COST PREDICTION VIA QUANTITATIVE ANALYSIS OF COMPLEXITY IN U.S. NAVY SHIPBUILDING

by

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B.S., Aerospace Engineering, United States Naval Academy

Submitted to the Department of Mechanical Engineering and Engineering Systems Division in Partial Fulfillment of the Requirements for the Degrees of

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and
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Abstract

As the sophistication and technology of ships increases, U.S. Navy shipbuilding must be an effective and cost-efficient acquirer of technology-dense one-of-a-kind ships all while meeting significant cost and schedule constraints in a fluctuating demand environment. A drive to provide world-class technology to the U.S. Navy's warfighters necessitates increasingly complex ships, which further augments the non-trivial problem of providing cost effective, on-schedule ships for the American taxpayer. The primary objective of this study was to quantify, assess, and analyze cost-predictive complexity-oriented benchmarks in the pre-construction phase of the U.S. Navy's ship acquisition process. This study used commercially-available software such as Mathwork's MATLAB software to analyze the numerical cost data and assess the fidelity of the predictive benchmarks to the datasets. The end result was that a consideration of complexity via the methods and algorithms established in this study supported an exponential cost versus complexity relationship to refine the current cost estimation methods and software currently in use in U.S. Navy shipbuilding. Specifically, it was found that for the subsystems under analysis, acquisition/contract cost per unit was highly correlated with unit complexity according to the relationship, cost/unit (\$M,USD) = $23.100 + e^{0.015C}$.

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List of Acronyms and Abbreviations

AMDR	Air and Missile Defense Radar
ASN	Assistant Secretary of the Navy
CBO	Congressional Budget Office
CGT	Compensated Gross Tonnage
CVN	Aircraft Carrier, Nuclear
DDG	Destroyer, Guided Missile
EVM	Earned Value Management
EVMS	Earned Value Management System
FFG	Frigate, Guided Missile
FFP	Firm Fixed Price
FMI	First Marine International
FY	Fiscal Year
GAO	Government Accountability Office
GD	General Dynamics
GSIBBS	Global Shipbuilding Industrial Base Benchmarking Study
GFE	Government Furnished Equipment
HII	Huntington Ingalls Industries
HM&E	Hull, Mechanical, and Electrical
JHSV	Joint High Speed Vessel
KDX	Korean Destroyer Experimental
LCS	Littoral Combat Ship
LHA	Landing Helicopter Assault
LPD	Landing Platform Dock
LSD	Landing Ship Dock
MIT	Massachusetts Institute of Technology
MCS	Mission Control System
MLP	Mobile Landing Platform
MRG	Main Reduction Gear
NAVSEA	Naval Seas Systems Command
NASSCO	National Steel and Shipbuilding Company
NG	Northrop Grumman
NGSB	Northrop Grumman Shipbuilding
NNSY	Norfolk Naval Shipyard
PEO	Program Executive Office
PHNSY	Pearl Harbor Naval Shipyard
PGC	Philadelphia Gear Company
PIE	Production in the Innovation Economy
PNSY	Portsmouth Naval Shipyard
PMS	Program Management Office (Ships)
PSNSY	Puget Sound Naval Shipyard
RD&A	Research, Development, and Acquisition
ROK	Republic of Korea

RMO	Repair, Modernization, and Overhaul
SOW	Statement of Work
USNS	United States Naval Ship (Non-commissioned)
USN	United States Navy
USS	United States Ship (Commissioned)
T-AKE	Auxiliary Cargo (K) and Ammunition (E) Ship
ZEDS	Zonal Electrical Distribution System

Biographical Note

Lieutenant Aaron Dobson is a native of Southlake, Texas, and he graduated from the US Naval Academy in 2005 with a Bachelor of Science in Aerospace Engineering. After graduation and commissioning, he attended Navy Pilot training in Corpus Christi, Texas, where he earned his wings in March 2007 and then went on to fly the P-3C Orion.

In the spring of 2008, LT Dobson made a direct accession to the Engineering Duty Officer Community and reported for his qualification tour at SPAWAR Space Field Activity in Chantilly, Virginia. After serving in two communication satellite acquisition programs, LT Dobson reported to Massachusetts Institute of Technology (MIT) in April 2011. At MIT Dobson aspires to earn his Engineer's Degree in Naval Architecture & Marine Engineering and a Master of Science in Engineering & Management. He will graduate in June 2014, and report to Sasebo, Kyushu, Japan for duty as Ship Superintendent of various ship classes.

Dobson's future goals are to combine the business education and naval architecture education received at MIT for application in the field of surface ship program management.

Acknowledgements

Captain Mark Thomas, Professor Olivier de Weck, and Dr. Eric Rebentisch's persistent and insightