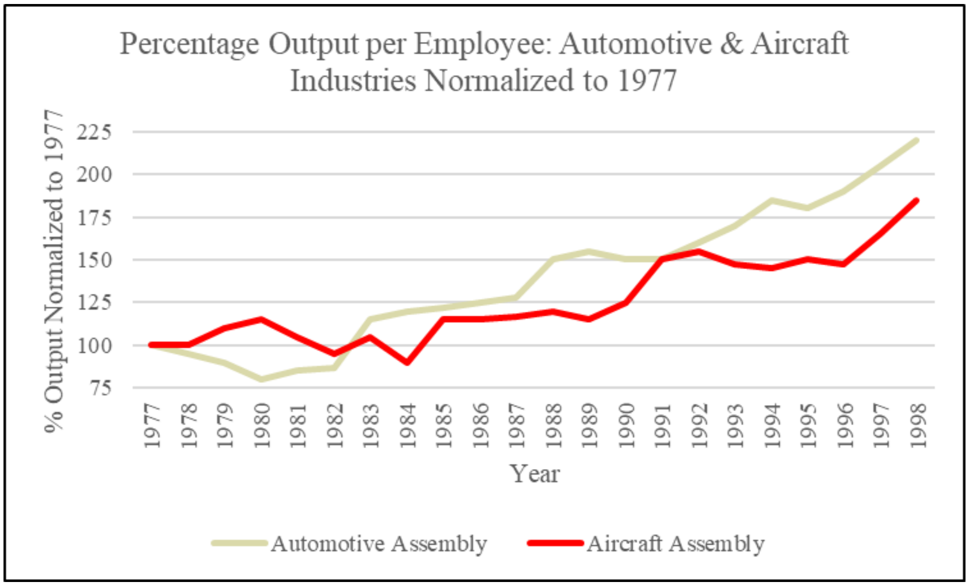

Figure 64: Employee Work Output for Automotive Industries and Aircraft Industries

Learning Retention

- *Figures:* 65 and 66
- *Ship Class Applicability:* Class A, B, C, and D Ships. Learning retention was applicable to all areas including shipbuilding.
- *References:* Figure 66 was developed from Kohn (2014) while Figure 65 was developed from Teichart (2010).
- *Description:* Figure 65, which was developed based on research completed by Teichart (2010), showed the percent remembered over time after a class or some other educational or training opportunity had ended. Kohn (2014), through Figure 66, also substantiates this assessment, through his research on memory retention versus the number of days since the training occurred.
- *Analysis of the Figures:* There was a large body of knowledge associated with learning retention. This research was focused on learning in low-rate production environments. Obviously, a constituent element of learning was retention, or the inverse, which was forgetting. Figures 65 and 66 covers this topic, which was developed by Teichart (2010) and Kohn (2014), respectfully. Teichart (2010) suggests that at the end of a class, people only remember seventy-five percent of what they just learned. As such, their knowledge retention, or forgetting begins at this level and declines to a level that after a month, they only remember less than ten percent of what they had originally learned. Teichart (2010) continues by also stating that even if a person remembered one-hundred percent of what they had just learned from a class, that after a month, they would still only remember about ten percent of what they had initially learned one month prior. Kohn (2014) has a

similar view as Teichart (2010), which was reflected by Figure 66. Kohn (2014) suggested that people within one hour will forget an average of fifty percent of what they have learned, and that within twenty-four hours, they will have forgotten seventy percent. Within a week, knowledge retention, per Kohn (2014) drops to an average of only ten percent, which was reflected via Figure 66. Both Figures 65 and 66 were rooted within the context of Ebbinghaus (1885, 1913) who first published research on the “forgetting curve”. He theorized that the longer humans wait to apply new knowledge, then the less they will retain and remember. These facts were incorporated into the characterization developed by the researcher via Chapter 5.

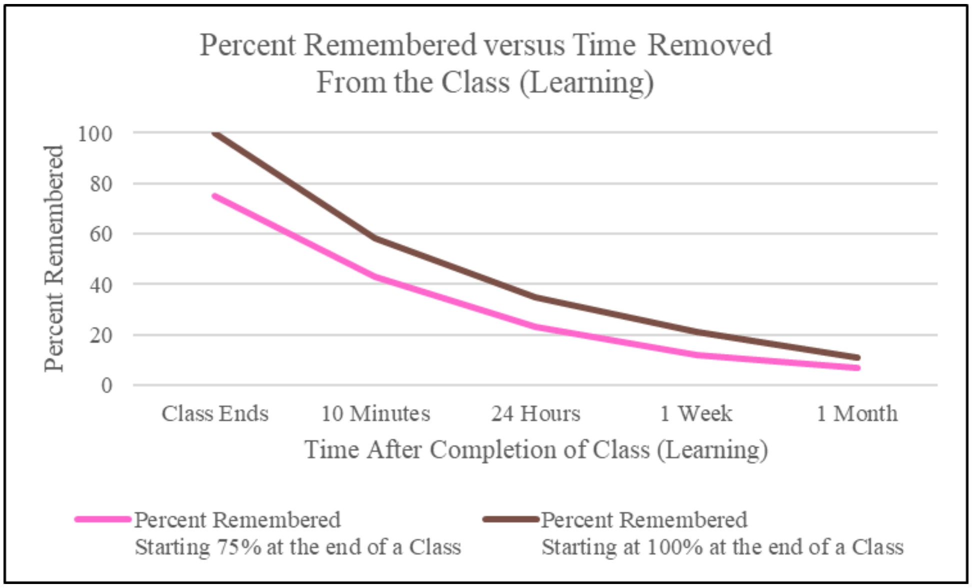

Figure 65: Percent Remembered versus Time Removed from a Training Opportunity

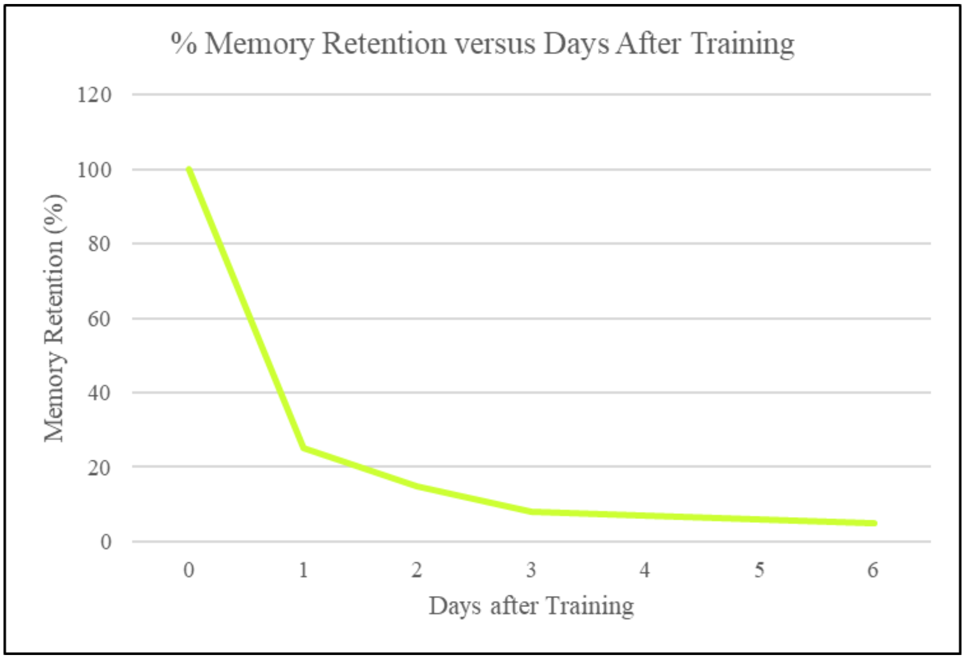

Figure 66: Memory Retention versus Days After a Training Opportunity

Learning Efficiencies

- *Figures:* 67
- *Ship Class Applicability:* Birkler et al (1994) completed research to support the development of Figure 67 for Class C Ships. However, extending its' applicability to other ship classes was a logical deduction realizing that different ship complexities will alter the shape of the curve displayed in Figure 67; however, the researcher was assuming that the general shape of the curve can be extended to other ship classes. Additional conclusions in regards to this figure was discussed in Chapter 5.
- *References:* As indicated, Figure 67 was based on research contained within Birkler et al (1994).

- *Description:* Using Birkler et al. (1994), Figure 67 was developed to highlight the relative efficiency of shipbuilders versus years of experience when working on Class C ships; however, as indicated, the researcher assumed that applicability can be extended to other ship classes. The slope of this curve may vary some based-on ship complexity; however, the researcher was assuming that this was a reasonable assumption to make to apply this curve to Class A, B, and D Ships.
- *Analysis of the Figure:* Figure 67 shows that it takes four years for a shipbuilder to obtain eighty percent efficiency. Birkler et al (1994) conveys that it takes fifteen or more years for a shipbuilder to obtain one-hundred percent efficiency. With one year of experience, a shipbuilder's efficiency was only fifty percent because of lack of knowledge, information, and/or training.

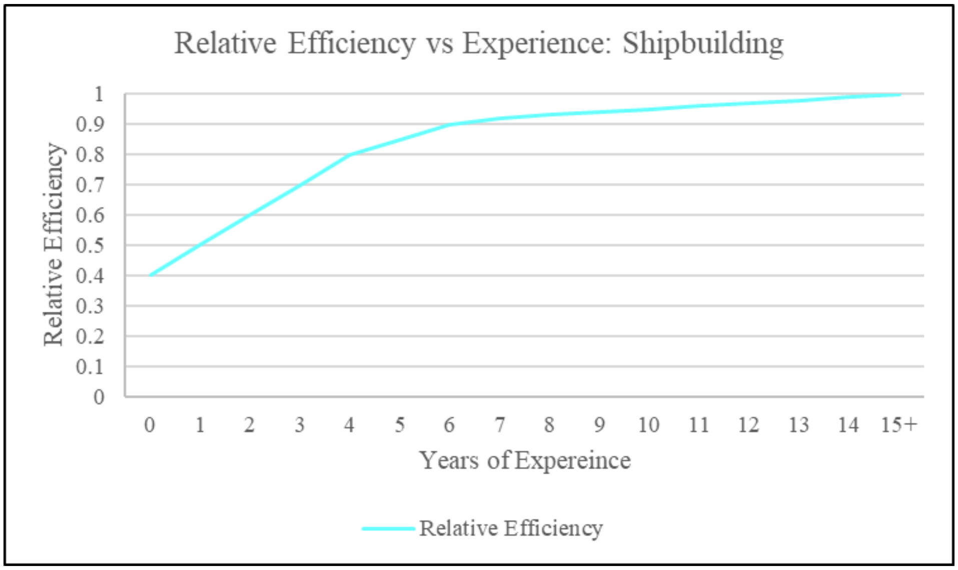

Figure 67: Relative Efficiency versus Years of Experience

### WBS 7 - Iterate Through Different Learning Curve Theories using Class A Ship Data and WBS 8 - Iterate Through Different Learning Curve Theories using Class B, Class C, and Class D Ship Data

The fundamental objective of this research was to develop a characterization that was reflective of learning in low-rate production environments. There were various learning curve theories that have been published, but as indicated, none of these learning curve theories accurately predicts learning in low-rate production environments. Following the research methodology, the next step in this methodology was to assess the Class A, B, and D Ship labor hours versus the five leading learning curve theories. Only labor hours were being assessed against these learning curve theories because labor hours were the principal parameter that was utilized for these theories. Only Class A, B, and D labor hours were being used because labor hours for these three ship classes was in the public domain, as indicated by Table 9. As Table 9 also indicated, labor hours associated with Class C Ships does not reside in the public domain. The five learning curve theories that were most often referenced and cited, and were also addressed in the Literature Review were:

- Wright (Wright, 1936)
- Crawford (Crawford, 1944)
- Stanford-B (Stanford Research Institute, 1949)
- DeJong (DeJong, 1957)
- Sigmond S Curve (1973)

Wright's (1936) theory has been discussed in great detail because, as indicated, he has been acknowledged as the "Father" of the learning curve theory. All other researcher's since him have based their work on his efforts. In addition to Wright, Crawford (1944), Stanford-B (1949), DeJong (1957), and Sigmond S Curve (1973) were the next most referenced and comprise the five most fundamental theories.  As indicated, Wright's Theory and Crawford's Theory, per Martin (2019) and Teplitz (1991) were the most common learning curve models, and they have the largest use across all industries.  The remaining three learning curve theories, per Teplitz (1991), were primarily used to support cost estimating, but they can provide additional insights into learning, and they were DeJong, Stanford-B, and the Sigmond (S) Curve.  As such, WBS 7 and WBS 8 of the research methodology utilizes the labor hours associated with Class A, B, and D Ships, and then applies those hours to each specific theory to assess their ability to predict the associated actual labor curve.

Figure 7 provided the labor hours for Class A Ships normalized to the first ship of the class while Figure 14 provided the labor hours for Class B Ships normalized to the first ship of the class.  In terms of Class D Ships, Figures 39, 40, and 41 were used to develop the actual labor hours for each of the four ships associated with Class D Ships.  As indicated previously with Class D Ships, three of the four ships were still under construction.  As such, the labor hours to complete construction has a high probability of growing.  As a matter a fact, according to O'Rourke (2022) for Class D Ships, ship number two has a sixty-four percent probability of procurement cost growth, Ship Number 3 has a seventy-eight percent probability of procurement cost growth, and Ship Number 4 has an eighty percent probability of cost growth for Class D Ships.  It is important to note that O'Rourke's reference was to procurement cost growth and labor hours was a major contributor to procurement costs along with material.  Also, since three out of four of the Class D Ships were still under construction, the effects of a two ship buy associated with ship numbers three and four was still to be determined.  O'Rourke (2022) also captured the cost growth associated with and without the cost reductions associated with a two ship buy. This assessment was also included with the analysis of the five leading learning curve theories referenced herein.

Per Lessig (2019), Capaccio (2020), and O'Rourke (2022), an eighty-two percent learning curve was applied to Class D Ships during the contracting process for those ships. The information within the public domain did not provide the contracted learning curves applied to Class A, B, or C Ships. However, since these four classes of ships were all low-rate production ships and since the DAU (2018) and Teplitz (1991) states that the learning curve associated with shipbuilding is between "80% to 85%", then for the purposes of this research, the researcher utilized an eighty-two percent learning curve. However, the OLCC that the researcher developed was not dependent on an eighty-two percent learning curve or any specific learning curve number because the OLCC developed was based on a low-rate production environment and not a high-rate production environment, which the five fundamental learning curve theories presented were all based upon as well as all of the published learning curve theories until now as a result of this research.

## Wright's Learning Curve Theory

The first theory to be analyzed using actual labor hours was Wright's Theory. As indicated, the researcher employed Wright's approach to the ship data obtained from the public domain, and specifically to labor hours. As such, utilizing Wright's (1936) theory on Class A, B, and D Ships yielded an assessment focused on the cumulative average graph which was a plot of the average number of hours taken to produce each Class A, B, and D Ships versus an increasing number of ships. It should be noted that Wright (1936) was analyzing units of a given batch as that batch size increased. Obviously, since Class A, B, and D Ship data was low-rate production, vice as has been previously discussed, Wright developed his graphs based on high-rate production of a two-seater aircraft made at Curtiss-Wright during the late 1920's and 1930's, then this assessment was different.

Wright (1936), which was also captured by many other references, such as Learning Curve Analysis (2010) and Teplitz (1991), developed the following equation to define a learning curve:

$$Y = aX^b \qquad \text{(Equation 15)}$$

where:

$Y$ = cost

$a$ = actual or theoretical first unit cost

$X$ = quantity

$b$ = slope of the learning curve

As indicated, Wright's (1936) theory is based on cumulative average unit costs; as such, applying this to Class A, B, and D ships yields Figures 68, 70, 72, and 74. Figure 68 and Figure 70 both show that the learning curve for labor hours for Class A and Class B Ships were divergent compared to Wright's theory based on cumulative average unit costs. Figures 72 and 74 also showed the same results. Both of these figures display Class D Ships but Figure 72 was reflective of a two ship buy for the third and fourth ships of this class while Figure 74 showed the impact without a two ship buy. As previously indicated, three of the four ships associated with Class D Ships were still in production. As such, the labor hours for these three ships were projected values.

Wright (1936) observed that plotting the cumulative average cost curve on a log-log graph resulted in a straight line. According to Wright (1936), this straight line always has a negative slope to reflect learning such that each doubling of units resulted in a constant rate of reduction in quantity referred to as a learning curve slope as per SCEA (2010) and Teplitz (1991). Figures 69, 71, 73, and 75 are graphs plotting the cumulative average labor hours as a log-log graph. For each Figure, the eighty-two percent learning curve plots as a straight line, which correlates with Wright's Theory; however, plotting the actual unit labor hours for Class A, B, and D Ships does not result in a straight line because, as was the fundamental foundation for this research, current learning curve theories were not reflective of low-rate production environments. Chapter 5 uses these results to support associated conclusions accordingly.

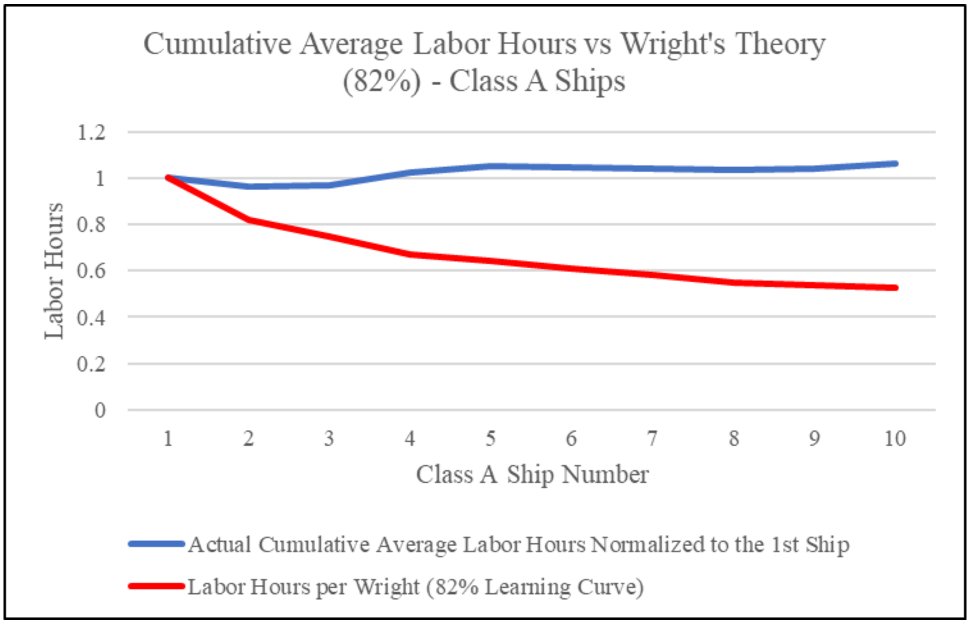

Figure 68: Cumulative Average Labor Hours Class A Ships

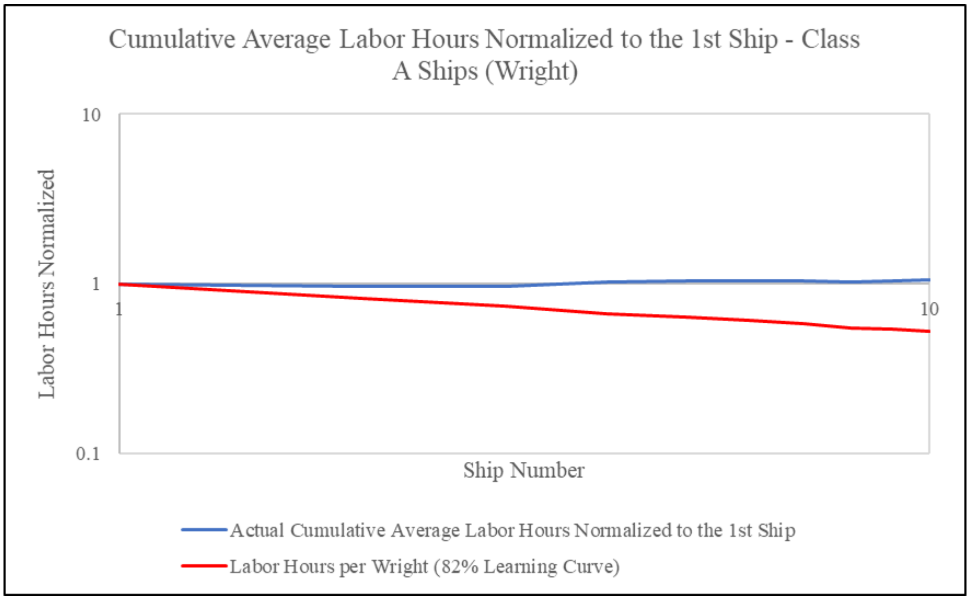

Figure 69: Cumulative Average Labor Hours Log-Log Plot Class A Ships

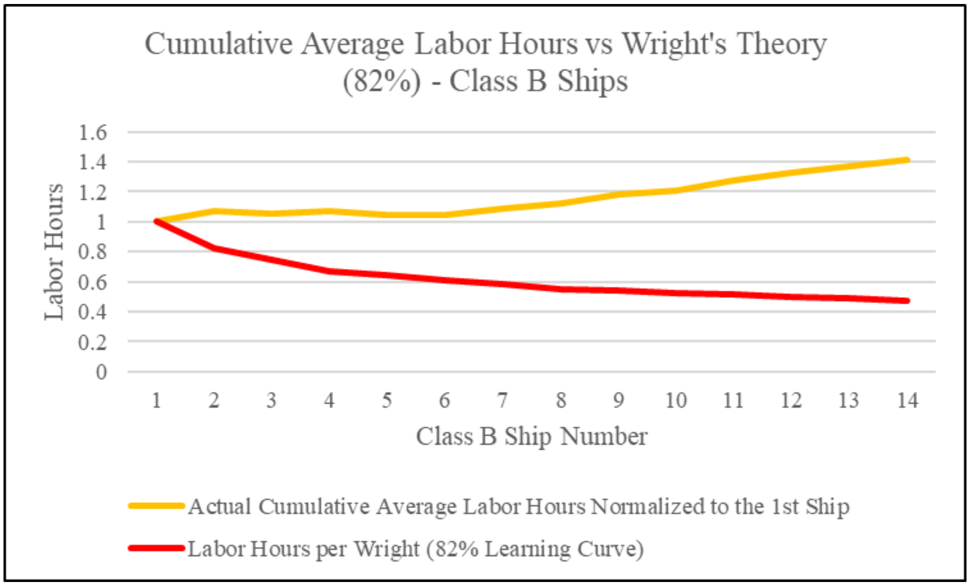

Figure 70: Cumulative Average Labor Hours Class B Ships

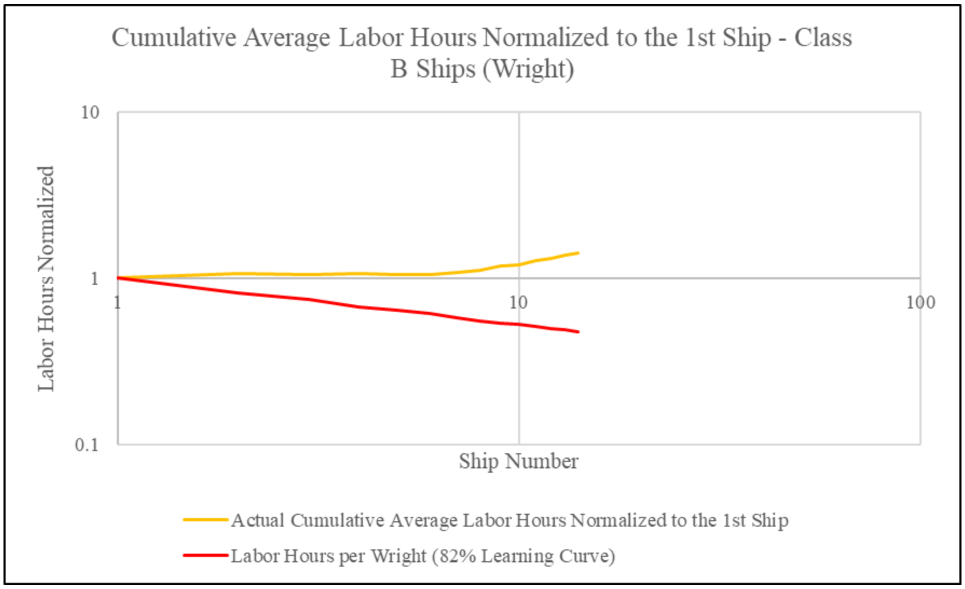

Figure 71: Cumulative Average Labor Hours Log-Log Plot Class B Ships

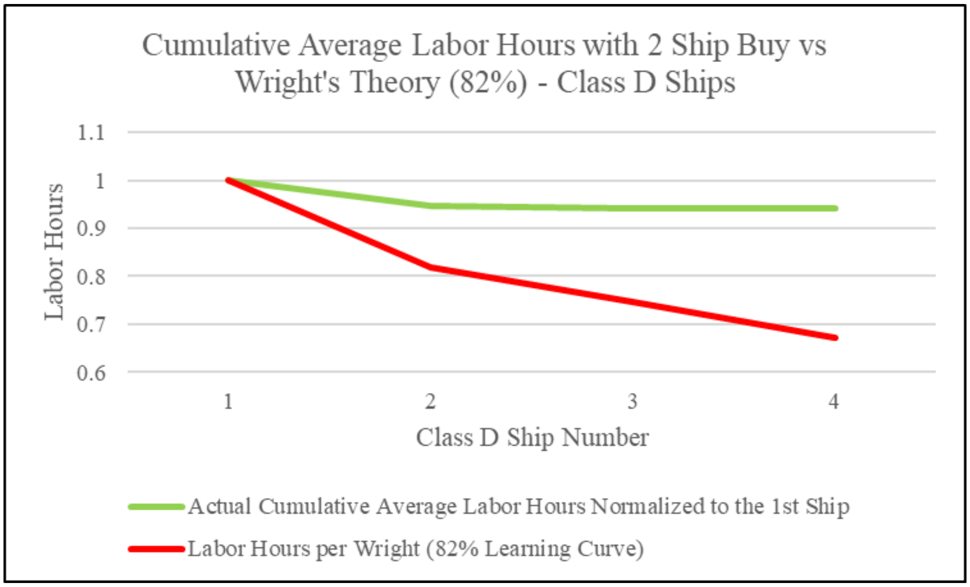

Figure 72: Cumulative Average Labor Hours Class D Ships with Two Ship Buy

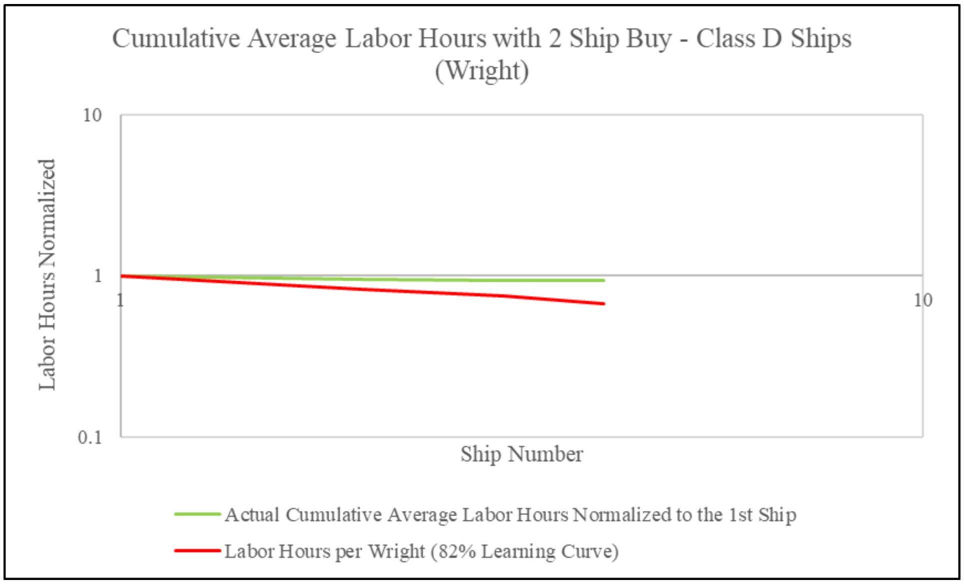

Figure 73: Cumulative Average Labor Hours Log-Log Plot Class D Ships with Two Ship Buy

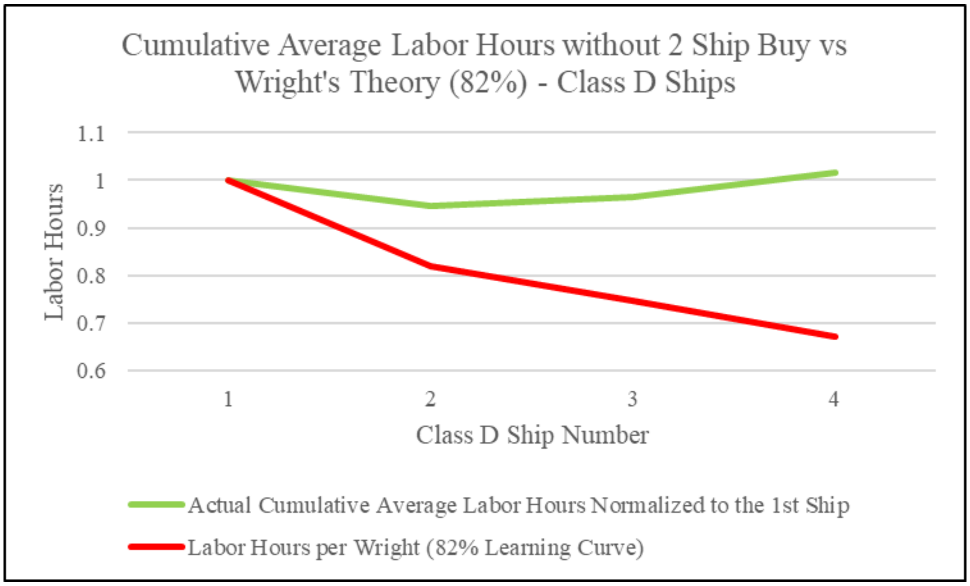

Figure 74: Cumulative Average Labor Hours Class D Ships without Two Ship Buy

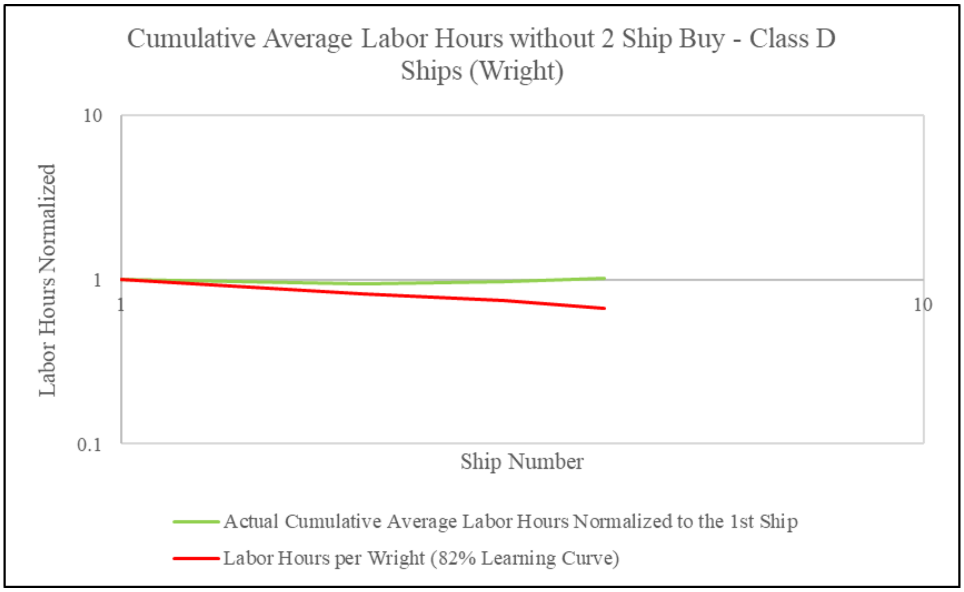

Figure 75: Cumulative Average Labor Hours Log-Log Plot Class D Ships without Two Ship Buy

## Crawford's Learning Curve Theory

The next theory was based on the research of Crawford (1944). Crawford was working for Lockheed Aircraft Corporation, and he, like Wright, observed the production of airframes. He also observed a constant rate of learning every time production doubled. However, in lieu of characterizing his observations on a cumulative average approach, he plotted unit cost production. As such, the unit graph plots the actual number of hours taken to produce each ship of the class as the number of ships produced increased. Equation 15 was still applicable, but the focus was on individual unit production. Wright (1936) was the recognized founder of learning curves, but Crawford (1944), according to Martin (2019) and Teplitz (1991) "has gained the largest following". As Teplitz (1991) states, both theories were based on observations in production environments, but in the case of Wright, his theory was based on cumulative average while Crawford was based on individual units. Teplitz (1991) also stated that learning curve analysis and theory was based on these two standards, and that all other learning curves were founded on these two theories. One of the fundamental elements of this research was that Wright (1936) and Crawford (1944) based their observations in a production environment, but it was a high-rate production environment, which was completely different from a low-rate production environment, like naval shipbuilding, which led to a different characterization compared to Wright's and Crawford's theories.

Figures 76, 78, 80, and 82 displayed Class A, B, and D Ships using Crawford's (1944) theory. Crawford (1944), like Wright (1936) also plotted his observations on log-log paper. However, instead of using cumulative averages, he plotted unit production of airframes that were being built at Lockheed. As such, upon plotting the unit costs on log-log paper, he observed a straight-line plot thereby his theory stated that the unit cost of production reduces at a constant rate with each double quantity produced. In regards to this research, Figures 77, 79, 81, and 83 are log-log plots for Class A, B, and D Ships. Just as was the case with Wright, using Crawford's Theory yielded the same results that his theory did not reflect actual labor hours to build these classes of ships.

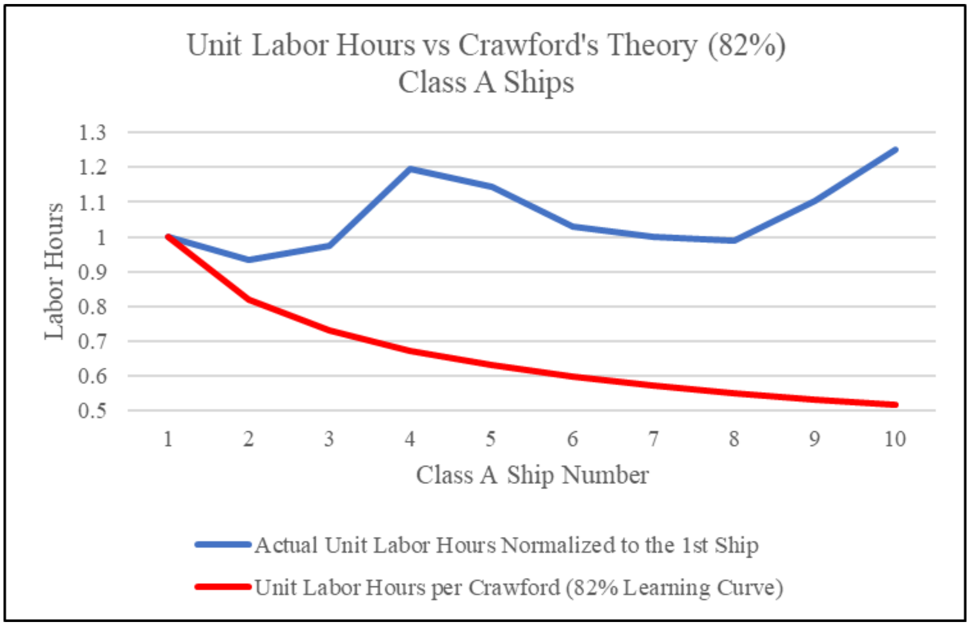

Figure 76: Unit Labor Hours Class A Ships

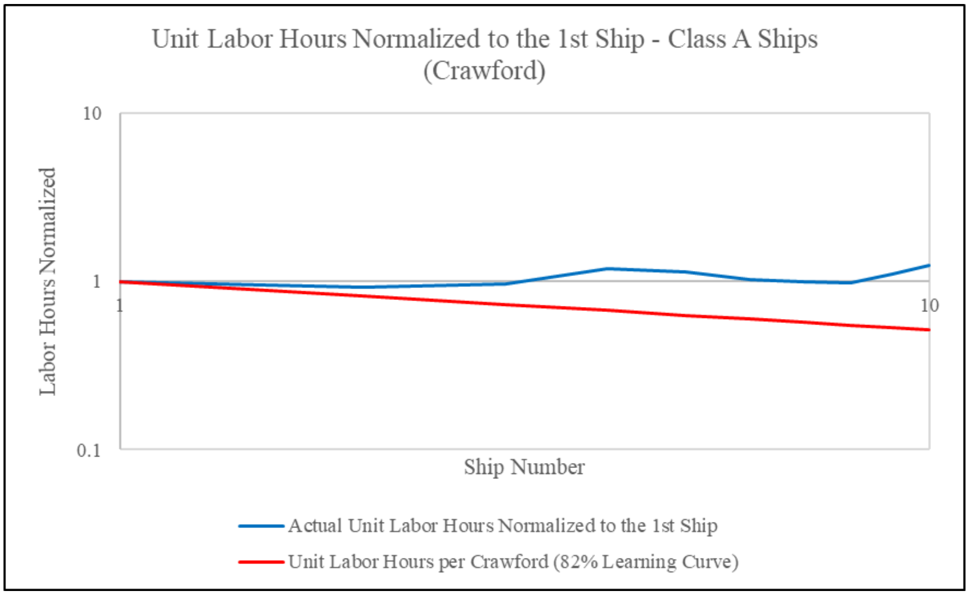

Figure 77: Unit Labor Hours Log-Log Class A Ships

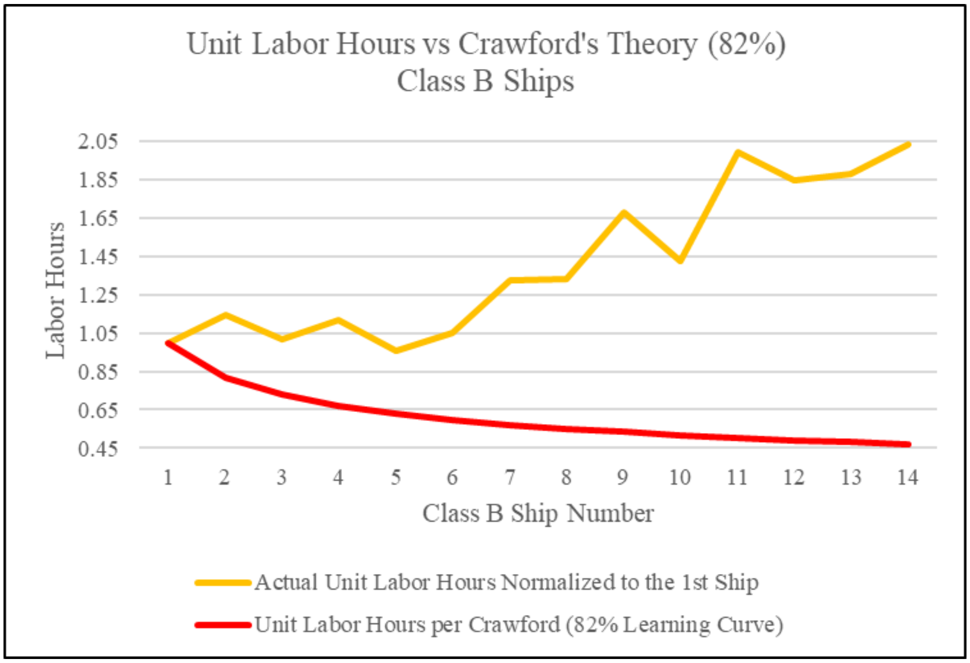

Figure 78: Unit Labor Hours Class B Ships

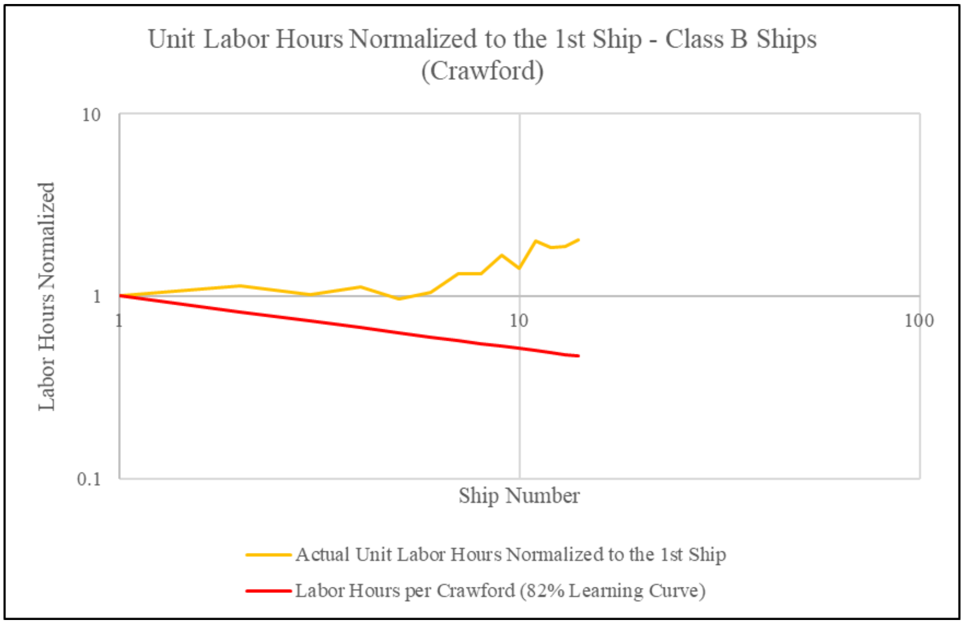

Figure 79: Unit Labor Hours Log-Log Class B Ships

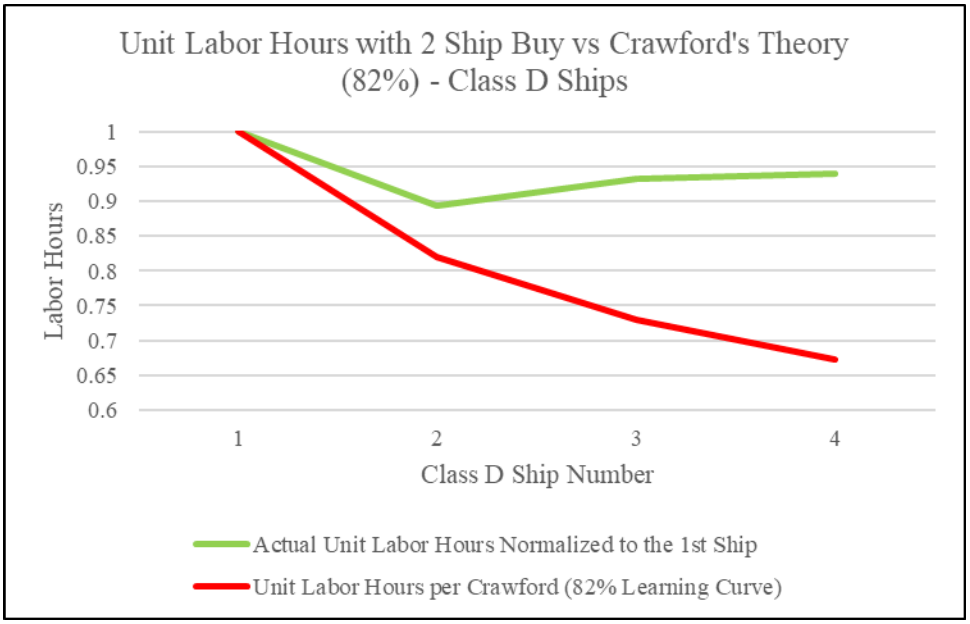

Figure 80: Unit Labor Hours Class D Ships with Two Ship Buy

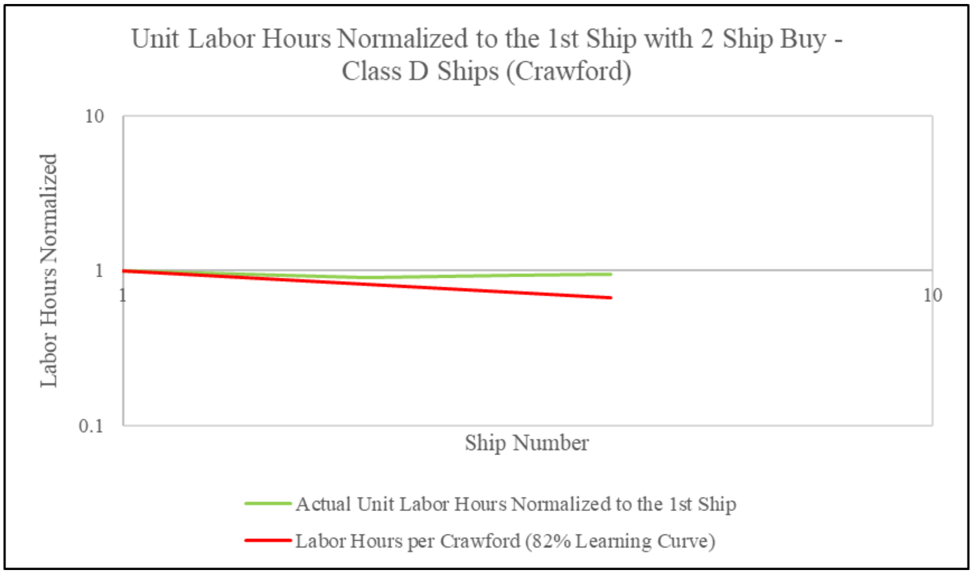

Figure 81: Unit Labor Hours Log-Log Class D Ships with Two Ship Buy

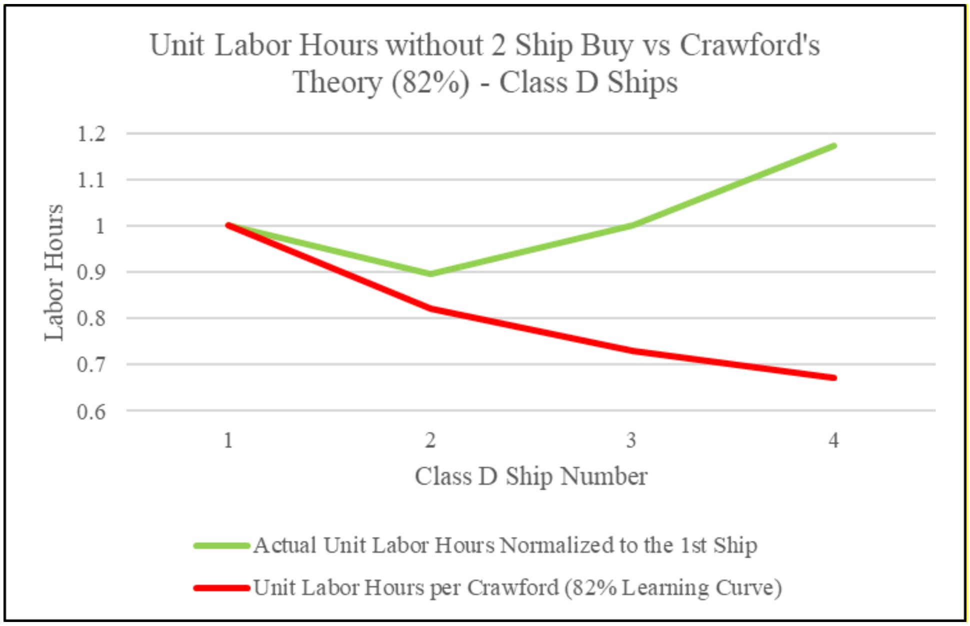

Figure 82: Unit Labor Hours Class D Ships without Two Ship Buy

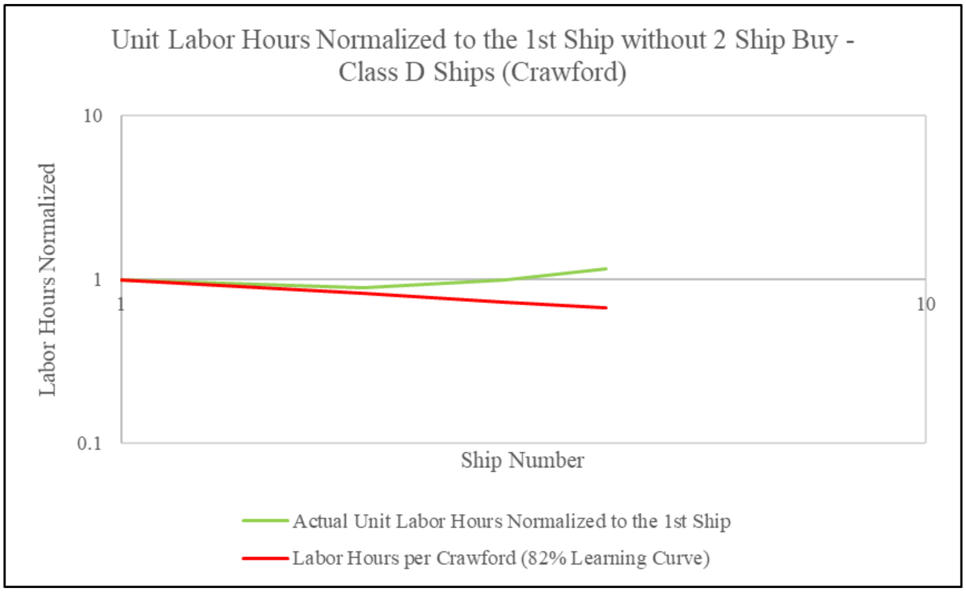

Figure 83: Unit Labor Hours Log-Log Class D Ships without Two Ship Buy

Wright’s Theory was developed before Crawford developed his. The only real difference between the two theories was that Wright’s Theory was based on the cumulative average curve while Crawford’s was based on the unit curve. Both theories were based on observations made in regards to airframe manufacturing. As indicated, Wright’s Theory and Crawford’s Theory, per Martin (2019) and Teplitz (1991) were the most common learning curve theories, and they have the largest use across all industries. The remaining three learning curve models, per Teplitz (1991), were primarily used to support cost estimating, but they provided additional insights into learning, and they were DeJong, Stanford-B, and the Sigmond (S) Curve.

## DeJong Model

The DeJong Model originated with Guibert (1945) who espoused that learning will eventually be reduced to the point that it will level off or plateau. His theory was based on the fact that with Wright’s Theory and Crawford’s Theory, the log-log plots of learning produced a line with a negative slope. As such, per Guibert, “an extrapolated negative sloped line will eventually intersect with the x-axis thereby suggesting that learning and improvement could eventually lead to zero production time to build a product.” As Teplitz (1991) states, “improvement does not go on unchecked forever. The learning curve must flatten out at some point.” DeJong (1957) draws upon Wright’s Theory and Crawford’s Theory in regards to a negative sloped line representing learning; however, DeJong (1957) refers to this negative sloped line as the “start-up” phase, but when performance times stop improving, then the “steady-phase” has been obtained. DeJong (1957) also stated that the steady phase has a slope of zero and may also include a small rate of improvement. DeJong referred to his theory as the asymptotic model. This model, per Teplitz (1991), considers the “man-machine interface.”

DeJong's (1957) Theory provides an allowance for machine time versus human labor since the actual machines used to produce products cannot experience a learning curve. Only the percentage of labor used to produce a product, per DeJong (1957), can experience a learning curve as the number of units produced increases. DeJong (1957) refers to this factor as "incompressibility" because he viewed the machine time as incompressible. Per DeJong (1957), Teplitz (1991), and Moore, Elshaw, Badiru, & Ritschel (2015), the human time was compressible due to learning. However, DeJong's Theory (1957), and as was affirmed by Teplitz (1991), stated that the flattening of the learning curve (or plateau as previously stated) was due to this incompressibility.

DeJong (1957) utilized Wright's formula and associated the factor M, representing incompressibility, into equation 15, yielding:

$$Y = a\ [M + (1 - M)\ X^{b}] \qquad \text{(Equation 16)}$$

As Teplitz (1991) and Moore, Elshaw, Badiru, & Ritschel (2015) stated, the major issue with using the DeJong model was determining the value for M, the incompressibility factor, which ranges from one to zero. A value of one represents a production process that was a fully machine and equipment intensive operation while a value of zero represents a labor-intensive operational process or production line. Cochran (1968), based on his research and utilizing DeJong's Theory (1957), provided a range of incompressibility factors, M, for different types of production operations, which are delineated by Table 10. Due to the variability associated with M, per Teplitz (1991), the results associated with the DeJong Model are "of questionable value." Given the fact that M has variability, the researcher utilized Table 10 and selected the operation type of subassembly to utilize for shipbuilding. After which, the researcher used equation 16 of DeJong's Theory to determine the unit labor hours with an eighty-two percent learning and an incompressibility factor of 0.43.

DeJong's (1957) Theory also includes a method to determine the unit production time limit which was illustrated via Equation 17.

$$Y_{limit} = Y_x / 1 + [(1 – M/M) * x^b] \qquad \text{(Equation 17)}$$

As was previously discussed, DeJong's Theory was based on an asymptotic model, per Teplitz (1991), and as such, there was not an actual limit meaning, per Teplitz (1991), "it would not be appropriate to attempt to solve [equation 17] with the objective of determining at what unit the limit would be reached." This was because the limit was "being asymptotically approached, this performance time will never be attained," per Teplitz (1991). McCarthy (2020) also discusses an asymptotic model by addressing "production steady state" as well as the influences that could cause individual or organizational learning to "level off." This was provided as background for completeness, and could be the subject of future research in regards to low-rate production.

In regard to this research methodology, DeJong's Theory was then applied to Class A, B, and D Ship data, and DeJong's Theory was applied to both Wright's Theory and Crawford's Theory since, as Teplitz (1991) stated, "Wright's Theory and Crawford's Theory are the fundamental theories that all other theories are based upon." As a side note, this approach has not been taken by any researcher until now; as such, this resulted in the development of Figures 84 through 91.

| **Production/Manufacturing Operation** | **Incompressibility Factor M** | **Comments** |
|---|---|---|
| Labor Intensive Operation Only | 0 | $Y=aX^b$<br>M = 0 when operations are completely labor intensive. |
| Assembly | 0.33 | $Y=aX^b$<br>Learning Varies. |
| Subassembly | 0.43 | |
| Heat Treating | 0.5 | |
| Stamping | 0.67 | |
| Machine Shop | 0.77 | |
| Machine Intensive Fully Automated Operation Only | 1 | $Y = a$<br>M = 1 when operations are fully automated. No learning occurring. |

Table 10: Manufacturing Operations versus Incompressibility Factor

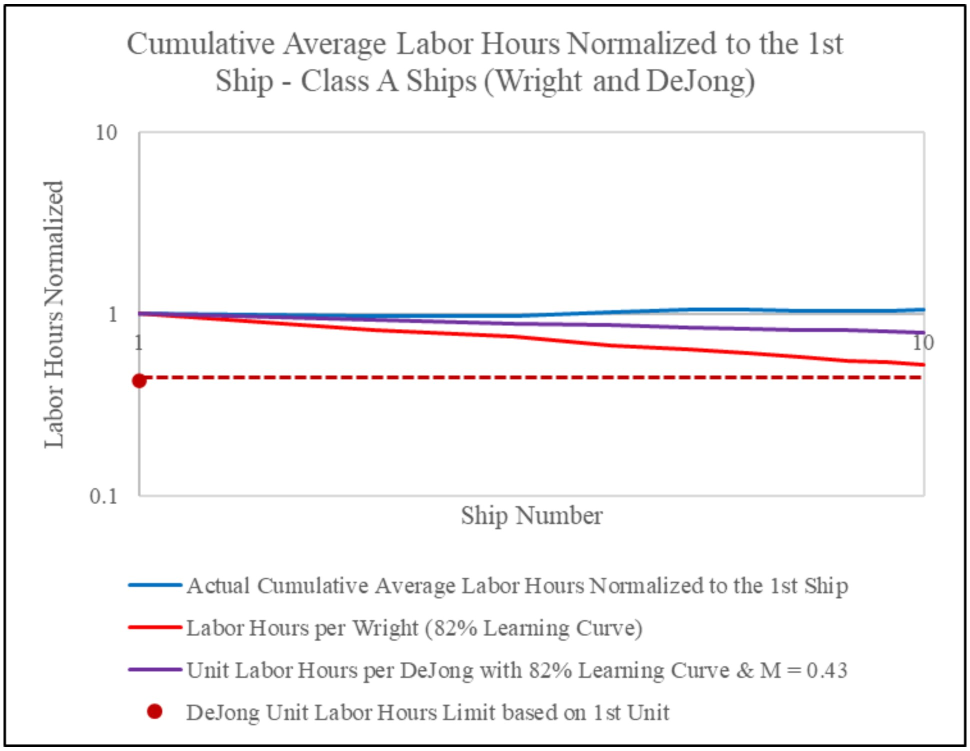

Figure 84: Cumulative Labor Hours Class A Ships (Wright and DeJong)

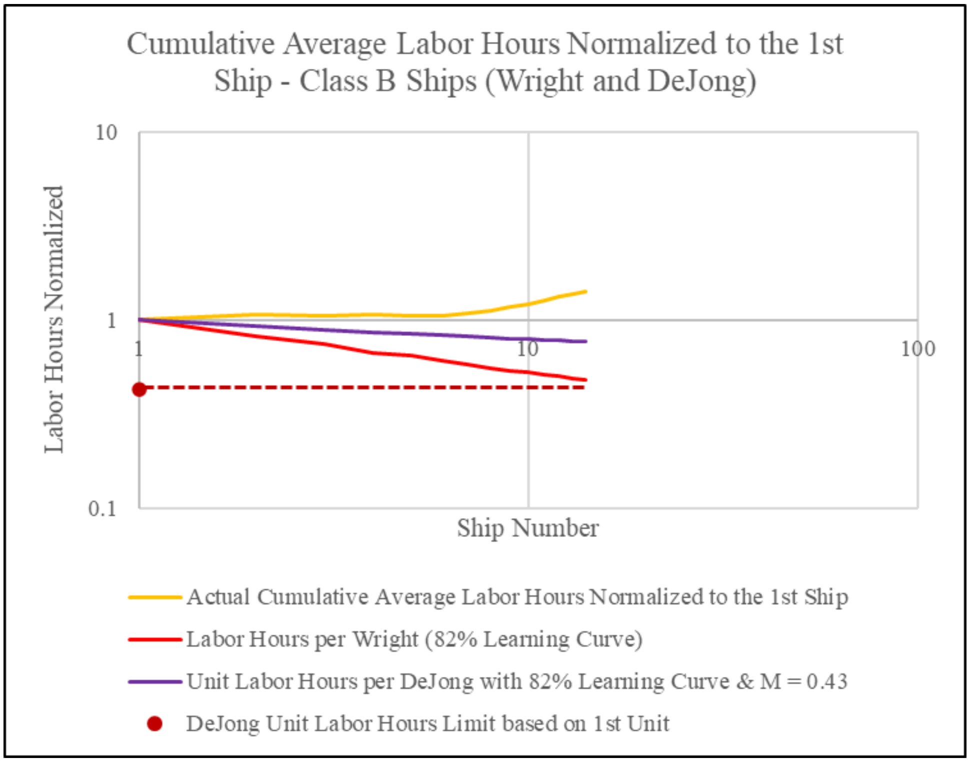

Figure 85: Cumulative Labor Hours Class B Ships (Wright and DeJong)

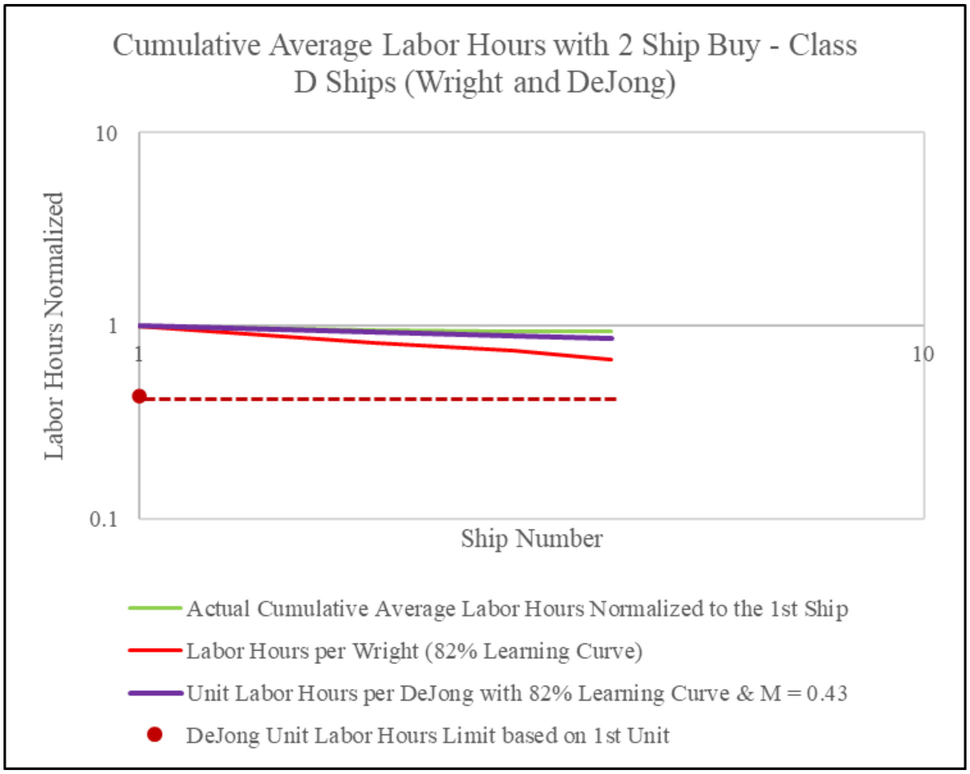

Figure 86: Cumulative Labor Hours Class D Ships with Two Ship Buy (Wright and DeJong)

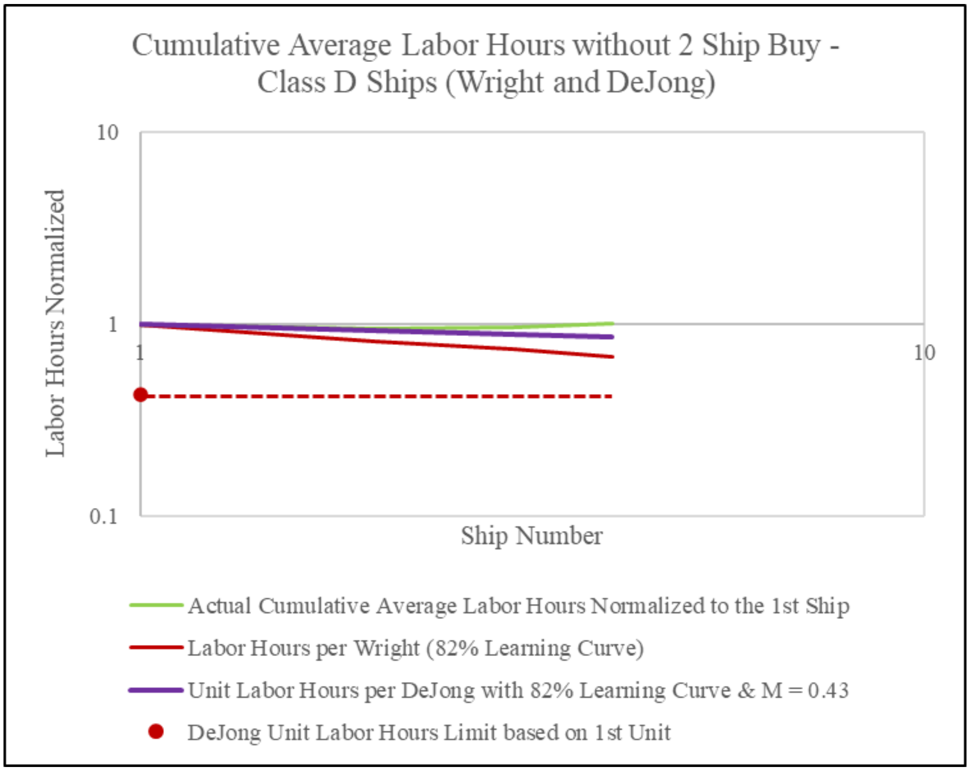

Figure 87: Cumulative Labor Hours Class D Ships without Two Ship Buy (Wright and DeJong)

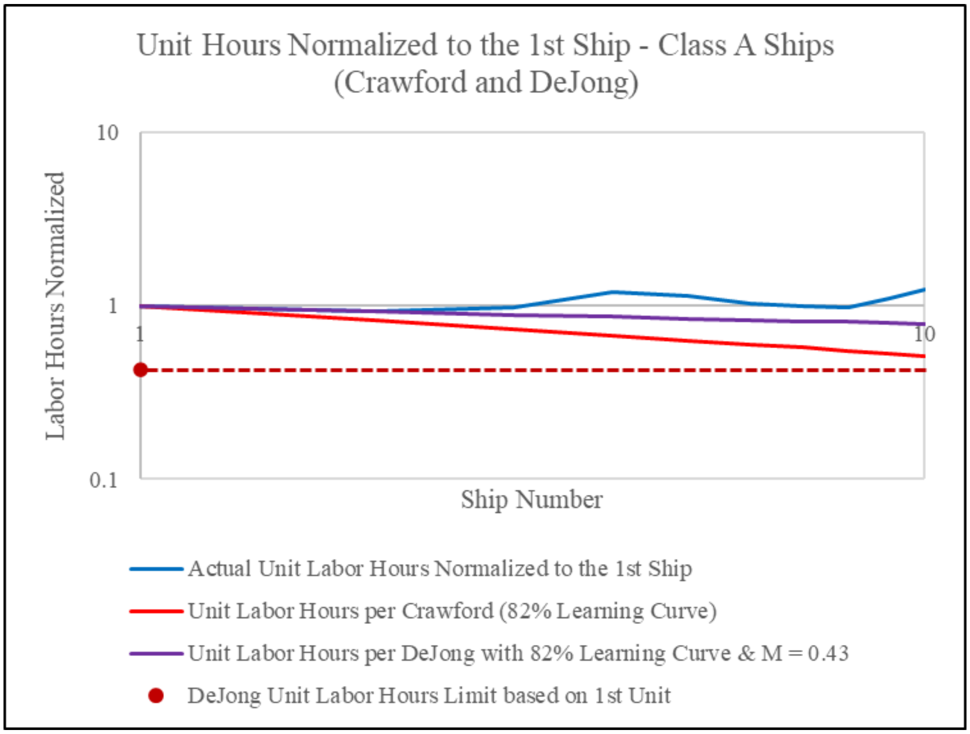

Figure 88: Unit Hours Class A Ships (Crawford and DeJong)

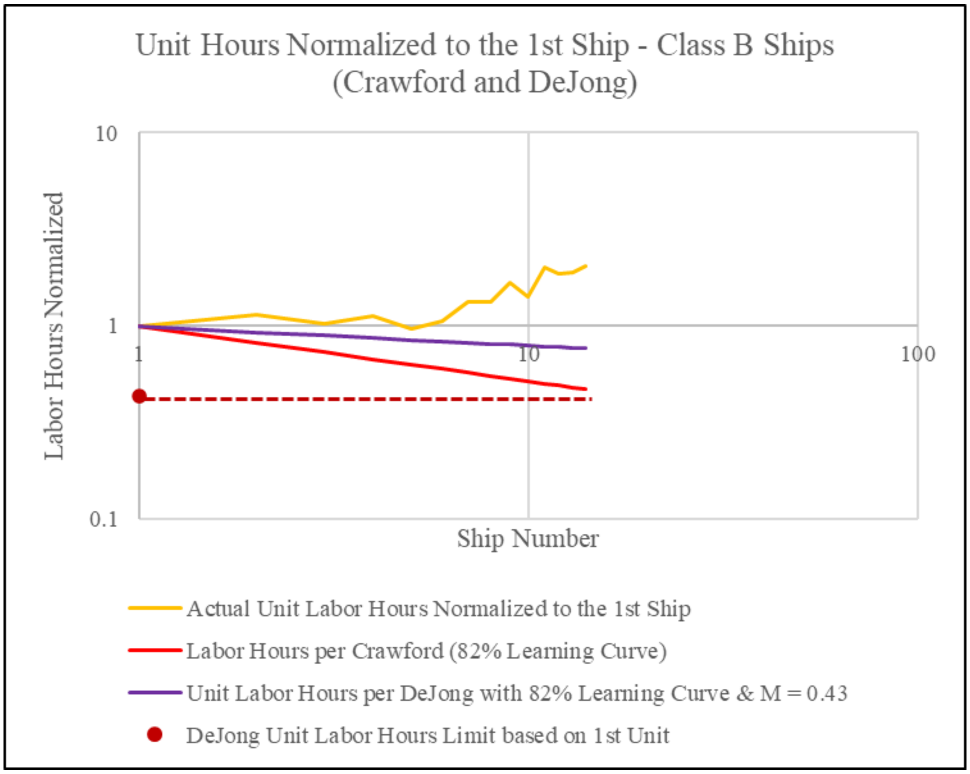

Figure 89: Unit Hours Class B Ships (Crawford and DeJong)

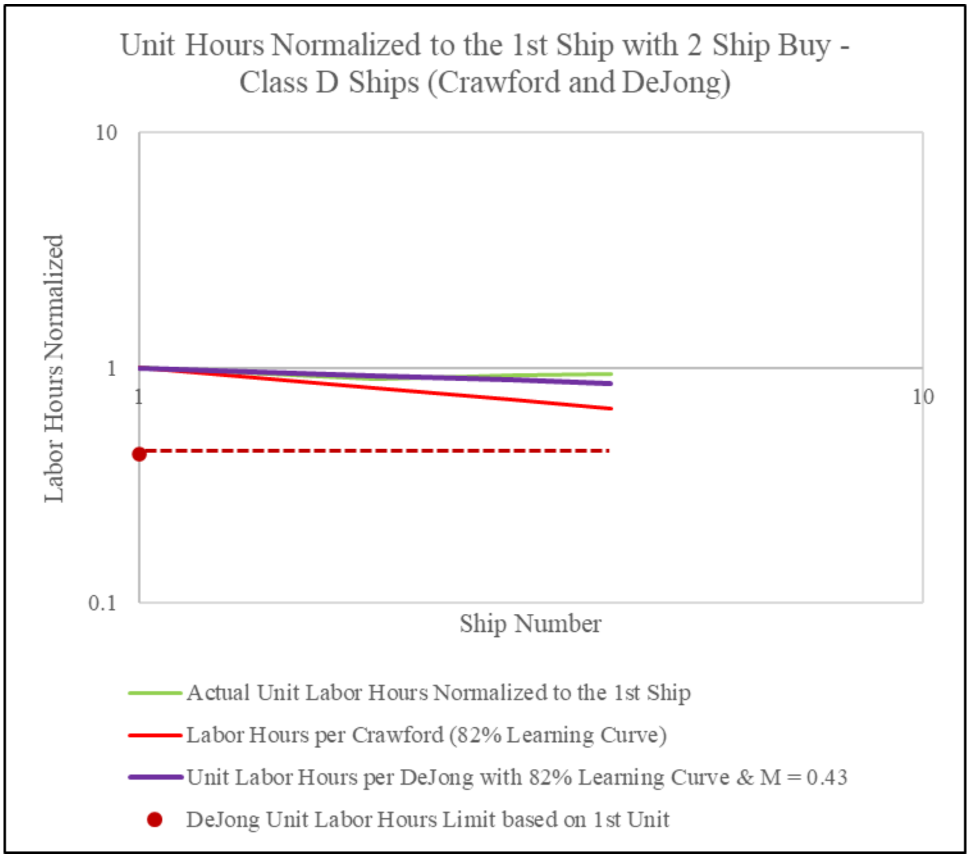

Figure 90: Unit Hours Class D Ships with Two Ship Buy (Crawford and DeJong)

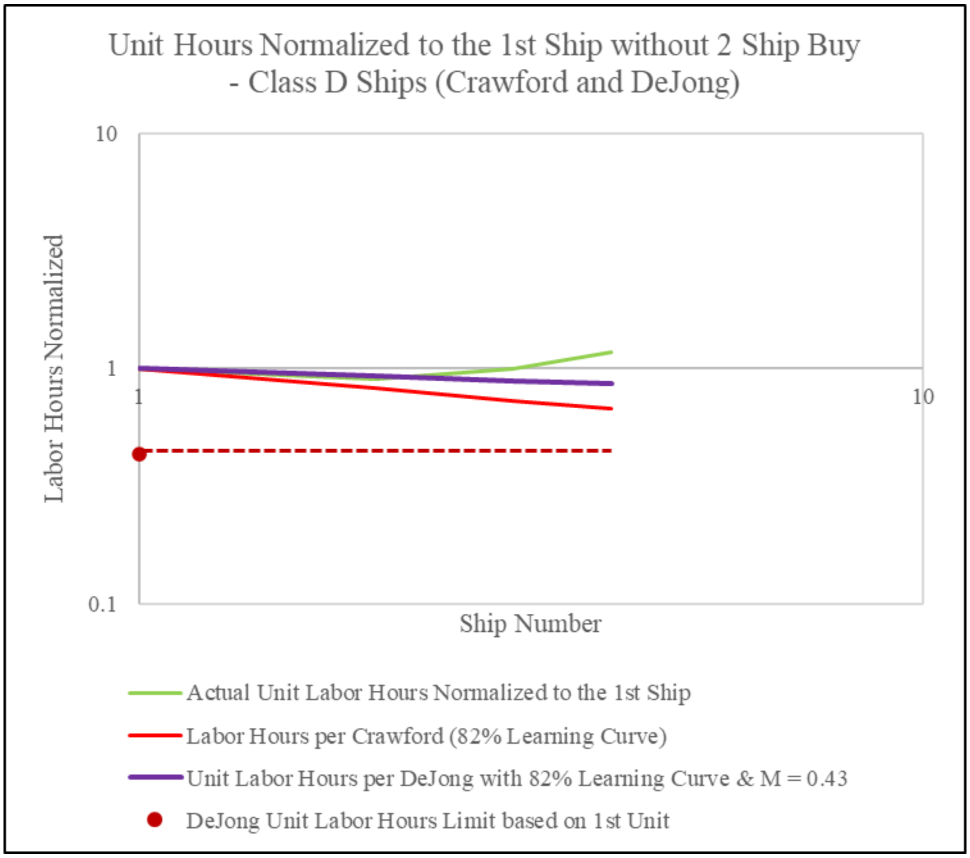

Figure 91: Unit Hours Class D Ships without Two Ship Buy (Crawford and DeJong)

Figures 84 through 87 reflected an assessment of Class A, B, and D Ships using Wright's (1936) Theory covering cumulative average labor hours along with DeJong's asymptotic theory (1957) or also called DeJong's unit production time limit approach. The application of DeJong's Theory was closer to predicting Class D Ships as compared to Wright's Theory when plotted on a log-log graph; however, with only four data points, the prediction was still greater than sixteen percent difference for Class D Ships as shown via Figure 86 and Figure 87.

Crawford's (1945) Theory, based on unit hours, as illustrated by Figures 88 through 91, was also divergent as compared to actual labor hours expended. The same was valid in regards to DeJong's Theory; however, with only four data points for Figures 90 and 91, the divergence was seven percent for the two ships buy, and without the two ships buy, the divergence for the four Class D was at thirty-one percent.

## Stanford-B Model

In 1949, the Stanford Research Institute published results after analyzing the production of aircraft for the United States Air Force, specifically in regards to learning. Within their report, the Stanford Research Institute (1949) developed a model that acknowledged prior experience as an enabler for learning within an aircraft production environment. As a side note, according to Teplitz (1991), the Stanford-B Model was also called: "B-curve, Beta curve, Boeing "Hump" curve, and Stanford-B curve." The fundamental assumption of the Stanford-B Model, per the Stanford Research Institute (1949), was that "carryover experience" will reduce production times on units of a new product as compared to no experience carryover. Due to this fact, Teplitz (1991) refers to this model as the "prior-learning model." According to Nadler & Smith (1963), the carryover of experience attributed to the Stanford Research Institute (1949) Stanford-B Model was due to "consistencies of design and complexity between old and new, rather than consistencies of know-how, engineering, or tooling effort." As such, to account for the learning carryover, the Stanford Research Institute (1949) added a B factor to Wright's equation delineated by equation 15 yielding:

$$Y = a * (X + B)^b \qquad \text{(Equation 18)}$$

As was the case with the incompressibility factor, M, for the DeJong Model, the B factor also has a substantial impact on the accuracy of the learning curve model. The larger the B factor, then the greater the impact on cost estimates both in terms of magnitude and length of effect, per Teplitz (1991) and Moore, Elshaw, Badiru, & Ritschel (2015). The B factor was usually given a value between one and ten, with four being the most common, (which the researcher used herein) per Garg and Milliman (1961). Garg and Milliman (1961) based their research on Boeing 707's while working for Boeing. As Teplitz (1991) suggests, the effect of the factor, B, in essence, moves the production "artificially" down the learning curve by adjusting the production numbers in an effort to account for worker experience that has been carried over to the production line that was being analyzed. As such, utilizing equation 18, and applying it to Class A, B, and D Ships yielded Figures 92 through 99.

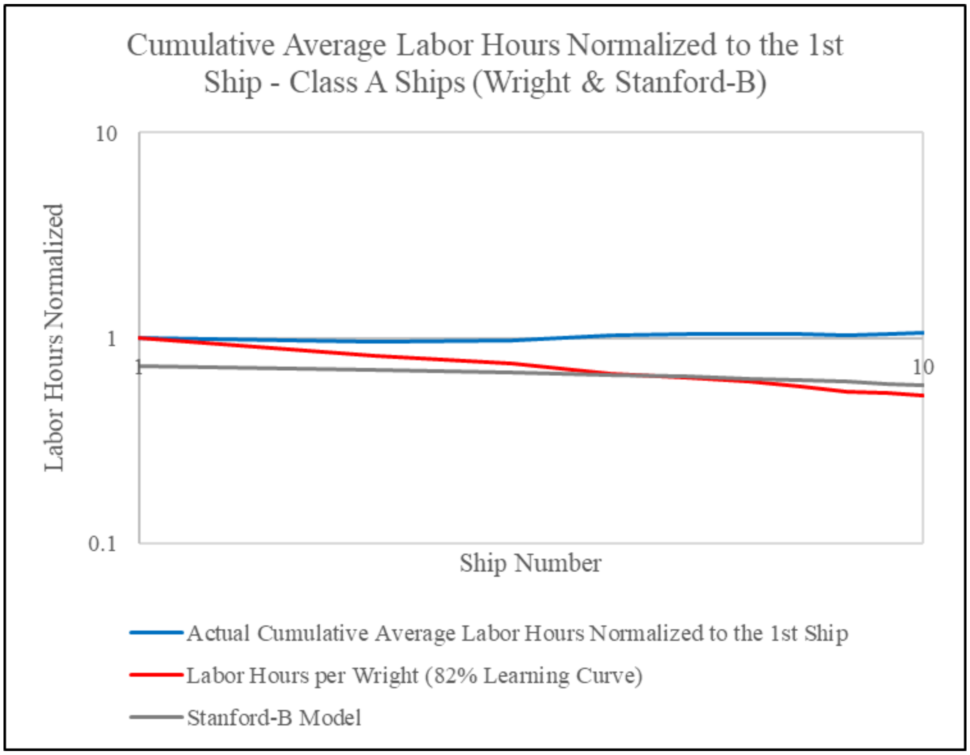

Figure 92: Cumulative Average Labor Hours Class A Ships (Wright and Stanford-B)

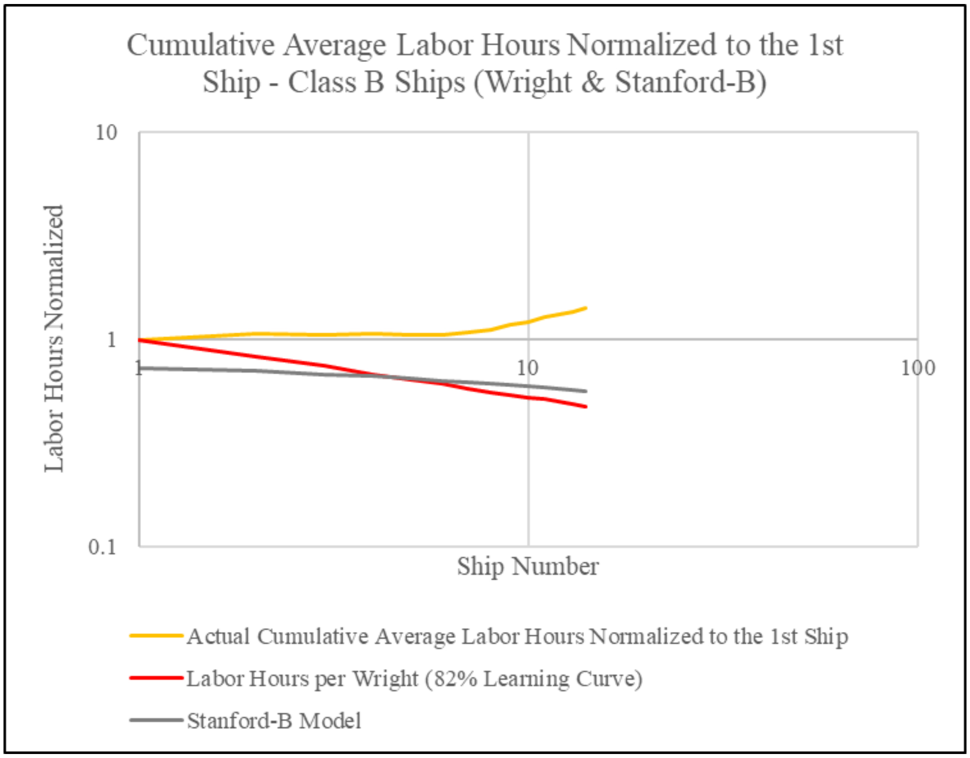

Figure 93: Cumulative Average Labor Hours Class B Ships (Wright and Stanford-B)

Figure 94: Cumulative Average Labor Hours Class D Ships with Two Ship Buy (Wright and Stanford-B)

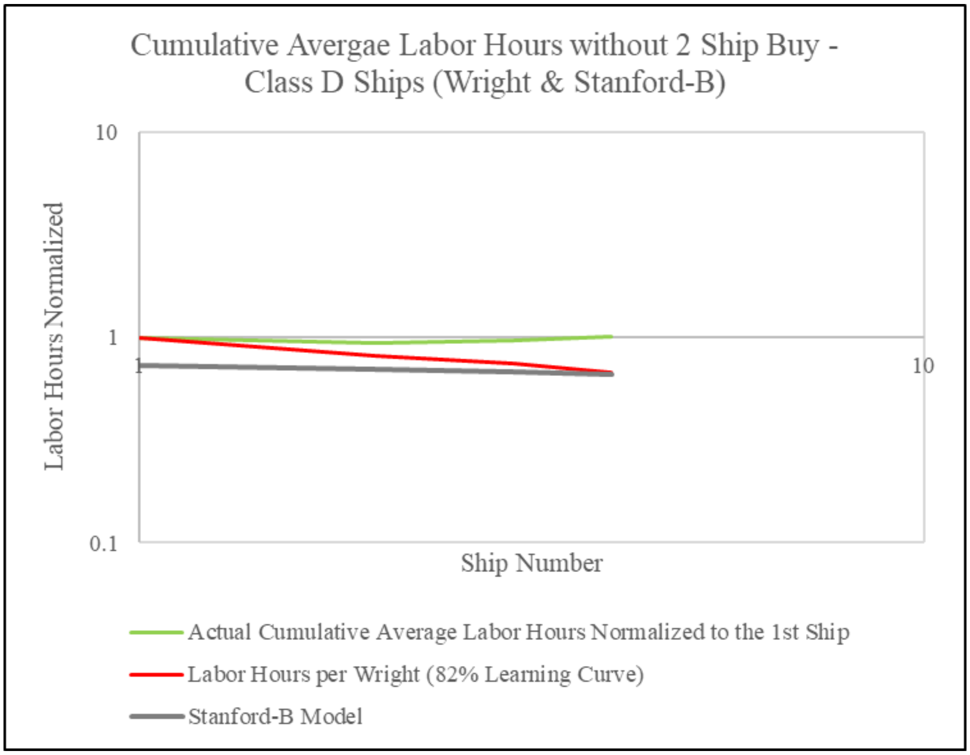

Figure 95: Cumulative Average Labor Hours Class D Ships without Two Ship Buy (Wright and Stanford-B)

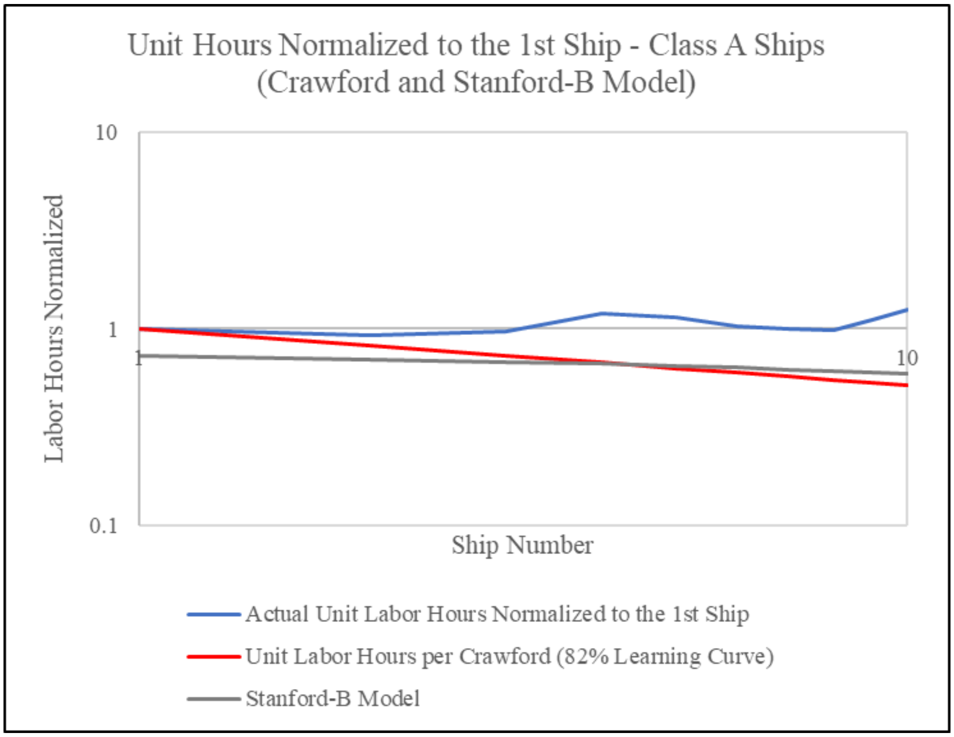

Figure 96: Unit Hours Class A Ships (Crawford and Stanford-B)

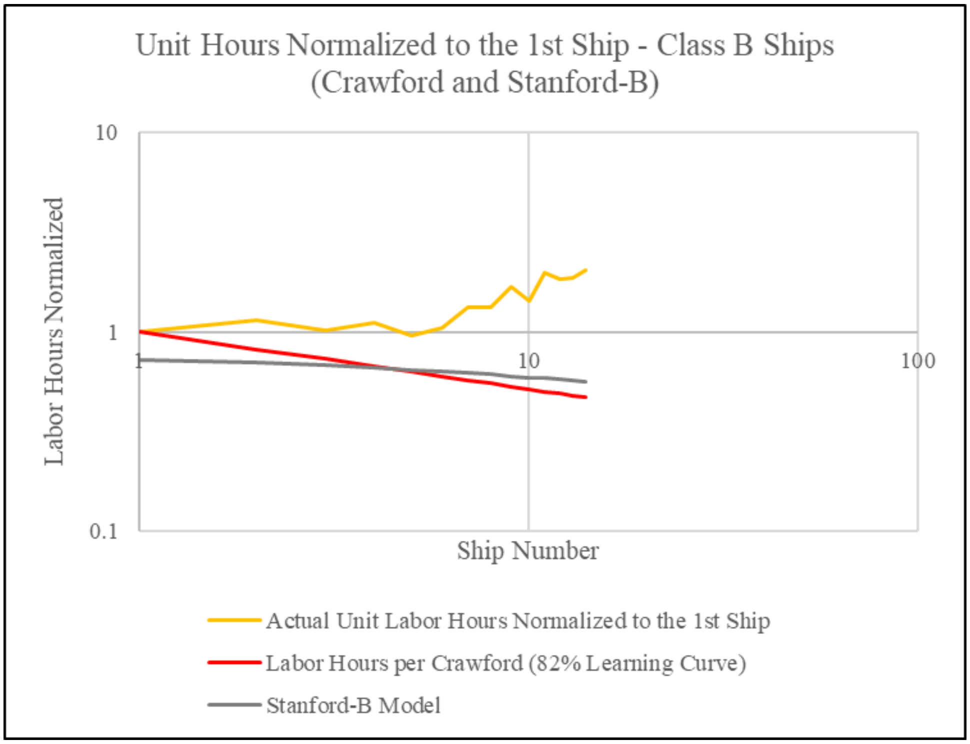

Figure 97: Unit Hours Class B Ships (Crawford and Stanford-B)

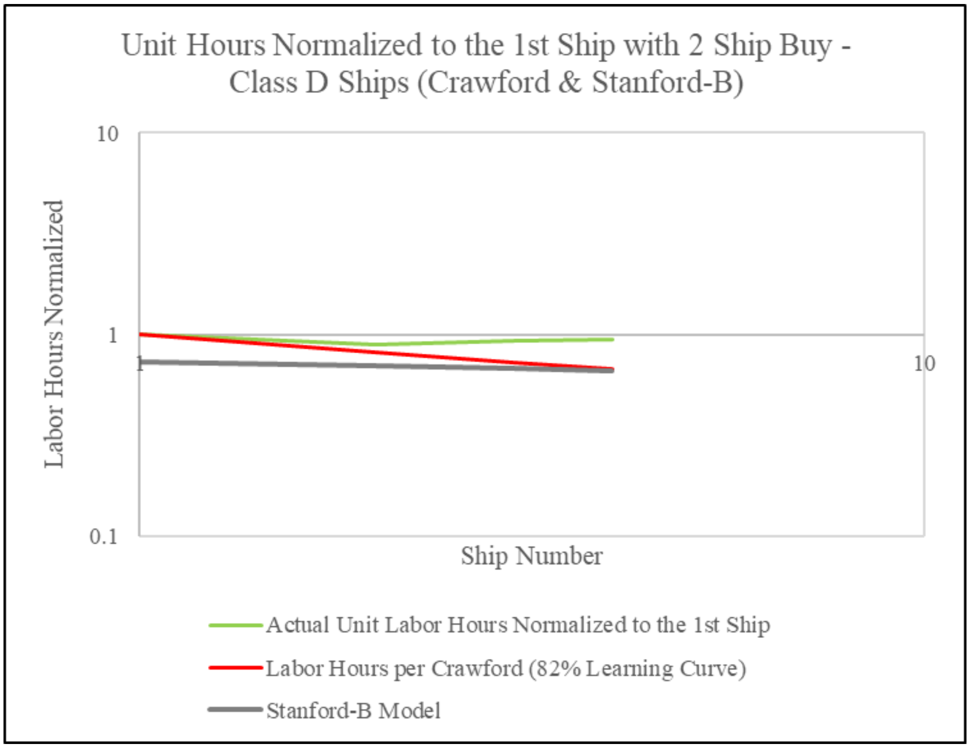

Figure 98: Unit Hours Class D Ships with Two Ship Buy (Crawford and Stanford-B)

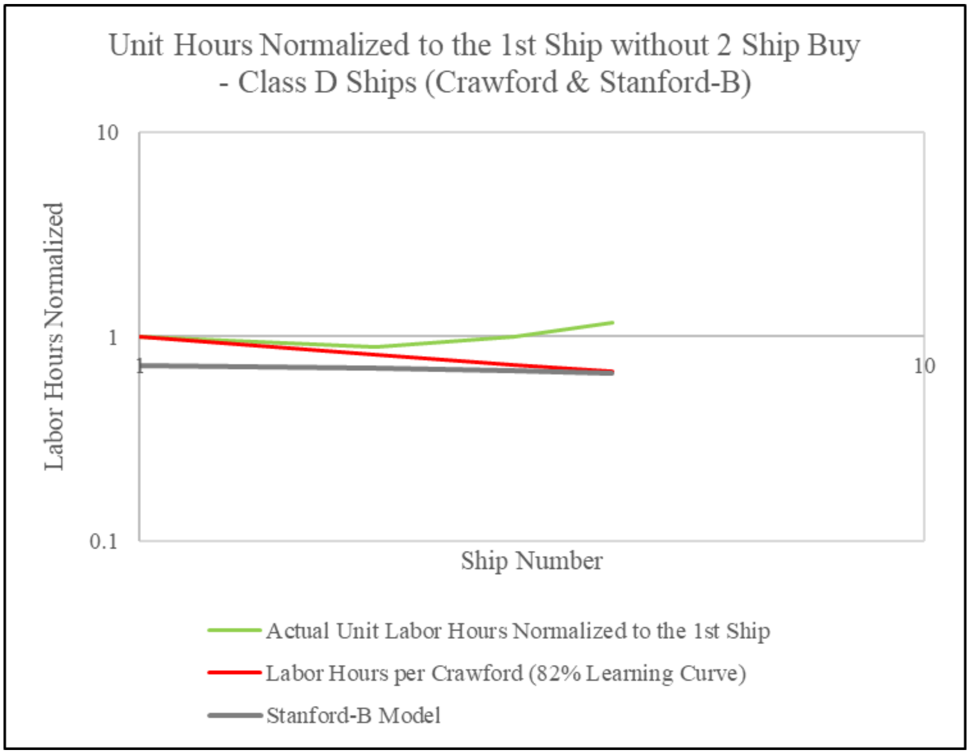

Figure 99: Unit Hours Class A Ships without Two Ship Buy (Crawford and Stanford-B)

As indicated, Figures 92 through 99 reflect Wright's Theory or Crawford's Theory with the Stanford-B Model added onto each graph. As was also indicated, the Stanford-B Model was based on the assumption that prior learning was also utilized by the production work force such that they will bring production of the first product further down the learning curve, per the Stanford Research Institute (1949). Due to this reason, Figures 92 through 99 showed that the Stanford-B line is relatively flat only because the curve starts on the 5th production unit due to prior learning. Due to this fact, the Stanford-B Model does not predict learning associated with Class A, B, or D Ships.

## Sigmoid S Curve

The last model was called the Sigmoid S Curve Model, and it was first espoused by Carr (1946). Carr (1946) stated that an influence on learning curves was a term he called the “start-up effect”. Carr (1946) stated that these effects were due to changes in the design or unfamiliarity associated with the product which may impact learning. Carr (1946) also stated that production workers could also have some carry-over learning, similar to the Stanford-B Model, and that they could also experience a plateau effect similar to the DeJong Model. Carr (1946) stated that these three phases of start-up effect, carry-over learning, and the plateau effect could also influence learning and could be described as an S-Curve or also called a cubic curve. Carr (1946) stated that the “first phase” of the learning curve, which occurred at the beginning, contained elements associated with both start-up effects and carry over learning, and that the third phase contained the plateau effect with limited learning occurring at this point. The second phase captured the learning that was occurring for a given production operation, and it connected the first and third phases. This theory was also captured by Carlson (1973, 1987) and Rowe (1976). Carr (1946) stated that those transitions occur after hundreds of items were produced, which as the researcher has been indicating, was aligned with high-rate production manufacturing and not low-rate production. Teplitz (1991) states that there was no way to determine exactly when each transition occurs. As a side note, Miller (1971) tried to develop a learning curve approach into one single learning curve formula; however, there are too many unknowns describing the S-Curve. As such, Carlson (1973) developed a formula that combined the DeJong Model and the Stanford-B Model together yielding equation 19:

$$Y = a * \{M + [(1-M) * (X + B)^b]\} \qquad \text{(Equation 19)}$$

As indicated previously, estimating the incompressibility factor, M, and the B factor will introduce variability into the development of the learning curve. Per Teplitz (1991) the transition from Phase 1 to Phase 2 and Phase 2 to Phase 3 did not usually occur on a specific unit but rather over several units. As such, the S-Curve approach was not widely accepted other than to potentially assess different learning curve slopes as each phase progresses. Using equation 19 for Ship Classes A, B, and D yields Figures 100 through 107 which also includes Wright's Theory too.

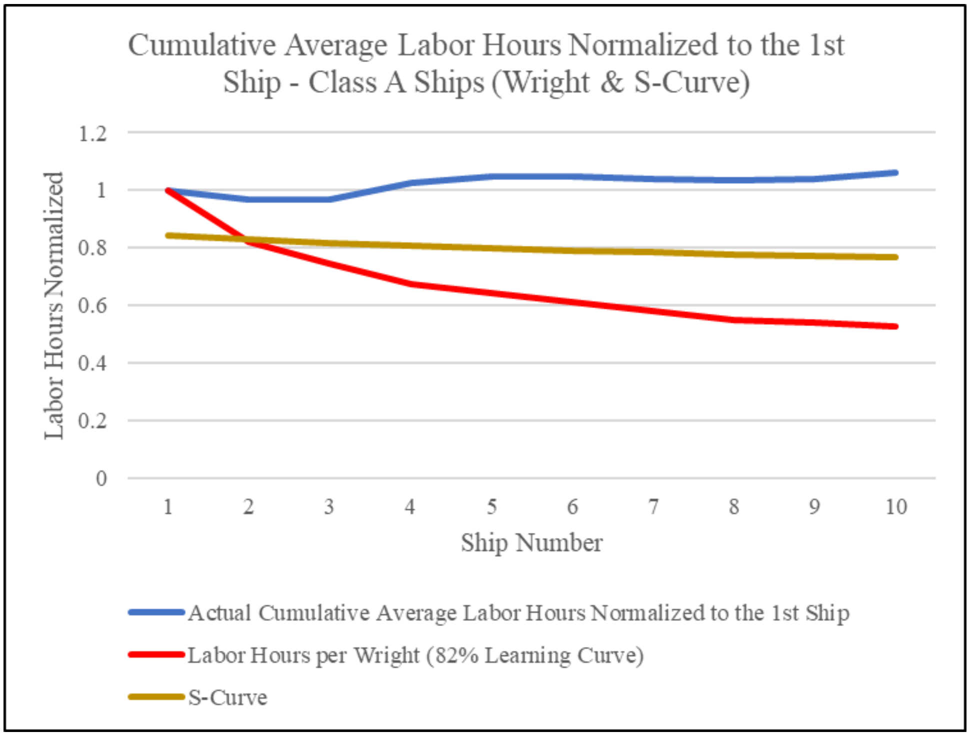

Figure 100: Cumulative Average Labor Hours Class A Ships (Wright and S-Curve)

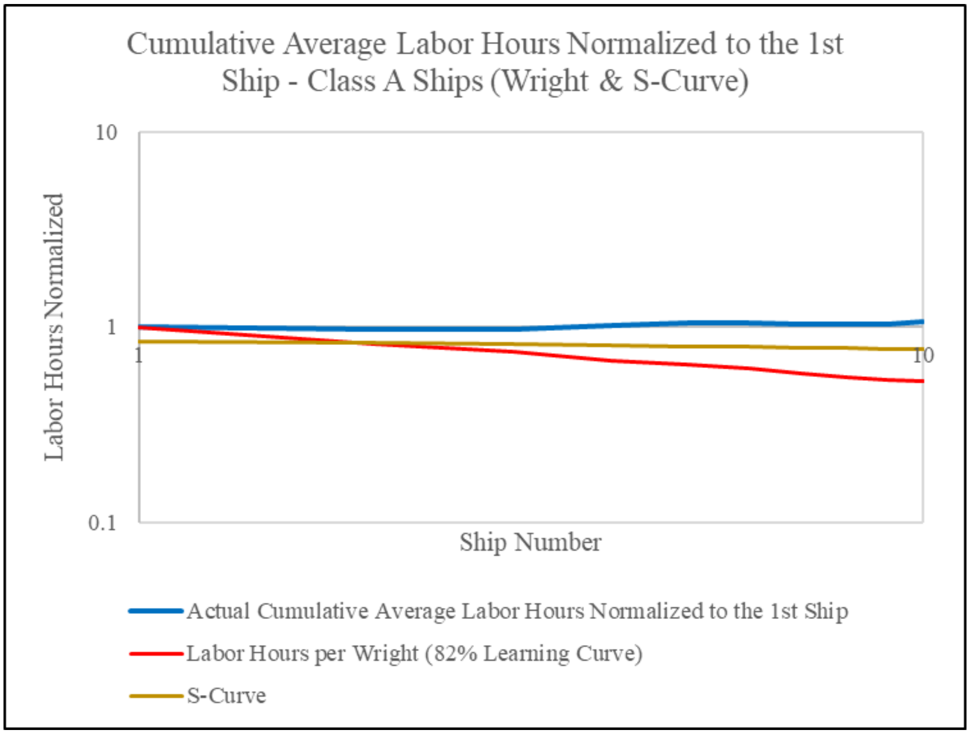

Figure 101: Cumulative Average Labor Hours Class A Ships (Wright and S-Curve)

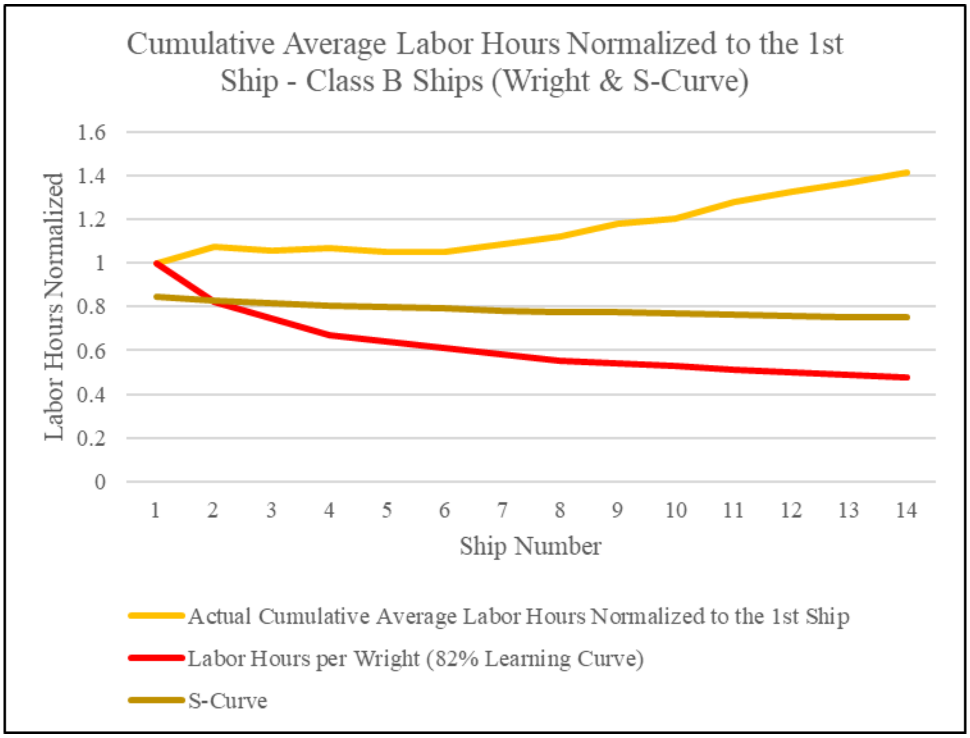

Figure 102: Cumulative Average Labor Hours Class B Ships (Wright and S-Curve)

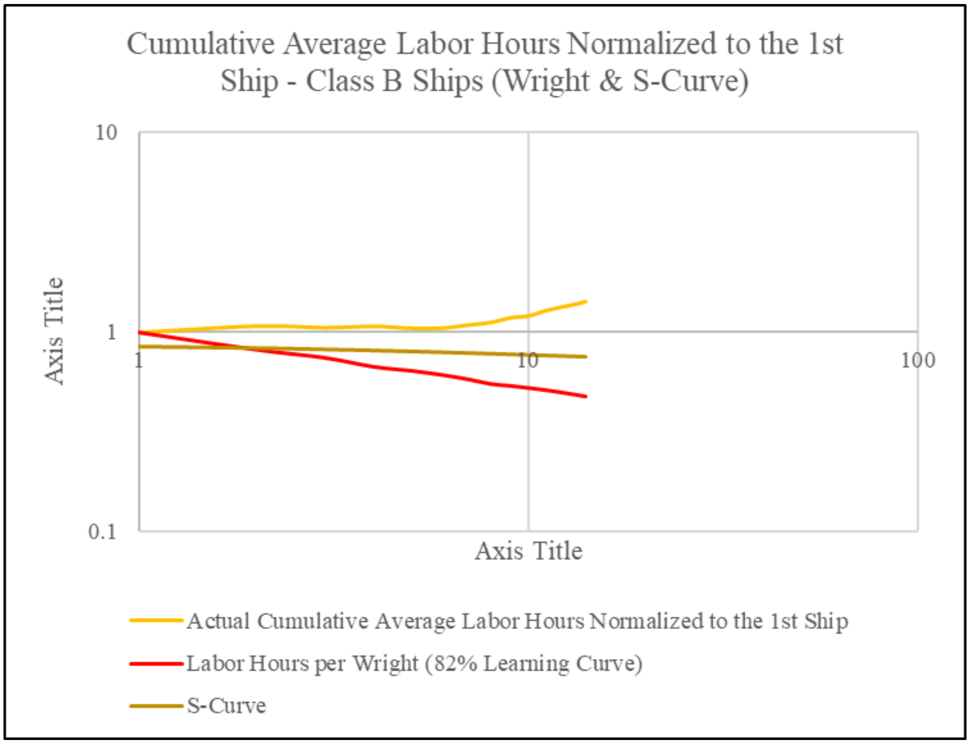

Figure 103: Cumulative Average Labor Hours Class B Ships (Wright and S-Curve)

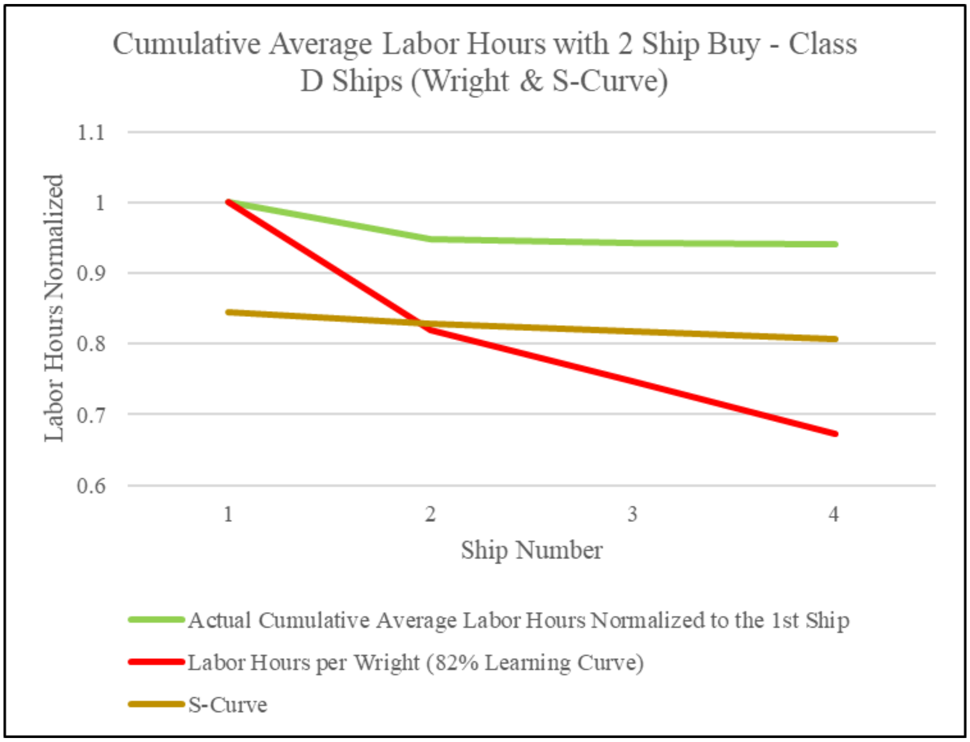

Figure 104: Cumulative Average Labor Hours Class D Ships with Two Ship Buy

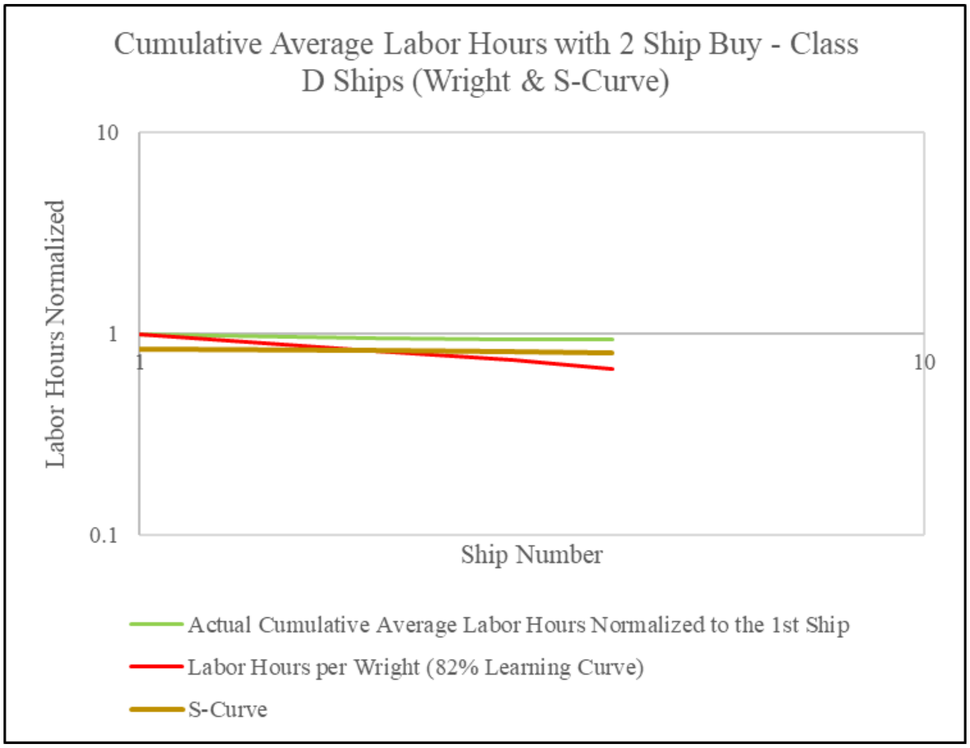

Figure 105: Cumulative Average Labor Hours Class D Ships with Two Ship Buy (Wright and S-Curve)

Figure 106: Cumulative Average Labor Hours Class D Ships without Two Ship Buy (Wright and S-Curve)

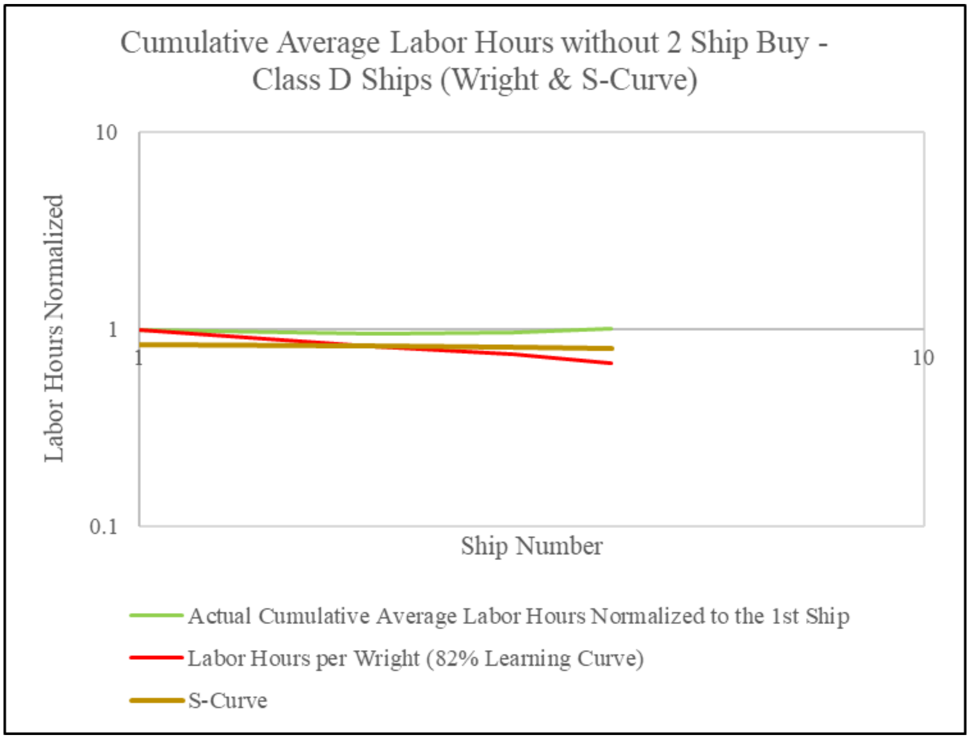

Figure 107: Cumulative Average Labor Hours Class D Ships without Two Ship Buy (Wright and S-Curve)

In regard to Figures 100 through 107, the S-Curve does not predict Class A, B, or D actual cumulative average labor hours. As Carr (1946) and Teplitz (1991) state, the S-Curve first phase was at least through ten units with the second phase through at least one-hundred units and the third phase was greater than three hundred units. Figures 108 through 115 is illustrative of Class A, B, and D Ships utilizing Crawford's Theory along with the S-Curve. As such, the S-Curve cannot characterize low-rate production environments.

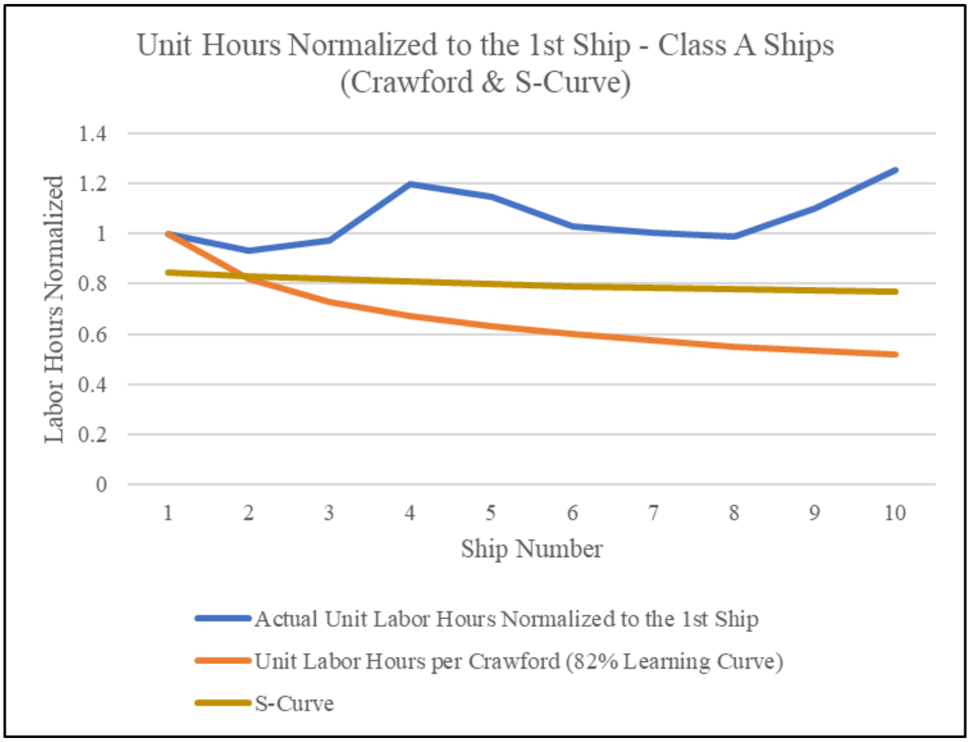

Figure 108: Unit Labor Hours Class A Ships (Crawford and S-Curve)

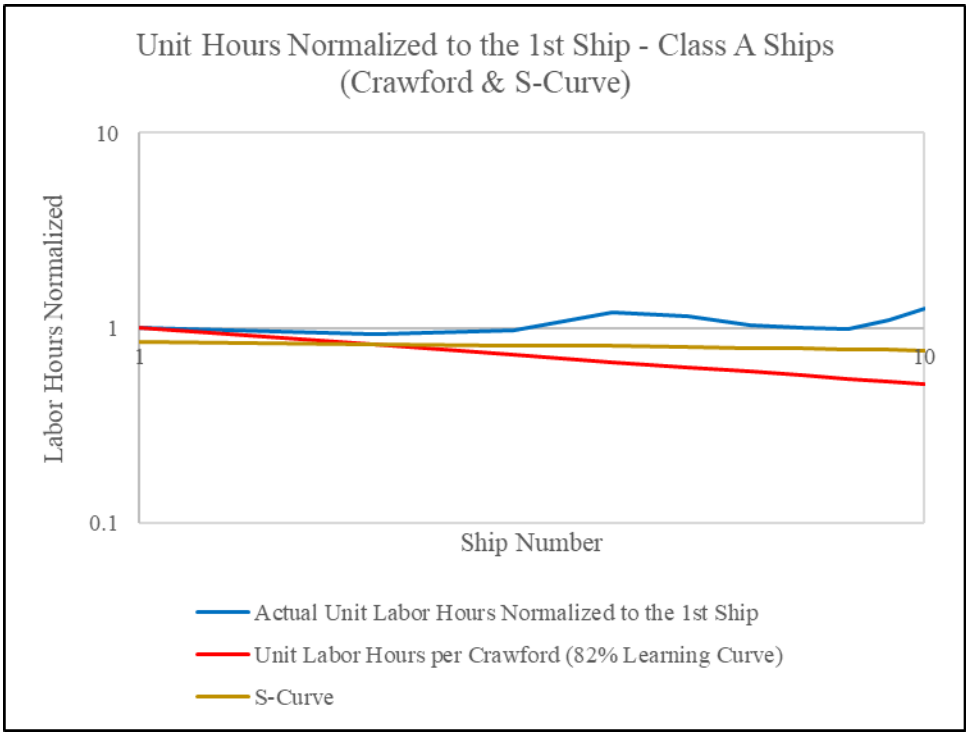

Figure 109: Unit Labor Hours Class A Ships (Crawford and S-Curve)

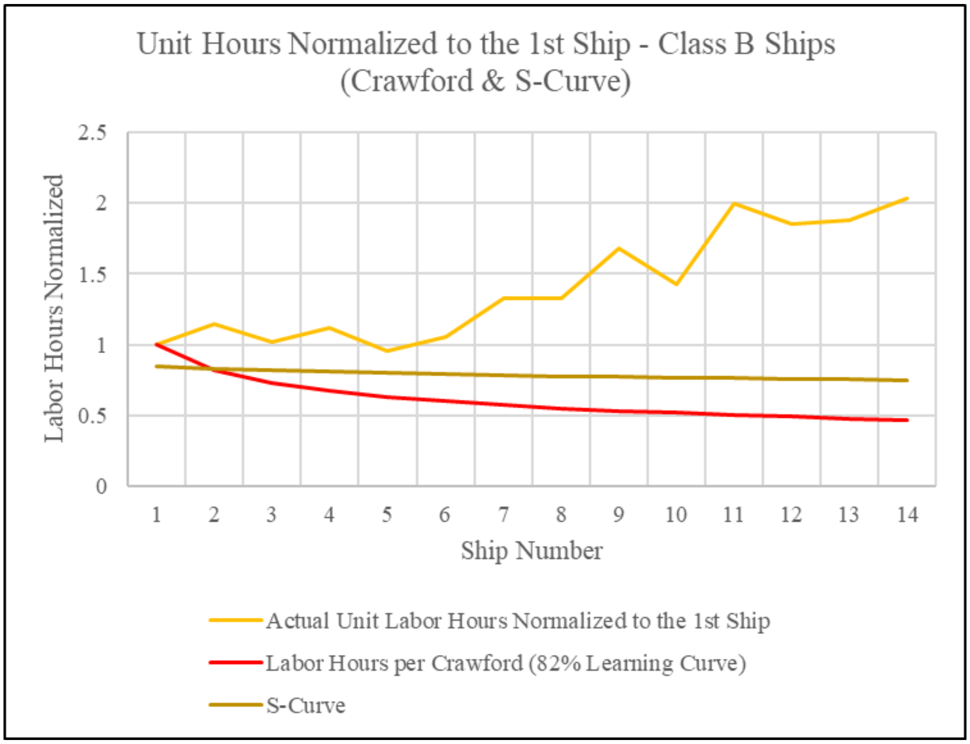

Figure 110: Unit Labor Hours Class B Ships (Crawford and S-Curve)

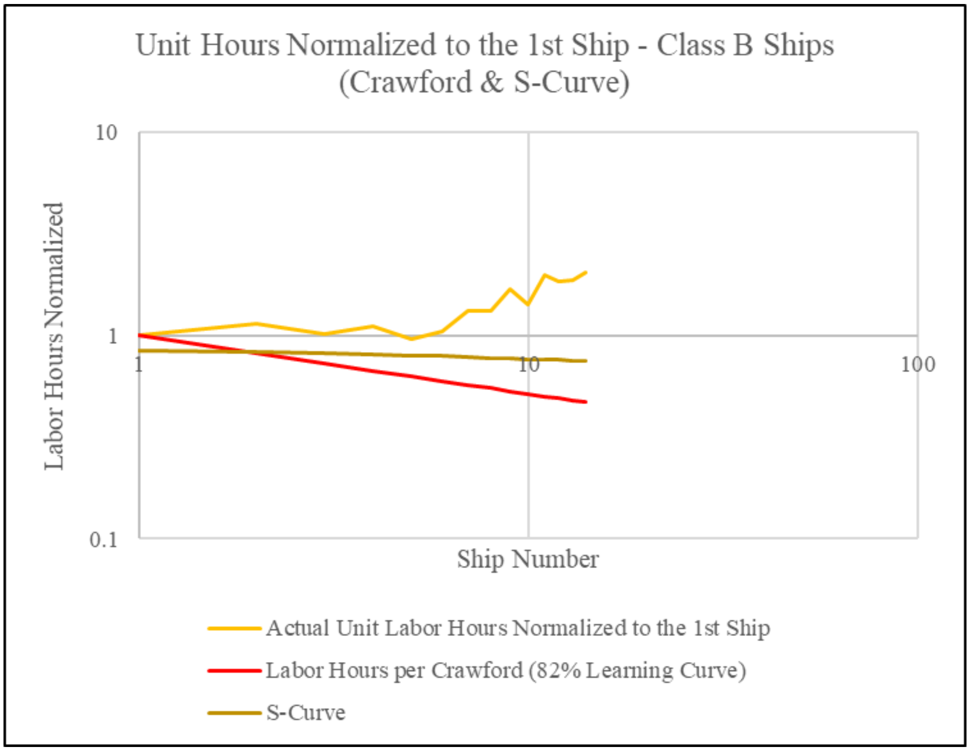

Figure 111: Unit Labor Hours Class B Ships (Crawford and S-Curve)

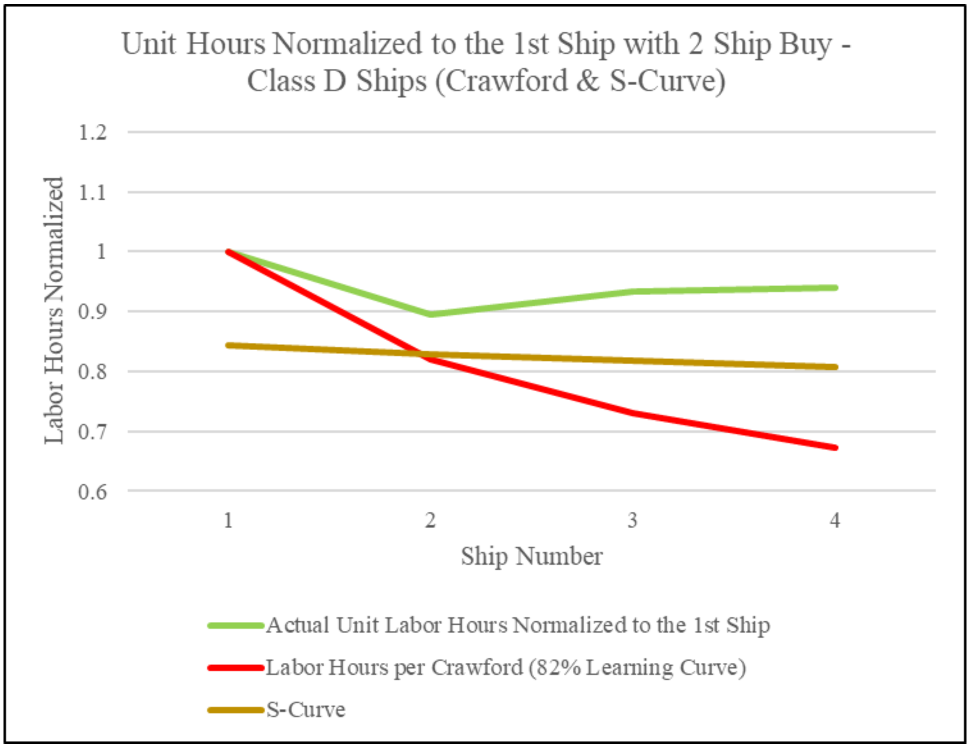

Figure 112: Unit Labor Hours Class D Ships with Two Ship Buy (Crawford and S-Curve)

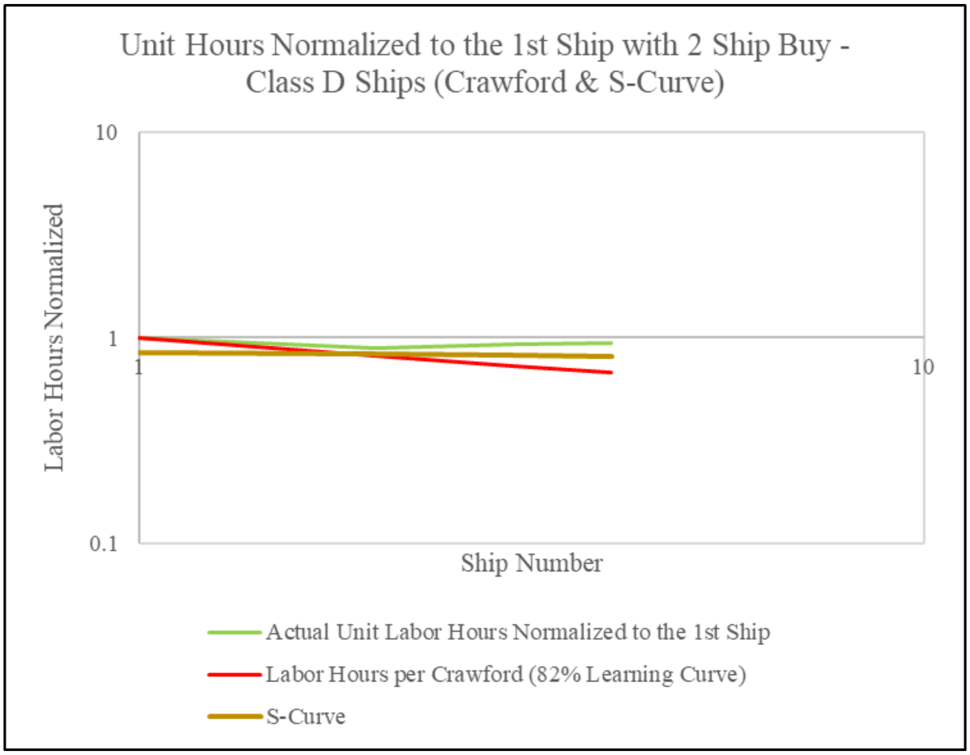

Figure 113: Unit Labor Hours Class D Ships with Two Ship Buy (Crawford and S-Curve)

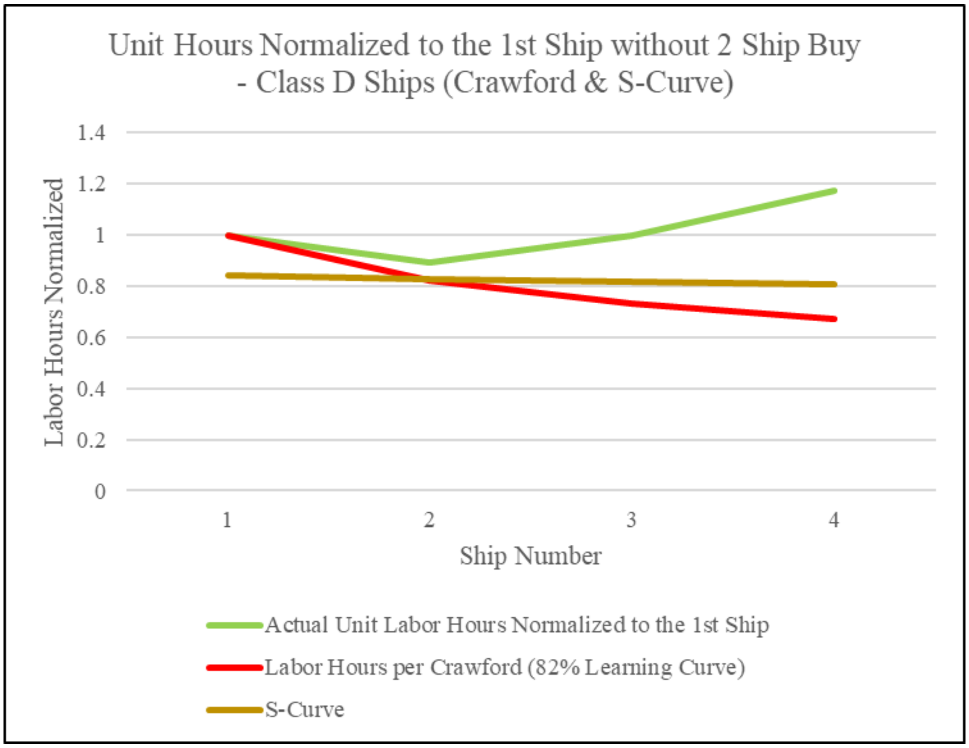

Figure 114: Unit Labor Hours Class D Ships without Two Ship Buy (Crawford and S-Curve)

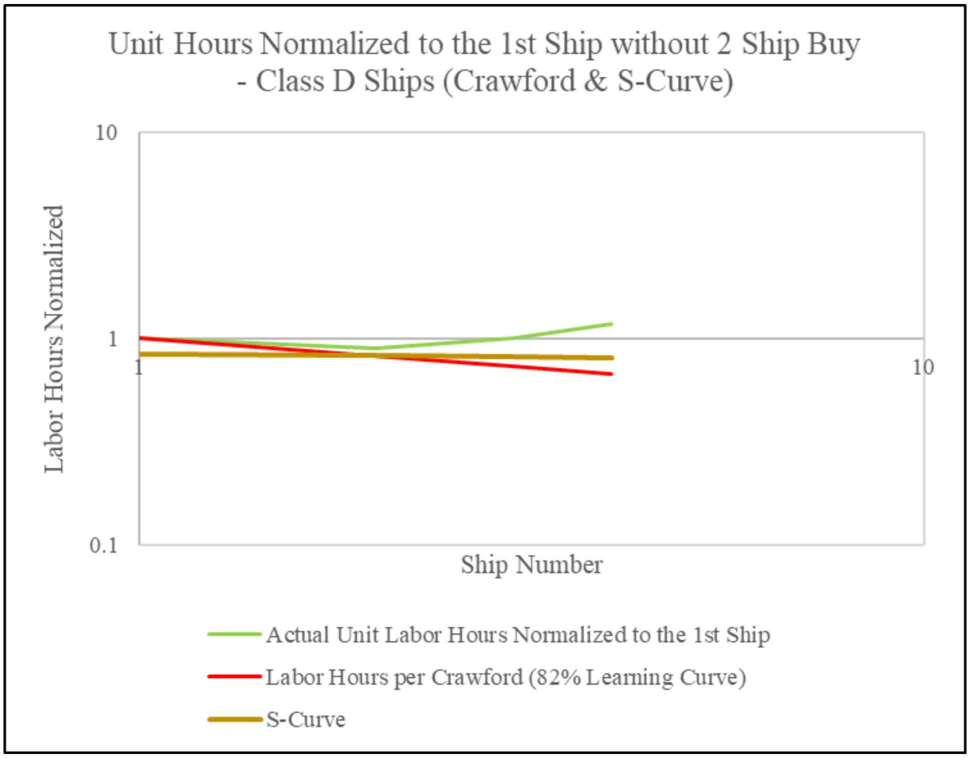

Figure 115: Unit Labor Hours Class D Ships without Two Ship Buy (Crawford and S-Curve)

# CHAPTER 5

# CONCLUSIONS

Continuing to follow the research methodology developed to support this unique research, WBS 9, Determine Key Factors Affecting Learning, was addressed herein to develop conclusions based on the results of this research. WBS 9 was specifically focused on Class A Ships. The remaining classes, Class B, C, and D were also discussed in this chapter too, but they are used to validate and triangulate the conclusions developed from Class A Ships.

## WBS 9 - Determine Key Factors and Conclusions Affecting Learning Utilizing Results from the Class A Ship Analysis

As the research methodology indicates, the researcher analyzed all of the results associated with the Class A Ship data to determine the key factors affecting learning based on this low-rate production data. While doing so, the researcher assessed the information to identify common themes or factors such that the relevant information based on the results could be addressed together vice discussing each table or figure individually. As such, Table 11 was developed to capture the key factors affecting learning associated with Class A Ships. Table 11 was based on bounding the complex system including the factors influencing learning, which was captured via Table 11. Table 11 also captured factors affecting learning of Class A Ships based on the literature review, which was addressed herein, and analyzing the figures associated with Class A Ships (Figures 7, 8, 9, 10, 11, 12, and 13) as well as analyzing the figures that are applicable to all ship classes (Figures 59, 60, 61, 62, 63, 64, 65, 66, and 67). The connectivity to the literature review of Table 11 was used to support the characterization developed accordingly, but was presented here to provide visibility to all of the key factors affecting learning and to provide visibility into the source of the parameters affecting learning.

| # | High Level Grouping | Parameters Affecting Learning | Source of Parameters | | | Class A (Figure) | Affects All Classes (Figure) |
|---|---|---|---|---|---|---|---|
| | | | Mentions Learning and Mentions Shipbuilding | Mentions Learning but Does Not Mention Shipbuilding | Does Not Mention Learning but Does Mention Shipbuilding | | |
| 1 | Company Experience and Capacity | Company Experience | - | - | - | - | - |
| 2 | | Competition | - | - | - | - | - |
| 3 | | Number of Ships Built Prior | - | - | - | - | - |
| 4 | | Number of Ships Built that were Similar | - | - | - | - | - |
| 5 | | Shipyard Capacity | - | - | Weisgerber (2021)<br>Clark (2021) | - | - |
| 6 | Changes | Requirements Changing | - | - | Abbott (1997) | 9<br>10 | - |
| 7 | | New or Immature Technology | - | - | Brimelow (2022)<br>Grazier (2021)<br>Lessig (2019) | - | - |
| 8 | | Requirements | - | - | - | 9<br>10 | - |
| 9 | | Specifications | - | - | - | - | - |
| 10 | | Material | - | - | - | - | - |
| 11 | | Changes | Miroyannia (2006) | - | Abbott (1997) | 9<br>10 | - |

Table 11: Factors Affecting Learning Associated with Class A Ships

| # | High Level Grouping | Parameters Affecting Learning | Source of Parameters | | | Class A (Figure) | Affects All Classes (Figure) |
|---|---|---|---|---|---|---|---|
| | | | Mentions Learning and Mentions Shipbuilding | Mentions Learning but Does Not Mention Shipbuilding | Does Not Mention Learning but Does Mention Shipbuilding | | |
| 12 | Changes (continued) | Requirements Instability | - | - | Abbott (1997) | 9<br>10 | - |
| 13 | | Number of Changes | - | - | Abbott (1997) | 9<br>10 | - |
| 14 | | Technology Insertions | - | - | Grazier (2021) | - | - |
| 15 | | Navy/Government Mandates | - | - | Capaccio (2020) | - | - |
| 16 | | Work Instruction Changes after Start of Construction | - | - | Grazier (2021) | - | - |

Table 11 (continued)

| # | High Level Grouping | Parameters Affecting Learning | Source of Parameters | | | Class A (Figure) | Affects All Classes (Figure) |
|---|---|---|---|---|---|---|---|
| | | | Mentions Learning and Mentions Shipbuilding | Mentions Learning but Does Not Mention Shipbuilding | Does Not Mention Learning but Does Mention Shipbuilding | | |
| 17 | Government Influences | Government Politics | - | - | Eckstein (2022)<br>Hooper (2022)<br>Katz (2022)<br>Shelbourne (2022)<br>Bergman (2020)<br>Perdue (2020)<br>Radelat (2020)<br>Tiron and Capaccio (2020)<br>Ress (2022)<br>Eckstein (2020)<br>Larter (2020)<br>Thompson (2019) | - | - |
| 18 | | Laws, Regulations | - | - | Ress (2022)<br>Eckstein (2020)<br>Larter (2020) | - | - |
| 19 | | Threat Assessments | - | - | Zengerle and Cowan (2022) | - | - |
| 20 | Industrial Base | Industrial Base Issues | Thompson (2019) | - | Limas-Villers (2022)<br>Clark and Walton (2020)<br>Eckstein (2020)<br>Ress (2020) | - | - |

Table 11 (continued)

| # | High Level Grouping | Parameters Affecting Learning | Source of Parameters | | | Class A (Figure) | Affects All Classes (Figure) |
|---|---|---|---|---|---|---|---|
| | | | Mentions Learning and Mentions Shipbuilding | Mentions Learning but Does Not Mention Shipbuilding | Does Not Mention Learning but Does Mention Shipbuilding | | |
| 21 | Information Maturity | Design Maturity at Construction Start | - | - | Grazier (2021) | 9<br>10 | - |
| 22 | | Technical Maturity at Construction Start | - | - | Grazier (2021) | 9<br>10 | - |
| 23 | | Degree of Design for Producibility | - | - | Schank et al (2016) | - | - |
| 24 | Commonality | Amount of Commonality Across the Ship and Class | - | - | Schank et al (2016) | - | - |
| 25 | Procurement Strategy | Budget | - | - | Limas-Villers (2022)<br>Ress (2022)<br>Talent (2021)<br>Connors (2020)<br>Eckstein (2020)<br>Perdue (2020) | - | - |
| 26 | | Acquisition Strategy | - | - | Osborn (2022)<br>Turner (2021)<br>Arena, Blickstein, Younossi, & Grammich (2006) | 11<br>13 | - |
| 27 | | Contract Strategy including Number of Contracts | - | - | Abbott (1997) | 8<br>11<br>13 | - |

Table 11 (continued)

| # | High Level Grouping | Parameters Affecting Learning | Source of Parameters | | | Class A (Figure) | Affects All Classes (Figure) |
|---|---|---|---|---|---|---|---|
| | | | Mentions Learning and Mentions Shipbuilding | Mentions Learning but Does Not Mention Shipbuilding | Does Not Mention Learning but Does Mention Shipbuilding | | |
| 28 | Procurement Strategy (continued) | Contract Impacts | - | - | Osborn (2022) | - | - |
| 29 | | Contract Strategy | - | - | Osborn (2022) | 11<br>13 | - |
| 30 | | Procurement Strategy (Multi-Year Procurement, Block Buy, Contract with Options) | - | - | Burgess (2022)<br>Decker (2022)<br>Capaccio (2020)<br>Katz (2021)<br>Weisberber (2021) | 8<br>11<br>13 | - |
| 31 | | Funding Strategy | - | - | Limas-Villers (2022)<br>Ress (2022)<br>Connors (2020)<br>Lessig (2016) | 11<br>13 | - |
| 32 | | Deisgn and Construction, Production Labor Hours | - | - | - | 7 | - |
| 33 | | Time Between Construction Starts | - | - | Lessig (2016) | 8<br>11 | - |

Table 11 (continued)

| # | High Level Grouping | Parameters Affecting Learning | Source of Parameters | | | Class A (Figure) | Affects All Classes (Figure) |
|---|---|---|---|---|---|---|---|
| | | | Mentions Learning and Mentions Shipbuilding | Mentions Learning but Does Not Mention Shipbuilding | Does Not Mention Learning but Does Mention Shipbuilding | | |
| 34 | Production Environment | Facilities | Miroyannia (2006) | - | - | - | - |
| 35 | | Tooling | - | - | - | - | - |
| 36 | | Number of Different Plants associated with Production | - | - | Fioretti (2007) | - | - |
| 37 | | Manufacturing Progress Function/Degree of Automation | - | - | - | - | - |
| 38 | | Make/Buy Decisions (Amount of Outsourcing) | - | - | - | - | - |
| 39 | Natural Disasters and Labor Strikes | Labor Strikes or Lay-offs | - | - | Fioretti (2007) | - | - |
| 40 | | Disasters | Baker, Degnan, Gabriel, Tucker (2001) | - | - | - | - |
| 41 | Training and Knowledge Management Strategies | Process Improvement & Lessons Learned Process | Miroyannia (2006) | - | Eckstein (2022)<br>Ennis, Dougherty, Lamb, Greenwell, and Zimmermann (1997) | - | - |
| 42 | | Training Strategy | Walpert (2001)<br>Lundquist (20210<br>Gagosz (2021)<br>O'Brien (2020) | Miller (2017)<br>Mishra, Henriksen, and Fahnoe (2013)<br>Di Stefano, Gino, Pisano, and Staats (2016) | - | - | - |

Table 11 (continued)

| # | High Level Grouping | Parameters Affecting Learning | Source of Parameters | | | Class A (Figure) | Affects All Classes (Figure) |
|---|---|---|---|---|---|---|---|
| | | | Mentions Learning and Mentions Shipbuilding | Mentions Learning but Does Not Mention Shipbuilding | Does Not Mention Learning but Does Mention Shipbuilding | | |
| 43 | Training and Knowledge Management Strategies (continued) | Knowledge Management Strategy | - | Di Stefano, Gino, Pisano, and Staats (2016)<br>Pappas (2014)<br>Ebbinghaus (1885)<br>Kohn (2014)<br>Meacham (2016)<br>Teichert (2010) | Abbott (2022)<br>Bloor et al (2016)<br>Schank et al (2016) | - | - |
| 44 | | Knowledge Retention | - | Pappas (2014)<br>Ebbinghaus (1885)<br>Kohn (2014)<br>Meacham (2016)<br>Teichert (2010) | X | - | 65<br>66<br>67 |
| 45 | | Time to Talent | Eckstein (2022)<br>Eckstein (2019)<br>Gagosz (2021)<br>O'Brien (2020)<br>Bloor et al (2016) | - | X | - | 65<br>66<br>67 |
| 46 | | Learning Styles, Techniques, Methods | Walpert (2001)<br>Lundquist (20210 | Di Stefano, Gino, Pisano, and Staats (2016) | X | - | - |
| 47 | | Lessons Learned Incorporation | Miroyannia (2006) | - | Ennis, Dougherty, Lamb, Greenwell, and Zimmermann (1997) | - | - |
| 48 | Company Organization | Production, Construction, Engineering, and Support Department Organization | - | - | Fioretti (2007) | 12 | - |
| 49 | | Procedures | - | Poleacovschi, Javernick-Will, Smith, and Pohl (2020) | Fioretti (2007) | - | - |

Table 11 (continued)

| # | High Level Grouping | Parameters Affecting Learning | Source of Parameters | | | Class A (Figure) | Affects All Classes (Figure) |
|---|---|---|---|---|---|---|---|
| | | | Mentions Learning and Mentions Shipbuilding | Mentions Learning but Does Not Mention Shipbuilding | Does Not Mention Learning but Does Mention Shipbuilding | | |
| 50 | Company Organization (continued) | Staffing Strategy including Visibility of Expertise | - | Poleacovschi, Javernick-Will, Smith, and Pohl (2020) | - | 12 | - |
| 51 | | Output/Productivity (Hours Expended to Produce a Given Output) | Baker, Degnan, Gabriel, Tucker (2001) | - | - | - | 63<br>64 |
| 52 | | Work Mix/Labor Elements | - | - | Abbott (1997)<br>Limas-Villers (2022)<br>Lundquist (2021) | 12 | - |
| 53 | Learning | Reverse Learning or Forgetting Curve | Miroyannia (2006) | Pappas (2014)<br>Ebbinghaus (1885)<br>Kohn (2014)<br>Meacham (2016)<br>Teichert (2010) | Diekmann, Horn, & O'Conner (1982) | 7 | 65<br>66<br>67 |
| 54 | | Repetitive Learning | - | - | Diekmann, Horn, & O'Conner (1982) | - | - |
| 55 | | Loss of Learning | Miroyannia (2006) | Pappas (2014)<br>Ebbinghaus (1885)<br>Kohn (2014)<br>Meacham (2016)<br>Teichert (2010) | X | 7 | 65<br>66<br>67 |
| 56 | | Relative Efficiency of Learning | - | - | X | - | 65<br>66<br>67 |

Table 11 (continued)

| # | High Level Grouping | Parameters Affecting Learning | Source of Parameters | | | Class A (Figure) | Affects All Classes (Figure) |
|---|---|---|---|---|---|---|---|
| | | | Mentions Learning and Mentions Shipbuilding | Mentions Learning but Does Not Mention Shipbuilding | Does Not Mention Learning but Does Mention Shipbuilding | | |
| 57 | Demographics | Personnel Age Distribution | Baker, Degnan, Gabriel, Tucker (2001) | - | Arena, Blickstein, Younossi, & Grammich (2006)<br>Eckstein (2021)<br>Gagosz (2021) | - | 59<br>60<br>61<br>62<br>63<br>64 |
| 58 | | Experience Distribution | McLeary (2020)<br>Eckstein (2019)<br>Thompson (2019)<br>Bloor et al (2016) | - | Arena, Blickstein, Younossi, & Grammich (2006)<br>Bloor et al (2016)<br>Ress (2021) | - | 59<br>60<br>61<br>62 |
| 59 | | Demographics | - | | Arena, Blickstein, Younossi, & Grammich (2006)<br>Limas-Villers (2022)<br>Lundquist (2021) | - | 59<br>60<br>61<br>62 |
| 60 | | Lack of Adequate & Experienced Employees | - | - | Lima-Villers (2022)<br>Ress (2021)<br>Lundquist (2021) | - | - |
| 61 | | Workforce Shortages | Baker, Degnan, Gabriel, Tucker (2001) | - | Lima-Villers (2022) | - | 63<br>64 |
| 62 | | Workforce Turnover | Baker, Degnan, Gabriel, Tucker (2001) | - | Weisgerber (2021)<br>Eckstein (2022) | - | 63<br>64 |

Table 11 (continued)

| # | High Level Grouping | Parameters Affecting Learning | Source of Parameters | | | Class A (Figure) | Affects All Classes (Figure) |
|---|---|---|---|---|---|---|---|
| | | | Mentions Learning and Mentions Shipbuilding | Mentions Learning but Does Not Mention Shipbuilding | Does Not Mention Learning but Does Mention Shipbuilding | | |
| 63 | Ship Complexity | Ship Construction Density, Ship Complexity, Design Complexity, and Complexity Associated with Ship Operations | - | - | Schank et al (2016)<br>Terwilliger (2015)<br>Gaspar, Ross, Rhodes, and Erickstad (2012)<br>Grant (2008)<br>Arena, Blickstein, Younossi, and Grammich (2006) | - | - |
| 64 | Stability and Predictability | Workforce Instability | Baker, Degnan, Gabriel, Tucker (2001) | - | Lima-Villers (2022) | - | 63<br>64 |
| 65 | | Instability in the Number of Ships and Navy's Procurement Plans | - | - | Abott (2022)<br>Eckstein (2022)<br>Grady (2022)<br>Limas-Villers (2022)<br>Axe (2021)<br>Katz (2021)<br>Turner (2021)<br>Weisgerner (2021)<br>Bergman (2020)<br>Connors (2020)<br>Fabey (2020)<br>Radelat (2020)<br>Arena, Blickstein, Younossi, & Grammich (2006)<br>Reed and Inhofe (2021) | - | - |
| 66 | | Predictability & Stability Associated with Future Work | - | - | Katz (2021)<br>Clark (2021)<br>Reed and Inhoe (2021) | - | - |

Table 11 (continued)

Based on bounding and the parameter assessment of the figures contained within Table 11, each Class A Ship Parameter, which was represented by Figures 8, 9, 10, 11, 12, and 13, has been analyzed versus Figure 7, labor hours via Chapter 4, and associated conclusions identified via this Chapter. This method not only allows for a more efficient deduction of the information, but this method also facilitated the development of a low-rate production learning characterization of Class A Ships, which was the objective of WBS 10. The results of WBS 9 were captured via Table 12, and the associated conclusions deduced follows Table 12.

| # | Key Parameters and Conclusions Affecting Learning Curves for Class A Ships | | | |
|---|---|---|---|---|
| | **Figure** | **Parameter Represented** | **Results of Analysis (Note 1)** | **Deductions/Conclusions Associated with Learning** |
| 1 | 8 | Major Ship Construction Milestones | Increasing times between delivery dates throughout the Class except for Ships 5 - 8. Some milestones associated with Ship 2 are similar to Ships 5 - 8. | Less time between delivery dates and contract awards dates correlates to less labor hours.<br>Ship 1, Ship 2, Ship 4, Ship 5, & Ship 7 had the best milestone performances.<br>There is an optimum number of months between delivery dates that correlates to fewer hours to support design, construction, and delivery of low-rate production ships. This optimum number is a range of months, and it is an enabler to learning and knowledge retention and is ship class dependent.<br>Multi-ship procurements reduces production durations because, in part, learning and knowledge retention are more easily facilitated then single ship procurements.<br>Multi-ship procurements resulted in shorter durations from the major ship milestone of keel laying to delivery. |
| 2 | 9 | Cumulation of Significant Changes | Increase in number of changes across the entire ship class except for Ship 2, which did not have any. | Ship 2 had no significant changes and the hours to build Ship 2 were less than the previous.<br>The class, other than Ship 2, experienced an increasing number of changes and the trend line for the labor hours also shows an increasing trend line too.<br>The accumulation of significant changes and requirements increases the labor hours to build each ship of a class associated with low-rate production manufacturing.<br>An environment associated with continual change results in a level of instability which is a disruptor in regards to learning. |
| 3 | 10 | Significant Changes Compared to Previous Ship | Ship 2 did not have any significant changes and took fewer hours to build compared to previous.<br><br>All Ships showed increasing hours to correspond to increasing number of changes compared to previous Ship except Ships 5 & 7. | No significant changes reduces hours to build each Ship.<br>Number of changes affects number of hours to build each ship.<br>See Item 4 to address Ships 5 & 7 which show an increase in changes but a decrease in hours.<br>Ship 4 incorporated numerous production changes which yielded fewer hours to construct Ship 5 along with the 2 Ship buy for Ships 5 & 6 and Ship 7 & 8.<br>If there are no significant changes from the previous ship or fewer changes compared to the previous ship, then there is a reduction in hours to build that ship. Fewer or no changes compared to the previous ship provides a more stable environment for learning.<br>The number of changes affects the number of hours to build each ship which directly impacts the amount of new information that has to be learned from ship to ship. |

Table 12: Conclusions in Regard to Learning Curves Associated with Class A Ships

| # | Key Parameters and Conclusions Affecting Learning Curves for Class A Ships | | | |
|---|---|---|---|---|
| | **Figure** | **Parameter Represented** | **Results of Analysis (Note 1)** | **Deductions/Conclusions Associated with Learning** |
| 4 | 11 | Procurement Strategy | Ships 1 & 2 were contracted together but procured separately. Ships 5 & 6 were procured together and Ships 7 & 8 were procured together.<br>Analysis with Figure AZ yields less time between delivery dates corresponds to fewer labor hours required to build each ship.<br>For non-2 Ship buys, longer time between contract awards yields more labor hours required to build each ship.<br>Number of changes does not impact procurement strategy nor milestones.<br>The 2 Ship buy "artificially" shows that the 2nd Ship takes longer to deliver based on contract award date. | Ships 5 & 7 show an increase in changes but a decrease in hours. This is due to the fact that the ships built during this time frame had the fewest months between major milestones such that learning effects were more possible. 2 Ship buys results in fewer labor hours to build each ship especially for the 2nd Ship of the 2 Ship buy. Ships with delivery dates that were within 3.4 years or less from the previous ships shows a reduction in labor hours. Ship 2 delivered 2.4 years after Ship 1, Ship 5 delivered 3 years after Ship 4, Ship 6 delivered 2.6 years after Ship 5, Ship 7 was 3.4 years after Ship 6, and Ship 8 was 2.6 years after Ship 7. In all cases, fewer hours were needed to build each while time between delivery dates of 4.5 years and greater resulted in more hours to build the next ship. 2 Ship Buy & minimizing time between deliveries is enabler to learning. Multi-ship procurement strategies increases that learning will be shared between associated ships. Two ship or multi-procurement buys results in fewer hours to build each ship especially for the second ship of a two ship buy, and can offset the impact of changes as compared to the previous ship. This procurement strategy is an enabler. Each ship class will have an optimum range of months between delivery dates that enables learning between each ship. Multi-ship procurements coupled with minimizing time between deliveries enables learning thereby reducing labor hours to support construction and delivery of low-rate production ships. |
| 5 | 12 | Principal Production Labor Elements | Labor elements that constitute more than 5% of the total are: Electrical, Machinery, Painters, Pipefitters, Riggers, Sheet Metal, Shipfitters, and Welders. | This equates to 80% of the production labor. The targeted learning and knowledge retention should address all areas but especially these 8 areas vice the 22 shown.<br>These 8 areas will also have the largest influence on the labor hours expended for each ship.<br>Data does not exist in the public domain providing the hours spent per year per ship.<br>Low-rate production shipbuilding is accomplished by principal production labor elements; as such, in order to develop a knowledge management culture, learning strategies that are developed must include these labor elements supporting low-rate production shipbuilding. |

Table 12 (continued)

| # | Key Parameters and Conclusions Affecting Learning Curves for Class A Ships | | | |
|---|---|---|---|---|
| | Figure | Parameter Represented | Results of Analysis (Note 1) | Deductions/Conclusions Associated with Learning |
| 6 | N/A | Principal Non-Production Labor Elements | This data does not exist in the public domain. However, the researcher assumes that engineering, management, administration, and production support are some of the key non-production elements associated with low rate production shipbuilding. | As such, no conclusions can be made directly in regards to Class A Ships. However, as Chapter 4 alludes, since all of the data associated with this research is based on low rate production of ships, the data obtained in the public domain for Classes B, C, and D is associated to Class A Ships.<br>Low-rate production shipbuilding is accomplished by principal non-production labor elements; as such, in order to develop a knowledge management culture, learning strategies that are developed must include these labor elements associated with low-rate production shipbuilding. |
| 7 | 13 | Funding Profiles and Strategy | Funding for Ships 1 through 4 was fairly consistent with a slight increase.<br>Ships 5 & 6 and 7 & 8 were 2 ship buys, as reflective in Figure AR1. Ship 10 was a multi-year procurement, with the longest duration between contract awards, was the most expensive ship of the class. | As covered via Item 4, the ship with the longest duration between deliveries required the most hours to build was Ship 10.<br>Ship 10 was the last ship of the class. It did not have the most changes indicating the time between deliveries impacts learning more than the number of changes.<br>The funding profiles and subsequent funding strategies are determined and developed by the customer which are not optimized to support and/or accommodate the shipbuilder thereby impacting the ability to maximize learning in low-rate production shipbuilding.<br>Time between deliveries and/or contract award dates has a greater influence on learning than the number of changes for low-rate production ships. |
| 8 | 59 | Shipbuilding Age Demographics - 2020 | Almost 50% are of retirement age or within 10 years of retirement age.<br>Only 23% are the next leaders within Shipbuilding (35 to 44 age demographic.<br>Approximately 28% are inexperienced (age 34 and younger). | In regards to knowledge management and learning, a concerted effort must occur to capture the shipbuilders that are retirement age to prepare the next set of leaders and to help the new hires move up their learning curve as efficiently as possible.<br>The demographic environment directly impacts learning and the knowledge management culture of low-rate production shipbuilding.<br>Utilizing the referenced 2020 demographic data, the large number of shipbuilders that are within ten years of retirement, as compared to previous years, is a learning disruptor because the bi-modal distribution of experience as well as a large percentage of shipbuilders that are close to retirement inhibits knowledge transfer which negatively affects learning.<br>The Class A Ships were built and delivered before 2020; as such, this demographic data set is not applicable to the Class A Ships. This demographic data is crucial to ensuring the development of a robust learning and knowledge management strategy to support each ship class, which is discussed throughout Chapter 5 herein. |

Table 12 (continued)

| # | Key Parameters and Conclusions Affecting Learning Curves for Class A Ships | | | |
|---|---|---|---|---|
| | **Figure** | **Parameter Represented** | **Results of Analysis (Note 1)** | **Deductions/Conclusions Associated with Learning** |
| 9 | 60 | Shipbuilding Age Demographic - 1999 | Approximately one-half the number of shipbuilders compared to 2020.<br>Up to as much as 27% are retirement eligible or are within 4 years.<br>At least 13% are inexperienced plus some percentage of the 31 - 40 age demographic are also inexperienced. | In regards to knowledge management and learning, a concerted effort must occur to capture the shipbuilders that are retirement age to prepare the next set of leaders and to help the new hires move up their learning curve s efficiently as possible.<br>The demographic environment directly impacts learning and the knowledge management culture of low-rate production shipbuilding. Utilizing the referenced 1999 demographic data, there were one half the number of shipbuilders as compared to the 2020 demographic data, and the demographic distribution is a skewed bell curve reflective of a more experienced workforce. With this distribution, the transfer of knowledge, and as a result, learning is more enabled compared to the 2020 demographic data.<br>In regards to the 1999 demographic data, only some of the Class A Ships were built during this time frame. |
| 10 | 61 | Shipbuilding Age Demographic - 1980 | 44% are retirement age are within 10 years of retirement.<br>37% are inexperienced.<br>Only 20% are the next future leaders of shipbuilding (35-44 age demographic.) | In regards to knowledge management and learning, a concerted effort must occur to capture the shipbuilders that are retirement age to prepare the next set of leaders and to help the new hires move up their learning curve s efficiently as possible.<br>Only this demographic data is applicable to Class A Ship data. In regards to 1980, Ship 3 was within 2 years of delivery and Ship 4 had just started.<br>Despite having a large percentage of inexperienced labor, Ship 4 was the start of delivering ships for less hours for the next 4 ships<br>The demographic environment directly impacts learning and the knowledge management culture of low-rate production shipbuilding. Increasing the number of low-rate production ships is a learning enabler to assist with offsetting a demographic environment with a bi-modal age distribution and/or a demographic environment with a skewed retirement age distribution. In regards to the 1980 demographic data, Class A Ships spanned the 1980's, and as such, this demographic data would represent some of the ships within this class. |

Table 12 (continued)

| # | Key Parameters and Conclusions Affecting Learning Curves for Class A Ships | | | |
|---|---|---|---|---|
| | **Figure** | **Parameter Represented** | **Results of Analysis (Note 1)** | **Deductions/Conclusions Associated with Learning** |
| 11 | 63 | Employee Work Output for Shipbuilding and Repair | US Shipbuilding output increased by 45% over 20 years.<br>This is across all US shipbuilding and repair and not just low rate production.<br>Shows a slight rise in output in 1982, 1984, 1990, and 1998 with lows in 1987 and 1993. | The increase in outputs as well as the decrease in outputs appears during 2 Ship procurement time frames as well as 1 Ship procurement time frames. They also occur during times frames that had shorter times between deliveries as well as longer times too. As such, deductions and conclusions cannot be made in regards to the factors impacting shipbuilding based on Class A Ship data. However, Baker, Degnan, Gabriel, Tucker (2001) offers some explanations, which are delineated with this this Chapter.<br>The employee work output for US shipbuilders has grown by forty-five percent over a twenty-year period from 1977 to 1998 (Baker, Degnan, Gabriel, and Tucker (2001)); however, this increase in work output is not attributable to ship procurement time frames or multi-ship procurement strategies, but rather, it is due to the learning characterization for each shipyard such as the organizational culture and the demographic environment. There are also other factors that influence work output, but they are outside the scope of this research. |
| 12 | 64 | Employee Work Output for Automotive and Aircraft Industries | US automotive and aircraft output increased by 120% and 85%, respectfully.<br>The automotive industry showed rises in output in 1983, 1989, 1994, and 1998 with lows in 1980, 1987, and 1995.<br>The aircraft industry showed rises in output in 1980, 1985, 1992, and 1998 with lows in 1982, 1984, 1989, and 1996. | Only 1998 shows a rise in output for shipbuilding, automotive, and aircraft industries.<br>None of the other years during this twenty year time frame in terms of yearly increases or decreases (except 1998).<br>The aircraft and automotive industries has an output per employee that is more than a factor of 4 per employee output for shipbuilding and repair.<br>The aircraft and automotive industries has an output per employee that is more than the employee output compared to the shipbuilding industry. The difference in output per employee is due to the differences in their production environments (i.e., low-rate versus high-rate production) which is impacted by their overall learning characterizations between low-rate production and high-rate production environments. |

Table 12 (continued)

| # | Key Parameters and Conclusions Affecting Learning Curves for Class A Ships | | | |
|---|---|---|---|---|
| | **Figure** | **Parameter Represented** | **Results of Analysis (Note 1)** | **Deductions/Conclusions Associated with Learning** |
| 13 | 65<br>66 | Memory Retention | In a day after learning a new skill without any refreshers or review, most people will only retain about 20 to 30% of what they learned.<br>In a month after learning a new skill without any refreshers or review, most people will only retain about 10 to 15% of what they learned. | All aspects of low rate production does not support knowledge retention due to the cadence of ship production associated with this environment. Certain specific shipbuilding skills will be completed daily, like basic skills associated with each labor element (Figure AG), but applying those skills to specific ship evolutions that occur only once every x years will result in the loss of how to complete that specific job due to reverse learning/loss of learning that skill for that specific job. Programs must be put in place to increase knowledge retention.<br>Most people after learning a new skill will only retain ten to fifteen percent of the knowledge that they learned after a month has transpired without any refreshers. As such, low-rate production environments that entail not using skills frequently increases the challenges associated with knowledge retention and learning. |
| 14 | 67 | Relative Efficiency vs Experience | For shipbuilding, it takes at least 4 years for a shipbuilder to obtain 80% efficiency.<br>After 1 year, a shipbuilder is only 50% efficient.<br>It takes over 15 years to approach 100% efficiency. | The low rate production environment of shipbuilding increases the challenges associated with shipbuilder efficiency due to knowledge retention issues.<br>Programs must be put in place to support shipbuilder efficiency also referred to as time to talent.<br>The low-rate production environment of shipbuilding increases the challenges associated with shipbuilder efficiency due to knowledge retention issues. |

Table 12 (continued)

As Note 1 indicated for this table, the analysis associated with this data was captured by Chapter 4 via the research methodology. The results of WBS 9 were captured via Table 12, and the associated conclusions deduced were delineated herein next.

## Key Parameter #1: Major Ship Construction Milestones

### Conclusion #1-1: Optimum Number of Months between Deliveries

- *Conclusion:* There is an optimum number of months between delivery dates that correlates to fewer hours to support design, construction, and delivery of low-rate production ships. This optimum number is a range of months, and it is an enabler to learning and knowledge retention and is ship class dependent.

- *Adjudication:* In terms of Item 1 of Table 12, assessing Class A major ship construction milestones associated with labor hours showed that less time between delivery dates generally correlates to less labor hours expended to build each ship. Ship 2 had the fewest number of months between deliveries meaning the number of months between the previous ship, in this case Ship 1, and the current ship, Ship 2, had the fewest number of months. Ship 2 was also delivered with the fewest number of hours for all of ship of Class A. Ship 2 also had the fewest number of changes too. Ships 6 and 8 had the next fewest number of months between ship deliveries. These two ships were the second ships of a two ship buy, and as such, this fact coupled with the fact that they had the next fewest number of months between deliveries helped to facilitate that these two ships, Ship 8 and Ship 6 had the third and fourth fewest hours to deliver both ships. Conversely, the ship with the most hours to deliver, which was Ship 10, also had the longest time between ship deliveries. The ship with the second highest number of hours to deliver, which was Ship 4, had the third the greatest number of months between ship deliveries. For Class A Ships, the optimum range of years between delivery dates is two and a half to three and a half years.

### Conclusion #1-2: Multi-Ship Procurements Reduces Production Durations

- *Conclusion:* Multi-ship procurements reduces production durations because, in part, learning and knowledge retention are more easily facilitated then single ship procurements.

- *Adjudication*: This conclusion was based on the relationship between schedule milestones and procurement strategies. For Class A Ships, Ship 4 was delivered in the fewest number of months followed by Ships 5, 7, and 1. This was, in part, due to build strategy changes and two ship buys enabling learning retention for these ships. Ship 5 has the second fewest months to build the ship, which occurred in eighty-two months. Ship 5 took advantage of the build strategy changes associated with Ship 4 as well as the fact that Ship 5 was the first ship of a two ship buy. Ship 7 was also the first ship of a two ship buy, so it too took advantage of both of these factors.

### Conclusion #1-3: Multi-ship Procurements Results in Shorter Durations from Keel to Delivery

- *Conclusion:* Multi-ship procurements resulted in shorter durations from the major ship milestone of keel laying to delivery.
- *Adjudication:* This conclusion was based on the relationship between schedule milestones and procurement strategy and was a sub-set of Conclusion #1-2. For Class A Ships, two ship buys contribute to shorter durations from keel to delivery, which enabled learning and supported a learning culture thereby contributing to less hours to build a ship. Utilizing Item 1 of Table 12, it should also be noted that, as indicated, Ships 5 and 6 were procured together as a two ship buy and so was Ships 7 and 8. Utilizing Figure 8, however, yields the fact that the number of months from keel to delivery was obtained in the fewest number of months for Ships 7 and 8 with fifty-six and fifty-five months respectfully. Ships 4 and 5 were the next fewest months at sixty months for both. Ship 4 experienced build strategy changes while Ship 5 was the first of a two ship buy. Ship 6

was the second of a two ship buy and it had the next lowest number of months from keel to delivery at seventy months.

### Key Parameter #2: Cumulation of Significant Changes

Conclusion #2-1: Requirements Stability, or Instability, Impacts the Labor Hours to Build the Ship Class

- *Conclusion:* The accumulation of significant changes and requirements increases the labor hours to build each ship of a class associated with low-rate production manufacturing.
- *Adjudication:* For Class A Ships, Ship 2 had the fewest number of changes and required the fewest hours to deliver. This stability in requirements enabled learning from the previous ship to be applied to Ship 2. As previously indicated, Ship 2 was contracted with Ship 1 but funded separately. The hours to build Ship 2 was less compared to any other ship of Class A. From a milestone perspective, Ship 2's milestones were about average for the class as a whole. Based on the lack of information in the public domain, the researcher cannot draw any additional conclusions in regards to Ship 2's schedule performance, especially in relation to other work that was on-going within the shipyard that built Ship 2 of Class A.

Conclusion #2-2: Requirements Instability is a Disruptor to Learning

- *Conclusion:* An environment associated with continual change results in a level of instability which is a disruptor in regard to learning.

- *Adjudication:* Low-rate production environments usually yields an environment with a high degree of change usually due to the long build durations which results in the customer trying to insert changes throughout the build duration. The net effect of this was an unstable baseline impacting ship over ship learning. For Class A Ships, other than Ship 2, the class experienced an increasing number of changes and the trend line for the labor hours required to build each ship also showed an increasing trend line too. As was discussed in Chapter 4, the cumulative changes were normalized to the third ship of the class because there were not any significant changes associated with the second ship of the class. As such, the changes had to be normalized to the third ship. Simply based on inspection yields the correlation between the increasing summation of hours to build each ship along with the summation of the changes over the ship class. As such, the number of changes was a contributor to the hours to build each ship.

### Key Parameter #3: Significant Changes Compared to the Previous Ship

#### Conclusion #3-1: Fewer or No Changes Compared to the Previous Ship Provides a More Stable Environment for Learning

- *Conclusion:* If there are no significant changes from the previous ship or fewer changes compared to the previous ship, then there is a reduction in hours to build that ship. Fewer or no changes compared to the previous ship provides a more stable environment for learning.
- *Adjudication:* For Class A Ships, only one ship, which was Ship 2, did not have any significant changes, and it took fewer hours to build due to a more stable environment for learning. Figure 7 provided the labor hours to build each ship while Figure 10 provided

the significant changes for each ship compared to the previous ship. Ships 6 and 8, which were the second ship of two ship buy, had fewer changes compared to the previous ship, which was a contributing factor for the shipbuilder to build these two ships for fewer hours than the previous ship.

### Conclusion #3-2: Changes Increases New Information that has to be Learned

- *Conclusion:* The number of changes affects the number of hours to build each ship which directly impacts the amount of new information that has to be learned from ship to ship.
- *Adjudication:* This conclusion was focused on an assessment of each of the previous Ships associated with the entire Ship Class as well as incorporating the elements associated with learning as was delineated by Table 12 Items 13 and 14, memory retention parameter and relative efficiency vs experience parameter. As was validated in support of Conclusions' #2-1 and #3-1, an increase in changes as compared to the previous ship results in more hours to build that ship. This was simply due to the fact that the areas of the ship that were impacted by the changes were new areas which have to be learned thereby negating the learning that had occurred previously. Factoring the memory retention and relative efficiency versus experience parameters into these yields reverse learning in these areas due to changes. As such, in areas of the ship that have experienced changes as compared to the previous ship, reverse learning not only was comprised of forgetting how a specific area of the ship was built due to the number of months or even years since that area of the ship was last constructed, but reverse learning was also impacted by having to un-learn how that area of the ship was built due to the

new changes associated with that specific ship. This phenomenon was applicable to all classes of ships.

**Key Parameter #4: Procurement Strategy**

Conclusion #4-1: Multi-Ship Procurements Increase the Opportunity Associated with Learning

- *Conclusion:* Multi-ship procurement strategies increases the probability that learning will be shared between those ships associated with the multi-ship procurement.
- *Adjudication:* Four of the Class A Ships, Ships 5 and 6 as well as Ships 7 and 8, were procured via two ship buys. Two ship or multi-ship procurements increased the probability that learning was shared between the ships that were part of the multi-ship procurement. Ships 5 and 7 had an increase in the number of changes but a decrease in the hours to build each ship, and they both had the fewest number of months between major milestones so that learning effects were more possible.

Conclusion #4-2: Two Ship Procurements results in Fewer Hours to Build and Deliver the Second Ship, and can Offset the Impact of Changes

- *Conclusion:* Two ship or multi-procurement buys results in fewer hours to build each ship especially for the second ship of a two ship buy, and can offset the impact of changes as compared to the previous ship. This procurement strategy is a learning enabler.
- *Adjudication:* Two ship or multi-ship procurement buys positively impacted a shipyard in a number of ways. For Class A Ships, these two ships were the first ship of a two ship buy, and they took fewer hours to build compared to the previous ship that shipyard built

but had more changes. This was attributed to the shorter durations between ship deliveries. Ship 7 experienced fewer hours to build then Ship 6 despite having more changes as compared to Ship 6 because Ship 7 was the first ship of a two ship buy. Ships 1 and 2 were contracted together but were funded separately. This still had a positive effect in that Ship 2 required fewer hours to build, and as already indicated, also had few changes as compared to Ship 1. As such, durations between ship deliveries affected the number of hours to build Class A Ships as well as to be able to accommodate changes. Less time between deliveries reduced the amount of learning that was lost thereby allowing a shipyard to be able to address changes in a more efficient manner from a learning characterization perspective.

Conclusion #4-3: Each Ship Class will have an Optimum Range of Months between Delivery Dates

- *Conclusion:* Each ship class will have an optimum range of months between delivery dates that enables learning between each low-rate production ship designed, built, tested, and delivered to its’ respective customer. This optimum range of months is also impacted by other factors such as capacity, available footprint, current workload, and so on. These additional factors are outside the scope of this research because more detailed company or agency specific information would be required, which is proprietary information.
- *Adjudication:* Ships with delivery dates that were closer together support learning being transferred from one ship to the next more effectively than ships that have longer durations between ship deliveries. Ship 2 was delivered 2.4 years after Ship 1, Ship 5

was delivered 3 years after Ship 4, Ship 6 was delivered 2.6 years after Ship 5, Ship 7 was 3.4 years after Ship 6, and Ship 8 was 2.6 years after Ship 7. In all cases, fewer hours were needed to build each of these ships while time between delivery dates of 4.5 years and greater resulted in more hours to build the next ship. For Class A Ships, ships with delivery dates that were within 3.4 years or less from the previous ships showed a reduction in labor hours to support delivery of that ship. This was a learning enabler by reducing the time between completing similar tasks associated with designing and building a ship especially compared to durations longer than 3.4 years. As indicated, there were multiple additional factors impacting the optimum time between deliveries that maximizes learning transfer and knowledge management.

### Conclusion #4-4: Multi-ship Procurements Coupled with Minimizing Time between Deliveries Reduces Labor Hours.

- *Conclusion:* Multi-ship procurements coupled with minimizing time between deliveries enables learning and knowledge transfer thereby reducing labor hours to support construction and delivery of low-rate production ships. Each ship class exhibits an optimum range of the number of ships associated with a multi-ship procurement as well as an optimum range of the number of months between successive deliveries.
- *Adjudication:* Class A Ships have benefited through fewer hours required to support construction and delivery on those ships that had two ship buys as well as minimized the time between deliveries. Class A Ships had two – two ship buys with both resulting in fewer hours to construct the second ship of the two-ship buy. For Class A Ships, there were only single ship procurements or two ship procurements. As such, regarding the

optimum number of ships that constitute a reduction in the labor hours, for Class A, the only deduction that can be made was two ships.

### Conclusion #4-5: Multiple Ship Procurement Contracts are Executed via Three Different Approaches with Each Reflecting Different Milestone Durations

- *Conclusion:* Multiple ship procurement contracts are executed in series, in parallel, or in a hybrid strategy resulting in milestones based on a contract award date which does not reflect actual ship delivery durations**.**
- *Adjudication:* Multiple ship procurement contracts were either executed in one of three strategies:
    - in series,
    - in parallel, or
    - a hybrid strategy whereby some ship construction milestones were obtained in series while others are obtained in parallel.

The execution of which strategy was chosen is based on many factors; however, for the purposes of this research, an understanding of the strategy utilized for each procurement contract as well as the subsequent construction strategy should be assessed accordingly because each strategy would impact learning differently. A multiple ship procurement strategy whereby the execution was done in series would have less knowledge transfer and learning as compared to a strategy whereby the low-rate production ships were constructed in parallel. Conversely, a hybrid construction strategy where some of the ship's milestones were obtained via parallel construction and some of the ship's milestones were obtained via series construction would result in learning and knowledge transfer to occur more than the series construction but not as much as the parallel construction strategy. There does not exist enough information in the public domain to be able to assess the degree or amount of influence these different approaches has on learning in low-rate production environments. As such, additional research in this area would only be able to occur within each company or agency as the resulting required information to perform this assessment would be proprietary to that specific company or agency. Regardless, for the purposes of this research, an understanding of these three strategies would at least provide context for the learning resident within each approach, and it also provides insights into the context for each ship construction milestone as they relate to contract award for that specific multiple ship procurement. For multiple ship procurements, the contract award date was the same for all ships within that specific contract. As such, without understanding the details associated with this procurement, the follow-on ships after the first ship of the contract could appear to take longer to build if they are all measured off of the contract award date for all of the ships affiliated with that specific contract. This exact issue was identified by the researcher for all four ship classes affiliated with this research. For Class A Ships, the second ship of both two ship procurements “artificially” [researcher’s quotes] shows that the second ship takes longer to build based on the contract award date. However, this was not the case because the second ship of the two ship procurements that occurred for Class A Ships started construction after the first ship. Data in the public domain does not provide the actual start of construction date for the second ship of the two ship buys for Class A Ships. Utilizing the data in the public domain for Class A Ships, the first ship of the two-ship buy for Ships 5 and 6 took eighty-two months to build while the second ship of the two-ship buy would have taken one-hundred and fourteen months to build based on the contract award date accordingly. The same deduction was also valid for Ships 7 and 8 for the Class A Ships. Using data in the public domain, Ships 7 and 8 took eighty-nine and one-hundred and twenty months to build respectfully, again based on the contract award date for Ships 7 and 8 for Class A Ships. It took fewer hours to build the second ship of these two ship contracts which would equate to shorter construction times.

### Key Parameter #5: Principal Production Labor Elements

#### Conclusion #5-1: Low-rate Production Shipbuilding is Accomplished by Principal Production Labor Elements

- *Conclusion:* Low-rate production shipbuilding is accomplished by principal production labor elements; as such, in order to develop a knowledge management culture, learning strategies that are developed must include these labor elements supporting low-rate production shipbuilding.
- *Adjudication:* Production labor profiles and distributions will vary from ship class to ship class due to the intended mission profiles associated with each ship class. Eighty percent of the production labor associated with Class A Ships involved the following eight labor elements of: electrical, machinery, painters, pipefitters, riggers, sheet metal workers, shipfitters, and welders. As such, any knowledge management actions should at least include these eight areas.

### Key Parameter #6: Principal Non-Production Labor Elements

Conclusion #6-1: Low-rate Production Shipbuilding is Accomplished by Principal Non-Production Labor Elements

- *Conclusion:* Low-rate production shipbuilding is accomplished by principal non-production labor elements; as such, in order to develop a knowledge management culture, learning strategies that are developed must include these labor elements associated with low-rate production shipbuilding.
- *Adjudication:* Non-production labor profiles and distributions will vary from ship class to ship class due to the intended mission profiles associated with each ship class. For Class A Ships, data does not exist in the public domain for the principal non-production labor elements. However, the researcher assumed that engineering, management, administration, and production support were some of the key non-production elements associated with low-rate production shipbuilding. Since both Class A Ships and Class B Ships were produced in low-rate production environments, there non-production labor profiles were more likely similar and can be assumed to be similar. For Class B Ships, the principal non-production labor elements are: administration, support, engineering, and management.

### Key Parameter #7: Funding Profiles and Strategies

Conclusion #7-1: Funding Profiles and Strategies Impacts Learning

- *Conclusion:* The funding profiles and subsequent funding strategies are determined and developed by the customer which are not optimized to support and/or accommodate the shipbuilder thereby impacting the ability to maximize learning in low-rate production shipbuilding.

- *Adjudication:* For Class A Ships, the ship with the longest duration between deliveries, which was due to the timing and profile of the funding to build that particular ship, required the greatest number of hours to build, which was Ship 10. Ship 10 was also the last ship of the class. As such, most of the learning gained from the previous ship was lost due to the longer duration between Ship 9 and Ship 10, which was over seven years. For Class A Ships, funding profiles with fewer months between contract awards as well as multi-ship procurements facilitated learning as evidence by the reduction in labor hours to build the second ship of a two ship buy for these two ship classes.

Conclusion #7-2: Time Between Deliveries versus Number of Changes

- *Conclusion:* Time between deliveries and/or contract award dates has a greater influence on learning than the number of changes for low-rate production ships.
- *Adjudication:* As was delineated within the Assumptions Section of this research, by definition, low-rate production shipbuilding not only refers to the periodicity of successive ship deliveries, but it also refers to the ship complexity as well as the large number of labor hours to design, build, test, and deliver ships of certain ship classes. This assumption was applicable to this conclusion discussion because low-rate production ships required a larger number of labor hours to produce as compared to high-rate production ships such that the impact from changes on low-rate production ships has the potential to be absorbed easier due to the large number of labor hours associated with low-rate production ships. The degree of the impacts associated with these changes

requires proprietary information which was beyond the scope of this research. For Class A Ships, Ship 10 required the greatest number of hours of all ships in this class to design, build, test, and deliver. Ships 10 also had the longest duration between ship deliveries of almost six years. Ship 3 had the longest duration between contract awards of seven years while Ships 9 and 10 had the second longest durations between contract awards of six and a half years. Ship 10 had the greatest number of changes while Ship 9 had the seventh greatest number of changes. Both Ships 9 and 10 were single ship procurements. In regards to Class A Ships, time between deliveries has a greater impact on learning than the number of changes.

### Key Parameter #8: Shipbuilding Age Demographics – 2020

Conclusion #8-1: 2020 Demographic Environment within Shipbuilding Impacts Learning

- *Conclusion:* The demographic environment directly impacts learning and the knowledge management culture of low-rate production shipbuilding. Utilizing the referenced 2020 demographic data, the large number of shipbuilders that are within ten years of retirement, as compared to previous years, is a learning disruptor because the bi-modal distribution of experience as well as a large percentage of shipbuilders that are close to retirement inhibits knowledge transfer which negatively affects learning.
- *Adjudication:* The Class A Ships were built and delivered before 2020; as such, this demographic data set was not applicable to the Class A Ships. This demographic data was crucial to ensuring the development of a robust learning and knowledge management strategy to support each ship class, which was discussed throughout Chapter 5.

### Key Parameter #9: Shipbuilding Age Demographics – 1999

Conclusion #9-1: 1999 Demographic Environment within Shipbuilding Impacts Learning

- *Conclusion:* The demographic environment directly impacts learning and the knowledge management culture of low-rate production shipbuilding. Utilizing the referenced 1999 demographic data, there were one half the number of shipbuilders as compared to the 2020 demographic data, and the demographic distribution is a skewed bell curve reflective of a more experienced workforce. With this distribution, the transfer of knowledge, and as a result, learning is more enabled compared to the 2020 demographic data.
- *Adjudication:* In regard to the 1999 demographic data, only some of the Class A Ships were built during this time frame. Using the 1999 shipbuilder demographic data, there were one-half the number of shipbuilders compared to the 2020 data. Approximately one-quarter of the shipbuilders in 1999 were within ten years of retirement age, and about twelve percent of the shipbuilders in 1999 were inexperienced. There were half the number of shipbuilders as compared to 2020 and about twenty percent less than 1980. As such, 1999 was a “valley” [researcher’s quotes] in the number of shipbuilders between 2020 and 1980. Over thirteen percent plus some percentage of the thirty-one to forty age group were inexperienced. As such, in regard to knowledge management and learning, a concerted effort must have occurred to capture the shipbuilders that were retirement age to prepare the next set of leaders and to help the new hires move up their learning curve as efficiently as possible. In regard to knowledge management and learning, for Class A Ships, the age demographic profile was more conducive to efficient learning and knowledge transfer as compared to the 2020 demographic data. As indicated, this

conclusion was based on demographic data describing shipbuilders in 1999. Additional data, not in the public domain, would be required to establish connectivity between the demographic data and the direct impact to labor hours.

### Key Parameter #10: Shipbuilding Age Demographics – 1980

Conclusion #10-1: 1980 Demographic Environment within Shipbuilding Impacts Learning

- *Conclusion:* The demographic environment directly impacts learning and the knowledge management culture of low-rate production shipbuilding. As such, in regards to knowledge management and learning, a concerted effort must have occurred to capture the shipbuilders that are retirement age to prepare the next set of leaders and to help the new hires move up their learning curve as efficiently as possible.
- *Adjudication:* In regard to the 1980 demographic data, Class A Ships spanned the 1980's, and as such, this demographic data would represent some of the ships within this class. Utilizing the referenced 1980 demographic data, there are twenty percent more shipbuilders in 1980 as compared to 1999, but approximately forty percent fewer shipbuilders in 1980 as compared to 2020. About forty-four percent in 1980 were retirement eligible or were eligible within ten years. Over thirty-five percent were inexperienced, and only twenty percent in 1980 were available to be the future leaders of shipbuilding by being in the thirty-five to forty-four age demographics. The 1980 demographic profile shows a very similar bi-modal distribution as the 2020 demographic profile. There were more low-rate production ships being built during the late 1970s and early 1980s which would enable learning thereby reducing the impacts associated with a bi-modal demographic distribution.

### Conclusion #10-2: Increasing the Number of Low-rate Production Ships Assists Offsetting a Demographic Environment that is a Learning Disruptor

- *Conclusion:* Increasing the number of low-rate production ships is a learning enabler to assist with offsetting a demographic environment with a bi-modal age distribution and/or a demographic environment with a skewed retirement age distribution.
- *Adjudication:* Despite having a large percentage of inexperienced labor in 1980 at thirty-seven percent and forty-four percent at retirement age or within ten years of retirement age, Ship 4 of Ship Class A, which would have been directly impacted by these demographics because its' contract date was 1980, was the start of delivering ships for less hours for the next four Class A Ships. As indicated previously, these four ships had fewer months between deliveries and were two ship procurements such that the number of ships procured within this low-rate production environment were increased as compared to the rest of the class. The average time between deliveries for these Class A Ships was twenty-seven months as compared to the rest of the ships that make up this class, which had an average time between deliveries of fifty-three months. The results of this were that the Class A Ships with an average of twenty-seven months between deliveries were designed, built, and tested for seven percent fewer labor hours as compared to the Class A Ships that had an average time between deliveries of fifty-three months. As such, the impacts to learning in low-rate production environment with a bi-modal and/or retirement aged demographic can be at least partially mitigated by increasing the number of ships that were being designed, built, and tested.

### Key Parameter #11: Employee Work Output for Shipbuilding and Repair

Conclusion #11-1: US Shipbuilder Work Output has Grown Forty-Five Percent over 20 Years

- *Conclusion:* The employee work output for US shipbuilders has grown by forty-five percent over a twenty-year period from 1977 to 1998 (Baker, Degnan, Gabriel, and Tucker (2001)); however, this increase in work output was not attributable to ship procurement time frames or multi-ship procurement strategies, but rather, it was due to the learning characterization for each shipyard through the organizational culture and the demographic environment. There were also other factors that influence work output, but they were outside the scope of this research.
- *Adjudication:* Figure 63 provided work output associated with shipbuilding for all shipyards including ship repair yards. Figure 63, which was derived from Baker, Degnan, Gabriel, Tucker (2001), covered not only shipbuilding but also ship repair. Baker, Degnan, Gabriel, Tucker (2001) did not separate shipbuilding from ship repair which was important because this research was focused on new construction shipbuilding and not ship repair or ship overhaul. Also, Figure 63 was for all shipyards and not just the shipyard that built Class A Ships, which placed less emphasis on Figure 63 specific relationship to Class A Ships. Figure 63 did not provide information at the specific shipyard level nor work output by ship class as this information did not exist in the public domain nor is there a feasible way to extract the needed information from Figure 63. However, the researcher did assess Figure 63 versus Figures 8, 9, 10, 11, 13, 60, and 61. Figure 63 showed a slight rise in shipbuilding output in 1982, 1984, 1990, and 1998, and it showed lows in output in 1987 and 1993. The increase in outputs as well as the decrease in outputs appears during two ship procurement time frames as well as one ship

procurement time frames. The increase in outputs as well as the decrease in outputs reflected via Figure 63 occurred during time frames associated with Class A Ships that exhibited both shorter and longer durations between deliveries as well as different procurement strategies for both single and two ship procurements. As substantiated by Baker, Degnan, Gabriel, and Tucker (2001), shipbuilding output per employee rose only forty-five percent over twenty years as compared to one-hundred and twenty percent for the automotive industry and eighty-five percent for the aircraft industry over the same time frame. Per Baker, Degnan, Gabriel, and Tucker (2001), this was due to several reasons, such as differences in workforce instability and age distributions, and other reasons. However, workforce stability and age demographics impacted learning through the shipbuilding environment and culture of learning resident in a given shipyard similar to the shipyards that built Class A Ships. The automotive and aircraft industries were included to provide a reference to compare shipbuilding too even though the automotive and aircraft industries were not produced in a low-rate environment.

### Key Parameter #12: Employee Work Output – Automotive and Aircraft Industries

<u>Conclusion #12-1: US Aircraft and Automotive Industries has an Output per Employee Larger than the Output per Employee in Shipbuilding</u>

- *Conclusion:* The aircraft and automotive industries has an output per employee that is more than the employee output compared to the shipbuilding industry. The difference in output per employee is due to the differences in their production environments (i.e., low-rate versus high-rate production) which is impacted by their overall learning curve characterizations between low-rate production and high-rate production environments.

- *Adjudication:* This conclusion was based on the information provided by Baker, Degnan, Gabriel, and Tucker (2001). As was the case with Conclusion #11-1, Figure 63 provided work output associated with shipbuilding for all shipyards including ship repair yards while Figure 64 provided work output associated with automotive and aircraft industries. Figures 63 and 64 did not provide information at the specific shipyard, aircraft, or automotive industry level nor associated work output by ship class, aircraft type, or automotive type. Similar to Conclusion #11-1, the work output associated with the aircraft and automotive industries was also influenced by workforce stability and age demographics too which impacts the learning characterization within these industries similar to shipbuilding. The only main difference in the learning characterizations of the aircraft and automotive industries compared to the shipbuilding industry as the fact that the learning environment associated with the aircraft and automotive industries was a high-rate production environment while the Class A Ships were within the context of a low-rate production environment. US automotive and aircraft employee work output increased by one hundred and twenty percent and eighty-five percent, respectfully, over a twenty-year period while shipbuilding and repair increased by forty-five percent over the same timeframe. The automotive industry showed rises in output in 1983, 1989, 1994, and 1998 with lows in 1980, 1987, and 1995 while the aircraft industry showed rises in output in 1980, 1985, 1992, and 1998 with lows in 1982, 1984, 1989, and 1996. Only 1998 showed a rise in output for shipbuilding, automotive, and aircraft industries. Figure 116 shows all three industries on one figure.

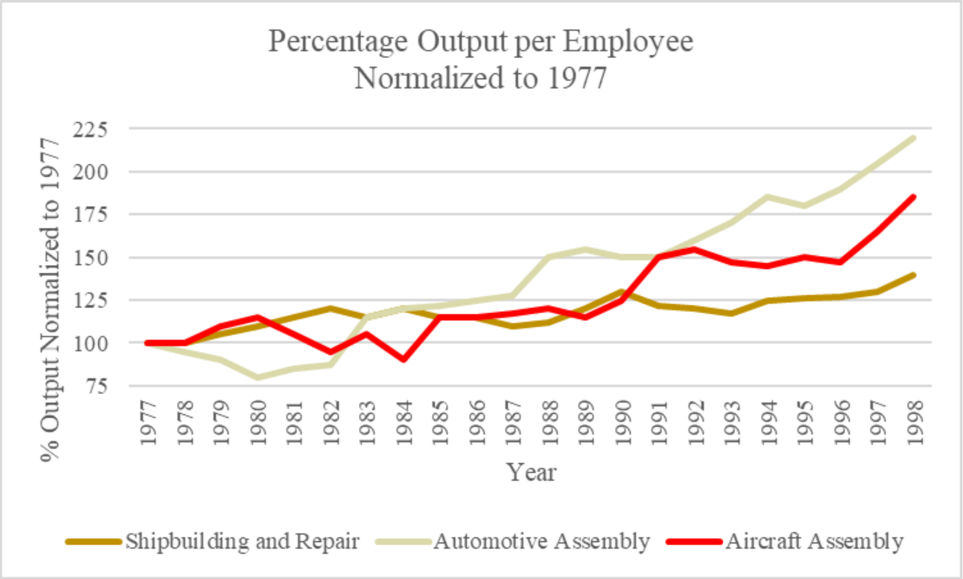

Figure 116: Output per Employee for Shipbuilding and Repair, Automotive Industry, and Aircraft Industry

**Key Parameter #13: Memory Retention**

Conclusion #13-1: Lack of Using Skills Results in Substantial Reduction in Knowledge Retention and Learning

- *Conclusion:* Most people after learning a new skill will only retain ten to fifteen percent of the knowledge that they learned after a month has transpired without any refreshers. As such, low-rate production environments that entail not using skills frequently increases the challenges associated with knowledge retention and learning.
- *Adjudication:* As Figures 65 and 66 illustrate, knowledge retention decreases within a day after training occurs. Training retention can be bolstered through refreshers as well as other learning strategies. Obviously, low-rate production environments were much more susceptible to this issue simply due to the very nature of their associated production

environment as compared to high-rate production environments. Teichert (2010), Kohn (2014), Meacham (2016), and Brain Science (2022) discussed that knowledge retention can be increased after learning a new skill through “booster events,” which would be an event that facilitates a person’s brain to associate the new information learned as important to assist with the memory retention process. Kohn (2014) simply stated that “if you use it, you won’t lose it!” Ebbinghaus (1885, 1913) covers recommendations in regards to how to increase memory retention thereby increasing knowledge retention; however, the associated strategies to employ to bolster retention and/or increase knowledge retention, especially in low-rate production environments, is the subject of future research. Neither Ebbinghaus (1885, 1913) nor Kohn (2014), or any other researcher, specifically discussed knowledge retention within the context of a low-rate production environments, such as shipbuilding. Additionally, future research within this area is viable including connectivity to requisite parsimony. However, the researcher has also additionally concluded that not every skill associated with low-rate production shipbuilding would erode following Figures 65 and 66. Basic shipbuilding skills such as drilling holes, cutting holes, and other fundamental operations would not experience a loss of learning. However, shipbuilding skills associated with using those fundamental skills to build parts of a system would experience some loss of learning while skills associated with building systems within the context of specific ship construction conditions would experience the highest loss of learning. A more in-depth assessment of this additional conclusion would also be the subject of future research and was beyond the scope of this research. This conclusion was derived from Class A Ships, and the other ship classes were discussed in this Chapter.

### Key Parameter #14: Relative Efficiency versus Experience

Conclusion #14-1: Shipbuilder Efficiency is Affected by the Knowledge Management Culture

- *Conclusion:* The low-rate production environment of shipbuilding increases the challenges associated with shipbuilder efficiency due to knowledge retention issues.
- *Adjudication:* After working one year in shipbuilding, a shipbuilder was only fifty percent efficient, and after four years, a shipbuilder was only eighty percent efficient. As Figure 67 shows, it takes over fifteen years of experience for a shipbuilder to approach one hundred percent efficiency. Figure 67 was for all shipbuilding, and it did not differentiate between low-rate production shipbuilding and high-rate production shipbuilding. Within the context of low-rate production shipbuilding, in the researcher's opinion, the slope of Figure 67 would be even less meaning that the time frame to reach fifty percent, eighty percent, and one hundred percent would take even longer. The exact slope of the low-rate production curve of relative efficiency versus years of experience would be the subject of future research. Conclusion #14-1 was applicable to all of shipbuilding. As such, programs need to be put in place by shipbuilders to increase shipbuilder efficiency thereby reducing the number of hours for a shipbuilder to become proficient and learn their craft.

## WBS 10 - Develop Ship Class A Low-Rate Production Learning Curve Characterization

Using the conclusions associated with WBS 9 including Table 11 and Table 12, the researcher has developed an Overall Learning Curve Characterization (OLCC) based on Class A Ship data. The OLCC was comprised of five learning parameters defined by learning enablers and learning disruptors. The five learning parameters were those that have been shown to be most influential with respect to learning in low-rate production environments. They were also five that summarize and/or define a larger population of sub-parameters, which was based on requisite saliency meaning factors will have different levels of importance. As such, the researcher selected factors, based on bounding of the complex system as well as analyzing the Class A Ship parameters represented by the figures developed for the Class A Ship data (Figures 7, 8, 9, 10, 11, 12, and 13) and figures developed that were applicable to all four ship classes (Figures 59, 60, 61, 62, 63, 64, 65, 66, and 67). Based on the requisite saliency of the parameters in Table 11 and the deductions from Table 12, the following five parameters, as shown in Table 13, were selected and identified as those that are most salient:

- Stability (S)
- Procurement Strategy (P)
- Industrial and Organizational Culture (I)
- Knowledge Management (K)
- Demographic Environment (E)

| Overall Learning Curve Characterization (OLCC) | | | |
|---|---|---|---|
| **Acronym** | **Learning Parameter** | **Learning Enablers (LE): Efficient Learning** | **Learning Disruptors (LD): Loss of Learning** |
| **S** | Stability (S) | Stable Baseline:<br>No Changes & Commonality from Ship to Ship of the Same Class | Dynamic Baseline:<br>Lots of Changes & Lack of Commonality from Ship to Ship of the Same Class |
| **P** | Procurement Strategy (P) | Multi-Ship Procurement:<br>Multi-Ship Serial Production with Optimized Construction Starts | Single Ship Procurement:<br>One-Off Ship Procurement with Extended Construction Start |
| **I** | Industrial & Organizational Culture (IO) | Synthesis:<br>Consistent and/or Predictable Staffing Demands per Department | Disintegration:<br>Variable and/or Unpredictable Staffing Demands per Department |
| **K** | Knowledge Management (KM) | Robust Integrated Learning & KM Culture | Lack of a Defined Learning & KM Culture |
| **E** | Demographical Environment (E) | Balanced Workforce & Experience Demographic:<br>Even Profile Distribution | Skewed Workforce & Experience Demographic:<br>Bi-modal Distribution and/or Retirement Aged Distribution |

Table 13: Overall Learning Curve Characterization

To assist with referencing this characterization, the acronym of SPIKE was developed by the researcher to capture this Class A Ship characterization. As such, the OLCC for learning in low-rate production environments was comprised of learning enablers (LE) and learning disruptors (LD) such that:

$$\text{OLCC}_{\text{Learning in Low-rate Production Environments}} = \text{LE} + \text{LD} \qquad \text{(Equation 20)}$$

From a parameter perspective, the OLCC is comprised of five parameters, such that:

$$\text{OLCC}_{\text{Learning in Low-rate Production Environments}} = f(S,P,I,K,E) \qquad \text{(Equation 21)}$$

Learning Enablers (LE) and Learning Disrupters (LD) together define the OLCC. LEs were characteristics that support efficient learning. As the name implies, they enable learning while LDs contribute to the loss of learning.

Next, the researcher is going to discuss each learning parameter as well as the LEs and LDs associated with each, and again, this was within the context of Class A Ships. From a research methodology perspective,

- WBS 11 utilized the conclusions deduced from Class B Ships to validate the conclusions deduced in regards to Class A Ships via WBS 9 as well as the OLCC delineated via WBS 10.
- Conversely, WBS 12 utilized the conclusions deduced from Class C and Class D Ships to validate through triangulation the conclusions deduced in regards to Class A Ships via WBS 9 as well as the OLCC delineated via WBS 10.

For each learning parameter, a description of the parameter as well as the associated facets of that parameter was discussed below. After which, a discussion involving the impacts of this parameter to learning in low-rate production environments was also covered within this section. This methodology to present this information was repeated below for all five principal learning parameters associated with learning in low-rate production environments.

OLCC Learning Parameter – Stability (S)

- *LE:* Stable Baseline
- *LD:* Dynamic Baseline
- *Description of Parameter:* Stability has been identified by the researcher as a key parameter characterizing learning in low-rate production environments as determined from bounding the complex system associated with learning in low-rate production environments as well as completing the assessment associated with Class A Ships. As such, stability was then characterized, using Tables 11 and 12, as associated with:
    - Changes
    - Government influences
    - Industrial base issues
    - Information maturity
    - Predictability

As Table 11 and 12 showed, changes impacts stability through requirements being changed or new requirements being brought forth onto successive ships of a class, and in this case, Class A Ships. The magnitude of the changes and/or the number of changes can also impact stability of the ship baseline that was produced. These changes were also brought forth through new and/or immature technology being brought forth to the ship. Changes, in general, as compared to the ship baseline, makes the next ship harder to build or at least increases unfamiliarity with the impacted areas due to changes whether they were technology changes or requirements and specification changes.

In addition to technology, requirements, and specification changes impacting stability of a ship's baseline, government action or inaction, for that matter, can also affect stability for a given ship or ship class. The Government's instability can come in the form of government politics, laws, and regulations being changed or added to a given ship contract. The government can also impact a ship or ship class through the completion of threat assessments or the mission profile of the ship or ship class can be changed as the world and world events continues to change. Regardless, the government can impact a ship or ship class in a way to cause instability in requirements or expectations associated with a ship or ship class.

The industrial base also impacts stability. The industrial base is the shipbuilder as well as all of the suppliers that support the production of a ship through the products that they provide. This research was focused on learning in low-rate production environments within a given shipyard. Suppliers were excluded from this research, but this may be a topic of future research. Focusing on industrial base issues related to a given shipyard producing Class A Ships was focused on workload stability within the shipyard. Workload stability or instability can create volatility across the shipyard creating uncertainty in the long-term viability of a given shipyard.

Information maturity was another aspect associated with stability or instability. If the design or technical aspects of the ship is still being developed after contract award and/or construction start, then this leads to additional instability associated with the program, which also impacts learning. This parameter was highlighted during the bounding process as well as the assessment completed on the Class A Ships.

The assessment of Class A Ships, using Figures 63 and 64, showed shipbuilder work output as well as automotive and aircraft industry work output. A constituent factor associated with the rather modest gains in shipbuilding work output was due, in part, to instability associated with the shipbuilding workforce. This instability was primarily due to the inconsistent Naval shipbuilding plan as a result of both the Navy and Congress, which was also identified as a result of the bounding associated with this complex system. During the bounding process, stability and predictability was highlighted in regards to the Navy's procurement plans associated with new construction naval shipbuilding. The Navy's and Congress shifting of ship construction priorities created an environment that each shipbuilder cannot adequately plan for the future. This instability has also impacted the recruiting challenges associated with new hires into the shipbuilding industry.

- *Impacts to Learning:* Stability and, the resultant of stability, predictability impacts learning. In terms of changes, a ship that was being constructed with changes as compared to the previous ship decreases ship over ship learning. Most changes were paid for by the customer; however, the changes do not take into account the erosion in learning that happens as a result of those changes. Meaning, every place where a new change was implemented, the engineers, designers, planners, production trades, and other shipbuilders have to unlearn the old system and old method to install the previous system and learn the new system as a result of the change. The result of this was that the shipbuilders involved with this change, in effect, moves "back-up" [researcher's quotes] the learning curve for this area of the ship. As the assessment of the Class A Ships yields, this then results in increased labor hours and increased schedule to build and deliver each impacted ship.

The government's influence on learning was really from an indirect perspective. The actions of the government, whether it be delaying funding, changing funding, eliminating funding, passing new laws or regulations, or completing threat assessments can and does change the shipbuilding landscape. As such, the shipbuilder responds accordingly to adjust. This creates instability across the shipyard. Obviously, the government did not intentionally effect learning, but the learning environment was impacted by government actions and influences. However, this did have a direct impact on the industrial base. The industrial base is made up of the shipbuilder plus all of the suppliers that provide products to the shipbuilder to support shipbuilding. Adjustments made by the industrial base, including companies going out of business due to government action or inaction, as may be the case, has an indirect impact to learning. It is an indirect impact because the action of the industrial base was not driven by learning. However, this parameter addressed herein because it was a factor affecting learning. Coupled with changes, the degree of design maturity, or in other words, the percentage of the ship that was complete from a design standpoint at contract award or at the start of construction has a direct impact on learning as well as time to learn the new systems or changes associated with each ship of the Class A Ships. It was very common for ships produced in low-rate production environments to start production with an incomplete design and a low technical maturity associated with new systems going on the ship as compared to the previous ship. This obviously impacts learning and actually causes reverse learning in areas where changes were occurring because the ship design was not complete yet before ship construction actually started. All of this was directly related to predictability. If a shipyard cannot plan or cannot convey predictability or stability of requirements or workforce needs or the longevity of a given class of ships, like Class A Ships, then this creates uncertainty in all aspects of shipbuilding which directly impacts learning. Lack of stability results in production breaks yielding loss of learning and loss of capabilities both for the shipyard as a whole as well as for each shipbuilder across the value stream. As such, if a ship has lots of changes and a lack of commonality from ship to ship of a ship class along with instability coupled with a lack of predictability, then this environment becomes a learning disruptor and learning is lost. However, if a ship class has a stable baseline with minimal to no changes and commonality from ship to ship, then stability will support efficient learning thereby creating a learning enabler.

OLCC Learning Parameter – Procurement Strategy (P)

- *LE:* Multi-Ship Procurement
- *LD:* Single Ship Procurement
- *Description of Parameter:* Similar to the other parameters, the procurement strategy was also multi-faceted. The procurement strategy includes budget and funding, which were two different entities of the bounded complex system. It also included the design and construction/production labor hours associated with Class A Ships. Budget, funding, and labor hours are also tied to the time between construction starts associated with Class A Ships. This was covered within Chapter 4 which showed varying gaps between construction starts associated with each Class A Ship. As was shown via the Class A Ships, the procurement strategy varied across the ship class with some ships being single ship procurements and others were two ship (multi-ship) procurements. It was important to note that just because a contract may be a two-ship procurement does not necessarily mean that both ships will be constructed at the same time. They made still be constructed

in series rather than a parallel fashion due to the acquisition strategy and associated funding and/or due to the shipbuilder’s capacity at the time of contract award.

- *Impacts to Learning:* The procurement strategy directly impacted learning in low-rate production environments even more so than high-rate production environments. The data associated with Class A Ships and the subsequent conclusions showed that two ship procurements had the resulting effect of reducing the hours required to build the ship especially for the second ship of two ship buys. As the assessment of the Class A Ships revealed, this was due to a number of reasons especially due to the two ship buy. A contributing factor and by-product of a two-ship buy was that less change occurs on the second ship of the two ship buy. The Class A Ship data and subsequent assessments provided those insights as well. Along with this, in those instances for the Class A Ships where the time between construction starts was less than 4 ½ years, labor hour performance was also better for those ships as well.

From a learning enabler standpoint, the two ship buy coupled with the side effects of not as many changes from ship to ship and less time between construction starts created an opportunity to support ship over ship learning. This learning enabler was the resultant of a multi-ship or in this case for Class A Ships, a two-ship procurement. One aspect that was not resident in the public domain or in the data, but was mentioned in the description of this parameter, was that the researcher surmises that the two-ship procurement could be executed in three ways. The first would be more of a serial production approach where the first ship would be built followed by the second ship being built. Learning would still be enabled but not as efficiently as if both ships could be built as simultaneously as possible within the constraints of the given shipyard, or at least in a hybrid approach. If that was viable, especially parallel construction, then the multi-ship procurement strategy, or in the case of a two ship buy for Class A Ships, would have the opportunity to maximize the learning from ship to ship for those ships included in the two-ship buy.

As can be alluded based on the learning enabler discussion, a learning distractor for the procurement strategy for Class A Ships was a one-off or single ship procurement especially if there are more than 4 ½ years between ships per the Class A Ship data and assessments. The data shows that the number of hours to design and build one-off Class A Ships was much more than two ship procurements for Class A Ships. A single ship procurement inhibits learning from the previous ship as well the next ship of the class.

OLCC Learning Parameter – Industrial and Organizational Culture (I)

- *LE:* Synthesis
- *LD:* Disintegration
- *Description of Parameter:* The industrial and organizational culture was made up of several different parts per the assessment and conclusions associated with Class A Ships, and they include: company experience, shipyard capacity, number of ships built in total and number of ships build related to that specific class. Even though Class A Ships were only produced by one shipbuilder, production environment does have an impact on the industrial and organizational culture associated with Class A Ships. The production environment was defined as facilities, tooling, manufacturing progress meaning the amount of automation, and the amount of outsourcing that occurred for a given ship class. In regard to Class A Ships, most of this information was not in the public domain, and as

such, could not be used to effectively develop conclusions other than the fourth ship of the class was built using a different construction methodology, which, given the data available, contributed to a reduction in production labor hours on successive ships. The researcher does suggest, however, that the parameters that constitute production environment would be contributors to reducing hours to support construction of Class A Ships and subsequently would support learning as discussed below. Company organization was another principal parameter associated with industrial and organizational culture associated with Class A Ships. The data and associated assessments of Class A Ships provided work mix and labor elements for the construction of Class A Ships. This work mix and labor element assessment was for production, engineering, and other support functions. This provided insights into the type of work required to support Class A Ships. In addition, the assessments provided insights into the productivity, in general, across all of shipbuilding; however, specific data in regards to the shipyard that built Class A Ships was not available in the public domain.

The net result of this was that a culture associated with the shipbuilder along with their industrial focus can be understood to gather insights with respect to the impact of the industrial and organizational culture associated with learning in low-rate production environments.

- *Impacts to Learning:* The Industrial and Organizational Culture associated with a shipyard, and in this case for the shipyard building Class A Ships, directly forecasts the learning culture within a shipyard building ships at a low production rate. A shipyard with a consistent and predictable culture through its’ staffing strategy, labor mix, and production environment would create a culture of synthesis thereby creating an environment where learning was enabled. This synthesis will provide an opportunity for efficient learning through sharing of knowledge and what was learned from ship to ship. Predictability would enabler too because consistency in the shipyard's organization would make it clear who the learning should be shared with in a visible and clear way. However, if the staffing demands in a functional area were variable and/or unpredictable or if available facilities were changing or not available or even partially available, then this would lead to an industrial and organization culture that was based on disintegration. This would then become a loss of learning due to this learning disruptor. The environment that the Class A Ships were built in faced some of these learning disruptors as captured by the assessments that were completed on the Class A Ships. The skills required over time showed variability primarily due to funding profiles and contracting strategies employed by the Navy and Congress. The uncertainty associated with these needs disrupted learning by providing a culture that learned information could not be readily captured and passed on due to unpredictable staffing requirements. Shipbuilders working in low-rate production environments, and the researcher would include all other production environments, need to have stability within their job functions and predictability in regards to their own future employment and opportunities. This coupled with an understanding of the work required through clear procedures as well as the tooling and facilities that can be utilized as efficiently as possible creates a shipbuilding culture that enables efficient learning. The more that the industrial and organizational culture erodes away from this then the staffing and labor mix becomes variable, unpredictable, and as such, the culture becomes a learning disruptor to the shipyard.

OLCC Learning Parameter – Knowledge Management (K)

- *LE:* Robust Integrated Learning and Knowledge Management Culture
- *LD:* Lack of a Defined Learning and Knowledge Management Culture
- *Description of Parameter:* The next core parameter associated with the OLCC was focused on knowledge management. Knowledge management, within the context of Class A Ships, was characterized by several different parameters, such as: the process associated with lessons learned, continuous improvements, process improvements, training strategies, learning styles, techniques, methods, and the knowledge management strategy inherent and/or developed within the shipyard. This knowledge management strategy was then assessed and analyzed within the context of knowledge retention and time to talent. Both knowledge retention and time to talent are also within the context of reverse learning/forgetting curves/loss of learning, and the relative efficiency of learning. The lack of a robust knowledge management culture coupled with a low-rate production environment yields shipbuilders committing similar or the same mistakes ship after ship thereby re-learning the same lessons learned.
- *Impacts to Learning:* Obviously, knowledge management was crucial to any production environment; however, it was absolutely critical in an environment of low-rate production, such as shipbuilding, with several years between doing the same step or work or set of instructions again for the next ship. As such, a shipyard not having a well-defined and very visible knowledge management implemented strategy would be very short-sighted. The knowledge management strategy must be grounded in:
  - learning and training strategies,

- an active and visible culture of not only capturing process improvements but implementing them based on learned experience,
- knowledge retention to support time to talent and learning efficiencies, and
- an understanding of reverse learning/forgetting/loss of learning so that strategies can be put in place.

Due to the nature of low-rate production of Class A Ships, the ability to influence funding cycles with the Navy and Congress was minimal, so a shipbuilder being able to adjust those cycles to optimize the time between ships was more than challenging. However, given that fact, the shipbuilder must proactively create a robust and integrated learning and knowledge management approach and culture across the shipyard for all work/labor elements. If this was employed, then the knowledge management strategy for the shipbuilder in a low-rate production environment would support efficient learning, then this would become a learning enabler. However, the lack of a defined learning and/or knowledge management culture within a shipyard or even a partially defined culture would result in the loss of learning such that the knowledge management culture, if it did not exist, becomes a learning disruptor.

This knowledge management culture should be focused on organizational learning, individual learning, and team or work crew learning. Each of these areas of learning must have a defined knowledge management implemented strategy to be a learning enabler. The researcher used the word “implemented” because so many organizations will have a knowledge management strategy but it was in “name only” [researcher’s quotes] meaning the company may have it written down as a procedure but it has not been implemented. The organizational knowledge management strategy must be part of the work processes associated with the shipyard, but rather, it needs to be made an integral part of the shipyard’s operations. From an individual learning standpoint as each person relates to knowledge management, the strategy must be adaptable enough so that each person can take their lessons learned and not only use it to support their future work and professional growth, but that it can be used to share with others who may be doing something similar. Lastly, in shipbuilding, all shipbuilders, no matter if they were in production or in a production support role, work with others in a group or work crew. The point is that the knowledge management strategy must also be established to address learning and knowledge capture for the work crew as well.

As per the loss of learning/reverse learning assessments that were completed conveyed, the loss of learning starts to occur as soon as a new skill was learned. As Kohn (2014) stated, booster events can occur to increase retention accordingly to counter human nature’s natural tendency to forget what has been learned. Obviously in shipbuilding with years between completing the same work again, shipbuilder will forget how they did something due to the gap in time from the last time they did something. This simple fact was why learning in low-rate production environments was different than high-rate production environments. All literature in the public domain, until now, did not recognize this difference in environments.

Shipbuilding was a very unique environment due to many reasons discussed, but the long building durations coupled with the long durations between products were the principal reasons for its’ complexity. The researcher deduced another concept as a result of this research based on Class A Ships. Learning and its antithesis, the loss of learning, occurs on three different levels for each shipbuilder, and the researcher would also espouse that this applies to all types of workers. The fundamental level of learning were those skills, that are usually repetitive and that a shipbuilder has to do every day. For example, a shipyard mechanic has learned how to use a drill and drill holes for instance. The action of drilling a hole was one of many that was a fundamental skill and one that would not be at risk of reverse learning. The next level takes those fundamental skills and applies them to specific jobs. As such, using the mechanic as an example, the mechanic may have learned the proper way to drill holes into foundations. Lastly, the next level of learning would be applying the general act of drilling a hole into a more specific task of drilling a hole in foundations that was installed in a specific location and orientation aboard ship requiring special tooling to support the drilling of a hole in a foundation. After learning to complete that specific operation successfully, the mechanic may not perform that exact same operation again until five years later because the mechanic was working on a low-rate production ship class. The point was that the fundamental aspect of drilling holes was a skill that, once learned, the mechanic will not forget how to do because the shipbuilder did this multiple times every day and/or it was a very basic skill that would not be forgotten once learned. The next skill of the proper way to not only drill holes but to drill them into a foundation would be the next level of skill using this example. This skill, if not exercised for a while because the shipbuilder had not done that specific job for a few years, then the shipbuilder would need some refresher but would only have lost the skill of drilling a hole in a foundation but they would not have lost the skill of drilling holes. As a result, with a little bit of training, and through a robust knowledge management process, this would then yield a shipbuilder with the requisite knowledge to successfully complete this task. However, if the shipbuilder was asked to drill the holes into a specific pump foundation and several years has lapsed since the last time he or she has done that operation, then the shipbuilder would have to re-learn that specific skill. The researcher did not find any information in the public domain that discuss this three-tiered discussion on learning and loss of learning versus the type of required skill to complete a job. This specific research area was added to future research efforts.

In summary, a robust and integrated learning and knowledge management strategy across the shipbuilding enterprise would yield efficient learning such that that the knowledge management culture would be a learning enabler. Obviously, the lack of a defined learning and knowledge management culture would create a learning disruptor.

OLCC Learning Parameter – Demographic Environment (E)

- *LE:* Balanced Workforce Demographic
- *LD:* Skewed Workforce Demographic
- *Description of Parameter:* The demographic environment associated with low-rate production ships, and in this case, Class A Ships, was very diverse as indicated via the Class A assessment as presented in Table 11 and 12. Table 11 highlighted that the demographic was multi-faceted and included:
  - Personnel age distribution
  - Experience distribution
  - Experienced employees versus inexperienced
  - Workforce shortages
  - Workforce turnover

All of these elements directly impacted the demographics associated with a shipbuilder, in this case, the shipbuilder associated with designing and building Class A Ships.

- *Impacts to Learning:* The demographic environment would facilitate a learning enabler through a balanced workforce in terms of experience meaning that the experience and age demographics associated with the workforce were even and were more of a bell curve. This would include having an adequate number of mid-careers shipbuilders to learn from those that are nearing retirement age so that the highly experienced shipbuilders can pass on their knowledge. This learning enabler than allows for an environment that would be conducive to learning through the sharing of knowledge. A balanced profile would be contrasted with a demographic environment that did not support learning, which was why this situation was referred to as a learning disruptor. A shipbuilding demographic environment becomes a disruptor to learning when the workforce was skewed or even bi-modal in regards to experience and the associated age profiles for a given shipyard. A high workforce turnover or shortage would also be other causes for learning disruptors associated with a demographic environment. A skewed or bi-modal experienced workforce distribution inhibits the flow and sharing of knowledge between different shipbuilders especially to the next generation of leaders, both technical and craft/trade leaders. Having a large population of shipbuilders that were of retirement age followed by a small population of shipbuilders who were their near-term successors would be a concern and considered a disruptor to learning because there would not be enough shipbuilders to learn from the experienced shipbuilders. As such, from a low-rate production learning curve perspective, an understanding of the details associated with the demographic environment of a shipyard, and in this case Class A Ships, must be done to be able to assess learning in this low-rate production environment.

### WBS 11 - Validation of Class A Ship Data and Conclusions Using Class B Ship Data and Conclusions

In order to assess the conclusions derived from Class A Ships, Class B data and information gained from Class B Ships was assessed against Class A Ships. The Class B Ship data and information identified in the public domain was reflected via Table 14 along with the Class A Ship data and information to support a comparison of learning curve parameters between the two ship classes. This assessment was also reflected via Table 15. As such, to support this validation, conclusions derived from Class A Ships was shown with Class B Ship assessments via Table 15 to assist with the comparison and analysis.

| # | High Level Grouping | Parameters Affecting Learning | Source of Parameters | | | Class A (Figure) | Affects All Classes (Figure) | Class B (Figure) |
|---|---|---|---|---|---|---|---|---|
| | | | Mentions Learning and Mentions Shipbuilding | Mentions Learning but Does Not Mention Shipbuilding | Does Not Mention Learning but Does Mention Shipbuilding | | | |
| 1 | Company Experience and Capacity | Company Experience | - | - | - | - | - | - |
| 2 | | Competition | - | - | - | - | - | - |
| 3 | | Number of Ships Built Prior | - | - | - | - | - | - |
| 4 | | Number of Ships Built that were Similar | - | - | - | - | - | - |
| 5 | | Shipyard Capacity | - | - | Weisgerber (2021)<br>Clark (2021) | - | - | - |
| 6 | Changes | Requirements Changing | - | - | Abbott (1997) | 9<br>10 | - | 17<br>18<br>19<br>20 |
| 7 | | New or Immature Technology | - | - | Brimelow (2022)<br>Grazier (2021)<br>Lessig (2019) | - | - | - |
| 8 | | Requirements | - | - | - | 9<br>10 | - | 17<br>18<br>19<br>20 |
| 9 | | Specifications | - | - | - | - | - | - |
| 10 | | Material | - | - | - | - | - | - |
| 11 | | Changes | Miroyannia (2006) | - | Abbott (1997) | 9<br>10 | - | 17<br>18<br>19<br>20 |

Table 14: Class A Ship Key Factors Affecting Learning Validated by Using Class B Ship Assessments

| | | | Source of Parameters | | | | | |
|---|---|---|---|---|---|---|---|---|
| **#** | **High Level Grouping** | **Parameters Affecting Learning** | **Mentions Learning and Mentions Shipbuilding** | **Mentions Learning but Does Not Mention Shipbuilding** | **Does Not Mention Learning but Does Mention Shipbuilding** | **Class A (Figure)** | **Affects All Classes (Figure)** | **Class B (Figure)** |
| 12 | Changes (continued) | Requirements Instability | - | - | Abbott (1997) | 9<br>10 | - | 17<br>18<br>19<br>20 |
| 13 | | Number of Changes | - | - | Abbott (1997) | 9<br>10 | - | 17<br>18<br>19<br>20 |
| 14 | | Technology Insertions | - | - | Grazier (2021) | - | - | 17<br>18<br>19<br>20 |
| 15 | | Navy/Government Mandates | - | - | Capaccio (2020) | - | - | 17<br>18<br>19<br>20 |
| 16 | | Work Instruction Changes after Start of Construction | - | - | Grazier (2021) | - | - | 17<br>18<br>19<br>20 |
| 17 | Government Influences | Government Politics | - | - | Eckstein (2022)<br>Hooper (2022)<br>Katz (2022)<br>Shelbourne (2022)<br>Bergman (2020)<br>Perdue (2020)<br>Radelat (2020)<br>Tiron and Capaccio (2020)<br>Ress (2022)<br>Eckstein (2020)<br>Larter (2020)<br>Thompson (2019) | - | - | 17<br>18<br>19<br>20 |
| 18 | | Laws, Regulations | - | - | Ress (2022)<br>Eckstein (2020)<br>Larter (2020) | - | - | 17<br>18<br>19<br>20 |
| 19 | | Threat Assessments | - | - | Zengerle and Cowan (2022) | - | - | 17<br>18<br>19<br>20 |

Table 14 (continued)

| # | High Level Grouping | Parameters Affecting Learning | Source of Parameters | | | Class A (Figure) | Affects All Classes (Figure) | Class B (Figure) |
|---|---|---|---|---|---|---|---|---|
| | | | Mentions Learning and Mentions Shipbuilding | Mentions Learning but Does Not Mention Shipbuilding | Does Not Mention Learning but Does Mention Shipbuilding | | | |
| 20 | Industrial Base | Industrial Base Issues | Thompson (2019) | - | Limas-Villers (2022)<br>Clark and Walton (2020)<br>Eckstein (2020)<br>Ress (2020) | - | - | 17<br>18<br>19<br>20 |
| 21 | Information Maturity | Design Maturity at Construction Start | - | - | Grazier (2021) | 9<br>10 | - | 17<br>18<br>19<br>20 |
| 22 | | Technical Maturity at Construction Start | - | - | Grazier (2021) | 9<br>10 | - | 17<br>18<br>19<br>20 |
| 23 | | Degree of Design for Producibility | - | - | Schank et al (2016) | - | - | 17<br>18<br>19<br>20 |
| 24 | Commonality | Amount of Commonality Across the Ship and Class | - | - | Schank et al (2016) | - | - | 17<br>18<br>19<br>20 |
| 25 | Procurement Strategy | Budget | - | - | Limas-Villers (2022)<br>Ress (2022)<br>Talent (2021)<br>Connors (2020)<br>Eckstein (2020)<br>Perdue (2020) | - | - | 21 - 24<br>26 - 29 |
| 26 | | Acquisition Strategy | - | - | Osborn (2022)<br>Turner (2021)<br>Arena, Blickstein, Younossi, & Grammich (2006) | 11<br>13 | - | 21 - 24<br>26 - 29 |
| 27 | | Contract Strategy including Number of Contracts | - | - | Abbott (1997) | 8<br>11<br>13 | - | 21 - 24<br>26 - 29 |

Table 14 (continued)

| # | High Level Grouping | Parameters Affecting Learning | Source of Parameters | | | Class A (Figure) | Affects All Classes (Figure) | Class B (Figure) |
|---|---|---|---|---|---|---|---|---|
| | | | Mentions Learning and Mentions Shipbuilding | Mentions Learning but Does Not Mention Shipbuilding | Does Not Mention Learning but Does Mention Shipbuilding | | | |
| 28 | Procurement Strategy (continued) | Contract Impacts | - | - | Osborn (2022) | - | - | 21 - 24<br>26 - 29 |
| 29 | | Contract Strategy | - | - | Osborn (2022) | 11<br>13 | - | 21 - 24<br>26 - 29 |
| 30 | | Procurement Strategy (Multi-Year Procurement, Block Buy, Contract with Options) | - | - | Burgess (2022)<br>Decker (2022)<br>Capaccio (2020)<br>Katz (2021)<br>Weisberber (2021) | 8<br>11<br>13 | - | 21 - 24<br>26 - 29 |
| 31 | | Funding Strategy | - | - | Limas-Villers (2022)<br>Ress (2022)<br>Connors (2020)<br>Lessig (2016) | 11<br>13 | - | 21 - 24<br>26 - 29 |
| 32 | | Deisgn and Construction, Production Labor Hours | - | - | - | 7 | - | 16 |
| 33 | | Time Between Construction Starts | - | - | Lessig (2016) | 8<br>11 | - | 16 |
| 34 | Production Environment | Facilities | Miroyannia (2006) | - | - | - | - | - |
| 35 | | Tooling | - | - | - | - | - | - |
| 36 | | Number of Different Plants associated with Production | - | - | Fioretti (2007) | - | - | 17<br>18<br>19<br>20 |
| 37 | | Manufacturing Progress Function/Degree of Automation | - | - | - | - | - | 17<br>18<br>19<br>20 |
| 38 | | Make/Buy Decisions (Amount of Outsourcing) | - | - | - | - | - | - |

Table 14 (continued)

| # | High Level Grouping | Parameters Affecting Learning | Source of Parameters | | | Class A (Figure) | Affects All Classes (Figure) | Class B (Figure) |
|---|---|---|---|---|---|---|---|---|
| | | | Mentions Learning and Mentions Shipbuilding | Mentions Learning but Does Not Mention Shipbuilding | Does Not Mention Learning but Does Mention Shipbuilding | | | |
| 39 | Natural Disasters and Labor Strikes | Labor Strikes or Lay-offs | - | - | Fioretti (2007) | - | - | 17<br>18<br>19<br>20 |
| 40 | | Disasters | Baker, Degnan, Gabriel, Tucker (2001) | - | - | - | - | - |
| 41 | Training and Knowledge Management Strategies | Process Improvement & Lessons Learned Process | Miroyannia (2006) | - | Eckstein (2022)<br>Ennis, Dougherty, Lamb, Greenwell, and Zimmermann (1997) | - | - | - |
| 42 | | Training Strategy | Walpert (2001)<br>Lundquist (20210<br>Gagosz (2021)<br>O'Brien (2020) | Miller (2017)<br>Mishra, Henriksen, and Fahnoe (2013)<br>Di Stefano, Gino, Pisano, and Staats (2016) | - | - | - | - |
| 43 | | Knowledge Management Strategy | - | Di Stefano, Gino, Pisano, and Staats (2016)<br>Pappas (2014)<br>Ebbinghaus (1885)<br>Kohn (2014)<br>Meacham (2016)<br>Teichert (2010) | Abbott (2022)<br>Bloor et al (2016)<br>Schank et al (2016) | - | - | - |
| 44 | | Knowledge Retention | - | Pappas (2014)<br>Ebbinghaus (1885)<br>Kohn (2014)<br>Meacham (2016)<br>Teichert (2010) | X | - | 65<br>66<br>67 | - |
| 45 | | Time to Talent | Eckstein (2022)<br>Eckstein (2019)<br>Gagosz (2021)<br>O'Brien (2020)<br>Bloor et al (2016) | - | X | - | 65<br>66<br>67 | - |
| 46 | | Learning Styles, Techniques, Methods | Walpert (2001)<br>Lundquist (20210 | Di Stefano, Gino, Pisano, and Staats (2016) | X | - | - | - |
| 47 | | Lessons Learned Incorporation | Miroyannia (2006) | - | Ennis, Dougherty, Lamb, Greenwell, and Zimmermann (1997) | - | - | - |

Table 14 (continued)

| # | High Level Grouping | Parameters Affecting Learning | Source of Parameters | | | Class A (Figure) | Affects All Classes (Figure) | Class B (Figure) |
|---|---|---|---|---|---|---|---|---|
| | | | Mentions Learning and Mentions Shipbuilding | Mentions Learning but Does Not Mention Shipbuilding | Does Not Mention Learning but Does Mention Shipbuilding | | | |
| 48 | Company Organization | Production, Construction, Engineering, and Support Department Organization | - | - | Fioretti (2007) | 12 | - | 25 |
| 49 | | Procedures | - | Poleacovschi, Javernick-Will, Smith, and Pohl (2020) | Fioretti (2007) | - | - | - |
| 50 | | Staffing Strategy including Visibility of Expertise | - | Poleacovschi, Javernick-Will, Smith, and Pohl (2020) | - | 12 | - | 25 |
| 51 | | Output/Productivity (Hours Expended to Produce a Given Output) | Baker, Degnan, Gabriel, Tucker (2001) | - | - | - | 63<br>64 | - |
| 52 | | Work Mix/Labor Elements | - | - | Abbott (1997)<br>Limas-Villers (2022)<br>Lundquist (2021) | 12 | - | 25 |
| 53 | Learning | Reverse Learning or Forgetting Curve | Miroyannia (2006) | Pappas (2014)<br>Ebbinghaus (1885)<br>Kohn (2014)<br>Meacham (2016)<br>Teichert (2010) | Diekmann, Horn, & O'Conner (1982) | 7 | 65<br>66<br>67 | - |
| 54 | | Repetitive Learning | - | - | Diekmann, Horn, & O'Conner (1982) | - | - | - |
| 55 | | Loss of Learning | Miroyannia (2006) | Pappas (2014)<br>Ebbinghaus (1885)<br>Kohn (2014)<br>Meacham (2016)<br>Teichert (2010) | X | 7 | 65<br>66<br>67 | - |
| 56 | | Relative Efficiency of Learning | - | - | X | - | 65<br>66<br>67 | - |

Table 14 (continued)

| # | High Level Grouping | Parameters Affecting Learning | Source of Parameters | | | Class A (Figure) | Affects All Classes (Figure) | Class B (Figure) |
|---|---|---|---|---|---|---|---|---|
| | | | Mentions Learning and Mentions Shipbuilding | Mentions Learning but Does Not Mention Shipbuilding | Does Not Mention Learning but Does Mention Shipbuilding | | | |
| 57 | Demographics | Personnel Age Distribution | Baker, Degnan, Gabriel, Tucker (2001) | - | Arena, Blickstein, Younossi, & Grammich (2006)<br>Eckstein (2021)<br>Gagosz (2021) | - | 59<br>60<br>61<br>62<br>63<br>64 | - |
| 58 | | Experience Distribution | McLeary (2020)<br>Eckstein (2019)<br>Thompson (2019)<br>Bloor et al (2016) | - | Arena, Blickstein, Younossi, & Grammich (2006)<br>Bloor et al (2016)<br>Ress (2021) | - | 59<br>60<br>61<br>62 | - |
| 59 | | Demographics | - | | Arena, Blickstein, Younossi, & Grammich (2006)<br>Limas-Villers (2022)<br>Lundquist (2021) | - | 59<br>60<br>61<br>62 | - |
| 60 | | Lack of Adequate & Experienced Employees | - | - | Lima-Villers (2022)<br>Ress (2021)<br>Lundquist (2021) | - | - | - |
| 61 | | Workforce Shortages | Baker, Degnan, Gabriel, Tucker (2001) | - | Lima-Villers (2022) | - | 63<br>64 | - |
| 62 | | Workforce Turnover | Baker, Degnan, Gabriel, Tucker (2001) | - | Weisgerber (2021)<br>Eckstein (2022) | - | 63<br>64 | - |
| 63 | Ship Complexity | Ship Construction Density, Ship Complexity, Design Complexity, and Complexity Associated with Ship Operations | - | - | Schank et al (2016)<br>Terwilliger (2015)<br>Gaspar, Ross, Rhodes, and Erickstad (2012)<br>Grant (2008)<br>Arena, Blickstein, Younossi, and Grammich (2006) | - | - | - |

Table 14 (continued)

| # | High Level Grouping | Parameters Affecting Learning | Source of Parameters | | | Class A (Figure) | Affects All Classes (Figure) | Class B (Figure) |
|---|---|---|---|---|---|---|---|---|
| | | | Mentions Learning and Mentions Shipbuilding | Mentions Learning but Does Not Mention Shipbuilding | Does Not Mention Learning but Does Mention Shipbuilding | | | |
| 64 | Stability and Predictability | Workforce Instability | Baker, Degnan, Gabriel, Tucker (2001) | - | Lima-Villers (2022) | - | 63<br>64 | - |
| 65 | | Instability in the Number of Ships and Navy's Procurement Plans | - | - | Abott (2022)<br>Eckstein (2022)<br>Grady (2022)<br>Limas-Villers (2022)<br>Axe (2021)<br>Katz (2021)<br>Turner (2021)<br>Weisgerner (2021)<br>Bergman (2020)<br>Connors (2020)<br>Fabey (2020)<br>Radelat (2020)<br>Arena, Blickstein, Younossi, & Grammich (2006)<br>Reed and Inhofe (2021) | - | - | - |
| 66 | | Predictability & Stability Associated with Future Work | - | - | Katz (2021)<br>Clark (2021)<br>Reed and Inhoe (2021) | - | - | - |

Table 14 (continued)

From a validation perspective of using Class B Ship data to validate Class A results, Table 14 showed that the Class B assessment yielded the same factors impacting learning in low-rate production environments as the Class A assessment delineated via Table 12. Further analyzing Table 14 revealed that the Class B Ships' key factors affecting learning provided two additional secondary parameters characterizing the labor workforce by major system and the labor elements associated with non-production labor; however, an analogous assessment for

Class A Ships did not exist in the public domain. These two items did not alter the OLCC developed using the Class B Ship information, but to be thorough, was noted accordingly. Utilizing the Class B Ship information to determine the key factors affecting learning and comparing that information to the Class A Ship key factors affecting learning validated that the characterization developed based on factors using Class A Ships was applicable to Class B Ships.

Next, utilizing the Class B Ship assessment, the researcher developed conclusions based on Ship Class B, and then compared the Ship Class B's conclusions (Table 15) to Ship Class A's conclusions (Table 12) to validate Ship Class A. Per the research methodology, the results were captured via Table 15, and the associated conclusions deduced follows Table 15.

| **#** | **Class A Ships** | | **Key Parameters and Conclusions Affecting Learning Curves for Class B Ships** | | | **Class B Ships Validation of Class A Ships Valid or Invalid** |
|---|---|---|---|---|---|---|
| | **Figure** | **Parameter Represented** | **Figure** | **Results of Analysis (See Note 1)** | **Deductions/Conclusions Associated with Learning** | |
| 1 | 8 | Major Ship Construction Milestones | 16 | All 4 Shipyards: 2nd Ship that each on one produced took the longest time.<br>Alpha Shipyard: 2nd Ship had the most number of months between delivery dates.<br>Beta & Gamma Shipyards: Ship with the fewest number of months between delivery dates had fewest hours to build.<br>Delta Shipyard: Increasing months and hours to build. 1st Ship for them, but 8th Ship of the Class, had fewest hours & duration. | For Beta, Gamma, & Delta Shipyards, less time between delivery dates correlates to less labor hours.<br>In terms of the best milestone performances per Shipyard:<br>Alpha: Their 3rd Ship, which was the last one.<br>Beta & Gamma: 2nd to last Ship had best milestone performance, which was their 3rd Ship.<br>Delta: Their 1st Ship.<br>There is an optimum number of months between delivery dates that correlates to fewer hours to support design, construction, and delivery of low-rate production ships. This optimum number is a range of months, and it is an enabler to learning and knowledge retention and is ship class dependent.<br>Multi-ship procurements reduces production durations because, in part, learning and knowledge retention are more easily facilitated then single ship procurements.<br>Multi-ship procurements resulted in shorter durations from the major ship milestone of keel laying to delivery.<br>The less time between contract awards, even for single source procurements, then the fewer hours required to build the ship as compared to the previous ship. | VALID |
| 2 | 9 | Cumulation of Significant Changes | 17<br>19 | Increasing number of changes across the ship class except for the 1st 3 Ships as well as Ship 6 & Ship 8.<br>This increase was for the entire ship class as well as with each of the 4 Shipyards. | The hours to build each ship, regardless of the Shipyard, showed an increase in hours to build with an increase in the number of changes.<br>The accumulation of significant changes and requirements increases the labor hours to build each ship of a class associated with low-rate production manufacturing.<br>An environment associated with continual change results in a level of instability which is a disruptor in regards to learning. | VALID |
| 3 | 10 | Significant Changes Compared to Previous Ship | 18<br>20 | This increase was for the entire ship class as well as with each of the 4 Shipyards.<br>Alpha Shipyard: Zero changes on the their 2nd Ship but hours rose by 5%. Other ships shows an increase in hours with increasing changes.<br>Beta Shipyard: Increase in changes on their 2nd Ship but a 3% decrease in hours. Other ships shows an increase in hours with increasing changes.<br>Gamma Shipyard: Increase in changes on their 2nd Ship but a 6% decrease in hours. Other ships shows an increase in hours with increasing changes.<br>Delta Shipyard: Increase in changes shows on their 2nd Ship and an increase of 7% in hours. Other ships shows an increase in hours with increasing changes. | The hours to build each ship, regardless of the Shipyard, showed an increase in hours to build with an increase in the number of changes, except for the 2nd Ship of the Alpha, Beta, and Gamma Shipyards.<br>If there are no significant changes from the previous ship or fewer changes compared to the previous ship, then there is a reduction in hours to build that ship. Fewer or no changes compared to the previous ship provides a more stable environment for learning.<br>The number of changes affects the number of hours to build each ship which directly impacts the amount of new information that has to be learned from ship to ship. | VALID |

Table 15: Validation of Ship Class A Conclusions Using Ship Class B Conclusions

| # | Class A Ships | | Key Parameters and Conclusions Affecting Learning Curves for Class B Ships | | | Class B Ships Validation of Class A Ships Valid or Invalid |
|---|---|---|---|---|---|---|
| | Figure | Parameter Represented | Figure | Results of Analysis (See Note 1) | Deductions/Conclusions Associated with Learning | |
| 4 | 11 | Procurement Strategy | 21<br>22<br>23<br>24 | Alpha Shipyard: 3 single Ship procurements with 7 years between last 2 Ships. Beta Shipyard: 2 single Ship procurements with 2 years between. 1 - 2 Ship procurement for their 1st 2 Ships then 6 years to the 2 single Ships. Gamma Shipyard: 2 single Ship procurements with 3 years between. 1 - 2 Ship procurement for their 1st 2 Ships then 5 years to the 2 single Ships. Delta Shipyard: 3 single Ship procurements with 1 year between the 1st 2 Ships and 2 years for the last one. | Ship 4 (2nd Beta Ship), Ship 5 & 7 (2nd & 3rd Gamma Ship), and Ship 10 (2nd Delta Ship) shows an increase in changes but a decrease in hours. This is due to the fact that the ships built during this time frame had the fewest months between major milestones such that learning effects were more possible. 2 Ship buys results in fewer labor hours to build each ship especially for the 2nd Ship of the 2 Ship buy even if there is an increase in changes. (Ships 4 & 5) Alpha Shipyard: No changes to the 2nd Ship, 56 months between deliveries & 5% increase in hours. 3rd Ship - lot of changes, less months between deliveries but 94% increase in hours. Beta Shipyard: 2nd Ship of 2 Ship buy with 23 months between deliveries was delivered for fewer hours while accommodating more changes. Gamma Shipyard: Benefitted from 2 Ship Buy with fewer hours, changes, & 13 months between deliveries. 3rd Ship started 5 years later increasing labor hours. Delta Shipyard: 2nd Ship addressed changes & only had 16 months between deliveries; 7% increase in hours.<br>2 Ship Buy & minimizing time between deliveries (~29 months or less) is enabler to learning. There is some variability b/w Shipyards in regards to which OLC parameter that has a larger influence.<br>Multi-ship procurement strategies increases the probability that learning will be shared between those ships. Multi-procurements results in fewer hours to build each ship, and can offset the impact of changes as compared to the previous ship. | VALID |
| 5 | 12 | Principal Production Labor Elements | 25 | Includes both production and non-production, so had to normalize to production to be able to compare to Class A Ships. May have some terminology differences. As such, labor elements that constitute more than 5% of the total are: Electrical, Mechanical, Painting, Production Support, Steelwork, Welding. | This equates to 98% of the production labor. The targeted learning and knowledge retention should address all areas but especially these 6 areas.<br>These 6 areas will also have the largest influence on the labor hours expended for each ship.<br>Data does not exist in the public domain providing the hours spent per year per ship.<br>Low-rate production shipbuilding is accomplished by principal production labor elements; as such, in order to develop a knowledge management culture, learning strategies that are developed must include these labor elements supporting low-rate production shipbuilding. | VALID |

Table 15 (continued)

| # | Class A Ships | | Key Parameters and Conclusions Affecting Learning Curves for Class B Ships | | | Class B Ships Validation of Class A Ships Valid or Invalid |
|---|---|---|---|---|---|---|
| | **Figure** | **Parameter Represented** | **Figure** | **Results of Analysis (See Note 1)** | **Deductions/Conclusions Associated with Learning** | |
| 6 | N/A | Principal Non-Production Labor Elements | 25 | Includes both production and non-production, so had to normalize to non-production. As such, labor elements that constitute more than 5% of the total are: Administration, Support, Engineering, and Management. | This equates to 100% of the non-production labor. The targeted learning and knowledge retention should address all areas.<br>These areas will also have the largest influence on the non-production labor hours expended for each ship.<br>Data does not exist in the public domain providing the hours spent per year per ship.<br>Low-rate production shipbuilding is accomplished by principal non-production labor elements; as such, in order to develop a knowledge management culture, learning strategies that are developed must include these labor elements associated with low-rate production shipbuilding. | VALID |
| 7 | 13 | Funding Profiles and Strategy | 26<br>27<br>28<br>29 | Funding for Ships 1 through 6 was fairly consistent.<br>Ships 2 & 4 as well as Ships 3 & 5 were 2 Ship Buys with the 2nd Ship of each requiring less funding.<br>Ships 7 & 8 increased but were fairly consistent. Ship 9 saw an additional increase but Ship 10 was close to Ships 7 & 8.<br>Ships 11 through 14 shows additional increase with Ships 11 & 14 being the most expensive. | As covered via Item 4, one of the Ships with the longest duration between deliveries and required the 2nd most hours to build was Ship 11.<br>Ship 14 was the last Ship of the Class and required the most hours to build. It did not have the most changes but was one of the longest between ship deliveries indicating the time between deliveries impacts learning more than the number of changes.<br>The funding profiles and subsequent funding strategies are determined and developed by the customer which are not optimized to support and/or accommodate the shipbuilder thereby impacting the ability to maximize learning in low-rate production shipbuilding.<br>Time between deliveries and/or contract award dates has a greater influence on learning than the number of changes for low-rate production ships. | VALID |
| 8 | 59 | Shipbuilding Age Demographics - 2020 | 59 | Almost 50% are of retirement age or within 10 years of retirement age.<br>Only 23% are the next leaders within Shipbuilding (35 to 44 age demographic.<br>Approximately 28% are inexperienced (age 34 and younger). | In regards to knowledge management and learning, a concerted effort must occur to capture the shipbuilders that are retirement age to prepare the next set of leaders and to help the new hires move up their learning curve as efficiently as possible.<br>The demographic environment directly impacts learning and the knowledge management culture of low-rate production shipbuilding. Utilizing the referenced 2020 demographic data, the large number of shipbuilders that are within ten years of retirement, as compared to previous years, is a learning disruptor because the bi-modal distribution of experience as well as a large percentage of shipbuilders that are close to retirement inhibits knowledge transfer which negatively affects learning. The Class A Ships were built in the United States whereas the Class B Ships were built in England. The Class A Ships were built and delivered before 2020; as such, this demographic data set is not applicable to the Class A Ships. As a matter a fact, only the Class D Ships would be applicable to this demographic data set. Due to the nature of the data for this conclusion, only Class D Ships can validate this information. | N/A<br>2020 Demographics for Class D Ships |

Table 15 (continued)

| # | Class A Ships | | Key Parameters and Conclusions Affecting Learning Curves for Class B Ships | | | Class B Ships Validation of Class A Ships Valid or Invalid |
|---|---|---|---|---|---|---|
| | **Figure** | **Parameter Represented** | **Figure** | **Results of Analysis (See Note 1)** | **Deductions/Conclusions Associated with Learning** | |
| 9 | 60 | Shipbuilding Age Demographic - 1999 | 60 | Approximately one-half the number of shipbuilders compared to 2020.<br>Up to as much as 27% are retirement eligible or are within 4 years.<br>At least 13% are inexperienced plus some percentage of the 31 - 40 age demographic are also inexperienced. | In regards to knowledge management and learning, a concerted effort must occur to capture the shipbuilders that are retirement age to prepare the next set of leaders and to help the new hires move up their learning curve s efficiently as possible.<br>In regards to the 1999 demographic data, only some of the Class A Ships were built during this time frame.<br>The demographic environment directly impacts learning and the knowledge management culture of low-rate production shipbuilding. Utilizing the referenced 1999 demographic data, there were one half the number of shipbuilders as compared to the 2020 demographic data, and the demographic distribution is a skewed bell curve reflective of a more experienced workforce. With this distribution, the transfer of knowledge, and as a result, learning is more enabled compared to the 2020 demographic data. | N/A<br>1999 Demographics for Class A & C Ships |
| 10 | 61 | Shipbuilding Age Demographic - 1980 | 61 | 44% are retirement age are within 10 years of retirement.<br>37% are inexperienced.<br>Only 20% are the next future leaders of shipbuilding (35-44 age demographic.) | In regards to knowledge management and learning, a concerted effort must occur to capture the shipbuilders that are retirement age to prepare the next set of leaders and to help the new hires move up their learning curve s efficiently as possible.<br>Only this demographic data is applicable to Class A and B Ship data. In regards to 1980, for Ship Class A, Ship 3 was within 2 years of delivery and Ship 4 had just started. Despite having a large percentage of inexperienced labor, Ship 4 was the start of delivering ships for less hours for the next 4 ships.<br>The demographic environment directly impacts learning and the knowledge management culture of low-rate production shipbuilding. Increasing the number of low-rate production ships is a learning enabler to assist with offsetting a demographic environment with a bi-modal age distribution and/or a demographic environment with a skewed retirement age distribution. | VALID |
| 11 | 63 | Employee Work Output for Shipbuilding and Repair | 63 | US Shipbuilding output increased by 45% over 20 years.<br>This is across all US shipbuilding and repair and not just low rate production.<br>Shows a slight rise in output in 1982, 1984, 1990, and 1998 with lows in 1987 and 1993. | The increase in outputs as well as the decrease in outputs appears during 2 Ship procurement time frames as well as 1 Ship procurement time frames. They also occur during times frames that had shorter times between deliveries as well as longer times too. As such, deductions and conclusions cannot be made in regards to the factors impacting shipbuilding based on Class A Ship data. However, Baker, Degnan, Gabriel, Tucker (2001) offers some explanations, which are delineated with this this Chapter. The employee work output for US shipbuilders has grown by forty-five percent over a twenty-year period from 1977 to 1998 (Baker, Degnan, Gabriel, and Tucker (2001)); however, this increase in work output is not attributable to ship procurement time frames or multi-ship procurement strategies, but rather, it is due to the learning characterization for each shipyard such as the organizational culture and the demographic environment. | VALID |

Table 15 (continued)

<table>
<tr><th rowspan="2">#</th><th colspan="2">Class A Ships</th><th colspan="3">Key Parameters and Conclusions Affecting Learning Curves for Class B Ships</th><th rowspan="2">Class B Ships Validation of Class A Ships Valid or Invalid</th></tr>
<tr><th>Figure</th><th>Parameter Represented</th><th>Figure</th><th>Results of Analysis (See Note 1)</th><th>Deductions/Conclusions Associated with Learning</th></tr>
<tr><td>12</td><td>64</td><td>Employee Work Output for Automotive and Aircraft Industries</td><td>64</td><td>US automotive and aircraft output increased by 120% and 85%, respectfully.<br>The automotive industry showed rises in output in 1983, 1989, 1994, and 1998 with lows in 1980, 1987, and 1995.<br>The aircraft industry showed rises in output in 1980, 1985, 1992, and 1998 with lows in 1982, 1984, 1989, and 1996.</td><td>Only 1998 shows a rise in output for shipbuilding, automotive, and aircraft industries.<br>None of the other years during this twenty year time frame in terms of yearly increases or decreases (except 1998).<br>The aircraft and automotive industries has an output per employee that is more than a factor of 4 per employee output for shipbuilding and repair. The aircraft and automotive industries has an output per employee that is more than the output per employee output compared to the shipbuilding industry. The difference in output per employee is due to the differences in their production environments (i.e., low-rate versus high-rate production) which is impacted by their overall learning characterizations between low-rate production and high-rate production environments.</td><td>VALID</td></tr>
<tr><td>13</td><td>65<br>66</td><td>Memory Retention</td><td>65<br>66</td><td>In a day after learning a new skill without any refreshers or review, most people will only retain about 20 to 30% of what they learned.<br>In a month after learning a new skill without any refreshers or review, most people will only retain about 10 to 15% of what they learned.</td><td>All aspects of low rate production does not support knowledge retention due to the cadence of ship production associated with this environment. Certain specific shipbuilding skills will be completed daily, like basic skills associated with each labor element, but applying those skills to specific ship evolutions that occur only once every x years will result in the loss of how to complete that specific job due to reverse learning/loss of learning that skill for that specific job. Programs must be put in place to increase knowledge retention.<br>Most people after learning a new skill will only retain ten to fifteen percent of the knowledge that they learned after a month has transpired without any refreshers. As such, low-rate production environments that entail not using skills frequently increases the challenges associated with knowledge retention and learning.</td><td>VALID</td></tr>
<tr><td>14</td><td>67</td><td>Relative Efficiency vs Experience</td><td>67</td><td>For shipbuilding, it takes at least 4 years for a shipbuilder to obtain 80% efficiency.<br>After 1 year, a shipbuilder is only 50% efficient.<br>It takes over 15 years to achieve 100% efficiency.</td><td>The low rate production environment of shipbuilding increases the challenges associated with shipbuilder efficiency due to knowledge retention issues.<br>Programs must be put in place to support shipbuilder efficiency also referred to as time to talent.<br>The low-rate production environment of shipbuilding increases the challenges associated with shipbuilder efficiency due to knowledge retention issues.</td><td>VALID</td></tr>
</table>

Table 15 (continued)

As indicated, the results of WBS 11 were captured via Table 15, and the associated deductions were delineated herein next including the validation results.

## Key Parameter #1: Major Ship Construction Milestones

### Conclusion #1-1: Optimum Number of Months between Deliveries

- *Conclusion:* There is an optimum number of months between delivery dates that correlates to fewer hours to support design, construction, and delivery of low-rate production ships. This optimum number is a range of months, and it is an enabler to learning and knowledge retention and is ship class dependent.
- *Adjudication:* Three of the four shipyards associated with Class B Ships supported this conclusion associated with Class A Ships in regard to this parameter, Major Ship Construction Milestones. For Class A Ships, the optimum range of years between delivery dates was two and a half to three and a half years while for Class B Ships, the optimum range of years between delivery dates was one to two years. This conclusion was derived from Class A Ships and validated by the data and conclusions associated with Class B Ships.
- *Validation:* **Valid**

### Conclusion #1-2: Multi-Ship Procurements Reduces Production Durations

- *Conclusion:* Multi-ship procurements reduces production durations because, in part, learning and knowledge retention are more easily facilitated then single ship procurements.
- *Adjudication*: This conclusion was based on the relationship between schedule milestones and procurement strategies. For Class A Ships, Ship 4 was delivered in the fewest number of months followed by Ships 5, 7, and 1. This was, in part, due to build strategy changes and two ship buys enabling learning retention for these ships. For Class

B Ships, Ship 11 was delivered in the fewest number of months followed by Ships 7, 9, and 5, due, in part, to two ship buys enabling learning. This conclusion was derived from Class A Ships, and validated by the data and conclusions associated with Class B Ships.

- *Validation:* **Valid**

Conclusion #1-3: Multi-ship Procurements Results in Shorter Durations from Keel to Delivery

- *Conclusion:* Multi-ship procurements resulted in shorter durations from the major ship milestone of keel laying to delivery.
- *Adjudication:* This conclusion was based on the relationship between schedule milestones and procurement strategy and was a sub-set of Conclusion #1-2. For Class A Ships, two ship buys contributed to shorter duration from keel to delivery, which enabled learning and supported a learning culture thereby contributing to less hours to build a ship. This was also valid for Class B Ships. This conclusion was derived from Class A Ships, and validated by the data and conclusions associated with Class B Ships.
- *Validation:* **Valid**

Conclusion #1-4: Time Between Contract Awards Affects Labor Hours to Build as Compared to the Previous Ship

- *Conclusion:* The less time between contract awards, even for single ship procurements, then the fewer hours required to build the ship as compared to the previous ship.
- *Adjudication:* For Class A Ships, the shorter the duration between contract award dates for single ship procurements and two ship procurements resulted in fewer hours to construct each ship. For Class B Ships, as the number of months between contract

awards increased, so did the number of hours to build each ship. This was valid for three of the four shipyards. The Gamma Shipbuilder showed a decrease in the number of months between the third and fourth ships that they built, but an increase in the number of hours to deliver the fourth ship that the Gamma Shipbuilder delivered to their customer. This conclusion was derived from Class A Ships, and validated by the data and conclusions associated with Class B Ships.

- *Validation:* **Valid**

**Key Parameter #2: Cumulation of Significant Changes**

<u>Conclusion #2-1: Requirements Stability, or Instability, Impacts the Labor Hours to Build the Ship Class</u>

- *Conclusion:* The accumulation of significant changes and requirements increases the labor hours to build each ship of a class associated with low-rate production manufacturing.
- *Adjudication:* For Class A Ships, Ship 2 had the fewest number of changes and required the fewest hours to deliver. This stability in requirements enabled learning from the previous ship to be applied to Ship 2. For Class B Ships, Ship 5 required the fewest hours to deliver, and it did have changes, but it was the second ship of a two ship buy offsetting the effects of the changes. The next series of Class B ships that had the fewest hours to build also did not have any changes associated with them, and they were Ships 3, 1, and 6. This conclusion was derived from Class A Ships, and validated by the data and conclusions associated with Class B Ships.
- *Validation:* **Valid**

Conclusion #2-2: Requirements Instability is a Disruptor to Learning

- *Conclusion:* An environment associated with continual change results in a level of instability which is a disruptor in regards to learning.
- *Adjudication:* Low-rate production environments usually yielded an environment with a high degree of change usually due to the long build durations which resulted in the customer trying to insert changes throughout the build duration. The net effect of this was an unstable baseline impacting ship over ship learning. For Class A Ships, other than Ship 2, the class experienced an increasing number of changes and the trend line for the labor hours required to build each ship also showed an increasing trend line too. For Class B Ships, the number of changes continued to grow through the ship class even though five of the fourteen Class B Ships did not have any significant changes. Even though these five ships did not have any documented significant changes, there impacts were still realized throughout the ship class. This conclusion was derived from Class A Ships, and validated by the data and conclusions associated with Class B Ships.
- *Validation:* **Valid**

**Key Parameter #3: Significant Changes Compared to Previous Ship**

Conclusion #3-1: Fewer or No Changes Compared to the Previous Ship Provides a More Stable Environment for Learning

- *Conclusion:* If there were no significant changes from the previous ship or fewer changes compared to the previous ship, then there was a reduction in hours to build that ship. Fewer or no changes compared to the previous ship provided a more stable environment for learning.

- *Adjudication:* For Class A Ships, only one ship, which was Ship 2, did not have any significant changes, and it took fewer hours to build. However, for Class B Ships, five ships of the class did not have any significant changes, which were the first three ships as well as Ship 6 and Ship 8, but two of those ships showed an increase in hours to build. For Class B Ships one of the ships had no changes but the hours to build rose by five percent, which was negligible. Two of the shipyards had one ship with an increase in changes but a decrease in hours to build. All of the other ships built by the four shipyards showed an increase in changes yielding an increase in hours to build each ship. This conclusion was derived from Class A Ships, and validated by the data and conclusions associated with Class B Ships.
- *Validation:* **Valid**

### Conclusion #3-2: Changes Increases New Information that has to be Learned

- *Conclusion:* The number of changes affects the number of hours to build each ship which directly impacts the amount of new information that has to be learned from ship to ship.
- *Adjudication:* This conclusion was focused on an assessment of each of the previous Ships associated with the entire Ship Class as well as incorporating the elements associated with learning as delineated by Table 12 Items 13 and 14, the memory retention parameter, and relative efficiency vs experience parameter. As was validated in support of Conclusions' #2-1 and #3-1, an increase in changes as compared to the previous ship results in more hours to build that ship. This was simply due to the fact that the areas of the ship that were impacted by the changes were new areas which have to be learned thereby negating the learning that had occurred previously. Factoring the memory

retention and relative efficiency versus experience parameters into these yielded reverse learning in these areas due to changes. As such, in areas of the ship that have experienced changes as compared to the previous ship, reverse learning not only was comprised of forgetting how a specific area of the ship was built due to the number of months or even years since that area of the ship was last constructed, but reverse learning was also impacted by having to un-learn how that area of the ship was built due to the new changes associated with that specific ship. This phenomenon was applicable to all classes of ships including Class A, B, C, and D Ships. This conclusion was derived from Class A Ships, and validated by the data and conclusions associated with Class B Ships.

- *Validation:* **Valid**

**Key Parameter #4: Procurement Strategy**

<u>Conclusion #4-1: Multi-Ship Procurements Increase the Opportunity Associated with Learning</u>

- *Conclusion:* Multi-ship procurement strategies increases the probability that learning will be shared between those ships associated with the multi-ship procurement.
- *Adjudication:* Four of the Class A Ships, Ships 5 and 6 as well as Ships 7 and 8, and four of the Class B Ships, Ships 2 and 4 as well as Ships 3 and 5, were procured via two ship buys. Two ship or multi-ship procurements increase the probability that learning was shared between the ships that were a part of the multi-ship procurement. This conclusion was derived from Class A Ships, and validated by the data and conclusions associated with Class B Ships.
- *Validation:* **Valid**

Conclusion #4-2: Two Ship Procurements results in Fewer Hours to Build and Deliver the Second Ship, and can Offset the Impact of Changes

- *Conclusion:* Two ship or multi-procurement buys results in fewer hours to build each ship especially for the second ship of a two ship buy, and can offset the impact of changes as compared to the previous ship. This procurement strategy is a learning enabler.
- *Adjudication:* Two ship or multi-ship procurement buys positively impacted a shipyard in a number of ways. For Class B Ships, the second ship of a two ship buy not only was a learning enabler for the second ship of the two-ship buy resulting in less hours to build the second ship as compared to the first ship, but these two ships also experienced changes compared to the previous ship. The two-ship buy for Class B Ships then offset the additional hours needed due to these changes. For Class A Ships, an increase in the number of changes, except for Ship 5 and Ship 7, corresponded to an increase in the number of hours to build. These two ships were the first ship of a two ship buy, and they took fewer hours to build compared to the previous ship that shipyard built but had more changes. This was attributed to the shorter durations between ship deliveries. For class B Ships, an increase in the number of changes, except for Ships 6, 7, 12, 13, 14, corresponded to an increase in the number of hours to build. For these ships, they had fewer changes than the previous ship built at their respective shipyard, but they required more hours to build. These ships had longer durations between ship deliveries. As such, durations between ship deliveries affected the number of hours to build Class A and Class B Ships, and they impacted the ability to accommodate changes. Less time between deliveries reduced the amount of learning that was lost thereby allowing a shipyard to be

able to address changes in a more efficient manner from a learning characterization perspective. This conclusion was derived from Class A Ships, and validated by the data and conclusions associated with Class B Ships.

- *Validation:* **Valid**

Conclusion #4-3: Each Ship Class will have an Optimum Range of Months between Delivery Dates

- *Conclusion:* Each ship class will have an optimum range of months between delivery dates that enables learning between each low-rate production ship designed, built, tested, and delivered to its' respective customer. This optimum range of months is also impacted by other factors such as capacity, available footprint, current workload, and so on. These additional factors are outside the scope of this research because more detailed company or agency specific information would be required, which is proprietary information.
- *Adjudication:* Ships with delivery dates that were closer together support learning being transferred from one ship to the next more effectively than ships that have longer durations between ship deliveries. For Class A Ships, ships with delivery dates that were within 3.4 years or less from the previous ships showed a reduction in labor hours to support delivery of that ship. This was a learning enabler by reducing the time between completing similar tasks associated with designing and building a ship especially compared to durations longer than 3.4 years. For Class B Ships, this fact was also valid. The optimum time frame was different since Class B Ships were a different ship class compared to Class A Ships, obviously. As indicated, there were multiple factors

impacting the optimum time between deliveries that maximized learning transfer and knowledge management. This conclusion was derived from Class A Ships, and validated by the data and conclusions associated with Class B Ships.

- *Validation:* **Valid**

Conclusion #4-4: Multi-ship Procurements Coupled with Minimizing Time between Deliveries Reduces Labor Hours.

- *Conclusion:* Multi-ship procurements coupled with minimizing time between deliveries enables learning and knowledge transfer thereby reducing labor hours to support construction and delivery of low-rate production ships. Each ship class exhibits an optimum range of the number of ships associated with a multi-ship procurement as well as an optimum range of the number of months between successive deliveries.
- *Adjudication:* Class A Ships and Class B Ships both benefited through fewer hours required to support construction and delivery on those ships that had two ship buys as well as minimized the time between deliveries. Class A Ships had two – two-ship buys with both resulting in fewer hours to construct the second ship of the two-ship buy. The same conclusion was deduced from Class B Ships thereby validating this conclusion. For both of these classes of ships, there were only single ship procurements or two ship procurements. As such, regarding the optimum number of ships that constitute a reduction in the labor hours, for Class A and B Ships, the only deduction that can be made was two ships. This conclusion was derived from Class A Ships, and validated by the data and conclusions associated with Class B Ships.
- *Validation:* **Valid**

### Conclusion #4-5: Multiple Ship Procurement Contracts are Executed via Three Different Approaches with Each Reflecting Different Milestone Durations

- *Conclusion:* Multiple ship procurement contracts are executed in series, in parallel, or in a hybrid strategy resulting in milestones based on a contract award date which does not reflect actual ship delivery durations**.**
- *Adjudication:* Multiple ship procurement contracts were either executed in one of three strategies:
    - in series,
    - in parallel, or
    - a hybrid strategy whereby some ship construction milestones were obtained in series while others were obtained in parallel.

The execution of which strategy was based on many factors; however, for the purposes of this research, an understanding of the strategy utilized for each procurement contract as well as the subsequent construction strategy should be assessed accordingly because each strategy would impact learning differently. A multiple ship procurement strategy whereby the execution was done in series would have less knowledge transfer and learning as compared to a strategy whereby the low-rate production ships were constructed in parallel. Conversely, a hybrid construction strategy where some of the ship's milestones were obtained via parallel construction and some of the ship's milestones were obtained via series construction would result in learning and knowledge transfer to occur more than the series construction but not as much as the parallel construction strategy. There does not exist enough information in the public domain to be able to assess the degree or amount of influence these different approaches had on learning in low-rate production environments. As such, additional research in this area would only be able to occur within each company or agency as the resulting required information to perform this assessment would be proprietary to that specific company or agency. Regardless, for the purposes of this research, an understanding of these three strategies would at least provide context for the learning resident within each approach, and it also provided insights into the context for each ship construction milestone as they relate to contract award for that specific multiple ship procurement.

For multiple ship procurements, the contract award date was the same for all ships within that specific contract. As such, without understanding the details associated with this procurement, the follow-on ships after the first ship of the contract could appear to take longer to build if they were all measured off of the contract award date for all of the ships affiliated with that specific contract. This exact issue was identified by the researcher for all four ship classes affiliated with the research contained herein. For Class A Ships, the second ship of both two ship procurements “artificially” [researcher’s quotes] showed that the second ship takes longer to build based on the contract award date. However, this was not the case because the second ship of the two ship procurements that occurred for Class A Ships started construction after the first ship. Data in the public domain does not provide the actual start of construction date for the second ship of the two ship buys for Class A Ships. Utilizing the data in the public domain for Class A Ships, the first ship of the two ship buy for Ships 5 and 6 took eighty-two months to build while the second ship of the two ship buy would have taken one-hundred and fourteen months to build based on the contract award date accordingly. The same was also valid for Ship 7 and 8 for the Class A Ships. Using data in the public domain, Ships 7 and 8 took eighty-nine and one-hundred and twenty months to build respectfully, again based on the contract award date for Ships 7 and 8 for Class A Ships. It took fewer hours to build the second ship of these two ship contracts which would equate to shorter construction times.

Similar to Class A Ships, Class B Ships also validated this same conclusion. For the Beta Shipbuilder, Ships 2 and 4 were a two-ship procurement as well as Ships 3 and 5 for the Gamma Shipbuilder. Utilizing the contract award date, the number of months from contract award to delivery increased by twenty-three months for the second ship of the two-ship buy for the Beta Shipbuilder, and twelve months for the Gamma Shipbuilder. As was the case for the Class A Ships, the second ship of both two ship procurements were delivered more cost effectively then the first ship. Again, as has been discussed, there was not enough information in the public domain to understand which build strategy was employed for the second ship of the two-ship buy; however, Class B Ships validated the conclusion that the second ship of a two-ship buy does not take longer to build despite not having the actual number of months to build the second ship of a two-ship buy because that level of data did not exist in the public domain.

As such, in conclusion, the second ship of a two-ship buy appeared to take longer to build, but it did not since it shares its’ contract award date with the first ship of the two-ship buy. This conclusion was also valid for the successive ships of any multiple ship procurement. This conclusion was derived from Class A Ships, and validated by the data and conclusions associated with Class B Ships.

- *Validation:* **Valid**

### Key Parameter #5: Principal Production Labor Elements

Conclusion #5-1: Low-rate Production Shipbuilding is Accomplished by Principal Production Labor Elements

- *Conclusion:* Low-rate production shipbuilding is accomplished by principal production labor elements; as such, in order to develop a knowledge management culture, learning strategies that are developed must include these labor elements supporting low-rate production shipbuilding.
- *Adjudication:* Production labor profiles and distributions varied from ship class to ship class due to the intended mission profiles and funding associated with each ship class. Eighty percent of the production labor associated with Class A Ships involved the following eight labor elements of: electrical, machinery, painters, pipefitters, riggers, sheet metal workers, shipfitters, and welders. As such, any knowledge management actions should at least include these eight areas. For Class B Ships, ninety-eight percent of the production labor associated with Class B Ships involved six major areas of electrical, mechanical, painting, production support, steel work, and welding. This conclusion was derived from Class A Ships, and validated by the data and conclusions associated with Class B Ships.
- *Validation:* **Valid**

### Key Parameter #6: Principal Non-Production Labor Elements

Conclusion #6-1: Low-rate Production Shipbuilding is Accomplished by Principal Non-Production Labor Elements

- *Conclusion:* Low-rate production shipbuilding is accomplished by principal non-production labor elements; as such, in order to develop a knowledge management culture, learning strategies that are developed must include these labor elements associated with low-rate production shipbuilding.
- *Adjudication:* Non-production labor profiles and distributions varied from ship class to ship class due to the intended mission profiles associated with each ship class. For Class A Ships, data did not exist in the public domain for the principal non-production labor elements. However, the researcher assumed that engineering, management, administration, and production support are some of the key non-production elements associated with low-rate production shipbuilding. Since both Class A Ships and Class B Ships were produced in low-rate production environments, then their non-production labor profiles were assumed to be similar. For Class B Ships, the principal non-production labor elements were: administration, support, engineering, and management. This conclusion was derived from Class A Ships, and validated by the data and conclusions associated with Class B Ships.
- *Validation:* **Valid**

## Key Parameter #7: Funding Profiles and Strategies

### Conclusion #7-1: Funding Profiles and Strategies Impacts Learning

- *Conclusion:* The funding profiles and subsequent funding strategies are determined and developed by the customer which are not optimized to support and/or accommodate the shipbuilder thereby impacting the ability to maximize learning in low-rate production shipbuilding.

- *Adjudication:* For Class A Ships, the ship with the longest duration between deliveries, which was due to the timing and profile of the funding to build that particular ship, required the greatest number of hours to build, which was Ship 10. Ship 10 was also the last ship of the class. As such, most of the learning gained from the previous ship was lost due to the longer duration between ships. For Class B Ships, the ship with the longest time between deliveries was Ship 11, and it required the second greatest number of hours to build. Ship 14 was the last ship of the class, and required the most hours to build. In both cases, the funding profile and associated procurement strategy contributed to the loss of learning for these ships. Conversely, for both Class A and Class B Ships, funding profiles with fewer months between contract awards as well as multi-ship procurements facilitated learning as evidence by the reduction in labor hours to build the second ship of a two ship buy for these two ship classes. As validation shows, the funding profiles and funding strategies, which were determined by the customer, has a direct effect on the learning associated with low-rate production shipbuilding. This conclusion was derived from Class A Ships, and validated by the data and conclusions associated with Class B Ships.
- *Validation*: **Valid**

Conclusion #7-2: Time Between Deliveries versus Number of Changes

- *Conclusion:* Time between deliveries and/or contract award dates has a greater influence on learning than the number of changes for low-rate production ships.
- *Adjudication:* As was delineated within the Assumptions Section of this research, by definition, low-rate production shipbuilding not only referred to the periodicity of

successive ship deliveries, but it also referred to the ship complexity as well as the large number of labor hours to design, build, test, and deliver ships of certain ship classes. This assumption was applicable to this conclusion discussion because low-rate production ships required a larger number of labor hours to produce as compared to high-rate production ships such that the impact from changes on low-rate production ships has the potential to be absorbed easier due to the large number of labor hours associated with low-rate production ships. The degree of the impacts associated with these changes required proprietary information which is beyond the scope of this research. For Class A Ships, Ship 10 required the greatest number of hours of all ships in this class to design, build, test, and deliver. Ship 10 also had the longest duration between ship deliveries of almost six years. Ship 3 had the longest duration between contract awards of seven years while Ships 9 and 10 had the second longest durations between contract awards of six and a half years. Ship 10 had the greatest number of changes while Ship 9 had the seventh greatest number of changes. Both Ships 9 and 10 were single ship procurements. In regards to Class A Ships, time between deliveries has a greater impact on learning than the number of changes. For Class B Ships, Ship 14 required the greatest number of hours of all ships in this class to design, build, test, and deliver followed by Ship 11. Ship 12 had the longest duration between ship deliveries of four and a half years, and Ship 11 had the longest duration between contract awards of seven and a half years. Ship 9 had the greatest number of changes followed by Ship 11. All of the ships of this class were single ship procurements other than Ships 2 and 4 as well as Ships 3 and 5. As such, the data associated with Class B Ships validated the conclusion from the data associated with Class A Ships that the time between deliveries and/or contract awards had a greater influence on learning than the number of changes for low-rate production ships. This conclusion was derived from Class A Ships, and validated by the data and conclusions associated with Class B Ships.

- *Validation:* **Valid**

### Key Parameter #8: Shipbuilding Age Demographics – 2020

Conclusion #8-1: 2020 Demographic Environment within Shipbuilding Impacts Learning

- *Conclusion:* The demographic environment directly impacts learning and the knowledge management culture of low-rate production shipbuilding. Utilizing the referenced 2020 demographic data, the large number of shipbuilders that are within ten years of retirement, as compared to previous years, is a learning disruptor because the bi-modal distribution of experience as well as a large percentage of shipbuilders that are close to retirement inhibits knowledge transfer which negatively affects learning.
- *Adjudication:* The Class A Ships were built in the United States whereas the Class B Ships were built in England. The Class A Ships were built and delivered before 2020; as such, this demographic data set is not applicable to the Class A Ships. As a matter a fact, only the Class D Ships would be applicable to this demographic data set. Due to the nature of the data for this conclusion, only Class D Ships validated this information.
- *Validation*: **Not Applicable - Demographic was for Class D Ships**

### Key Parameter #9: Shipbuilding Age Demographics – 1999

Conclusion #9-1: 1999 Demographic Environment within Shipbuilding Impacts Learning

- *Conclusion:* The demographic environment directly impacts learning and the knowledge management culture of low-rate production shipbuilding. Utilizing the referenced 1999 demographic data, there were one half the number of shipbuilders as compared to the 2020 demographic data, and the demographic distribution is a skewed bell curve reflective of a more experienced workforce. With this distribution, the transfer of knowledge, and as a result, learning is more enabled compared to the 2020 demographic data.
- *Adjudication:* In regards to the 1999 demographic data, only some of the Class A Ships were built during this time frame. The Class A, C, and D Ships were built in the United States whereas the Class B Ships were built in England. Also of note, for the purposes of this research, and given the similarities of the two countries, the researcher assumed that England has the same demographic profiles as the United States. Using the 1999 shipbuilder demographic data, there were one-half the number of shipbuilders compared to the 2020 data. Approximately one-quarter of the shipbuilders in 1999 were within ten years of retirement age, and about twelve percent of the shipbuilders in 1999 were inexperienced. There were half the number of shipbuilders as compared to 2020 and about twenty percent less than 1980. As such, 1999 was a “valley” [researcher’s quotes] in the number of shipbuilders between 2020 and 1980. Over thirteen percent plus some percentage of the thirty-one to forty age group are inexperienced. As such, in regards to knowledge management and learning, for Class A Ships, the age demographic profile was more conducive to efficient learning and knowledge transfer as compared to the 2020 demographic data. As indicated, this conclusion was based on demographic data describing shipbuilders in 1999, which from a ship class perspective would only be

directly applicable to the last Class A Ship. Additional data, not in the public domain, would be required to establish connectivity between the demographic data and the direct impact to labor hours. This conclusion was derived from Class A Ships and validated by the 1999 demographic data accordingly.

- *Validation*: **Valid within the context of Class A Ships since 1999 data was the basis for this demographic assessment.**

### Key Parameter #10: Shipbuilding Age Demographics – 1980

<u>Conclusion #10-1: 1980 Demographic Environment within Shipbuilding Impacts Learning</u>

- *Conclusion:* The demographic environment directly impacts learning and the knowledge management culture of low-rate production shipbuilding. As such, in regards to knowledge management and learning, a concerted effort must occur to capture the shipbuilders that are retirement age to prepare the next set of leaders and to help the new hires move up their learning curve as efficiently as possible.
- *Adjudication:* In regards to the 1980 demographic data, Class A and B Ships spanned the 1980's, and as such, this demographic data would represent some of the ships within each of these two classes. The Class A Ships were built in the United States whereas the Class B Ships were built in England. Also of note, for the purposes of this research, and given the similarities of the two countries, the researcher assumed that England has the same demographic profiles as the United States. Utilizing the referenced 1980 demographic data, there were twenty percent more shipbuilders in 1980 as compared to 1999, but approximately forty percent fewer shipbuilders in 1980 as compared to 2020. About forty-four percent in 1980 were retirement eligible or were eligible within ten years.

Over thirty-five percent were inexperienced, and only twenty percent in 1980 were available to be the future leaders of shipbuilding by being in the thirty-five to forty-four age demographics. The 1980 demographic profile shows a very similar bi-modal distribution as the 2020 demographic profile. There were more low-rate production ships being built during the late 1970's and early 1980's which would enable learning thereby reducing the impacts associated with a bi-modal demographic distribution. This conclusion was derived from Class A Ships, validated by the data and conclusions associated with Class B Ships.

- *Validation:* **Valid within the context of Class A and B Ships since 1980 data was the basis for this demographic assessment.**

### Conclusion #10-2: Increasing the Number of Low-rate Production Ships Assists Offsetting a Demographic Environment that is a Learning Disruptor

- *Conclusion:* Increasing the number of low-rate production ships is a learning enabler to assist with offsetting a demographic environment with a bi-modal age distribution and/or a demographic environment with a skewed retirement age distribution.
- *Adjudication:* The Class A Ships were built in the United States whereas the Class B Ships were built in England. For the purposes of this research, and given the similarities of the two countries, the researcher assumed, which is captured within the Assumptions Section, that England has the same demographic profiles as the United States. Despite having a large percentage of inexperienced labor in 1980 at thirty-seven percent and forty-four percent at retirement age or within ten years of retirement age, Ship 4, which would have been directly impacted by these demographics because its' contract date was

1980, was the start of delivering ships for less hours for the next four Class A Ships. As indicated previously, these four ships had fewer months between deliveries and were two ship procurements such that the number of ships procured within this low-rate production environment were increased as compared to the rest of the class. The average time between deliveries for these Class A Ships was twenty-seven months as compared to the rest of the ships that make up this class, which had an average time between deliveries of fifty-three months. The results of this were that the Class A Ships with an average of twenty-seven months between deliveries were designed, built, and tested for seven percent fewer labor hours as compared to the Class A Ships that had an average time between deliveries of fifty-three months. As such, the impacts to learning in low-rate production environments with a bi-modal and/or retirement aged demographic can be at least partially mitigated by increasing the number of ships that are being designed, built, and tested. As indicated, there were fourteen Class B Ships that were built by four different shipyards, and eight of the fourteen were delivered between 1980 and 1985. For Class B Ships, only three out of the remaining eight ships were delivered for the same or less hours than the previous ship. The average time between deliveries for these three ships was sixteen months compared to the remaining five ships of Class B which were delivered on average of six months between deliveries. It is important to note that this information was within the context of the fact that four different shipyards were involved building Class B Ships with one shipbuilder building three of the eight ships during this time frame, one shipbuilder built one ship during this time frame, and two built two during this time frame. However, analyzing this information for each individual shipbuilder within this time frame of 1980 to 1985 where eight ships were delivered yielded the fact that there were no two ship procurements during this time frame. It also yielded the fact that the cost to build each ship during this time frame increased for each ship. However, of the eight ships built during this time frame, one ship (Ship 14) experienced a ten percent reduction in the number of months to deliver compared to the previous ship for the same shipbuilder. Ship 14's cost grew by twenty-one percent. The remaining seven ships that were delivered after 1980 all experienced an increase in the number of months to deliver as compared to the previous ship, and their respective cost increased between thirty-two percent to fifty-one percent. As indicated for Class B Ships, the eight ships that would have been impacted by the referenced 1980 demographic assessment all exhibited cost increases to build each successive ship by the four shipbuilders. Given the demographic environment during this time frame, increasing the number of months between deliveries would increase the costs associated with ship deliveries, in part, due to the loss of learning driven by the learning disruptor of a bi-modal and retirement aged demographic distribution. As such, the Class B data and information validated the conclusions derived from the Class A data and information. This conclusion was derived from Class A Ships, and validated by the data and conclusions associated with Class B Ships.

- *Validation*: **Valid**

### Key Parameter #11: Employee Work Output for Shipbuilding and Repair

Conclusion #11-1: US Shipbuilder Work Output has Grown Forty-Five Percent over 20 Years

- *Conclusion:* The employee work output for US shipbuilders has grown by forty-five percent over a twenty-year period from 1977 to 1998 (Baker, Degnan, Gabriel, and

Tucker (2001)); however, this increase in work output is not attributable to ship procurement time frames or multi-ship procurement strategies, but rather, it is due to the learning characterization for each shipyard such as the organizational culture and the demographic environment. There are also other factors that influence work output, but they are outside the scope of this research.

- *Adjudication:* Figure 63 provided work output associated with shipbuilding for all shipyards including ship repair yards. Figure 63 did not provide information at the specific shipyard level nor work output by ship class as this information did not exist in the public domain nor was there a feasible way to extract the needed information from Figure 63. The increase in outputs as well as the decrease in outputs reflected via Figure 63 occur during time frames associated with Class A Ships that exhibited both shorter and longer durations between deliveries as well as different procurement strategies for both single and two ship procurements. As substantiated by Baker, Degnan, Gabriel, and Tucker (2001), shipbuilding output per employee rose only forty-five percent over twenty years as compared to one-hundred and twenty percent for the automotive industry and eighty-five percent for the aircraft industry over the same time frame. Per Baker, Degnan, Gabriel, and Tucker (2001), this was due to several reasons, such as differences in workforce instability and age distributions, and other reasons. However, workforce stability and age demographics impacted learning through the shipbuilding environment and culture of learning resident in a given shipyard similar to the shipyards that built Class A and B Ships. The automotive and aircraft industries were included herein to provide a reference to compare shipbuilding too even though the automotive and aircraft industries were not produced in a low-rate environment. This conclusion was derived from Class A Ships, and validated by the data and conclusions associated with Class B Ships within the context of Figure 63.

- *Validation*: **Valid**

### Key Parameter #12: Employee Work Output for Automotive and Aircraft Industries

Conclusion #12-1: US Aircraft and Automotive Industries has an Output per Employee Larger than the Output per Employee in Shipbuilding

- *Conclusion:* The aircraft and automotive industries has an output per employee that is more than the output per employee output compared to the shipbuilding industry. The difference in output per employee is due to the differences in their production environments (i.e., low-rate versus high-rate production) which is impacted by their overall learning characterizations between low-rate production and high-rate production environments.
- *Adjudication:* This conclusion was based on the information provided by Baker, Degnan, Gabriel, and Tucker (2001). As was the case with Conclusion #11-1, Figure 63 provides work output associated with shipbuilding for all shipyards including ship repair yards while Figure 64 provides work output associated with automotive and aircraft industries. Figures 63 and 64 did not provide information at the specific shipyard, aircraft, or automotive industry level nor associated work output by ship class, aircraft type, or automotive type. Similar to Conclusion #11-1, the work output associated with the aircraft and automotive industries was also influenced by workforce stability and age demographics too which impacts the learning characterization within these industries similar to shipbuilding. The only main difference in the learning characterizations of the

aircraft and automotive industries compared to the shipbuilding industry was the fact that the learning environment associated with the aircraft and automotive industries was a high-rate production environment while the Class A and B ships are within the context of a low-rate production environment. This conclusion was derived from Class A Ships, and validated by the data and conclusions associated with Class B Ships within the context of Figures 63 and 64.

- *Validation:* **Valid**

### Key Parameter #13: Memory Retention

#### Conclusion #13-1: Lack of Using Skills Results in Substantial Reduction in Knowledge Retention and Learning

- *Conclusion:* Most people after learning a new skill will only retain ten to fifteen percent of the knowledge that they learned after a month has transpired without any refreshers. As such, low-rate production environments that entail not using skills frequently increases the challenges associated with knowledge retention and learning.
- *Adjudication:* As Figures 65 and 66 illustrate, knowledge retention decreased within a day after training occurs. Training retention can be bolstered through refreshers as well as other learning strategies. Obviously, low-rate production environments were much more susceptible to this issue simply due to the very nature of their associated production environment as compared to high-rate production environments. As such, this conclusion was applicable to Class A Ships and was validated by Class B Ships simply due to their context. Teichert (2010), Kohn (2014), Meacham (2016), and Brain Science (2022) discussed that knowledge retention can be increased after learning a new skill through

"booster events", which was any event that facilitates a person's brain to associate the new information learned as important to assist with the memory retention process. Kohn (2014) simply states that "if you use it, you won't lose it!" Ebbinghaus (1885, 1913) covered recommendations in regards to how to increase memory retention thereby increasing knowledge retention; however, the associated strategies to employ to bolster retention and/or increase knowledge retention especially in low-rate production environments was the subject of future research. Neither Ebbinghaus (1885, 1913) nor Kohn (2014), or any other researcher, specifically discussed knowledge retention within the context of a low-rate production environment, such as shipbuilding. Additionally, future research within this area was viable including connectivity to requisite parsimony.

However, the researcher has also additionally concluded that not every skill associated with low-rate production shipbuilding would erode following Figures 65 and 66. Basic shipbuilding skills such as drilling holes, cutting holes, and other fundamental operations would not experience a loss of learning. However, shipbuilding skills associated with using those fundamental skills to build parts of a system would experience some loss of learning while skills associated with building systems within the context of specific ship construction conditions would experience the highest loss of learning. A more in-depth assessment of this additional conclusion would also be the subject of future research and was beyond the scope of this research. This conclusion was derived from Class A Ships, and validated by the data and conclusions associated with Class B Ships within the context of Figures 65 and 66.

- *Validation:* **Valid**

**Key Parameter #14: Relative Efficiency versus Experience**

Conclusion #14-1: Shipbuilder Efficiency is Affected by the Knowledge Management Culture

- *Conclusion:* The low-rate production environment of shipbuilding increases the challenges associated with shipbuilder efficiency due to knowledge retention issues.
- *Adjudication:* After working one year in shipbuilding, a shipbuilder would only be fifty percent efficient, and after four years, a shipbuilder would only be eighty percent efficient. As Figure 67 shows, it takes over fifteen years of experience for a shipbuilder to approach one hundred percent efficiency. Figure 67 was for all shipbuilding, and it did not differentiate between low-rate production shipbuilding and high-rate production shipbuilding. Within the context of low-rate production shipbuilding, in the researcher's opinion, the slope of Figure 67 would be even less meaning that the time frame to reach fifty percent, eighty percent, and one hundred percent would take even longer. The exact slope of the low-rate production curve of relative efficiency versus years of experience would be the subject of future research. Conclusion #14-1 was applicable to all of shipbuilding; as such, this conclusion is applicable to Class A Ships, and was validated by Class B Ships. This conclusion was derived from Class A Ships, and validated by the data and conclusions associated with Class B Ships within the context of Figure 67.
- *Validation*: **Valid**

Table 15 also provides the conclusions derived from Class B Ships, and their validation of Class A Ship's conclusions. In addition, Note 1 identified in Table 15 that the analysis of the data and information associated with this table occurred via Chapter 4 as per the research methodology.

In summary, as per the research methodology, only the hours to build each ship were assessed versus the different parameters associated with Class B Ships. As such, for the Class B Ship assessments, the labor hours to build each ship, Figures 14 and 15 were analyzed versus each parameter associated with each Class B Ships. After the Class B assessment was completed, the researcher developed conclusions associated with each parameter for Class B Ships. Afterwards, the conclusions associated with Class B Ships were compared to the conclusions associated with Class A Ships to then validate the Ship Class A conclusions. This then in turn was used to validate the OLCC for learning in low-rate production environments. Each conclusion was adjudicated to provide any clarifications or other supporting information to support the deductions made and to support the final validation associated with each conclusion. As such, Table 15 showed that the conclusions associated with the Class A Ship parameters were validated by the conclusions associated with the Class B Ships.

## WBS 12: Validation via Triangulation of Class A Ship Data and Conclusions by Using Class C and Class D Ship Data and Conclusions

Following the research methodology that was used to validate Class A Ship conclusions using Class B Ship conclusions, the researcher used Class C and Class D data and conclusions to validate the conclusions associated with Class A Ships. As such, this validation through triangulation of the conclusions derived from Class A Ships by using the Class C and D Ship's assessments was shown with the Class A assessment via the assessment below along with Table 16 and Table 17 to assist with the comparison and analysis. Each conclusion was adjudicated to provide any clarifications or other supporting information to support the deductions made as a result of this research and to support the final validation associated with each conclusion.

| # | High Level Grouping | Parameters Affecting Learning | Source of Parameters | | | Class A (Figure) | Affects All Classes (Figure) | Class C (Figure) | Class D (Figure) |
|---|---|---|---|---|---|---|---|---|---|
| | | | Mentions Learning and Mentions Shipbuilding | Mentions Learning but Does Not Mention Shipbuilding | Does Not Mention Learning but Does Mention Shipbuilding | | | | |
| 1 | Company Experience and Capacity | Company Experience | - | - | - | - | - | - | - |
| 2 | | Competition | - | - | - | - | - | - | - |
| 3 | | Number of Ships Built Prior | - | - | - | - | - | - | - |
| 4 | | Number of Ships Built that were Similar | - | - | - | - | - | - | - |
| 5 | | Shipyard Capacity | - | - | Weisgerber (2021)<br>Clark (2021) | - | - | - | - |
| 6 | Changes | Requirements Changing | - | - | Abbott (1997) | 9<br>10 | - | - | 44<br>45 |
| 7 | | New or Immature Technology | - | - | Brimelow (2022)<br>Grazier (2021)<br>Lessig (2019) | - | - | - | - |
| 8 | | Requirements | - | - | - | 9<br>10 | - | - | 44<br>45 |
| 9 | | Specifications | - | - | - | - | - | - | - |
| 10 | | Material | - | - | - | - | - | - | - |
| 11 | | Changes | Miroyannia (2006) | - | Abbott (1997) | 9<br>10 | - | - | 44<br>45 |
| 12 | | Requirements Instability | - | - | Abbott (1997) | 9<br>10 | - | - | 44<br>45 |
| 13 | | Number of Changes | - | - | Abbott (1997) | 9<br>10 | - | - | 44<br>45 |

Table 16: Factors Affecting Learning Associated with Class A, C, and D Ships

| # | High Level Grouping | Parameters Affecting Learning | Source of Parameters | | | Class A (Figure) | Affects All Classes (Figure) | Class C (Figure) | Class D (Figure) |
|---|---|---|---|---|---|---|---|---|---|
| | | | Mentions Learning and Mentions Shipbuilding | Mentions Learning but Does Not Mention Shipbuilding | Does Not Mention Learning but Does Mention Shipbuilding | | | | |
| 14 | Changes (continued) | Technology Insertions | - | - | Grazier (2021) | - | - | - | - |
| 15 | | Navy/Government Mandates | - | - | Capaccio (2020) | - | - | - | - |
| 16 | | Work Instruction Changes after Start of Construction | - | - | Grazier (2021) | - | - | - | - |
| 17 | Government Influences | Government Politics | - | - | Eckstein (2022)<br>Hooper (2022)<br>Katz (2022)<br>Shelbourne (2022)<br>Bergman (2020)<br>Perdue (2020)<br>Radelat (2020)<br>Tiron and Capaccio (2020)<br>Ress (2022)<br>Eckstein (2020)<br>Larter (2020)<br>Thompson (2019) | - | - | - | - |
| 18 | | Laws, Regulations | - | - | Ress (2022)<br>Eckstein (2020)<br>Larter (2020) | - | - | - | - |
| 19 | | Threat Assessments | - | - | Zengerle and Cowan (2022) | - | - | - | - |
| 20 | Industrial Base | Industrial Base Issues | Thompson (2019) | - | Limas-Villers (2022)<br>Clark and Walton (2020)<br>Eckstein (2020)<br>Ress (2020) | - | - | - | - |

Table 16 (continued)

| # | High Level Grouping | Parameters Affecting Learning | Source of Parameters | | | Class A (Figure) | Affects All Classes (Figure) | Class C (Figure) | Class D (Figure) |
|---|---|---|---|---|---|---|---|---|---|
| | | | Mentions Learning and Mentions Shipbuilding | Mentions Learning but Does Not Mention Shipbuilding | Does Not Mention Learning but Does Mention Shipbuilding | | | | |
| 21 | Information Maturity | Design Maturity at Construction Start | - | - | Grazier (2021) | 9<br>10 | - | - | 44<br>45 |
| 22 | | Technical Maturity at Construction Start | - | - | Grazier (2021) | 9<br>10 | - | - | 44<br>45 |
| 23 | | Degree of Design for Producibility | - | - | Schank et al (2016) | - | - | - | - |
| 24 | Commonality | Amount of Commonality Across the Ship and Class | - | - | Schank et al (2016) | - | - | - | - |
| 25 | Procurement Strategy | Budget | - | - | Limas-Villers (2022)<br>Ress (2022)<br>Talent (2021)<br>Connors (2020)<br>Eckstein (2020)<br>Perdue (2020) | - | - | - | - |
| 26 | | Acquisition Strategy | - | - | Osborn (2022)<br>Turner (2021)<br>Arena, Blickstein, Younossi, & Grammich (2006) | 11<br>13 | - | 33<br>34 | 46<br>54 - 57 |
| 27 | | Contract Strategy including Number of Contracts | - | - | Abbott (1997) | 8<br>11<br>13 | - | 31<br>32<br>33<br>34 | 43<br>46<br>54-57 |
| 28 | | Contract Impacts | - | - | Osborn (2022) | - | - | - | - |
| 29 | | Contract Strategy | - | - | Osborn (2022) | 11<br>13 | - | 33<br>34 | 46<br>54 - 57 |

Table 16 (continued)

| # | High Level Grouping | Parameters Affecting Learning | Source of Parameters | | | Class A (Figure) | Affects All Classes (Figure) | Class C (Figure) | Class D (Figure) |
|---|---|---|---|---|---|---|---|---|---|
| | | | Mentions Learning and Mentions Shipbuilding | Mentions Learning but Does Not Mention Shipbuilding | Does Not Mention Learning but Does Mention Shipbuilding | | | | |
| 30 | Procurement Strategy (continued) | Procurement Strategy (Multi-Year Procurement, Block Buy, Contract with Options) | - | - | Burgess (2022)<br>Decker (2022)<br>Capaccio (2020)<br>Katz (2021)<br>Weisberber (2021) | 8<br>11<br>13 | - | 31<br>32<br>33<br>34 | 43<br>46<br>54 - 57 |
| 31 | | Funding Strategy | - | - | Limas-Villers (2022)<br>Ress (2022)<br>Connors (2020)<br>Lessig (2016) | 11<br>13 | - | 33<br>34 | 46<br>54 - 57 |
| 32 | | Deisgn and Construction, Production Labor Hours | - | - | - | 7 | - | N/A | 39<br>40<br>41<br>42 |
| 33 | | Time Between Construction Starts | - | - | Lessig (2016) | 8<br>11 | - | 31<br>32<br>33<br>34 | 43<br>46 |
| 34 | Production Environment | Facilities | Miroyannia (2006) | - | - | - | - | - | - |
| 35 | | Tooling | - | - | - | - | - | - | - |
| 36 | | Number of Different Plants associated with Production | - | - | Fioretti (2007) | - | - | - | - |
| 37 | | Manufacturing Progress Function/Degree of Automation | - | - | - | - | - | - | - |
| 38 | | Make/Buy Decisions (Amount of Outsourcing) | - | - | - | - | - | - | - |

Table 16 (continued)

| # | High Level Grouping | Parameters Affecting Learning | Source of Parameters | | | Class A (Figure) | Affects All Classes (Figure) | Class C (Figure) | Class D (Figure) |
|---|---|---|---|---|---|---|---|---|---|
| | | | Mentions Learning and Mentions Shipbuilding | Mentions Learning but Does Not Mention Shipbuilding | Does Not Mention Learning but Does Mention Shipbuilding | | | | |
| 39 | Natural Disasters and Labor Strikes | Labor Strikes or Lay-offs | - | - | Fioretti (2007) | - | - | - | - |
| 40 | | Disasters | Baker, Degnan, Gabriel, Tucker (2001) | - | - | - | - | - | - |
| 41 | Training and Knowledge Management Strategies | Process Improvement & Lessons Learned Process | Miroyannia (2006) | - | Eckstein (2022)<br>Ennis, Dougherty, Lamb, Greenwell, and Zimmermann (1997) | - | - | - | - |
| 42 | | Training Strategy | Walpert (2001)<br>Lundquist (20210<br>Gagosz (2021)<br>O'Brien (2020) | Miller (2017)<br>Mishra, Henriksen, and Fahnoe (2013)<br>Di Stefano, Gino, Pisano, and Staats (2016) | - | - | - | - | - |
| 43 | | Knowledge Management Strategy | - | Di Stefano, Gino, Pisano, and Staats (2016)<br>Pappas (2014)<br>Ebbinghaus (1885)<br>Kohn (2014)<br>Meacham (2016)<br>Teichert (2010) | Abbott (2022)<br>Bloor et al (2016)<br>Schank et al (2016) | - | - | - | - |
| 44 | | Knowledge Retention | - | Pappas (2014)<br>Ebbinghaus (1885)<br>Kohn (2014)<br>Meacham (2016)<br>Teichert (2010) | X | - | 65<br>66<br>67 | - | - |
| 45 | | Time to Talent | Eckstein (2022)<br>Eckstein (2019)<br>Gagosz (2021)<br>O'Brien (2020)<br>Bloor et al (2016) | - | X | - | 65<br>66<br>67 | - | - |
| 46 | | Learning Styles, Techniques, Methods | Walpert (2001)<br>Lundquist (20210 | Di Stefano, Gino, Pisano, and Staats (2016) | X | - | - | - | - |
| 47 | | Lessons Learned Incorporation | Miroyannia (2006) | - | Ennis, Dougherty, Lamb, Greenwell, and Zimmermann (1997) | - | - | - | - |

Table 16 (continued)

| # | High Level Grouping | Parameters Affecting Learning | Source of Parameters | | | Class A (Figure) | Affects All Classes (Figure) | Class C (Figure) | Class D (Figure) |
|---|---|---|---|---|---|---|---|---|---|
| | | | Mentions Learning and Mentions Shipbuilding | Mentions Learning but Does Not Mention Shipbuilding | Does Not Mention Learning but Does Mention Shipbuilding | | | | |
| 48 | Company Organization | Production, Construction, Engineering, and Support Department Organization | - | - | Fioretti (2007) | 12 | - | 35<br>36 | 47 - 53 |
| 49 | | Procedures | - | Poleacovschi, Javernick-Will, Smith, and Pohl (2020) | Fioretti (2007) | - | - | - | - |
| 50 | | Staffing Strategy including Visibility of Expertise | - | Poleacovschi, Javernick-Will, Smith, and Pohl (2020) | - | 12 | - | 35<br>36 | 47 - 53 |
| 51 | | Output/Productivity (Hours Expended to Produce a Given Output) | Baker, Degnan, Gabriel, Tucker (2001) | - | - | - | 63<br>64 | - | - |
| 52 | | Work Mix/Labor Elements | - | - | Abbott (1997)<br>Limas-Villers (2022)<br>Lundquist (2021) | 12 | - | 35<br>36 | 47 - 53 |
| 53 | Learning | Reverse Learning or Forgetting Curve | Miroyannia (2006) | Pappas (2014)<br>Ebbinghaus (1885)<br>Kohn (2014)<br>Meacham (2016)<br>Teichert (2010) | Diekmann, Horn, & O'Conner (1982) | 7 | 65<br>66<br>67 | - | - |
| 54 | | Repetitive Learning | - | - | Diekmann, Horn, & O'Conner (1982) | - | - | - | - |
| 55 | | Loss of Learning | Miroyannia (2006) | Pappas (2014)<br>Ebbinghaus (1885)<br>Kohn (2014)<br>Meacham (2016)<br>Teichert (2010) | X | 7 | 65<br>66<br>67 | - | - |
| 56 | | Relative Efficiency of Learning | - | - | X | - | 65<br>66<br>67 | - | - |

Table 16 (continued)

| # | High Level Grouping | Parameters Affecting Learning | Source of Parameters | | | Class A (Figure) | Affects All Classes (Figure) | Class C (Figure) | Class D (Figure) |
|---|---|---|---|---|---|---|---|---|---|
| | | | Mentions Learning and Mentions Shipbuilding | Mentions Learning but Does Not Mention Shipbuilding | Does Not Mention Learning but Does Mention Shipbuilding | | | | |
| 57 | Demographics | Personnel Age Distribution | Baker, Degnan, Gabriel, Tucker (2001) | - | Arena, Blickstein, Younossi, & Grammich (2006)<br>Eckstein (2021)<br>Gagosz (2021) | - | 59<br>60<br>61<br>62<br>63<br>64 | - | - |
| 58 | | Experience Distribution | McLeary (2020)<br>Eckstein (2019)<br>Thompson (2019)<br>Bloor et al (2016) | - | Arena, Blickstein, Younossi, & Grammich (2006)<br>Bloor et al (2016)<br>Ress (2021) | - | 59<br>60<br>61<br>62 | - | - |
| 59 | | Demographics | - | | Arena, Blickstein, Younossi, & Grammich (2006)<br>Limas-Villers (2022)<br>Lundquist (2021) | - | 59<br>60<br>61<br>62 | - | - |
| 60 | | Lack of Adequate & Experienced Employees | - | - | Lima-Villers (2022)<br>Ress (2021)<br>Lundquist (2021) | - | - | - | - |
| 61 | | Workforce Shortages | Baker, Degnan, Gabriel, Tucker (2001) | - | Lima-Villers (2022) | - | 63<br>64 | - | - |
| 62 | | Workforce Turnover | Baker, Degnan, Gabriel, Tucker (2001) | - | Weisgerber (2021)<br>Eckstein (2022) | - | 63<br>64 | - | - |
| 63 | Ship Complexity | Ship Construction Density, Ship Complexity, Design Complexity, and Complexity Associated with Ship Operations | - | - | Schank et al (2016)<br>Terwilliger (2015)<br>Gaspar, Ross, Rhodes, and Erickstad (2012)<br>Grant (2008)<br>Arena, Blickstein, Younossi, and Grammich (2006) | - | - | - | - |

Table 16 (continued)

| # | High Level Grouping | Parameters Affecting Learning | Source of Parameters | | | Class A (Figure) | Affects All Classes (Figure) | Class C (Figure) | Class D (Figure) |
|---|---|---|---|---|---|---|---|---|---|
| | | | Mentions Learning and Mentions Shipbuilding | Mentions Learning but Does Not Mention Shipbuilding | Does Not Mention Learning but Does Mention Shipbuilding | | | | |
| 64 | Stability and Predictability | Workforce Instability | Baker, Degnan, Gabriel, Tucker (2001) | - | Lima-Villers (2022) | - | 63<br>64 | - | - |
| 65 | | Instability in the Number of Ships and Navy's Procurement Plans | - | - | Abott (2022)<br>Eckstein (2022)<br>Grady (2022)<br>Limas-Villers (2022)<br>Axe (2021)<br>Katz (2021)<br>Turner (2021)<br>Weisgerner (2021)<br>Bergman (2020)<br>Connors (2020)<br>Fabey (2020)<br>Radelat (2020)<br>Arena, Blickstein, Younossi, & Grammich (2006)<br>Reed and Inhofe (2021) | - | - | - | - |
| 66 | | Predictability & Stability Associated with Future Work | - | - | Katz (2021)<br>Clark (2021)<br>Reed and Inhoe (2021) | - | - | - | - |

Table 16 (continued)

Note 1 from Table 16 conveyed that the analysis of the data was captured via Chapter 4. From a validation perspective of using Class C and Class D Ship data to validate Class A results, Table 16 showed that the Class C and Class D assessment yielded the same factors impacting learning in low-rate production environments as the Class A assessment except in two areas because the data did not exist in the public domain. For Class C Ships, hours expended to build each ship did not exist in the public domain, and for Class D Ships, since three of the four ships were still in production, the impact of changes could not be adequately addressed. It is for these reasons that these two ship classes were analyzed together and subsequently used together to triangulate to the Class A information and subsequent deductions. The researcher did espouse that the trends should be comparable, which was discussed below. However, the triangulation of Class C and Class D Ships did provide additional information to support the learning characterization of Class A Ships, and it validated the learning characterization associated with Class A Ships as captured below and via Table 17.

Utilizing the Class C and Class D Ship assessment, the researcher developed conclusions accordingly and then compared the Class C and Class D Ship's conclusions to the Class A Ship's conclusions to validate Class A Ships using Class C and Class D Ship's information, which was captured below and by Table 17. As was done with Class A Ships, the various parameters identified via Table 16 were analyzed versus the labor hours to build the Class C and Class D Ships since the principal parameter was based on labor hours. Per the research methodology, Table 17 captured the results of the analysis associated with Class C and Class D Ships followed by deductions in regards to learning based on this analysis. After which, the key factors associated with Class C and Class D Ships were compared to Class A Ships to determine if the Class A conclusions were validated by Ship Class C and Ship Class D.

As was discussed in WBS 9, Class C and Class D Ships were added to Table 11 to develop Table 17 to show the factors affecting learning tied to specific figures for all four classes of ships. Just as was the case for Class B Ships, Figure 17 was used to develop the conclusions associated with Class C and Class D Ships. These conclusions were compared to the conclusions developed for Class A Ships thereby triangulating the validity (Brewer and Sousa-Poza (2019)) of Class A Ships using Class C and Class D Ships.

| # | Class A Ships | | Key Parameters and Conclusions Affecting Learning Curves for Class C and Class D Ships | | | | Class C Ships and Class D Ships Triangulation of Class A Ships Valid or Invalid |
|---|---|---|---|---|---|---|---|
| | **Figure** | **Parameter Represented** | **Figure Class C** | **Figure Class C & D** | **Results of Analysis (See Note 1)** | **Deductions/Conclusions Associated with Learning** | |
| 1 | 8 | Major Ship Construction Milestones | 31<br>32 | 31<br>32<br>43 | Class C Ships:<br>Epsilon Shipyard: Major milestones fairly consistent across the class. Ship 24 (6th Ship for Epsilon) tripled in months between deliveries with no impact to delivery.<br>Zeta Shipyard: Major milestone durations continued to grow through the duration of the class.<br>Epsilon & Zeta: Time between contract award to launch correlates to contract award to delivery.<br>Labor hours associated with Class C Ships does not exist in the public domain.<br><br>Class D Ships:<br>There is approximately seven years between deliveries associated with the first two ships of this ship class. The last two ships of this class have about four years between deliveries. These two ships are a 2 ship buy. | Class C Ships:<br>The optimum number of months between deliveries is four to ten months.<br><br>The number of months to build correlates to the number of months to launch.<br><br>In terms of milestones, multi-ship procurements supports learning retention thereby enabling reductions to production milestones<br><br>Class D Ships:<br>Less time between delivery dates correlates to less labor hours. | 🟩 VALID |
| 2 | 9 | Cumulation of Significant Changes | N/A | 45 | Class D Ships:<br>Increase in changes across the class. The last ship does not show any changes because the shipyard just started construction. | Ship 2, Ship 3, and Ship 4 is still in production, so a deduction cannot be made now in regards to the impacts of changes on hours to build each ship for this class.<br><br>3 of the 4 Class D Ships are under construction and are experiencing changes during construction resulting in an unstable baseline. | 🟩 VALID |

Table 17: Class C and Class D Conclusions to Triangulate to Class A Ships

| # | Class A Ships | | Key Parameters and Conclusions Affecting Learning Curves for Class C and Class D Ships | | | | Class C Ships and Class D Ships Triangulation of Class A Ships Valid or Invalid |
|---|---|---|---|---|---|---|---|
| | **Figure** | **Parameter Represented** | **Figure Class C** | **Figure Class C & D** | **Results of Analysis (See Note 1)** | **Deductions/Conclusions Associated with Learning** | |
| 3 | 10 | Significant Changes Compared to Previous Ship | N/A | 44 | Class D Ships:<br>Increase in changes across the class. The last ship does not show any changes because the shipyard just started construction. | Class D Ships:<br>Ship 2, Ship 3, and Ship 4 is still in production, so a deduction cannot be made now in regards to the impacts of changes on hours to build each ship for this class. | VALID |
| 4 | 11 | Procurement Strategy | 37<br>38 | 37<br>38<br>46 | Class C Ships:<br>Epsilon Shipyard: The number of ships associated with the procurement strategy correlates to the months between delivery dates. Ship 24 (6th Ship for Epsilon) had longest duration between deliveries but shortest build duration.<br>Zeta Shipyard: The number of ships associated with the procurement strategy correlates to the months between delivery dates up to 3 ships.<br><br>Class D Ships:<br>1st 2 Ships were single procurements while Ship 3 and Ship 4 were a 2 ship procurement. | Class C Ships:<br>The more ships included in the muti-ship procurement, then the fewer the months between delivery dates up to 3 to 4 ships. More than 4 ships within a multi-procurement strategy results in a reduction in months between delivery dates for the 1st 4 ships, but then the number of months between delivery dates averages about 5 1/4 months. The 6th ship for the Epsilon Shipyard experiences the inverse of this because the number of months between deliveries increased but the number of months to deliver decreases to the lowest.<br><br>Class D Ships:<br>2 Ship Buy & minimizing time between deliveries is enabler to learning. | VALID |
| 5 | 12 | Principal Production Labor Elements | 35 | 35<br>47<br>48<br>49<br>50<br>51 | Class C Ships:<br>The labor elements that constitute more than five percent of the total are: Electrical, Machinery, Painters, Pipefitters, Shipfitters, and Welders.<br><br>Class D Ships:<br>The labor elements that constitute a majority of the total are: Electrical, Fitters, Machinery, Outfitting, Pipefitters, and Welders. | Class C Ships:<br>This equates to 72% of the production labor. The targeted learning and knowledge retention should address all areas but especially these 6 areas.<br><br>Class D Ships:<br>This equates to more than a majority of the production labor. The targeted learning and knowledge retention should address all areas but especially these 6 areas. | VALID |

Table 17 (continued)

| # | Class A Ships | | Key Parameters and Conclusions Affecting Learning Curves for Class C and Class D Ships | | | | Class C Ships and Class D Ships Triangulation of Class A Ships Valid or Invalid |
|---|---|---|---|---|---|---|---|
| | **Figure** | **Parameter Represented** | **Figure Class C** | **Figure Class C & D** | **Results of Analysis (See Note 1)** | **Deductions/Conclusions Associated with Learning** | |
| 6 | N/A | Principal Non-Production Labor Elements | 36 | 36<br>52<br>53 | Class C Ships:<br>In terms of labor elements that constitute more than 5% of the total, they are: naval architects and marine engineers are the largest constituent group associated with engineers and designers followed by general designers and management. The remaining designers and engineers are discipline specific, such as mechanical, piping, structural, and electrical engineers and designers, then followed by planning and production control shipbuilders.<br><br>Class D Ships:<br>The labor elements that constitute more than a majority are: construction support, production support, and engineering support. | Class C Ships:<br>This equates to 87% of the non-production labor. The targeted learning and knowledge retention should address all areas.<br><br>These areas will also have the largest influence on the non-production labor hours expended for each ship.<br><br>Class D Ships:<br>This equates to more than a majority of the production labor. The targeted learning and knowledge retention should address all areas but especially in these areas.<br>These areas will also have the largest influence on the non-production labor hours expended for each ship. | VALID |
| 7 | 13 | Funding Profiles and Strategy | 37<br>38 | 37<br>38<br>54<br>55<br>56<br>57 | Class C Ships:<br>A multi-procurement strategy was employed for both shipbuilders. Epsilon Shipyard had 1 contract with 4 ships, 2 contracts with 3 ships, and 1 contract with 2 ships. Zeta Shipyard had 1 contract with 1 contract with 11 ships, 1 contract with 4 ships, and 1 contract with 3 ships.<br><br>Class D Ships:<br>Have multi-year funding profiles and Ships 3 and 4 were a 2 ship procurement. | Class C Ships:<br>Time between deliveries impacts the number of months to build each ship for the Epsilon Shipyard and 3 ships for the Zeta Shipyard. For the Zeta Shipyard, more than 3 ships in a procurement strategy actually increases the time between deliveries.<br><br>Class D Ships:<br>Time between deliveries impacts the number of months to build each ship. Multi-year funding provides a conduit to learning up to the funding amount for each given year vice receiving all of the required funding in the beginning of the contract. | VALID |

Table 17 (continued)

| # | Class A Ships | | Key Parameters and Conclusions Affecting Learning Curves for Class C and Class D Ships | | | | Class C Ships and Class D Ships Triangulation of Class A Ships Valid or Invalid |
|---|---|---|---|---|---|---|---|
| | **Figure** | **Parameter Represented** | **Figure Class C** | **Figure Class C & D** | **Results of Analysis (See Note 1)** | **Deductions/Conclusions Associated with Learning** | |
| 8 | 59 | Shipbuilding Age Demographics - 2020 | 62 | 59<br>62 | Class C Ships:<br>Production Planning shows a bi-modal distribution of employees with 40% at retirement age and 33% within 10 years of retirement, but only 7% within 5 years of retirement.<br>Class C & Class D:<br>Almost 50% are of retirement age or within 10 years of retirement age.<br>Only 23% are the next leaders within Shipbuilding (35 to 44 age demographic.<br>Approximately 28% are inexperienced (age 34 and younger). | Class C Ships:<br>The 7% within 5 years of retirement is of a concern because this demographic population will not be able to retain all of the knowledge from the retirement eligible demographic.<br>Class C and Class D<br>In regards to knowledge management and learning, a concerted effort must occur to capture the shipbuilders that are retirement age to prepare the next set of leaders and to help the new hires move up their learning curve as efficiently as possible. | N/A for Class C Ships<br>VALID for Class D Ships |
| 9 | 60 | Shipbuilding Age Demographic - 1999 | 60 | 60 | Approximately one-half the number of shipbuilders compared to 2020.<br>Up to as much as 27% are retirement eligible or are within 4 years.<br>At least 13% are inexperienced plus some percentage of the 31 - 40 age demographic are also inexperienced. | In regards to knowledge management and learning, a concerted effort must occur to capture the shipbuilders that are retirement age to prepare the next set of leaders and to help the new hires move up their learning curve s efficiently as possible. | VALID for Class C Ships<br>N/A for Class D Ships |

Table 17 (continued)

| # | Class A Ships | | Key Parameters and Conclusions Affecting Learning Curves for Class C and Class D Ships | | | | Class C Ships and Class D Ships Triangulation of Class A Ships Valid or Invalid |
|---|---|---|---|---|---|---|---|
| | **Figure** | **Parameter Represented** | **Figure Class C** | **Figure Class C & D** | **Results of Analysis (See Note 1)** | **Deductions/Conclusions Associated with Learning** | |
| 10 | 61 | Shipbuilding Age Demographic - 1980 | 60 | 60 | 44% are retirement age are within 10 years of retirement.<br>37% are inexperienced.<br>Only 20% are the next future leaders of shipbuilding (35-44 age demographic.) | In regards to knowledge management and learning, a concerted effort must occur to capture the shipbuilders that are retirement age to prepare the next set of leaders and to help the new hires move up their learning curve s efficiently as possible.<br>Only this demographic data is applicable to Class A Ship data. In regards to 1980, Ship 3 was within 2 years of delivery and Ship 4 had just started.<br>Despite having a large percentage of inexperienced labor, Ship 4 was the start of delivering ships for less hours for the next 4 ships. | VALID for Class C Ships<br>N/A for Class D Ships |
| 11 | 63 | Employee Work Output for Shipbuilding and Repair | 63 | 63 | US Shipbuilding output increased by 45% over 20 years.<br>This is across all US shipbuilding and repair and not just low rate production.<br>Shows a slight rise in output in 1982, 1984, 1990, and 1998 with lows in 1987 and 1993. | The increase in outputs as well as the decrease in outputs appears during 2 Ship procurement time frames as well as 1 Ship procurement time frames. They also occur during times frames that had shorter times between deliveries as well as longer times too. As such, deductions and conclusions cannot be made in regards to the factors impacting shipbuilding based on Class A Ship data. However, Baker, Degnan, Gabriel, Tucker (2001) offers some explanations, which are delineated with this this Chapter. | VALID |

Table 17 (continued)

| # | Class A Ships | | Key Parameters and Conclusions Affecting Learning Curves for Class C and Class D Ships | | | | Class C Ships and Class D Ships Triangulation of Class A Ships Valid or Invalid |
|---|---|---|---|---|---|---|---|
| | **Figure** | **Parameter Represented** | **Figure Class C** | **Figure Class C & D** | **Results of Analysis (See Note 1)** | **Deductions/Conclusions Associated with Learning** | |
| 12 | 64 | Employee Work Output for Automotive and Aircraft Industries | 64 | 64 | US automotive and aircraft output increased by 120% and 85%, respectfully.<br>The automotive industry showed rises in output in 1983, 1989, 1994, and 1998 with lows in 1980, 1987, and 1995.<br>The aircraft industry showed rises in output in 1980, 1985, 1992, and 1998 with lows in 1982, 1984, 1989, and 1996. | Only 1998 shows a rise in output for shipbuilding, automotive, and aircraft industries.<br>None of the other years during this twenty year time frame in terms of yearly increases or decreases (except 1998).<br>The aircraft and automotive industries has an output per employee that is more than a factor of 4 per employee output for shipbuilding and repair. | VALID |
| 13 | 65<br>66 | Memory Retention | 65 | 66 | In a day after learning a new skill without any refreshers or review, most people will only retain about 20 to 30% of what they learned.<br>In a month after learning a new skill without any refreshers or review, most people will only retain about 10 to 15% of what they learned. | All aspects of low rate production does not support knowledge retention due to the cadence of ship production associated with this environment. Certain specific shipbuilding skills will be completed daily, like basic skills associated with each labor element. Applying those skills to specific ship evolutions that occur only once every x years will result in the loss of how to complete that specific job due to reverse learning/loss of learning that skill for that specific job.<br>Programs must be put in place to increase knowledge retention. | VALID |
| 14 | 67 | Relative Efficiency vs Experience | 67 | 67 | For shipbuilding, it takes at least 4 years for a shipbuilder to obtain 80% efficiency meaning 20% of the shipbuilder's work has to be re-worked.<br>After 1 year, a shipbuilder is only 50% efficient.<br>It takes over 15 years to achieve 100% efficiency. | The low rate production environment of shipbuilding increases the challenges associated with shipbuilder efficiency due to knowledge retention issues.<br>Programs must be put in place to support shipbuilder efficiency also referred to as time to talent. | VALID |

Table 17 (continued)

As Note 1 indicated for Table 17, the analysis associated with this data was captured by Chapter 4 via the research methodology.

As indicated, the results of WBS 12 were captured via Table 17, and the associated deductions were delineated herein next including the validation of the results.

**Key Parameter #1: Major Ship Construction Milestones**

Conclusion #1-1: Optimum Number of Months between Deliveries

- *Conclusion:* There is an optimum number of months between delivery dates that correlates to fewer hours to support design, construction, and delivery of low-rate production ships. This optimum number is a range of months, and it is an enabler to learning and knowledge retention and is ship class dependent.
- *Adjudication:* Three of the four shipyards associated with Class B Ships supported this conclusion associated with Class A Ships in regards to this parameter, Major Ship Construction Milestones. For Class A Ships, the optimum range of years between delivery dates was two and a half to three and a half years while for Class B Ships, the optimum range of years between delivery dates was one to two years. For Class C Ships, as indicated, labor hours associated with Class C Ships did not exist in the public domain; however, based on analyzing the data for each shipbuilder, the optimum number of months between deliveries was approximately four to ten months. For Class D Ships, only one ship has been delivered. As such, due to the relative immaturity of this class, deductions involving Class D ships in their impact to this parameter cannot be deduced at this time. This conclusion was derived from Class A Ships, validated by the data and

conclusions associated with Class B Ships, and validated by triangulation utilizing the data and conclusions associated with Class C and D Ships.

- *Validation:* **Valid**

Conclusion #1-2: Multi-Ship Procurements Reduces Production Durations

- *Conclusion:* Multi-ship procurements reduces production durations because, in part, learning and knowledge retention are more easily facilitated then single ship procurements.
- *Adjudication*: This conclusion was based on the relationship between schedule milestones and procurement strategies. For Class A Ships, Ship 4 was delivered in the fewest number of months followed by Ships 5, 7, and 1. This was, in part, due to build strategy changes and two ship buys enabling learning retention for these ships. For Class B Ships, Ship 11 was delivered in the fewest number of months followed by Ships 7, 9, and 5, due, in part, to two ship buys enabling learning. For Class C Ships, the number of months between deliveries declined as the number of ships associated with each multi-procurement contract increased. The multi-ship procurement contracts associated with both shipbuilders were either three or four ships. However, the Zeta Shipbuilder did receive one contract for eleven ships. The number of months between deliveries did not decrease over the duration of this multi-ship contract, but rather the number of months between deliveries actually oscillated every three to four ships. This could potentially lead to a conclusion that there was an optimum number of ships associated with multi-ship procurements; however, more detailed company or agency specific information would be required, which would be proprietary information and was beyond the scope of

this research. For Class D ships, less time between delivery dates correlates to less labor hours to support construction. This conclusion was derived from Class A Ships, validated by the data and conclusions associated with Class B Ships, and validated by triangulation utilizing the data and conclusions associated with Class C and D Ships.

- *Validation:* **Valid**

Conclusion #1-3: Multi-ship Procurements Results in Shorter Durations from Keel to Delivery

- *Conclusion:* Multi-ship procurements resulted in shorter durations from the major ship milestone of keel laying to delivery.
- *Adjudication:* This conclusion was based on the relationship between schedule milestones and procurement strategy and was a sub-set of Conclusion #1-2. For Class A Ships, two ship buys contributed to shorter duration from keel to delivery, which enabled learning and supports a learning culture thereby contributing to less hours to build a ship. This was also Valid for Class B Ships. Only the Epsilon Shipbuilder associated with Class C Ships validated this conclusion. The Zeta Shipbuilder’s durations between keel to delivery oscillated throughout the 18 ships that they delivered including the eleven ship multi-procurement contract as was delineated via Conclusion #1-2. This conclusion was derived from Class A Ships, validated by the data and conclusions associated with Class B Ships, and validated by triangulation utilizing the data and conclusions associated with Class C and D Ships.
- *Validation:* **Valid**

Conclusion #1-4: Time Between Contract Awards Affects Labor Hours to Build as Compared to the Previous Ship

- *Conclusion:* The less time between contract awards, even for single ship procurements, then the fewer hours required to build the ship as compared to the previous ship.
- *Adjudication:* For Class A Ships, the shorter the duration between contract award dates for single ship procurements and two ship procurements resulted in fewer hours to construct each ship. For Class B Ships, as the number of months between contract awards increased, so did the number of hours to build each ship. This was valid for three of the four shipyards. The Gamma Shipbuilder showed a decrease in the number of months between the third and fourth ships that they built, but an increase in the number of hours to deliver the fourth ship that the Gamma Shipbuilder delivered to their customer. As indicated, Class C Ship data in regards to hours to design, build, and deliver each ship does not reside in the public domain. As such, Class C Ship data cannot be used to validate this conclusion, but Class D Ship data can be used. Based on current projections of Class D Ship hours that will be spent based on information within the public domain, Class D Ships validated that less time between contract awards reduced the hours to build a ship. This conclusion was derived from Class A Ships, validated by the data and conclusions associated with Class B Ships, and validated by triangulation utilizing the data and conclusions associated with Class C and D Ships.
- *Validation:* **Valid**

## Key Parameter #2: Cumulation of Significant Changes

Conclusion #2-1: Requirements Stability, or Instability, Impacts the Labor Hours to Build the Ship Class

- *Conclusion:* The accumulation of significant changes and requirements increases the labor hours to build each ship of a class associated with low-rate production manufacturing.
- *Adjudication:* For Class A Ships, Ship 2 had the fewest number of changes and required the fewest hours to deliver. This stability in requirements enabled learning from the previous ship to be applied to Ship 2. For Class B Ships, Ship 5 required the fewest hours to deliver, and it did have changes, but it was the second ship of a two ship buy offsetting the effects of the changes. However, the next series of Class B ships that had the fewest hours to build also did not have any changes associated with them, and they were Ships 3, 1, and 6. Data in regards to changes associated with Class C Ships did not exist within the public domain; however, for Class D Ships, data did exist in regards to the accumulation of changes; however, Class D Ships are currently under construction, and they are experiencing growth in requirements during construction resulting in requirements instability. This instability, in the researcher's opinion, will result in an increase in labor hours to complete the construction for the three Class D Ships that are currently in various stages of construction. This conclusion was derived from Class A Ships, validated by the data and conclusions associated with Class B Ships, and validated by triangulation utilizing the data and conclusions associated with Class C and D Ships.
- *Validation*: **Valid**

Conclusion #2-2: Requirements Instability is a Disruptor to Learning

- *Conclusion:* An environment associated with continual change results in a level of instability which is a disruptor in regards to learning.
- *Adjudication:* Low-rate production environments usually yielded an environment with a high degree of change due to the long build durations which resulted in the customer trying to insert changes throughout the build duration. The net effect of this was an unstable baseline impacting ship over ship learning. For Class A Ships, other than Ship 2, the class experienced an increasing number of changes and the trend line for the labor hours required to build each ship also showed an increasing trend line too. For Class B Ships, the number of changes continued to grow through the ship class even though five of the fourteen Class B Ships did not have any significant changes. Even though these five ships did not have any documented significant changes, there impacts were still realized throughout the ship class. No information resides within the public domain in regards to changes associated with Class C Ships. However, Class D Ships are currently under construction, and they are experiencing growth in requirements during construction resulting in requirements instability. This instability, in the researcher’s opinion, will result in an increase in labor hours to complete the construction for the three Class D Ships that are currently in various stages of construction. This conclusion was derived from Class A Ships, validated by the data and conclusions associated with Class B Ships, and validated by triangulation utilizing the data and conclusions associated with Class C and D Ships.
- *Validation:* **Valid**

## Key Parameter #3: Significant Changes Compared to Previous Ship

### Conclusion #3-1: Fewer or No Changes Compared to the Previous Ship Provides a More Stable Environment for Learning

- *Conclusion:* If there are no significant changes from the previous ship or fewer changes compared to the previous ship, then there is a reduction in hours to build that ship. Fewer or no changes compared to the previous ship provides a more stable environment for learning.
- *Adjudication:* For Class A Ships, only one ship, which was Ship 2, did not have any significant changes, and it took fewer hours to build. However, for Class B Ships, five ships of the class did not have any significant changes, which were the first three ships as well as Ship 6 and Ship 8, but two of those ships showed an increase in hours to build. For Class B Ships, one of the ships had no changes but the hours to build rose by five percent, which is negligible. Two of the shipyards had one ship with an increase in changes but a decrease in hours to build. All of the other ships built by the four shipyards showed an increase in changes yielding an increase in hours to build each ship. For Class C Ships, no information resides within the public domain in regards to changes. However, Class D Ships are currently under construction, and they are experiencing growth in requirements during construction of each ship resulting in requirements instability. This instability, in the researcher’s opinion, will result in an increase in labor hours to complete the construction for the three Class D Ships that are currently under various stages of construction. This conclusion was derived from Class A Ships, validated by the data and conclusions associated with Class B Ships, and validated by triangulation utilizing the data and conclusions associated with Class C and D Ships.

- *Validation:* **Valid**

Conclusion #3-2: Changes Increases New Information that has to be Learned

- *Conclusion:* The number of changes affects the number of hours to build each ship which directly impacts the amount of new information that has to be learned from ship to ship.
- *Adjudication:* This conclusion was focused on an assessment of each of the previous ships associated with the entire ship class as well as incorporating the elements associated with learning as delineated by Table 12 Items 13 and 14, memory retention parameter and relative efficiency vs experience parameter. As was validated in support of Conclusions' #2-1 and #3-1, an increase in changes as compared to the previous ship results in more hours to build that ship. This was simply due to the fact that the areas of the ship that were impacted by the changes were new areas which have to be learned thereby negating the learning that had occurred previously. Factoring the memory retention and relative efficiency versus experience parameters into these yields reverse learning in these areas due to changes. As such, in areas of the ship that have experienced changes as compared to the previous ship, reverse learning not only was comprised of forgetting how a specific area of the ship was built due to the number of months or even years since that area of the ship was last constructed, but reverse learning was also impacted by having to un-learn how that area of the ship was built due to the new changes associated with that specific ship. This phenomenon is applicable to all classes of ships including Class A, B, C, and D Ships. As indicated, changes impacting Class C Ships was not resident within the public domain, but Class C Ships would also experience this same type of reverse learning. This conclusion was derived from Class A

Ships, validated by the data and conclusions associated with Class B Ships, and validated by triangulation utilizing the data and conclusions associated with Class C and D Ships.

- *Validation:* **Valid**

### Key Parameter #4: Procurement Strategy

Conclusion #4-1: Multi-Ship Procurements Increase the Opportunity Associated with Learning

- *Conclusion:* Multi-ship procurement strategies increases the probability that learning will be shared between those ships associated with the multi-ship procurement.
- *Adjudication:* Four of the Class A Ships, Ships 5 and 6 as well as Ships 7 and 8, and four of the Class B Ships, Ships 2 and 4 as well as Ships 3 and 5, were procured via two ship buys. Two ship or multi-ship procurements increase the probability that learning will be shared between the ships that were part of the multi-ship procurement. For Class C Ships as indicated previously, only the first Flight of this class was utilized for this research. Class C Ships were partially procured via a multi-ship procurement strategy. The Epsilon Shipbuilder built thirteen Flight I Class C Ships which included:
    - Three procurements (contracts) of one ship each,
    - Two procurements (contracts) of three ships each, and
    - One procurement (contract) of four ships.

  The Zeta Shipbuilder built eighteen Flight I Class C Ships which included:
    - One procurement (contract) of three ships,
    - One procurement (contract) of four ships, and
    - One procurement (contract) for eleven ships.

As indicated, labor hours to build Class C Ships did not reside in the public domain; however, months between delivery dates did exist. All of the multi-ship procurement contracts, other than the eleven-ship contract for the Zeta Shipbuilder, showed a decreasing trend in months between delivery dates. This correlates to less hours to build and deliver these ships which was indicative of an environment that was based on ship over ship learning. For Class D Ships, the first two ships of this class were single ship procurements; whereas, Ships 3 and 4 were procured together via a two ship buy. Only one ship of this class has been delivered so far; however, a two ship buy coupled with minimizing time between deliveries were enablers to learning. This conclusion was derived from Class A Ships, validated by the data and conclusions associated with Class B Ships, and validated by triangulation utilizing the data and conclusions associated with Class C and D Ships.

- *Validation:* **Valid**

Conclusion #4-2: Two Ship Procurements results in Fewer Hours to Build and Deliver the Second Ship, and can Offset the Impact of Changes

- *Conclusion:* Two ship or multi-procurement buys results in fewer hours to build each ship especially for the second ship of a two ship buy, and can offset the impact of changes as compared to the previous ship. This procurement strategy is a learning enabler.

  *Adjudication:* Two ship or multi-ship procurement buys positively impacts a shipyard in a number of ways. For Class B Ships, the second ship of a two ship buy not only was a learning enabler for the second ship of the two ship buy resulting in less hours to build the second ship as compared to the first ship, but these two ships also experienced changes compared to the previous ship. The additional hours needed to implement these changes was offset by the two-ship buy for Class B Ships. For Class A Ships, an increase in the number of changes, except for Ship 5 and Ship 7, corresponded to an increase in the number of hours to build. These two ships were the first ship of a two ship buy, and they took fewer hours to build compared to the previous ship that shipyard built but had more changes. This was attributed to the shorter durations between ship deliveries. For class B Ships, an increase in the number of changes, except for Ships 6, 7, 12, 13, 14, corresponded to an increase in the number of hours to build. For these ships, they had fewer changes than the previous ship built at their respective shipyard, but they required more hours to build. These ships had longer durations between ship deliveries. As such, durations between ship deliveries affected the number of hours to build Class A and Class B Ships, which also impacted the ability to accommodate changes. Less time between deliveries reduces the amount of learning that was lost thereby allowing a shipyard to be able to address changes in a more efficient manner from a learning characterization perspective. As indicated, labor hours to build Class C Ships did not reside in the public domain; however, months between delivery dates did exist. All of the multi-ship procurement contracts, other than the eleven-ship contract for the Zeta Shipbuilder, showed a decreasing trend in months between delivery dates. This correlates to less hours to build and deliver these ships which was indicative of an environment that was based on ship over ship learning. For the Zeta Shipbuilder, based on the analysis of the data, the procurement of the eleven ships together did not result in the same reduction in delivery times as did the contracts associated with fewer ships. For Class D Ships, the first two ships of this class were single ship procurements whereas Ships 3 and 4 were procured together via a two ship buy. Only one ship of this class has been delivered so far; however, a two ship buy coupled with minimizing time between deliveries were enablers to learning. This conclusion was derived from Class A Ships, validated by the data and conclusions associated with Class B Ships, and validated by triangulation utilizing the data and conclusions associated with Class C and D Ships.

- *Validation:* **Valid**

Conclusion #4-3: Each Ship Class will have an Optimum Range of Months between Delivery Dates

- *Conclusion:* Each ship class will have an optimum range of months between delivery dates that enables learning between each low-rate production ship designed, built, tested, and delivered to its' respective customer. This optimum range of months is also impacted by other factors such as capacity, available footprint, current workload, and so on. These additional factors are outside the scope of this research because more detailed company or agency specific information would be required, which is proprietary information.
- *Adjudication:* Ships with delivery dates that were closer together support learning being transferred from one ship to the next more effectively than ships that have longer durations between ship deliveries. For Class A Ships, ships with delivery dates that were within 3.4 years or less from the previous ships shows a reduction in labor hours to support delivery of that ship. This was a learning enabler by reducing the time between completing similar tasks associated with designing and building a ship especially

compared to durations longer than 3.4 years. For Class B Ships, this fact was also valid thereby validating this conclusion. The optimum time frame was different since Class B Ships are a different ship class compared to Class A Ships, obviously. As indicated, there were multiple factors impacting the optimum time between deliveries that maximizes learning transfer and knowledge management. For Class B Ships, twenty-nine months or less between deliveries, coupled with two ship buys, was an optimal time between ships with fewer hours required to support delivery. As has been discussed, labor hours to build each Class C Ship did not exist in the public domain; however, for this parameter, reduction in the number of months between delivery dates does correlate to the number of months associated with build durations for this class of ships. Fewer months to build a low-rate production ship did corelate to fewer hours to build a low-rate production ship. As a result, for Class C Ships produced by the Epsilon Shipbuilder, the optimum number of months between delivery dates was seven months, and for the Zeta Shipbuilder, the optimum number of months between delivery dates was six months. Most of these ships were produced using a multi-ship procurement strategy approach, which was also already indicated as a contributing factor supporting learning transfer from ship to ship. Three of the current four ships associated with Class D Ships are still in production; however, the plan of record for these ships validates this conclusion because it shows two-ship procurements with a reduction in labor hours accordingly. This conclusion was derived from Class A Ships, validated by the data and conclusions associated with Class B Ships, and validated by triangulation utilizing the data and conclusions associated with Class C and D Ships.

- *Validation*: **Valid**

Conclusion #4-4: Multi-ship Procurements Coupled with Minimizing Time between Deliveries Reduces Labor Hours.

- *Conclusion:* Multi-ship procurements coupled with minimizing time between deliveries enables learning and knowledge transfer thereby reducing labor hours to support construction and delivery of low-rate production ships. Each ship class exhibits an optimum range of the number of ships associated with a multi-ship procurement as well as an optimum range of the number of months between successive deliveries.
- *Adjudication:* Class A Ships and Class B Ships both benefited through fewer hours required to support construction and delivery on those ships that had two ship buys as well as minimized the time between deliveries. Class A Ships had two – two ship buys with both resulting in fewer hours to construct the second ship of the two ship buy. The same conclusion was deduced from Class B Ships thereby validating this conclusion. For both of these classes of ships, there were only single ship procurements or two ship procurements. As such, regarding the optimum number of ships that constitute a reduction in the labor hours, for Class A and B Ships, the only deduction that can be made is two ships. In regards to Class C Ships, again, labor hours associated with this class of ship does not exist on the public domain; however, multi-ship procurements of three and four ships showed a reduction in the time between deliveries. Lastly, for Class D Ships, the plan of record shows two-ship procurements with a reduction in labor hours accordingly. This conclusion was derived from Class A Ships, validated by the data and conclusions associated with Class B Ships, and validated by triangulation utilizing the data and conclusions associated with Class C and D Ships.
- *Validation:* **Valid**

### Conclusion #4-5: Multiple Ship Procurement Contracts are Executed via Three Different Approaches with Each Reflecting Different Milestone Durations

- *Conclusion:* Multiple ship procurement contracts are executed in series, in parallel, or in a hybrid strategy resulting in milestones based on a contract award date which does not reflect actual ship delivery durations**.**
- *Adjudication:* Multiple ship procurement contracts were either executed in one of three strategies:
    - in series,
    - in parallel, or
    - a hybrid strategy whereby some ship construction milestones are obtained in series while others are obtained in parallel.

The execution of which strategy was chosen was based on many factors; however, for the purposes of this research, an understanding of the strategy utilized for each procurement contract as well as the subsequent construction strategy should be assessed accordingly because each strategy would impact learning differently. A multiple ship procurement strategy whereby the execution was done in series would have less knowledge transfer and learning as compared to a strategy whereby the low-rate production ships were constructed in parallel. Conversely, a hybrid construction strategy where some of the ship's milestones were obtained via parallel construction and some of the ship's milestones were obtained via series construction would result in learning and knowledge transfer to occur more than the series construction but not as much as the parallel construction strategy. There did not exist enough information in the public domain to be able to assess the degree or amount of influence these different approaches has on learning in low-rate production environments.  As such, additional research in this area would only be able to occur within each company as the resulting required information to perform this assessment would be proprietary to that specific company.  Regardless, for the purposes of this research, an understanding of these three strategies would at least provide context for the learning resident within each approach, and it also provided insights into the context for each ship construction milestone as they relate to contract award for that specific multiple ship procurement.

For multiple ship procurements, the contract award date was the same for all ships within that specific contract.  As such, without understanding the details associated with this procurement, the follow-on ships after the first ship of the contract could appear to take longer to build if they were all measured off of the contract award date for all of the ships affiliated with that specific contract.  This exact issue was identified by the researcher for all four ship classes affiliated with the research contained herein.  For Class A Ships, the second ship of both two ship procurements “artificially” [researcher’s quotes] shows that the second ship takes longer to build based on the contract award date. However, this was not the case because the second ship of the two ship procurements that occurred for Class A Ships started construction after the first ship.  Data in the public domain did not provide the actual start of construction date for the second ship of the two ship buys for Class A Ships.  Utilizing the data in the public domain for Class A Ships, the first ship of the two ship buy for Ships 5 and 6 took eighty-two months to build while the second ship of the two-ship buy would have taken one-hundred and fourteen months to build based on the contract award date accordingly.  The same was also valid for Ship 7 and 8 for the Class A Ships.  Using data in the public domain, Ships 7 and 8 took eighty-nine and one-hundred and twenty months to build respectfully, again based on the contract award date for Ships 7 and 8 for Class A Ships. It took fewer hours to build the second ship of these two ship contracts which would equate to shorter construction times.

Similar to Class A Ships, Class B Ships also validated this same conclusion. For the Beta Shipbuilder, Ships 2 and 4 were a two-ship procurement as well as Ships 3 and 5 for the Gamma Shipbuilder. Utilizing the contract award date, the number of months from contract award to delivery increased by twenty-three months for the second ship of the two ship buy for the Beta Shipbuilder, and twelve months for the Gamma Shipbuilder. As was the case for the Class A Ships, the second ship of both two ship procurements were delivered more cost effectively then the first ship. Again, as has been discussed, there was not enough information in the public domain to understand which build strategy was employed for the second ship of the two-ship buy; however, Class B Ships validated the conclusion that the second ship of a two-ship buy did not take longer to build despite not having the actual number of months to build the second ship of a two-ship buy because that level of data did not exist in the public domain.

Class C and Class D Ships validates this conclusion too via triangulation to the conclusion developed as a result of the Class A Ships. As has been indicated, both shipbuilders affiliated with Class C Ships had multiple ship procurement contracts, and in each case, the follow-on ships associated with each procurement showed an increasing number of months to build each ship because of the common contract award date even though the actual start date for each successive ship affiliated with each multiple ship procurement contract was in actuality a different date. Class D Ships had one – two ship contract which also validates this conclusion along with the Class C Ships. As such, in conclusion, the second ship of a two ship buy appeared to take longer to build, but it did not since it shares its' contract award date with the first ship of the two ship buy. This conclusion was also valid for the successive ships of any multiple ship procurement. This conclusion was derived from Class A Ships, validated by the data and conclusions associated with Class B Ships, and validated by triangulation utilizing the data and conclusions associated with Class C and D Ships.

- *Validation:* **Valid**

### Key Parameter #5: Principal Production Labor Elements

Conclusion #5-1: Low-rate Production Shipbuilding is Accomplished by Principal Production Labor Elements

- *Conclusion:* Low-rate production shipbuilding is accomplished by principal production labor elements; as such, in order to develop a knowledge management culture, learning strategies that are developed must include these labor elements supporting low-rate production shipbuilding.
- *Adjudication:* Production labor profiles and distributions will vary from ship class to ship class due to the intended mission profiles and funding profiles associated with each ship class. Eighty percent of the production labor associated with Class A Ships involved the following eight labor elements of: electrical, machinery, painters, pipefitters, riggers, sheet metal workers, shipfitters, and welders. As such, any knowledge management actions should at least include these eight areas. For Class B Ships, ninety-eight percent of the production labor associated with Class B Ships involved six major areas of electrical, mechanical, painting, production support, steel work, and welding.

For Class C Ships, the principal areas included: electrical, machinery, painters, pipefitters, shipfitters, and welders, and for Class D Ships, the areas were: electrical, fitters, machinery, outfitting, pipefitters, and welders. As such, the important conclusion that has been validated and triangulated was that there is a defined labor profile to focus knowledge management actions. This conclusion was derived from Class A Ships, validated by the data and conclusions associated with Class B Ships, and validated by triangulation utilizing the data and conclusions associated with Class C and D Ships.

- *Validation:* **Valid**

### Key Parameter #6: Principal Non-Production Labor Elements

<u>Conclusion #6-1: Low-rate Production Shipbuilding is Accomplished by Principal Non-Production Labor Elements</u>

- *Conclusion:* Low-rate production shipbuilding is accomplished by principal non-production labor elements; as such, in order to develop a knowledge management culture, learning strategies that are developed must include these labor elements associated with low-rate production shipbuilding.
- *Adjudication:* Non-production labor profiles and distributions will vary from ship class to ship class due to the intended mission profiles and funding profiles associated with each ship class. For Class A Ships, data did not exist in the public domain for the principal non-production labor elements. However, the researcher assumed that engineering, management, administration, and production support were some of the key non-production elements associated with low-rate production shipbuilding. Since both Class A Ships and Class B Ships were produced in low-rate production environments, there

non-production labor profiles were assumed to be similar. For Class B Ships, the principal non-production labor elements were: administration, support, engineering, and management. The information in the public domain associated with Class C Ships was primarily focused on the different disciplines within engineers and designers. However, management, planning, and production control were also highlighted as the principal non-production labor to support the production of Class C Ships. Class D Ships highlighted construction support, production support, and engineering support. This conclusion was derived from Class A Ships, validated by the data and conclusions associated with Class B Ships, and validated by triangulation utilizing the data and conclusions associated with Class C and D Ships.

- *Validation:* **Valid**

### Key Parameter #7: Funding Profiles and Strategies

Conclusion #7-1: Funding Profiles and Strategies Impacts Learning

- *Conclusion:* The funding profiles and subsequent funding strategies are determined and developed by the customer which are not optimized to support and/or accommodate the shipbuilder thereby impacting the ability to maximize learning in low-rate production shipbuilding.
- *Adjudication:* For Class A Ships, the ship with the longest duration between deliveries, which was due to the timing and profile of the funding to build that particular ship, required the greatest number of hours to build, which was Ship 10. Ship 10 was also the last ship of the class. As such, most of the learning gained from the previous ship was lost due to the longer duration between ships. For Class B Ships, the ship with the

longest time between deliveries was Ship 11, and it required the second greatest number of hours to build. Ship 14 was the last ship of the class, and required the most hours to build. In both cases, the funding profile and associated procurement strategy contributed to the loss of learning for these ships. Conversely, for both Class A and Class B Ships, funding profiles with fewer months between contract awards as well as multi-ship procurements facilitated learning as evidence by the reduction in labor hours to build the second ship of a two ship buy for these two ship classes. For Class C Ships, both shipbuilders were able to build some of the ships of this class via a multi-ship procurement strategy approach. Multi-ship procurement strategies also had the effect of less time between deliveries. However, the Zeta Shipbuilder had one contract that was comprised of eleven ships, which resulted in increasing the number of months between deliveries associated with those eleven Class C Ships especially as compared to procurement strategies of two to four ships for both the Epsilon and Zeta Shipbuilders. The data and conclusions associated with Class C Ships validated the conclusions derived from Class A Ships. In regards to Class D Ships, Ships 3 and 4 were associated with a multi-ship procurement strategy whereby Ship 4 was projected to be delivered for fewer labor hours with less time between deliveries. As validation showed, the funding profiles and funding strategies, which were determined by the customer, has a direct effect on the learning associated with low-rate production shipbuilding. This conclusion was derived from Class A Ships, validated by the data and conclusions associated with Class B Ships, and validated by triangulation utilizing the data and conclusions associated with Class C and D Ships.

- *Validation*: **Valid**

### Conclusion #7-2: Time Between Deliveries versus Number of Changes

- *Conclusion:* Time between deliveries and/or contract award dates has a greater influence on learning than the number of changes for low-rate production ships.
- *Adjudication:* As was delineated within the Assumptions Section of this research, by definition, low-rate production shipbuilding not only referred to the periodicity of successive ship deliveries, but it also referred to the ship complexity as well as the large number of labor hours to design, build, test, and deliver ships of certain ship classes. This assumption was applicable to this conclusion discussion because low-rate production ships require a larger number of labor hours to produce as compared to high-rate production ships such that the impact from changes on low-rate production ships has the potential to be absorbed easier due to the large number of labor hours and longer production durations associated with low-rate production ships. The degree of the impacts associated with these changes requires proprietary information which was beyond the scope of this research. For Class A Ships, Ship 10 required the greatest number of hours of all ships in this class to design, build, test, and deliver. Ships 10 also had the longest duration between ship deliveries of almost six years. Ship 3 had the longest duration between contract awards of seven years while Ships 9 and 10 had the second longest durations between contract awards of six and a half years. Ship 10 had the greatest number of changes while Ship 9 had the seventh greatest number of changes. Both Ships 9 and 10 were single ship procurements. In regards to Class A Ships, time between deliveries had a greater impact on learning than the number of changes. For Class B Ships, Ship 14 required the greatest number of hours of all ships in this class to design, build, test, and deliver followed by Ship 11. Ship 12 had the longest duration

between ship deliveries of four and a half years, and Ship 11 had the longest duration between contract awards of seven and a half years.  Ship 9 had the greatest number of changes followed by Ship 11.  All of the ships of this class were single ship procurements other than Ships 2 and 4 as well as Ships 3 and 5.  As such, the data associated with Class B Ships validated the conclusion from the data associated with Class A Ships that the time between deliveries and/or contract awards has a greater influence on learning than the number of changes for low-rate production ships.

For Class C Ships, as has been indicated, hours to design, build, test, and deliver Class C Ships did not exist in the public domain.  However, due to the fact that there were thirty-one ships associated with Flight 1 of the Class C Ships that were built over a fifteen-year time frame, the researcher utilized the total number of months to build a Class C Ship to equate to the number of hours to build each Class C Ship meaning the more months to build a Class C Ship equated to more hours to build that specific Class C Ship.  This was a valid assumption captured within the Assumptions Section accordingly.  As has been indicated, thirty-one Class C Ships were procured via five multi-ship procurement contracts.  As such, the Class C Ships that were procured via the five different multi-ship procurement contracts had different contract award dates with different delivery dates.  The piece of data that did not exist in the public domain was the actual construction start date for each ship associated with a multi-ship procurement strategy.  This was important because as Conclusion #4-5 discussed, the second ship of a two-ship procurement as well as successive ships of a multi-ship procurement strategy can appear to take longer to build when in actuality they did not because the construction start date was after the contract award date for each ship associated with each multi-ship procurement contract. To determine the validity of this conclusion using Class C Ship data, the researcher utilized the number of months from keel to delivery for each Class C Ship affiliated with a multi-ship procurement strategy. Using this information within the context of a multi-ship procurement strategy of two to four Class C Ships, then this conclusion was validated by Class C Ship data because as the number of months between delivery dates decreased then so did the number of months from keel to delivery which would equate to fewer hours to build each Class C Ship. Single ship procurements as well as well as ship procurements of eleven ships did not validate this conclusion. As noted, this conclusion was only validated for two to four ship procurement strategies because that was the basis of the data associated with Class C Ships. In terms of Class D Ships, based on the current information available in the public domain coupled with the fact that three of the four ships of this class have not been delivered yet, the time between deliveries impacted the number of hours to build each ship. The basis for a reduction in costs to build Ship 4 of this class was due to a two-ship procurement strategy as well as reducing the time between ship deliveries. This conclusion was derived from Class A Ships, validated by the data and conclusions associated with Class B Ships, and validated by triangulation utilizing the data and conclusions associated with Class C and D Ships.

- *Validation:* **Valid**

### Key Parameter #8: Shipbuilding Age Demographics – 2020

Conclusion #8-1: 2020 Demographic Environment within Shipbuilding Impacts Learning

- *Conclusion:* The demographic environment directly impacts learning and the knowledge management culture of low-rate production shipbuilding. Utilizing the referenced 2020 demographic data, the large number of shipbuilders that are within ten years of retirement, as compared to previous years, is a learning disruptor because the bi-modal distribution of experience as well as a large percentage of shipbuilders that are close to retirement inhibits knowledge transfer which negatively affects learning.

- *Adjudication:* The Class A Ships were built in the United States whereas the Class B Ships were built in England. The Class A Ships were built and delivered before 2020; as such, this demographic data set was not applicable to the Class A Ships. As a matter a fact, only the Class D Ships would be applicable to this demographic data set. Also of note, for the purposes of this research, and given the similarities of the two countries, the researcher assumed that England has the same demographic profiles as the United States. Using the 2020 shipbuilder demographic data, there were double the number of shipbuilders then there were twenty years ago. Approximately one-half of the shipbuilders in 2020 were within ten years of retirement age. Over one-quarter of the shipbuilders in 2020 were inexperienced. As such, in regards to knowledge management and learning, for Class D Ships, a concerted effort must have occurred to capture the knowledge associated with the shipbuilders that were retirement age to prepare the next set of leaders and to help the new hires move up their learning curve as efficiently as possible. As indicated, this conclusion was based on demographic data describing shipbuilders in 2020, which from a Ship Class perspective would only be directly applicable to Class D Ships, and specifically, the end of Ship 1, most of Ship 2, and the beginning of Ship 3. However, given the demographics delineated using the 2020 demographic data, this conclusion was validated, and that in order to increase the probability that learning was enabled for Class D Ships, the shipbuilder must develop a strategy to address this learning disruptor due to the bi-modal workforce experience demographic. It should also be noted the 2020 demographic data was captured prior to the COVID-19 global pandemic, which would impact the demographic data accentuating this learning disruptor. Due to the nature of the data for this conclusion, only Class D Ships can validate this information.

- *Validation:* **Valid within the context of Class D Ships since 2020 data was the basis for this demographic assessment.**

### Key Parameter #9: Shipbuilding Age Demographics – 1999

<u>Conclusion #9-1: 1999 Demographic Environment within Shipbuilding Impacts Learning</u>

- *Conclusion:* The demographic environment directly impacts learning and the knowledge management culture of low-rate production shipbuilding. Utilizing the referenced 1999 demographic data, there were one half the number of shipbuilders as compared to the 2020 demographic data, and the demographic distribution is a skewed bell curve reflective of a more experienced workforce. With this distribution, the transfer of knowledge, and as a result, learning is more enabled compared to the 2020 demographic data.
- *Adjudication:* In regards to the 1999 demographic data, only some of the Class A Ships were built during this time frame. The Class A, C, and D Ships were built in the United States whereas the Class B Ships were built in England. Also of note, for the purposes of this research, and given the similarities of the two countries, the researcher assumed that England has the same demographic profiles as the United States. Using the 1999 shipbuilder demographic data, there were one-half the number of shipbuilders compared

to the 2020 data. Approximately one-quarter of the shipbuilders in 1999 were within ten years of retirement age, and about twelve percent of the shipbuilders in 1999 were inexperienced. There are half the number of shipbuilders as compared to 2020 and about twenty percent less than 1980. As such, 1999 was a “valley” [researcher’s quotes] in the number of shipbuilders between 2020 and 1980. Over thirteen percent plus some percentage of the thirty-one to forty age group were inexperienced. As such, in regards to knowledge management and learning, a concerted effort must have occurred to capture the shipbuilders that are retirement age to prepare the next set of leaders and to help the new hires move up their learning curve as efficiently as possible. This conclusion cannot be validated using the labor hour data for the last Class A Ship because given the low-rate production, only one ship would be applicable to this demographic time frame. As such, in regards to knowledge management and learning, for Class A Ships, the age demographic profile was more conducive to efficient learning and knowledge transfer as compared to the 2020 demographic data. As indicated, this conclusion was based on demographic data describing shipbuilders in 1999, which from a ship class perspective would only be directly applicable to the last Class A Ship. Additional data, not in the public domain, would be required to establish connectivity between the demographic data and the direct impact to labor hours. This conclusion was derived from Class A Ships and validated by the 1999 demographic data accordingly.

- *Validation:* **Valid within the context of Class A Ships since 1999 data was the basis for this demographic assessment.**

### Key Parameter #10: Shipbuilding Age Demographics – 1980

Conclusion #10-1: 1980 Demographic Environment within Shipbuilding Impacts Learning

- *Conclusion:* The demographic environment directly impacts learning and the knowledge management culture of low-rate production shipbuilding. As such, in regards to knowledge management and learning, a concerted effort must have occurred to capture the shipbuilders that are retirement age to prepare the next set of leaders and to help the new hires move up their learning curve as efficiently as possible.
- *Adjudication:* In regards to the 1980 demographic data, only Class D Ships would not be applicable. Class A, B, and C Ship construction spanned the 1980s, and as such, this demographic data would represent some of the ships within each of these three classes. The Class A, C, and D Ships were built in the United States whereas the Class B Ships were built in England. Also of note, for the purposes of this research, and given the similarities of the two countries, the researcher assumed that England has the same demographic profiles as the United States. Utilizing the referenced 1980 demographic data, there were twenty percent more shipbuilders in 1980 as compared to 1999, but approximately forty percent fewer shipbuilders in 1980 as compared to 2020. About forty-four percent in 1980 were retirement eligible or were eligible within ten years. Over thirty-five percent were inexperienced, and only twenty percent in 1980 were available to be the future leaders of shipbuilding by being in the thirty-five to forty-four age demographics. The 1980 demographic profile shows a very similar bi-modal distribution as the 2020 demographic profile. There were more low-rate production ships being built during the late 1970s and early 1980s which would enable learning thereby reducing the impacts associated with a bi-modal demographic distribution. This

conclusion was derived from Class A Ships, validated by the data and conclusions associated with Class B Ships, and validated by triangulation utilizing the data and conclusions associated with Class C Ships.

- *Validation:* **Valid**

Conclusion #10-2: Increasing the Number of Low-rate Production Ships Assists Offsetting a Demographic Environment that is a Learning Disruptor

- *Conclusion:* Increasing the number of low-rate production ships is a learning enabler to assist with offsetting a demographic environment with a bi-modal age distribution and/or a demographic environment with a skewed retirement age distribution.
- *Adjudication:* The Class A Ships were built in the United States whereas the Class B Ships were built in England. For the purposes of this research, and given the similarities of the two countries, the researcher assumed, which is captured within the Assumptions Section, that England has the same demographic profiles as the United States. Despite having a large percentage of inexperienced labor in 1980 at thirty-seven percent and forty-four percent at retirement age or within ten years of retirement age, Ship 4, which would have been directly impacted by these demographics because its' contract date was 1980, was the start of delivering ships for less hours for the next four Class A Ships. As indicated previously, these four ships had fewer months between deliveries and were two ship procurements such that the number of ships procured within this low-rate production environment were increased as compared to the rest of the class. The average time between deliveries for these Class A Ships was twenty-seven months as compared to the rest of the ships that made up this class, which had an average time between deliveries of

fifty-three months. The results of this were that the Class A Ships with an average of twenty-seven months between deliveries were designed, built, and tested for seven percent fewer labor hours as compared to the Class A Ships that had an average time between deliveries of fifty-three months. As such, the impacts to learning in low-rate production environment with a bi-modal and/or retirement aged demographic can be at least partially mitigated by increasing the number of ships that are being designed, built, and tested. As indicated, there were fourteen Class B Ships that were built by four different shipyards, and eight of the fourteen were delivered between 1980 and 1985. For Class B Ships, only three out of the remaining eight ships were delivered for the same or less hours than the previous ship. The average time between deliveries for these three ships was sixteen months compared to the remaining five ships of Class B which were delivered on average of six months between deliveries. It is important to note that this information was within the context of the fact that four different shipyards were involved building Class B Ships with one shipbuilder building three of the eight ships during this time frame, one shipbuilder built one ship during this time frame, and two built two during this time frame. However, analyzing this information for each individual shipbuilder within this time frame of 1980 to 1985 where eight ships were delivered yielded the fact that there were no two ship procurements during this time frame. It also yielded the fact that the cost to build each ship during this time frame increased for each ship. However, of the eight ships during this time frame, one ship (Ship 14) experienced a ten percent reduction in the number of months to deliver compared to the previous ship for the same shipbuilder. Ship 14’s cost grew by twenty-one percent. The remaining seven ships that were delivered after 1980 all experienced an increase in the number of months to deliver as compared to the previous ship, and their respective cost increased between thirty-two percent to fifty-one percent.  As indicated for Class B Ships, the eight ships that would have been impacted by the referenced 1980 demographic assessment all exhibited cost increases to build each successive ship by the four shipbuilders.  Given the demographic environment during this time frame, increasing the number of months between deliveries would increase the costs associated with ship deliveries, in part, due to the loss of learning driven by the learning disruptor of a bi-modal and retirement aged demographic distribution.  As such, the Class B data and information validates the conclusions derived from the Class A data and information.  For Class C Ships, Ships 24 through 31 for the Epsilon Shipbuilder and Ships 10 through 23 for the Zeta Shipbuilder were built between 1980 and 1985, and as such, the 1980 demographic data would then be applicable accordingly.  As also has been indicated, labor hours to build Class C Ships was not in the public domain.  For the Epsilon Shipbuilder, the average time between deliveries from 1980 to 1985 was ten months while the average time between deliveries for the Epsilon Shipbuilder from 1976 to 1979 was six months.  It should be noted that the Epsilon Shipbuilder also had multi-ship procurement contracts during this time frame as well which obviously positively impacted the time frame between deliveries. In regards to the Zeta Shipbuilder, the average time between deliveries was five months from 1980 to 1985 while the average time between deliveries from 1977 to 1979 was eight months.  The Zeta Shipbuilder also had multi-ship procurements which, as has already been discussed, supported learning accordingly.  However, the bi-modal demographic distribution did impact learning, and can be offset by utilizing other learning enablers like multi-ship procurement contracts.  The Class C data and associated analysis that was just discussed validates the Class A data and associated conclusions. Class D Ships were built and delivered after the 1980 demographic data; as such, this information was not applicable to Class D Ships. This conclusion was derived from Class A Ships, validated by the data and conclusions associated with Class B Ships, and validated by triangulation utilizing the data and conclusions associated with Class C Ships.

- *Validation:* **Valid**

### Key Parameter #11: Employee Work Output for Shipbuilding and Repair

Conclusion #11-1: US Shipbuilder Work Output has Grown Forty-Five Percent over 20 Years

- *Conclusion:* The employee work output for US shipbuilders has grown by forty-five percent over a twenty-year period from 1977 to 1998 (Baker, Degnan, Gabriel, and Tucker (2001)); however, this increase in work output is not attributable to ship procurement time frames or multi-ship procurement strategies, but rather, it is due to the learning characterization for each shipyard such as the organizational culture and the demographic environment. There are also other factors that influence work output, but they are outside the scope of this research.
- *Adjudication:* Figure 63 provided work output associated with shipbuilding for all shipyards including ship repair yards. Figure 63 did not provide information at the specific shipyard level nor work output by ship class as this information did not exist in the public domain nor was there a feasible way to extract the needed information from Figure 63. The increase in outputs as well as the decrease in outputs reflected via Figure 63 occur during time frames associated with Class A Ships that exhibited both shorter

and longer durations between deliveries as well as different procurement strategies for both single and two ship procurements. As substantiated by Baker, Degnan, Gabriel, and Tucker (2001), shipbuilding output per employee rose only forty-five percent over twenty years as compared to one-hundred and twenty percent for the automotive industry and eighty-five percent for the aircraft industry over the same time frame. Per Baker, Degnan, Gabriel, and Tucker (2001), this was due to several reasons, such as differences in workforce instability and age distributions, and other reasons. However, workforce stability and age demographics impacted learning through the shipbuilding environment and culture of learning resident in a given shipyard similar to the shipyards that built Class A, B, C, and D Ships. The automotive and aircraft industries were included herein to provide a reference to compare shipbuilding too even though the automotive and aircraft industries were not produced in a low-rate environment. This conclusion was derived from Class A Ships, validated by the data and conclusions associated with Class B Ships, and validated by triangulation utilizing the data and conclusions associated with Class C and D Ships within the context of Figure 63.

- *Validation*: **Valid**

### Key Parameter #12: Employee Work Output for Automotive and Aircraft Industries

Conclusion #12-1: US Aircraft and Automotive Industries has an Output per Employee Larger than the Output per Employee in Shipbuilding

- *Conclusion:* The aircraft and automotive industries has an output per employee that is more than the output per employee output compared to the shipbuilding industry. The difference in output per employee is due to the differences in their production environments (i.e., low-rate versus high-rate production) which is impacted by their overall learning characterizations between low-rate production and high-rate production environments.

- *Adjudication:* This conclusion was based on the information provided by Baker, Degnan, Gabriel, and Tucker (2001). As was the case with Conclusion #11-1, Figure 63 provides work output associated with shipbuilding for all shipyards including ship repair yards while Figure 64 provides work output associated with automotive and aircraft industries. Figures 63 and 64 did not provide information at the specific shipyard, aircraft, or automotive industry level nor associated work output by ship class, aircraft type, or automotive type. Similar to Conclusion #11-1, the work output associated with the aircraft and automotive industries was also influenced by workforce stability and age demographics too which impacts the learning characterization within these industries similar to shipbuilding. The only main difference in the learning characterizations of the aircraft and automotive industries compared to the shipbuilding industry was the fact that the learning environment associated with the aircraft and automotive industries was a high-rate production environment while the Class A, B, C, and D Ships were within the context of a low-rate production environment. This conclusion was derived from Class A Ships, validated by the data and conclusions associated with Class B Ships, and validated by triangulation utilizing the data and conclusions associated with Class C and D Ships within the context of Figures 63 and 64.
- *Validation:* **Valid**

## Key Parameter #13: Memory Retention

### Conclusion #13-1: Lack of Using Skills Results in Substantial Reduction in Knowledge Retention and Learning

- *Conclusion:* Most people after learning a new skill will only retain ten to fifteen percent of the knowledge that they learned after a month has transpired without any refreshers. As such, low-rate production environments that entail not using skills frequently increases the challenges associated with knowledge retention and learning.
- *Adjudication:* As Figures 65 and 66 illustrate, knowledge retention decreases within a day after training occurs. Training retention can be bolstered through refreshers as well as other learning strategies. Obviously, low-rate production environments were much more susceptible to this issue simply due to the very nature of their associated production environments as compared to high-rate production environments. As such, this conclusion was applicable to Class A Ships and was validated by Class B, C, and D Ships simply due to their context. Teichert (2010), Kohn (2014), Meacham (2016), and Brain Science (2022) discussed that knowledge retention can be increased after learning a new skill through “booster events,” which was any event that facilitates a person’s brain to associate the new information learned as important to assist with the memory retention process. Kohn (2014) simply states that “if you use it, you won’t lose it!” Ebbinghaus (1885, 1913) covered recommendations in regards to how to increase memory retention thereby increasing knowledge retention; however, the associated strategies to employ to bolster retention and/or increase knowledge retention especially in low-rate production environments is the subject of future research. Neither Ebbinghaus (1885, 1913) nor Kohn (2014), or any other researcher, specifically discussed knowledge retention within

the context of a low-rate production environment, such as shipbuilding. Additionally, future research within this area is viable including connectivity to requisite parsimony.

However, the researcher has also concluded that not every skill associated with low-rate production shipbuilding would erode following Figures 65 and 66. Basic shipbuilding skills such as drilling holes, cutting holes, and other fundamental operations would not experience a loss of learning. However, shipbuilding skills associated with using those fundamental skills to build parts of a system would experience some loss of learning while skills associated with building systems within the context of specific ship construction conditions would experience the highest loss of learning. A more in-depth assessment of this additional conclusion would also be the subject of future research and was beyond the scope of this research. This conclusion was derived from Class A Ships, validated by the data and conclusions associated with Class B Ships, and validated by triangulation utilizing the data and conclusions associated with Class C and D Ships within the context of Figures 65 and 66.

- *Validation:* **Valid**

## Key Parameter #14: Relative Efficiency versus Experience

Conclusion #14-1: Shipbuilder Efficiency is Affected by the Knowledge Management Culture

- *Conclusion:* The low-rate production environment of shipbuilding increases the challenges associated with shipbuilder efficiency due to knowledge retention issues.
- *Adjudication:* After working one year in shipbuilding, a shipbuilder is only fifty percent efficient, and after four years, a shipbuilder is only eighty percent efficient. As Figure 67 shows, it takes over fifteen years of experience for a shipbuilder to approach one hundred

percent efficiency. Figure 67 was for all shipbuilding, and it did not differentiate between low-rate production shipbuilding and high-rate production shipbuilding. Within the context of low-rate production shipbuilding, in the researcher's opinion, the slope of Figure 67 would be even less meaning that the time frame to reach fifty percent, eighty percent, and one hundred percent would take even longer. The exact slope of the low-rate production curve of relative efficiency versus years of experience would be the subject of future research. Conclusion #14-1 was applicable to all of shipbuilding; as such, this conclusion is applicable to Class A Ships, and was validated for Class B, C, and D Ships. This conclusion was derived from Class A Ships, validated by the data and conclusions associated with Class B Ships, and validated by triangulation utilizing the data and conclusions associated with Class C and D Ships within the context of Figure 67.

- *Validation*: **Valid**

As such, utilizing the Ship Class C and Ship Class D information to determine the key factors and conclusions affecting learning and comparing that information to the Class A Ship factors and conclusions affecting learning validated that the characterization developed using Class A Ships was validated via Class C and Class D Ships. Table 17 also captured this assessment as well.

In summary, as per the research methodology, only the hours to build each ship were assessed versus the different parameters associated with Class C and Class D Ships. As indicated previously, labor hours associated with Class C Ships was not in the public domain; as such, Class D data was used accordingly. After the Class C and Class D assessment was completed, the researcher developed conclusions associated with each parameter for Class C and Class D Ships. Afterwards, the conclusions associated with Class C and Class D Ships were compared to the conclusions associated with Class A Ships. This then in turn was used to validate the OLCC for learning on low-rate production environments. As such, Table 17 showed that the conclusions associated with Class A Ships were validated through triangulation by the conclusions associated with the Class C and Class D Ships.

## WBS 13: Low-Rate Production Overall Learning Curve Characterization versus Learning Curve Theories

As has been discussed throughout, the objective of this research was to develop a learning curve characterization for low-rate production shipbuilding. The results of WBS 7 and WBS 8 was that the leading learning curve theories of Wright (1936), Crawford (1944), DeJong (1957), Stanford-B (1949), and the Sigmoid S Curve (1973) did not characterize learning in low-rate production environments. Even though not stated in these five learning curve theories, they were intended for high-rate production environments, and not environments where a product is delivered once every few years. As such, this research has developed an overall learning curve characterization (OLCC), which was discussed via this research.

The learning curve theories of Wright (1936), Crawford (1944), DeJong (1957), Stanford-B (1949), and the Sigmoid S Curve (1973) did not and cannot characterize learning in low-rate production environments because these theories do not address the learning enablers nor the learning disruptors, which for low-rate production environments, were of much larger influence then high-rate production environments. Simply stated, in a high-rate production environment, which by its very nature has minimal loss of learning or reverse learning because the product was being produced in a manner that the skills to design, build, test, and deliver the product were not only not forgotten, but they can be optimized through learning. However, in low-rate production environments, not only does the time between products erodes learning, but the parameters that define the OLCC were amplified because they were residing in an environment that was counter to learning. As such, if left unchecked, the learning disruptors will quickly erode and eventually eradicate ship over ship learning. Employing tactical and strategic approaches using the learning enablers can reduce the impacts associated with the learning disruptors.

As stated, the researcher obtained and read all eighteen reports that were available from the Truman Library in regards to Wright's research. The researcher also read Wright (1936) and Wright (1943), and he was focused on various factors affecting the cost of airplanes, which included learning. After reviewing this information, the researcher deduced that Wright never intended his work to be used in different contexts. Wright's world view was completely different then today not just because his initial research was prior to the start of WWI and carried through WWII as well as the fact that he was influenced by WWI, but Wright was focused on airplane and airframe manufacturing in an effort to make the production as cost efficient as possible to support WWII. Other researcher's adopted Wright's Theory and started to expand it to other areas. Wright's Theory was accurate when it is used in a similar context that Wright based his research on; however, as has been clearly researched and demonstrated, Wright's Theory as well as all other derivatives of Wright's Theory, did not predict learning in low-rate production environments. The researcher believes that Wright did not intend his research to be used for all environments. In the researcher's opinion, Wright's research was focused on the context of his world view while he was performing his research. As such, not only does

Wright’s Theory not apply to low-rate production environments, but Wright never intended for his Theory to be used beyond the context that supported his research.

## WBS 14: Overall Learning Curve Characterization (OLCC)

This research has clearly shown that that learning in low-rate production environments does not exist in the public domain nor does the five leading learning curve theories address or characterize learning that exists in this unique environment within the context of low-rate production. A series of conclusions was deduced by the researcher by developing these conclusions using Class A Ship data, and then utilizing the research methodology, validated those conclusions based on Class A Ship data using Class B Ship data, and then triangulated the Class A Ship conclusions using Class C and Class D Ship data. The conclusions developed then was used by the researcher, per the research methodology, to develop a low-rate production learning curve characterization. The researcher developed the term, overall learning curve characterization (OLCC) to classify and describe the unique learning environment associated with these types of environments. The OLCC is based on the acronym, SPIKE, which the researcher also derived as well.

Table 18 provides a summary of the conclusions derived from Class A Ships, validated by Class B Ships, and triangulated by Class C and D Ships. Table 18 also provides connectivity to the overall learning characterization defined by the acronym SPIKE.

| Key Parameter # | Key Parameter | Conclusions Deduced from Class A Ship Data | | Validation & Triangulation of Class A Ship Conclusions | | | SPIKE |
|---|---|---|---|---|---|---|---|
| | | **Conclusion #** | **Conclusion Topic Summary** | **Validation using Class B Ships** | **Triangulation using Class C Ships** | **Triangulation using Class D Ships** | **Contribution to SPIKE** |
| 1 | Major Ship Construction Milestones | 1-1 | Optimum number of months between deliveries. | VALID | VALID | VALID | Stability (S) |
| | | 1-2 | Multi-ship procurements reduces production durations. | VALID | VALID | VALID | |
| | | 1-3 | Multi-ship procurements results in shorter durations from keel to delivery. | VALID | VALID | VALID | |
| | | 1-4 | Time between contract awards affects labor hours to build as compared to the previous ship. | VALID | VALID | VALID | |
| 2 | Cumulation of Significant Changes | 2-1 | Requirements stability, or instability, impacts the labor hours to build the sip class. | VALID | VALID | VALID | |
| | | 2-2 | Requirement instability is a disruptor to learning. | VALID | VALID | VALID | |
| 3 | Significant Changes Compared to Previous Ship | 3-1 | Fewer or no changes compared to the previous ship provides a more stable environment for learning. | VALID | VALID | VALID | |
| | | 3-2 | Changes increases the new information that has to be learned. | VALID | VALID | VALID | |

Table 18: Learning in Low-Rate Production Environments Summary of Conclusions, Validation, and Connectivity to SPIKE

| **Key Parameter #** | **Key Parameter** | **Conclusions Deduced from Class A Ship Data** | | **Validation & Triangulation of Class A Ship Conclusions** | | | **SPIKE** |
|---|---|---|---|---|---|---|---|
| | | **Conclusion #** | **Conclusion Topic Summary** | **Validation using Class B Ships** | **Triangulation using Class C Ships** | **Triangulation using Class D Ships** | **Contribution to SPIKE** |
| 4 | Procurement Strategy | 4-1 | Multi-ship procurements increase the opportunity associated with learning. | VALID | VALID | VALID | Procurement Strategy (P) |
| | | 4-2 | Two ship or multi-ship procurements results in fewer hours to build and deliver the second ship, and can offset the impact of changes. | VALID | VALID | VALID | |
| | | 4-3 | Each ship class will have an optimum range of months between delivery dates. | VALID | VALID | VALID | |
| | | 4-4 | Multi-ship procurements coupled with minimizing time between deliveries reduces labor hours. | VALID | VALID | VALID | |
| | | 4-5 | Multi-ship procurement contracts are executed via three different approaches with each reflecting different milestone durations. | VALID | VALID | VALID | |
| 5 | Principal Production Labor Elements | 5-1 | Low-rate production shipbuilding is accomplished by principal production labor elements. | VALID | VALID | VALID | Industrial & Organizational Culture (I) |
| 6 | Principal Non-Production Labor Elements | 6-1 | Low-rate production shipbuilding is accomplished by principal non-production labor elements. | VALID | VALID | VALID | |
| 7 | Funding Profiles and Strategies | 7-1 | Funding profiles and strategies impacts learning. | VALID | VALID | VALID | |
| | | 7-2 | Time between deliveries versus number of changes. | VALID | VALID | VALID | Stability (S) |

Table 18 (continued)

| **Key Parameter #** | **Key Parameter** | **Conclusions Deduced from Class A Ship Data** | | **Validation & Triangulation of Class A Ship Conclusions** | | | **SPIKE** |
|---|---|---|---|---|---|---|---|
| | | **Conclusion #** | **Conclusion Topic Summary** | **Validation using Class B Ships** | **Triangulation using Class C Ships** | **Triangulation using Class D Ships** | **Contribution to SPIKE** |
| 8 | Shipbuilding Age Demographics - 2020 | 8-1 | 2020 demographic environment within shipbuilding impacts learning.<br>(Only applicable to Class D Ships.) | N/A | N/A | VALID | Demographic Environment (E) |
| 9 | Shipbuilding Age Demographics - 1999 | 9-1 | 1999 demographic environment within shipbuilding impacts learning.<br>(Not applicable for Class B & D Ships.) | N/A | VALID | N/A | |
| 10 | Shipbuilding Age Demographics - 1980 | 10-1 | 1980 demographic environment within shipbuilding impacts learning.<br>(Not applicable for Class D Ships.) | VALID | VALID | N/A | |
| | | 10-2 | Increasing the number of low-rate production ships assists offsetting a demographic environment that is a learning disruptor. | VALID | VALID | N/A | |
| 11 | Employee Work Output for Shipbuilding and Repair | 11-1 | US Shipbuilders work output has grown 45 percent over 20 years. | VALID | VALID | VALID | Knowledge Management (K) |
| 12 | Employee Work Output for Automotive and Aircraft Industries | 12-1 | US aircraft and automotive industries has an output per employee larger than the output per employee in shipbuilding. | VALID | VALID | VALID | |
| 13 | Memory Retention | 13-1 | Lack of using skills results in substantial reduction in knowledge retention and learning. | VALID | VALID | VALID | |
| 14 | Relative Efficiency versus Experience | 14-1 | Shipbuilder efficiency is affected by the knowledge management culture. | VALID | VALID | VALID | |

Table 18 (continued)

Table 19 provides a summary of SPIKE, which was captured via WBS 10, and Table 19 also provides a summary of the conclusions derived from Class A, B, C, and D Ship data. Specific conclusions for Class A, B, C, and D Ships are captured via WBS 9, WBS 11, and WBS 12. Table 19 was provided in this section as the validation of Table 13, which was derived from the conclusions deduced from Class A Ship data and information. The conclusions deduced from the Class B, C, and D data and information validated and triangulated the Class A Ship conclusions. As such, Table 19 was validated accordingly.

| **Overall Learning Curve Characterization (OLCC)** | | | |
|---|---|---|---|
| **Acronym** | **Learning Parameter** | **Learning Enablers (LE): Efficient Learning** | **Learning Disruptors (LD): Loss of Learning** |
| **S** | Stability (S) | Stable Baseline:<br>No Changes & Commonality from Ship to Ship of the Same Class | Dynamic Baseline:<br>Lots of Changes & Lack of Commonality from Ship to Ship of the Same Class |
| **P** | Procurement Strategy (P) | Multi-Ship Procurement:<br>Multi-Ship Serial Production with Optimized Construction Starts | Single Ship Procurement:<br>One-Off Ship Procurement with Extended Construction Start |
| **I** | Industrial & Organizational Culture (IO) | Synthesis:<br>Consistent and/or Predictable Staffing Demands per Department | Disintegration:<br>Variable and/or Unpredictable Staffing Demands per Department |
| **K** | Knowledge Management (KM) | Robust Integrated Learning & KM Culture | Lack of a Defined Learning & KM Culture |
| **E** | Demographical Environment (E) | Balanced Workforce & Experience Demographic:<br>Even Profile Distribution | Skewed Workforce & Experience Demographic:<br>Bi-modal Distribution and/or Retirement Aged Distribution |

Table 19: Overall Learning Curve Characterization Validation

## WBS 15: Iteration

Following a thorough systems engineering approach in regard to the principle of system darkness along with the principles of emergence, minimal critical specification, and other systems engineering principles, (Whitney, Bradley, Baugh, and Chesterman (2015)), the researcher, after completing the associated research and conclusions, iterated through the research methodology delineated in Chapter 3 to determine if additional information or research was needed to be completed accordingly. For brevity and efficiency, the researcher added the required information throughout the research contained herein rather than adding additional sections. As such, listed below is a summary of the results of the researcher's efforts via WBS 15, Iteration.

- *WBS 1 - Value Stream Bounding and Framing:* The researcher did not have to modify the bounding and framing associated with this research. However, throughout the completion of this research, additional limitations and assumptions were developed and added accordingly.
- *WBS 2 - Learning Curve Body of Knowledge:* The researcher has been researching learning curves and characterizations since 2016, and still continues to the current day. As such, throughout this entire process, the researcher has continued to add additional recent sources to the body of knowledge as factors that influence learning were published accordingly. This did not change the conclusions nor the OLCC that the researcher developed, but rather, assisted the researcher in remaining current with the published literature associated with this area of research.
- *WBS 3 – Determine Type of Data Required:* The researcher did assess all of the data that was used to support this research and verified that the type of data utilized was

appropriate and was based on what exists within the public domain. As such, no additional actions were required.

- *WBS 4 – Identify and Obtain Class A, B, C, and D Ship Data:* The researcher did add Class D Ships to the research to provide insights into a low-rate production ship class that was more current even though it was a ship class that was still in production. The researcher also performed multiple searches of data within the public domain and verified that all data associated with learning curves had been captured for Class A, B, C, and D Ships.
- *WBS 5 and 6 – Assess and Analyze Class A, B, C, and D Ship Data:* Other than adding the Class D Ship data, no additional analysis of the ship data was required. Since the research contained herein was focused on learning curves, the principal data used to support this research involved labor hours, schedule durations and milestones, significant changes to the ship(s), procurement strategies, labor elements, demographics, work output, knowledge and memory retention, and work efficiency versus shipbuilding experience.
- *WBS 7 and 8 – Iterate Through Difference Learning Curve Theories Using Class A, B, C, and D Data:* The researcher assessed each learning curve theory using Class A, B, C, and D Ships. As indicated, the only two changes that occurred after the researcher iterated through the research methodology was:
    - adding Class D Ships to this WBS and
    - analyzing one additional learning curve theory because by adding one more than the researcher could then analyze all five fundamental learning curve theories that exists.

Labor hours to design, build, test, and deliver Class C Ships does not exist in the public domain. As such, this was the only parameter that could not be directly assessed accordingly, which did not affect the final OLCC.

- *WBS 9 – Determine Key Factors and Conclusions Affecting Learning for Class A Ships:* The researcher iterated a number of times to determine the list of factors which were developed from the extensive research that was completed as a result of WBS 2 and captured via Chapter 2. In addition, as delineated within WBS 2, the researcher continued researching daily this topic to continue to remain at the forefront of this area of research. After identifying the factors impacting learning in low-rate production environments, the researcher determined the key factors, which required several iterations, associated with learning in low-rate production environments. These were then used to support WBS 10.
- *WBS 10 – Develop Class A Low-Rate Learning Characterization:* The researcher used the Class A Ship data as well as the key factors affecting learning for Class A Ships and developed, after several iterations, a low-rate overall learning curve characterization (OLCC) for Class A Ships. The principal aspect that the researcher iterated on was the characterization of the learning enablers and learning disruptors for each learning parameter.
- *WBS 11 – Validate Class A Ship Conclusions using Class B Ship Conclusions:* The researcher analyzed the conclusions deduced from Ship Class A by using Class B Ship data. The results of this were that the Ship Class B data and associated conclusions validated the Ship Class A conclusions. No additional iterations were required.

- *WBS 12 – Triangulate Ship Class A Conclusions using Ship Class C and Ship Class D Conclusions:* The researcher validated through triangulation the conclusions deduced from the Ship Class A data by using Ship Class C and Ship Class D data. The results of this effort were that the Ship Class C and Ship Class D data and associated conclusions validated through triangulation the Ship Class A conclusions. No additional iterations were required.
- *WBS 13 – Low-Rate Learning Characterization versus Learning Curve Theories:* As a result of this research, the researcher has clearly shown and proven that the five principal learning curve theories did not characterize learning in low-rate production environments. As has already been delineated from an iteration perspective in regards to WBS 7 and WBS 8, the only change that occurred as a result of iterating back through the research methodology was the addition of the fifth learning curve theory. There were many learning curve theories, but they all were derived from five principal learning curve theories. As such, the researcher adjusted the research methodology so that all five learning curve theories could be assessed versus the Class A, B, C, and D Ship Data. As has already been discussed, none of the five theories was able to characterize learning in low-rate production environments, which substantiates this research.
- *WBS 14 – Validate the OLCC:* Through the iteration process via WBS 15, the researcher determined that WBS 14 should also include a visual to show connectivity between the conclusions and the OLCC. As such, the researcher developed a table to clearly show the connectivity between the conclusions derived from Class A Ship data, and their subsequent validation using Ship Classes B, C, and D, to the OLCC which was defined by the acronym of SPIKE.

- *WBS 15 – Iteration:* As delineated within this section, the researcher, following a good system engineering approach, iterated back through the research methodology to adjust and adapt as more details associated with this complex system were learned as a result of this research.

## Limitations

As with any research endeavor, there were limitations, which were summarized via Table 21. Table 21 provided the limitations associated with the deductions made by the researcher based on the research methodology and subsequently executed accordingly. In addition, there were also other limitations associated with executing research on a complex system of systems and associated complex problems. As Keating (2000) states, “systems-based initiatives will have limited success in contexts fraught with defensiveness, emotion, or political divisiveness.” As the contextual review provided in Chapter 2, there were external factors associated with learning in low-rate production environments that influence the learning environment and learning curves associated with low-rate production environments including, as Keating (2000) conveys, “political and emotional topics.” In regard to the context of this research, the political and emotional aspects were associated with the instability of not only funding, but the continually changing political landscape. These issues not only directly impacts learning within this environment, but it also limits the effectiveness of any learning and knowledge management strategy developed and subsequently employed. As such, if the OLCC delineated via SPIKE was employed, its’ effectiveness would be limited by the political and emotional influences, as Keating (2000) conveys. This issue increased the challenges associated with defining the boundary associated with research due to multiple perspectives associated with various stakeholders that were directly or indirectly involved. These were discussed accordingly herein via WBS 1. Complex problems many times do not support structured approaches to address them accordingly. However, SPIKE was developed by the researcher to bring structure to this very complex problem that was rooted in a very turbulent environment characterized by shifting requirements, instability, and competing priorities. SPIKE was developed based on a low-rate production environment. Without further research, the utilization of SPIKE would be limited to:

- low-rate production environments,
- non-government shipyards,
- new construction shipbuilding, and
- ships that were built at one shipyard versus requiring multiple yards to build each ship,

As such, other than the specific limitations of the various aspects associated with the research captured via Table 20, the limitations of this research were characterized by the extreme and very complicated environment that this complex system resides within influenced by a “multitentacled” [researcher’s quotes] set of wicked problems.

| # | Section within Dissertation | Limitation: Category | Limitation | Comments |
|---|---|---|---|---|
| 1 | Chapter 4 | Age Demographics | For the age demographics assessments, the researcher had to assume that the age ranges also correlated to years of experience. Meaning, younger people were inexperienced while older people were experienced. The public domain data did not provide years of experience, but rather just age groupings. | - |
| 2 | Throughout | Automation | The researcher did not consider the effects of automation or increased mechanization. These processes shifts work from people to machines. Many of the details would be proprietary and beyond the scope of the research. | - |
| 3 | Class D Ships | COVID-19 Impacts | The COVID-19 global pandemic occurred during the construction of the Class D Ships. The impacts to learning, due to the pandemic, has impacted the Class D data accordingly. The degree of impact was assumed to be low; however, the actual impacts are to be determined and would require proprietary information, and was beyond the scope of this research. | - |
| 4 | Chapter 4<br>Conclusion #11-1<br>Conclusion #12-1 | Factors Affecting Work Output | Some of the figures in the public domain were for shipbuilding and repair, and was for all ship classes. Information and data on just low-rate production ships was obviously not available. | - |

Table 20: Limitations Associated with This Research

| # | Section within Dissertation | Limitation: Category | Limitation | Comments |
|---|---|---|---|---|
| 5 | Chapter 4 WBS 5 and WBS 6 Conclusion #7-2 | Impact of Changes | Utilizing information contained in the public domain, the researcher identified the most significant changes impacting each ship of this class. As each were identified using the references contained herein, the researcher simply counted each change. The researcher also assumed that the impact of each change was the same meaning that the researcher did not quantify the difference in the impacts associated with each change. This was an assumption and limitation with respect to this research; however, due to the limited information contained within the public domain in regards to the number of systems impacted by each change, this assumption was a logical conclusion to pursue accordingly. | This was both an assumption and a limitation. Analyzing the degree of impact of each change would require proprietary information, which was beyond the scope of this research. |
| 6 | Conclusion #4-5 | Multi-Ship Procurements Strategies | There was a lack of information in the public domain to be able to assess the degree or amount of influence that the execution of different multi-ship procurement strategies (in series, in parallel, or in a hybrid approach) has on learning in low rate production environments. | Additional research into this area could only be able to occur with in each company as the required information to perform this assessment would be proprietary information specific to each company. |
| 7 | Conclusion #1-2<br>Conclusion #4-2<br>Conclusion #7-1 | Multi-Ship Procurements Strategies | The optimum number of low rate production ships to procure associated with a with multi-ship procurement strategy cannot be determine utilizing data and information within the public domain. | This was ship class dependent, and in order to complete this research, more detailed information, which would be proprietary, would be needed from each company or agency to effectively complete this research. As such, this effort could not occur utilizing information that resides in the public domain. |

Table 20 (continued)

| # | Section within Dissertation | Limitation: Category | Limitation | Comments |
|---|---|---|---|---|
| 8 | Conclusion #4-3 | Optimization of Duration between Ship Deliveries | The optimum range of months between deliveries impacts learning and knowledge transfer from ship to ship. However, there were other factors impacting the optimum range of months between ship deliveries such as capacity, available footprint, current workload, and so on. The impacts of these factors, in terms of identifying the over-arching optimum range of months between deliveries, was outside the scope of the research. | The research herein developed conclusions related to the optimum range of months between deliveries from a learning perspective. However, determining the optimum range of months within the context of not just learning and knowledge transfer, but within the perspective of other factors influencing low rate production shipbuilding, was beyond the scope of this research. In addition, proprietary information would be required to research this accordingly; and as such, would have to be completed by each company or agency. |
| 9 | Throughout | Public Domain Data | The data and associated assessments made herein were based on data that exists within the public domain. No proprietary data was utilized during the completion of the research contained herein. | - |
| 10 | Conclusion #1-1<br>Conclusion #1-3<br>Conclusion #7-2 | Schedule Milestones | The keel date for naval ship construction can be arbitrary, and was not always associated with initial ship construction. Actual start of ship construction was not available in the public domain. Actual construction start was usually not contract award, which was the only information provided in the public domain. As such, the researcher had to make the associated assumptions, which was a limitation as well. | - |
| 11 | Conclusion #1-1<br>Conclusion #7-2 | Schedule Milestones | The public domain does not provide actual construction starts for the second ship of a two ship buy, or the succeeding ships for multi-ship procurements. | - |

Table 20 (continued)

## Contribution to the Learning Curve Body of Knowledge

There obviously exists a large body of knowledge covering learning. However, the research contained herein addresses learning as it relates to learning curves in low-rate production environments, such as naval shipbuilding. The various theories impacting learning curves has been explored in detailed as part of this research. Through the literature review completed, the researcher has confirmed that there was gap in the body of knowledge associated with learning curves specifically addressing the low-rate production of naval ships. The results of this research have addressed this gap in knowledge accordingly.

The research completed has a significant impact not only on the body of knowledge involving learning curves, but also on the expectations associated with the design, production, test, and delivery of complex naval ships built at naval shipyards. In addition, the results of the research were also a concise assessment of learning curve theories, their applicability, and the fact that, until now, there has not been published research addressing learning curves associated with the low-rate production environments.

The results of the completed research also identified the principal factors associated with learning curves in low-rate production environments. These principal aspects formed the basis of the development of a characterization of learning in a low-rate production environments, which the researcher has developed the terminology of overall learning curve characterization (OLCC) defined by stability (S), procurement strategy (P), industrial and organizational culture (I), knowledge management (K), and demographic environment (E), which the researcher has defined as the acronym entitled SPIKE. The results developed by this research was also generalizable to other low-rate production complex systems such as one-of-a-kind systems like the space program, oil well platforms, and other low production rate industries.

In addition to the contributions just discussed along with those contained within Table 21, the research herein also contributes to both the systems engineering body of knowledge and the engineering management body of knowledge. From the engineering management perspective of “getting things done”, Sousa-Poza (2019) and of “…directing and controlling activities which have a technological component,” Keating et al (2017), the research captured herein was aimed at one of the most fundamental components of any production, manufacturing, and technical environment, which was learning curves and how they were conveyed. The other principal impacted area as a result of this research was contract definitions and requirements. Learning curve performance expectations was part of most production and manufacturing contracts, and as has been discussed, learning curves were assumed to occur over each progressive component, item, and in this case, ships that were produced and delivered. These requirements are part of each contract, and the learning curve performance expectations can be as high as eighteen to twenty percent for shipbuilding contracts per ship. As already discussed, this percentage was based on Wright’s (1936) work that has continued to be brought forward as the theory to utilize for learning for ship over ship performance. As has already been discussed, this is an incorrect assumption which yields an output that the contractor does not meet the contracted learning curve thereby providing a product that is over-budget. The outcomes were also affected too because the contractor would not be able to meet the expectations that the customer had in regards to meeting the forecasted learning for that given product, and in this case, a low-rate production ship. As has been stated several times throughout, this was all within the context of low-rate production environments because from an engineering management perspective, Wright (1936) and Crawford (1944) theories were being applied due to the lack of a learning characterization that includes the unique context of low-rate production environments.

Engineering management is about managing and controlling technical products. As Keating et al (2017) states, it is both an "art and science." Management of learning from ship to ship as well as the impacts to contract performance because of the attainment or lack of attainment of meeting the contracted and budgeted learning curves is an engineering management function. It is a science because it can be tracked and progressed, and it is very objective, but it is also an art because learning is subjective, and in some cases, people may choose not to learn and/or don't learn, which can't be calculated and is beyond the scope of the research contained herein.

As Jones, Galison, & Slaton (2013) convey, art is a subjective representation of knowledge while science acquires and adds to knowledge. Featherstone (2016) espouses that science and art are the "same thing." The researcher does agree with Featherstone (2016), that science and art are both trying to address that "one of the most primitive innate needs of humans is to understand the world around us, and then share that understanding." The research herein was focused on trying "to understand the world around us." In low-rate production environments, there are many factors creating a complex system that has to be understood and managed, and for this research, what has to be managed was highly technical in nature, and specifically, what has to be managed, daily, is learning. This management of learning has both learning that affects each person working on a given product, and it has the management of the requirements to build a given product, and in this case, ships, which in turn directly affects the success and performance of the ship and contract. This then affects future contracts and how investors value the impacted company. This was not to say that learning was the sole influencer impacting company performance; however, it was a major contributor, and on large contracts, was one of the top drivers. In summary, from an engineering management ("get things done", Sousa-Poza, 2019) perspective, the results of this research have had a direct impact on engineering management, especially in the areas of learning curves.

From a system engineering perspective, meaning, as was previously covered, “solving problems” (Sousa-Poza, 2019) “…is a dynamically structured approach to understand and effectively resolve contextually embedded complex system problems with minimal human costs” (Keating, 2018). As such, the research herein also contributes to the systems engineering body of knowledge. In regards to systems engineering contributions, the researcher dissected Keating’s (2018) definition of systems engineering to illustrate, very clearly, the contributions of this research to the systems engineering body of knowledge.

As such, “dynamically structured approach” is one of the fundamental tenets of the research methodology that was employed herein. The methodology developed and outlined was flexible and iterated through each major step as the research matured. The methodology was structured, logically, and was not a prescriptive approach, but rather, one that adapted as more was learned about the system through the data analysis. The research methodology developed was specific within the context of low-rate production environments. Other learning curve theories utilize Wright’s (1936) work as their foundation or starting point, and then they develop their theories based on his research along with Crawford (1944). The issue with this, of course, was that they are assuming, by default, that the context of the application that they were utilizing for their learning curve theory also entails the same contextual relationships that Wright (1936) employed too, which is a fallacy. As such, the contribution to systems engineering for this research was a research methodology that was based on the context of the environment that it was employed upon, and not utilizing a methodology that was developed for a different context. The learning curve characterization, which has already been covered in detail, also contributed to the systems engineering body of knowledge. The environment and context of this system as well as the system itself, which was designing, building, testing, and delivering ships or products that take a very long time to build, by their very nature, were "complex systems" with numerous wicked complex problems. Building low-rate production ships, as well as other products they take numerous years to build, was made up of numerous systems residing within a large system which resides within an even larger system making this even more complex.

The next portion of Keating's (2018) definition of systems engineering was really the root of the research contained herein, which was to "understand and effectively resolve contextually embedded complex system problems." As the research completed has shown, one of the main issues driving this complex problem was that the learning curve theory that was being applied now was based on a context that was not indicative of or predictive of the environment that was characterized by low-rate production. This was because there has not been a characterization developed for these unique environments, so obviously, the results of this research were a contribution to the body of knowledge for systems engineering.

The last part of Keating's (2018) definition stating "with minimal human costs" was very accurate and perceptive. Organizations that build very complex products, which have very long cycle times with very low numbers being built, spend an inordinate amount of people resources and company resources to address these very complex systems, and specifically, learning curves from product to product as well as the associated contractual ramifications. Simply stated, large amounts of "human costs" were being expended in low-rate production environments trying to address the impacts of product over product learning curves in this unique environment.

Lastly, the researcher would submit that even though engineering management and systems engineering was addressed separately herein, they are really inseparable. All systems must be managed, and when problems arise, a strategy must be developed to address those issues. Once the strategy was developed, the implementation of that strategy must be managed such that system engineering needs engineering management and engineering management needs systems engineering. Drawing from biology, the researcher views this relationship similar to a symbiotic relationship. Engineering management and systems engineering show an innate relationship with one another. The two must work together. An organization cannot successfully survive with only focusing on engineering management or only on systems engineering. Many companies myopically focus on engineering management and do not have an understanding of systems engineering.

The researcher also completed a contextual assessment based on various public domain information, which was captured within Chapter 2. This information was not directly related to learning or learning curves, but impacts the context that learning resides within for low-rate production environments. This information focuses on factors that compliments the conclusions and has connectivity to the research included herein. As indicated, this contextual information does not mention learning or learning curves, but rather, the researcher identified connectivity between this information and the research contained herein.

The researcher obtained and read all of Wright’s reports that were in the public domain. Many of his reports were written during World War II, and they have been recently de-classified. After reading them, the researcher concluded that Wright did not intend for his analysis and research to be applied beyond the context that the research occurred. His research and analysis were focused strictly on the learning curves associated with airplane fuselage manufacturing only. Fundamentally, Wright's research was simply based on collecting labor hours spent on production manufacturing of aircraft fuselages (which the researcher has identified as high-rate production manufacturing), and then he decided to plot the data on log-log paper. When he did this, the data plotted in a straight line such that he then observed that the doubling of unit production resulted in a constant percent reduction in labor hours that he stated was due to learning. Based on the research detailed herein, in high-rate production environments, this phenomenon has been proven multiple times over multiple environments with the common denominator being that the fact that they were all produced in high-rate production environments. However, as has been clearly shown herein, Wright (1936), Crawford (1944), DeJong (1957), Stanford-B (1949), and the Sigmoid S Curve (1973), which represent the five fundamental learning curve theories, do not characterize learning in low-rate production environments such as naval shipbuilding. This is due to the fact that low-rate production environments were impacted by various parameters, which have been addressed; whereas, the five leading learning curve theories do not take these parameters into consideration. The principal parameters that the researcher has identified as the leading factors impacting learning curves in low-rate production environments have been captured and articulated via the OLCC defined by SPIKE. In addition, by definition, low-rate production environments produce products at a very low rate of one product every four or more years and requiring numerous hours to design, build, and test. As such, applying a traditional learning curve yields a large number of hours to be reduced due to learning from product to product over a very long-time frame, which as SPIKE defines, leads to learning disruptors. As such, traditional learning curves should not be used on low-rate production environments whereas SPIKE characterizes learning curves in low-rate production environments.

The results of this research were also a concise assessment of learning curve theories and their applicability. In addition, the research contained herein has had an impact not only on the body of knowledge involving learning curves, but also on the body of knowledge and associated expectations with learning curves in low-rate production environments such as naval ships. The results provided by this research was applicable to this complex system, but was also applicable to other complex systems that experience low production rates or one-of-a-kind systems like the space program, oil well platforms, and other products. Until now, there has not been any learning curve research focused on these types of complex systems characterized by a low-rate production environment.

Listed below are the contributions made by this research to the learning curve body of knowledge:

- Learning Curve Theories versus Ship Classes:
    - An assessment and analysis of the five main learning curve theories versus four different ship classes that were produced in low-rate production environments.
- Literature Review:
    - The researcher completed an extensive, thorough, and diverse literature review associated with learning and learning curves highlighting the gap in the body of knowledge associated with learning curves in low-rate production environments, such as naval ships.
    - The researcher completed an extensive contextual review associated with literature that does not mention learning or learning curves, but rather was focused on the contextual environment that low-rate production products, such as ships, resides within.

  - The researcher obtained and read all of Wright's reports that were in the public domain. Many of his reports were written during World War II, and they have been recently de-classified. After reading them, the researcher concluded that Wright did not intend for his analysis and research to be applied beyond the context that his research occurred. His research and analysis were focused strictly on the learning curves associated with airplane fuselage manufacturing only.
- Data:
  - The researcher developed conclusions based on low-rate production data to develop a low-rate production learning characterization.
  - Exhaustive and complete data search within the public domain as well as the associated deductions from this data and information was completed as a result of this research.
- Low-Rate Production Environments:
  - The identification of learning occurring within the context of high-rate production learning versus a newly identified area put forth by the research contained herein recognizing learning within low-rate production environments.
  - Ultimately, this research develops a theory of learning associated with low-rate production environments which compliments the learning curve theories of Wright, Crawford, and other researchers that were associated with high-rate production environments.
- OLCC and SPIKE
  - The researcher identified the primary contributing factors impacting learning curves within low-rate production naval ships.

  - A learning curve characterization reflective of low-rate production environments such as naval ships.
  - The development of an overall learning curve characterization (OLCC) including: an acronym (SPIKE), which defines the OLCC, of: stability (S), procurement strategy (P), industrial and organizational culture (I), knowledge management (K), and demographic environment (E). These were the principal learning parameters associated with learning in low-rate production environments. The development of the characterization to include learning enablers which support efficient learning, and learning disruptors, which contributes to the loss of learning or reverse learning, defining the OLCC.
- Research Methodology
  - The development of a comprehensive research methodology focused on low-rate production, that was used for this research, and can also be used by others to continue research in this area and other areas.
  - The use of low-rate production data to develop a low-rate production learning characterization.
  - The results of the research are based on data from four ship classes obtained as part of the literature review and associated research on learning and learning curves while executing the research methodology designed by the researcher specifically for the research contained herein. The results and associated conclusions were based on the data, as a result of the research performed herein, and was inclusive of the environment that low-rate production resides within.

- Wright’s (1936) Theory
    - The researcher, using Wright's data, re-created the graphs from Wright's 1936 paper entitled "Factors Affecting the Cost of Airplanes". The researcher also utilized Wright's process to analyze the associated graphs produced. The researcher, with this additional knowledge gained, repeated this same process, throughout the research, on each Class of Ship. This also helped the researcher to understand the context of Wright's research.

Table 21 provides the various contributions to the learning curve body of knowledge that the research herein has contributed too in regards to learning in low-rate production environments.

| # | Section within Dissertation | Contribution: Category | Contribution | Comments |
|---|---|---|---|---|
| 1 | Chapter 3, 4, and 5 | Learning Curve Theories versus Ship Classes | Assessment of the 5 main learning curve theories versus four different ship classes. | - |
| 2 | Chapter 2 | Literature Review | The researcher completed an extensive, thorough, and diverse literature review associated with learning and learning curves highlighting the gap in the body of knowledge associated with learning curves in low-rate production environments, such as naval ships. | - |
| 3 | Chapter 2 | Literature Review | The researcher completed an extensive contextual review associated with literature that does not mention learning or learning curves, but rather is focused on the contextual environment that Low-Rate production products, such as ships, resides within. | There have been a number of articles written recently that address aspects of learning not from a learning or learning curve theory perspective, but they discuss factors that are within the scope and context of a learning environment, and as such, are addressed herein too. |
| 4 | Chapter 2 | Literature Review | The researcher obtained and read all of Wright's reports that were in the public domain. Many of his reports were written during World War II, and they have been recently de-classified. After reading them, the researcher concluded that Wright did not intend for his analysis and research to be applied beyond the context that his research occurred. His research and analysis were focused strictly on the learning curves associated with airplane fuselage manufacturing only. | - |

Table 21: Contributions to the Learning Curve Body Knowledge as a Result of This Research

| # | Section within Dissertation | Contribution: Category | Contribution | Comments |
|---|---|---|---|---|
| 5 | Chapter 5 | Low-Rate Data to Develop Low-Rate Characterization | Developed conclusions based on low-rate production data to develop a low-rate production learning characterization. | - |
| 6 | Throughout | Low-Rate Production Environments | The identification of learning occurring within the context of high-rate production learning versus a newly identified area put forth by the research contained herein recognizing learning within low-rate production environments. | - |
| 7 | Chapter 5 | Low-Rate Production Environments | Ultimately, this research develops a theory of learning associated with low-rate production environments which compliments the learning curve theories of Wright, Crawford, and other researchers that are associated with high-rate production environments. | - |
| 8 | Chapter 5 | OLCC and SPIKE | Identification of the primary contributing factors impacting learning within low-rate production naval ships. | - |

Table 21 (continued)

| # | Section within Dissertation | Contribution: Category | Contribution | Comments |
|---|---|---|---|---|
| 9 | Chapter 3 and 5 | OLCC and SPIKE | A learning characterization reflective of low-rate production environments such as naval ships. | The research methodology developed herein has also contributed to the body of knowledge because the methods developed and utilized have not been executed before. This research methodology then facilitated the development of a low-rate production learning characterization which is based on low-rate production data. Whereas, applications to date utilize a learning curve characterization that was actually developed in support of aircraft production and then extended to other applications accordingly. As such, the significance of this research was the development of a learning characterization of complex systems, such as naval shipbuilding, that exists within a low-rate production environment. |

Table 21 (continued)

| # | Section within Dissertation | Contribution: Category | Contribution | Comments |
|---|---|---|---|---|
| 10 | Chapter 5 | OLCC, SPIKE, & Learning Enablers and Learning Disruptors | The development of an overall learning characterization (OLCC) including: an acronym (SPIKE), which defines the OLC, of: stability (S), procurement strategy (P), industrial and organizational culture (I), knowledge management (K), and demographic environment (E). These were the principal learning parameters associated with learning in low-rate production environments. The development of the characterization to include learning enablers which support efficient learning, and learning disruptors, which contributes to the loss of learning or reverse learning, defining the OLCC. | - |
| 11 | Chapter 4 | Public Domain Data | Exhaustive and complete data search within the public domain as well as the associated deductions from this data and information. | - |
| 12 | Chapters 3, 4, & 5 | Research Methodology | The development of a comprehensive research methodology focused on low-rate production, that was used for this research, and can also be used by others to continue research in this area and other areas. | - |

Table 21 (continued)

| # | Section within Dissertation | Contribution: Category | Contribution | Comments |
|---|---|---|---|---|
| 13 | Chapter 3 and 4 | Research Methodology | The use of low-rate production data to develop a low-rate production learning characterization. | - |
| 14 | Chapter 3 | Research Methodology | The results of the research are based on data from four ship classes obtained as part of the literature review and associated research on learning and learning curves while executing the research methodology designed by the researcher specifically for the research contained herein. The results and associated conclusions are based on the data as a result of the research performed herein and is inclusive of the environment that low-rate production resides within. | - |
| 15 | Chapter 2 | Wright's (1936) Theory | The researcher, using Wright's data, re-created the graphs from Wright's 1936 paper entitled "Factors Affecting the Cost of Airplanes". The researcher also utilized Wright's process to analyze the associate graphs produced. | The researcher, with this additional knowledge gained, repeated this same process throughout the research contained herein on each Class of Ship that was analyzed using Wright's Theory.<br>This also helped the researcher to understand the context of Wright's research. |

Table 21 (continued)

## Future Research Opportunities

The researcher utilized designing and building low-rate production ships as the industry to analyze learning curves in low-rate production environments.  The researcher would suggest that there are other future research opportunities such as:

- Additional research into each individual element of SPIKE including a further assessment of training, educational programs, and booster events to increase knowledge retention and the transfer of knowledge.
- Variety and complexity were considered by the researcher to support this research; however, research focusing on assessing variety, since it is a measure of complexity and the complexity of a system, would provide research opportunities in terms of the type of complexity that low-rate production environments exists within.  This research may provide insights into learning strategies that could be employed to increase knowledge retention within low-rate production environments.  Additional research into this area to support different learning and knowledge management strategies is important because in order to control a system, the regulator must match the variety and disturbances of the environment (Ashby (1957) and Ashby (1991)).  As such, designing a system regulator to adjust to the environment is critical to be able to control a system.  For this additional research area, the knowledge management strategies would not be used to control the system, but they would support the development of the knowledge culture by having a more in-depth understanding of complexity using the research completed by Keating (2018).
- The researcher utilized Flight I data only of the Class C Ships.  As such, future research could entail assessing the other flights associated with Class C Ships.

- The development of an OLCC in other environments including high-rate production environments.
- The human view point associated with learning in low-rate production environments could also be researched. As Handley and Knapp (2014) states, "analyses that measure the human impact on system performance; cost-benefit analyses that consider the influence of manpower, personnel, and training on total costs; and requirement analyses that include the human specifications to adequately operate and maintain the system." As such, using the research completed by Handley and Knapp (2014) to develop human view point models of "HV-F," which focuses on training, could assist in the development of additional learning strategies associated with low-rate production environments.
- The impacts of different generations on learning within low-rate production environments. As such, this research would focus on Traditionalists, Baby Boomers, Generation X, Millennials (Generation Y), and Generation Z, and how their generational characteristics impacts learning especially in low-rate production environments.
- The degree of reverse learning versus the depth, breadth, and type of skills lost over time. The impacts of this research to the decomposition of learning from a skill perspective ranging from general skills, trade unique skills, and specialty skills both in complexity and environment as well as associated booster events to increase longevity of retention. Each of these 3 stages of work (basic/fundamental skills, skills requiring proficiency, and skills that are contextual and environmental based) would have different learning curves and knowledge retention time frames.

- Strategies and techniques to quantify the OLCC and SPIKE as well as the knowledge management transfer associated with bridging this gap.
- Learning from a system perspective especially in low-rate production environments. For example, learning as a result of an error or mistake that stays within the system but does not require a re-design of the system versus learning as a result of a design issue that does require a re-design of the system versus learning as a result of emergent circumstances that supports innovation.
- The impact of a ship being the last ship of a class and its' effect on learning.
- Some of the learning concepts could be applicable or could be made applicable to government shipyards, but they have different inputs and a different world view. This too may be the subject of future research.
- Life cycle costs were not included herein including overhaul and repair of naval ships. Overhaul and repair of naval ships have different inputs and a different world view, but many of the concepts contained herein may be generalizable and could be the subject of future research.
- Relative efficiency versus years of experience was for all of shipbuilding. The development of a shipbuilding curve that was focused on low-rate production shipbuilding would be an opportunity for future research.
- Impacts to the OLCC and SPIKE as a result of out-sourcing labor, suppliers, more employees working from home, and or the increased specialization of labor in certain areas.
- The relationship between the Yerkes-Dodson Law and learning especially in low-rate production environments such that shipbuilders can increase the probability that there

are performing at the most optimum level. This would also include relationships between performance and the various shipbuilding tasks to build a ship within a complex environment and system.

- Research in regards to the other factors affecting the optimum range of months between deliveries due to capacity, footprint, current workload, and so on.
- Where applicable based on which variables can be controlled, develop robust engineering solutions using orthogonal arrays to evaluate low-rate production learning to determine the optimum "balance" of factors affecting low-rate production of ships or other low-rate production environments. This research would be based on the research developed by Unal, Braun, Moore, and Lepsch (2001) and Yenjay, Unal, and Lepsch (2006).
- Research safety and quality as they relate to learning in low-rate production environments.
- Various strategies to bolster knowledge retention and/or increase knowledge retention especially in low-rate production environments would be areas of future research.
- Research into the constituent areas that comprise the various organizations within low-rate production environments such as planning, engineering, manufacturing shops, welding, pipe manufacturing, and other areas to develop a learning characterization for each of these areas. The research contained herein has developed an OLCC for learning in low-rate production environments for the entire enterprise. This area of future research would be the development of an OLCC for individual production labor areas and non-production labor areas within the context of the larger low-rate production environment.

- Research into quantifying SPIKE.  This would require data that does not exist in the public domain.  Even though not included as a part of the research methodology and as captured by areas of future research, the researcher employed, from a quantification standpoint, the SPIKE OLCC to learning in low-rate production environments to each class of ship analyzed and researched herein.  Quantifying SPIKE would be the subject of future research to further develop algorithms, criteria, and guidance realizing, as indicated, data that does not exist in the public domain would be required.  Table 22 captures this initial quantification, and the associated figures displays the outputs via polar plots for each class of ships.  The determination of the actual percentages for each of these areas would be the subject of future research.  Table 22 was just provided to illustrate the potential future research.

| Acronym | Learning Parameter | OLCC | Learning in Low Rate Production Ships | | | | Comments |
|---|---|---|---|---|---|---|---|
| | | | Class A Ships | Class B Ships | Class C Ships | Class D Ships | |
| S | Stability | LE: Stable Baseline | 0% | 0% | 0% | 0% | A stable baseline in low rate production shipbuilding has been shown not to exist. |
| | | LD: Dynamic Baseline | 100% | 100% | 100% | 100% | |
| P | Procurement Strategy | LE: Multi-Ship Procurement | 40% | 30% | 90% | 50% | Counted the number of ships involved with a multi-ship versus the number that were not. |
| | | LD: Single Ship Procurement | 60% | 70% | 10% | 50% | |
| I | Industrial & Organizational Culture | LE: Synthesis | 10% | 10% | 10% | 10% | Subject of future research to determine an algorithm, but assumed minimal. |
| | | LD: Disintegration | 90% | 90% | 90% | 90% | |
| K | Knowledge Management | LE: Robust & Integrated Culture | 10% | 10% | 10% | 10% | Subject of future research to determine an algorithm, but assumed minimal. |
| | | LD: Lack of a Defined Culture | 90% | 90% | 90% | 90% | |
| E | Demographic Environment | LE: Balanced & Experienced Workforce | 25% | 44% | 44% | 50% | Used the % associated with those within 10 years of retirement vs those who weren't. |
| | | LD: Skewed & Inexperienced Workforce | 75% | 56% | 56% | 50% | |
| SPIKE OLCC Assessment | | | Future Research | | | | - |

Table 22: Initial Implementation of SPIKE for Class A, Class B, Class C, and Class D Ships

Figures 117, 118, 119, and 120 were the polar plots of Class A, Class B, Class C, and Class D Ships respectfully using the OLCC as defined by SPIKE. Figure 121 was a plot of all four classes together, which shows that learning in low-rate production shipbuilding was skewed towards learning disruptions.

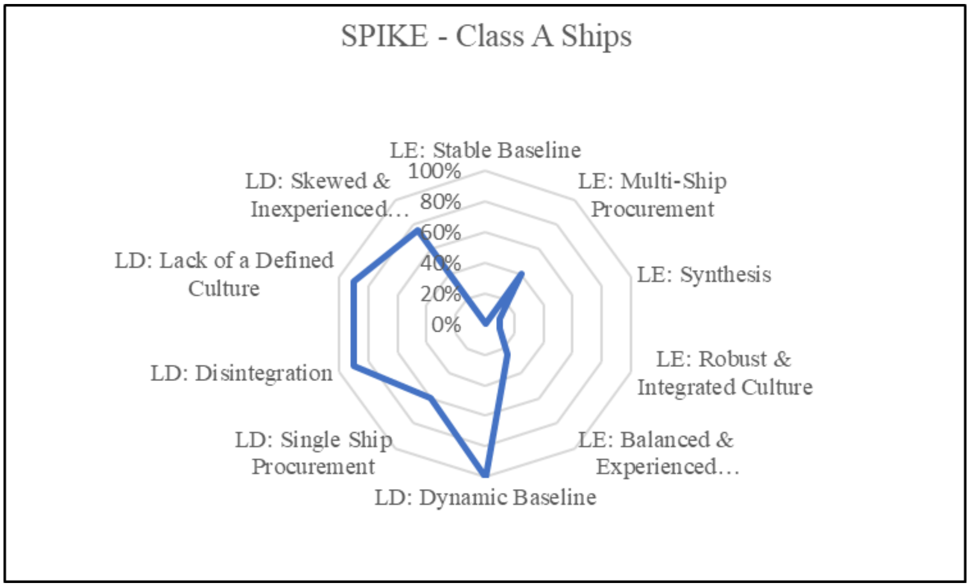

Figure 117: Class A SPIKE OLCC Assessment

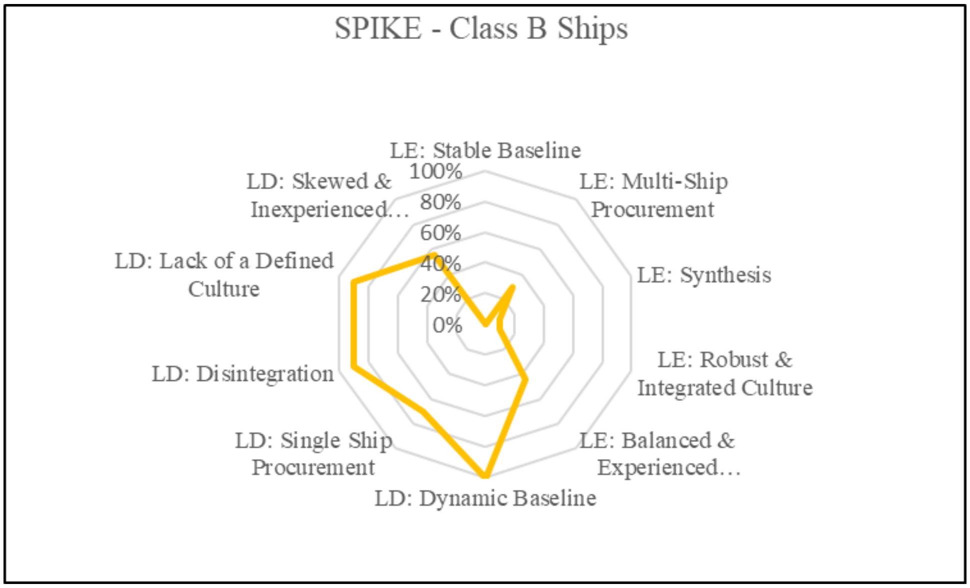

Figure 118: Class B SPIKE OLCC Assessment

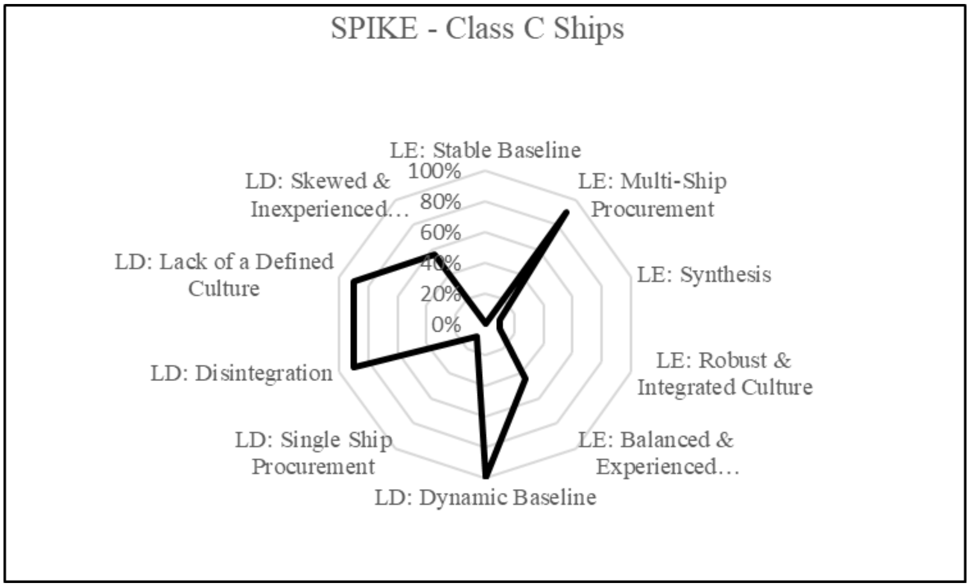

Figure 119: Class C SPIKE OLCC Assessment

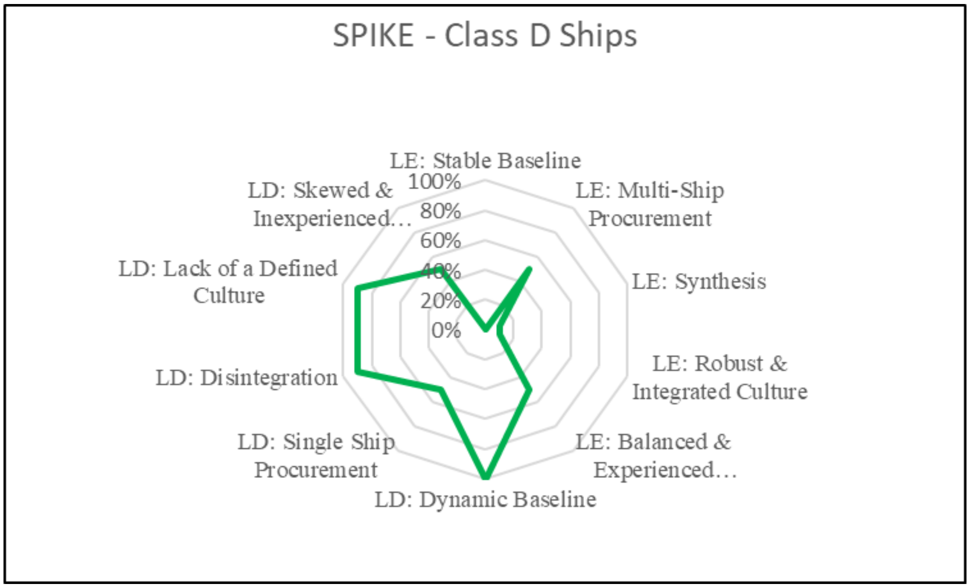

Figure 120: Class D SPIKE OLCC Assessment

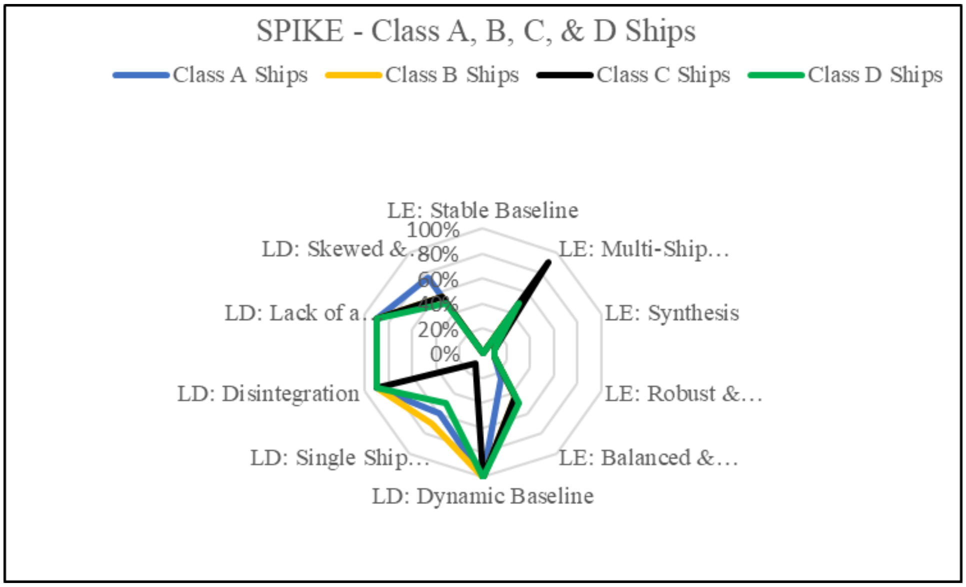

Figure 121: Class A, B, C, and D SPIKE OLCC Assessment

Table 23 provides a listing of future research opportunities. Obviously, all of the potential research opportunities captured via Table 23 would require additional bounding, framing, literature reviews, and other systems engineering efforts to develop these further.  In addition, many would require data that does not exist in the public domain.

| # | Section within Dissertation | Future Research Opportunity: Category | Future Research Opportunity | Comments |
|---|---|---|---|---|
| 1 | WBS 10 | Additional Research into Each Individual Element of SPIKE | Additional research on each individual element of SPIKE such as further assessment of training and educational programs including booster events to increase knowledge retention and transfer of knowledge. | - |
| 2 | Chapter 4 and 5 | Assessment of Complexity within Low-Rate Production Environments to Develop Associated Learning Strategies | Variety and Complexity. Of course these were considered by the researcher to support this research; however, research focusing on assessing variety, since it is a measure of complexity and the complexity of a system, would provide research opportunities in terms of the type of complexity that low-rate production environments exists within. This research may provide insights into learning strategies that could be employed to increase knowledge retention within low-rate production environments. Additional research into this area to support different learning and knowledge management strategies is important because in order to control a system, the regulator must match the variety and disturbances of the environment (Ashby (1957) and Ashby (1991)). As such, designing a system regulator to adjust to the environment is critical to be able to control a system. For this additional research area, the knowledge management strategies would not be used to control the system, but they would support the development of the knowledge culture by having a more in-depth understanding of complexity using the research completed by Keating (2018). | Keating (2018) would also be used to advance this future research as well as other researchers. |
| 3 | Class C Ship Data | Class C Ships | The researcher utilized Flight I data only of the Class C Ships. As such, future research could entail assessing the other flights associated with Class C Ships. | The researcher does not expect any additional conclusions to be developed. |
| 4 | Literature Assessment of Wright's Era until the 1990's | Conscious and Unconscious Learning Curves | Thurstone (1917) references conscious and unconscious learning. The research contained herein does not address conscious or unconscious learning within the context of low-rate production learning curves; however, this could be the topic of future research. | - |
| 5 | Throughout | Development of an OLCC for Other Environments | The development of an OLCC in other environments including high rate production environments. | - |

Table 23: Future Research Opportunities

| # | Section within Dissertation | Future Research Opportunity: Category | Future Research Opportunity | Comments |
|---|---|---|---|---|
| 6 | Chapter 3 | Human Viewpoint Associated with the Development of Learning Strategies in Low-Rate Production Environments | The human view point associated with learning in low-rate production environments. As Handley and Knapp (2014) states, "analyses that measure the human impact on system performance; cost-benefit analyses that consider the influence of manpower, personnel, and training on total costs; and requirement analyses that include the human specifications to adequately operate and maintain the system...". As such, using the research completed by Handley and Knapp (2014) to develop human view point model of "HV-F", which focuses on training, could assist in the development of additional learning strategies associated with low-rate production environments. | Understanding the human viewpoint would be essential to developing an integrated training and knowledge management culture within low-rate production environments. The development of this strategy is beyond the scope of the research contained herein, but is viable for future research. Handley and Knapp (2014) would be utilized to support this research. |
| 7 | Conclusion #8-1<br>Conclusion #9-1<br>Conclusion #10-1 | Impacts of Different Generations on Learning Curves within Low-Rate Production Environments | The impacts of different generations on learning within low-rate production environments. As such, this research would focus on Traditionalists, Baby Boomers, Generation X, Millennials (Generation Y), and Generation Z, and how their generational characteristics impacts learning especially in low-rate production environments. | - |

Table 23 (continued)

| # | Section within Dissertation | Future Research Opportunity: Category | Future Research Opportunity | Comments |
|---|---|---|---|---|
| 8 | Conclusion #13-1 | Impacts of Reverse Learning's Affects on Skills | The degree of reverse learning versus the depth, breadth, and type of skills lost over time. The impacts of this research to the decomposition of learning from a skill perspective ranging from general skills, trade unique skills, and specialty skills both in complexity and environment as well as associated booster events to increase longevity of retention. Each of these 3 stages of work (basic/fundamental skills, skills requiring proficiency, and skills that are contextual and environmental based) will have different learning curves and knowledge retention time frames. | The researcher concluded, as a corollary to Conclusion #13-1, that basic shipbuilding skills would not experience as much of a loss of learning while more complex skills based on specific ship's conditions, would experience a more dramatic loss of learning. This topic is beyond the scope of the research included herein, but is viable future research, however. |
| 9 | WBS 10<br>WBS 14 | Implementation of the OLCC and SPIKE | Strategies and techniques to quantify the OLCC and SPIKE as well as the knowledge management transfer associated with bridging this gap. | - |
| 10 | Throughout | Incorporation of Mistakes and Errors into a Low-Rate Production Learning Organization | Learning from a system perspective especially in low-rate production environments such as: learning as a result of an error or mistake that stays within the system but does not require a re-design of the system versus learning as a result of a design issue that does require a re-design of the system versus learning as a result of emergent circumstances that supports innovation. | - |
| 11 | Throughout | Last Ship of a Class and It's Effect on Learning | The impact of a ship being the last ship of a class and its' effect on learning. | - |

Table 23 (continued)

| # | Section within Dissertation | Future Research Opportunity: Category | Future Research Opportunity | Comments |
|---|---|---|---|---|
| 12 | Chapter 3 | Learning in Low-Rate Production Environments Associated with Government Shipyards | Some of the learning concepts could be applicable or could be made applicable to government shipyards, but they have different inputs and a different world view. This too may be the subject of future research. | - |
| 13 | Chapter 3 | Learning in Low-Rate Production Environments Associated with Overhaul and Repair | Life cycle costs are not included herein including overhaul and repair of naval ships. Overhaul and repair of naval ships has different inputs and a different world view, but many of the concepts contained herein may be generalizable and could be the subject of future research. | - |
| 14 | Conclusion #14-1 | Low-Rate Production Shipbuilding - Relative Efficiency versus Years of Experience | Relative efficiency versus years of experience is for all of shipbuilding. The development of a shipbuilding curve that is focused on low-rate production shipbuilding would be an opportunity for future research. | This would require information that is not in the public domain. |
| 15 | Chapter 3 | OLCC and SPIKE Impacts as a Result of Increased Out-Sourcing, Working from Home, and/or Increased Specialization | Impacts to the OLCC and SPIKE as a result of out-sourcing labor, suppliers, more employees working from home, and or the increased specialization of labor in certain areas. | This may require data that does not exist in the public domain. |
| 16 | Throughout | Relationship between Yerkes-Dodson Law and Optimizing Learning Curves in Low-Rate Production Environments | The relationship between the Yerkes-Dodson Law and learning curves especially in low-rate production environments such that shipbuilders can increase the probability that there are performing at the most optimum level. This would also include relationships between performance and the various shipbuilding tasks to build a ship within a complex environment and system. | - |
| 17 | Conclusion #4-3 | Research in regards to Other Factors Impacting the Optimum Range of Months between Deliveries | Research in regards to the other factors affecting the optimum range of months between deliveries due to capacity, footprint, current workload, and so on. | These additional factors are outside the scope of this research, but are viable topics to complete additional research on in the future. |

Table 23 (continued)

| # | Section within Dissertation | Future Research Opportunity: Category | Future Research Opportunity | Comments |
|---|---|---|---|---|
| 18 | Chapter 3 and 4 | Robust Engineering Assessment of Learning in Low-Rate Production Environments | Orthogonal arrays. Where applicable based on which variables can be controlled, develop robust engineering solutions using orthogonal arrays to evaluate low-rate production learning to determine the optimum "balance" of factors affecting low-rate production of ships or other low-rate production environments. This research would be based on the research developed by Unal, Braun, Moore, and Lepsch (2001) and Yenjay, Unal, and Lepsch (2006). | Various assumptions would have to be developed to support employing this approach as well as researching the impacts of complexity to this research methodology. Unal, Braun, Moore, and Lepsch (2001) and Yenjay, Unal, and Lepsch (2006) would be utilized to support this research. |
| 19 | Overarching | Safety and Quality within the Context of Learning in Low-Rate Production Environments | Research safety and quality as they relate to learning in low-rate production environments. | Meaning, is quality and safety affected in the similar way as learning when in a low-rate production environment. |

Table 23 (continued)

| # | Section within Dissertation | Future Research Opportunity: Category | Future Research Opportunity | Comments |
|---|---|---|---|---|
| 20 | Conclusion #13-1 | Strategies to Bolster Knowledge Retention | Various strategies to bolster knowledge retention and/or increase knowledge retention especially in low-rate production environments. | Knowledge management, which the researcher has shown herein, can be an enabler supporting the OLC. Requisite parsimony is a systems engineering principle that would be a key contributor to this future research. Various strategies and knowledge management capture tools are the subject of this potential future research. |
| 21 | Throughout | Development of an OLCC for Individual Areas within Low-Rate Production Environment | Research into the constituent areas that comprise the various organizations within low rate production environments such as planning, engineering, manufacturing shops, welding, pipe manufacturing, and other areas to develop a learning characterization for each of these areas. The research contained herein has developed an OLCC for learning in low-rate production environments for the entire enterprise. This area of future research would be the development of an OLCC for individual production labor areas and non-production labor areas within the context of the larger low-rate production environment. | This research may require information that does not exist in the public domain. |

Table 23 (continued)

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# VITA

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## EDUCATION

| | |
|---|---|
| Doctor of Philosophy in Engineering, Old Dominion University | December 2022 |
| Master of Engineering Management, Old Dominion University | May 1994 |
| Bachelor of Science in Mechanical Engineering, Old Dominion University | May 1990 |

## NEWPORT NEWS SHIPBUILDING

| | |
|---|---|
| Deputy Chief Engineer | November 2018 – Present |
| Program Manager, COLUMBIA Class Submarines | February 2018 – December 2018 |
| Program Manager, Cost Reduction | February 2018 – December 2018 |
| Program Manager, VIRGINIA Class Submarines | August 2015 – December 2018 |
| Program Manager, Submarine Operations and Quality | January 2013 – August 2015 |
| Program Manager, CVN 79 and CVN 80 | April 2006 – January 2013 |
| Engineering Manager, Washington Engineering Office | July 2004 – September 2007 |
| Engineering Manager, CVN 21 | January 2003 – August 2004 |
| Engineering Manager, CVN 76 PSA/SRA | July 2002 – November 2003 |
| Deputy Engineering Manager, CVN 76 | January 2002 – June 2003 |
| Manager, Systems Engineering, Power, CVN 77 | January 1999 – December 2001 |
| Engineering Supervisor, Main Propulsion | April 1996 – December 2001 |
| Engineer, CVN, CVNO, 688 Class, Fleet Support, Ship Repair | June 1990 – April 1996 |

## PROFESSIONAL SOCIETIES

ASME, SNAME, ASNE, Navy League, Naval Submarine League, ASEM, INCOSE, ASEE

## COMMUNITY SERVICE

Old Dominion University: Alumni Association; College of Engineering Advisory Board
Boy Scouts of America: Assistant Scoutmaster, Eagle Scout
Nansemond-Suffolk Academy: Past Chair of the Board of Trustees
Georgia Tech Parents Association

## HONORS and AWARDS

Old Dominion University: Leadership Award, 2016; Service Award, 2012; Wall of Honor, 2004
Top 40 Under 40, 2006
Chief of Naval Operations Environmental Award, 2004
Phi Kappa Phi National Honor Society, 2002
Peninsula Engineer's Council Young Engineer of the Year, 2000
Omicron Delta Kappa National Honorary Leadership Society, 1989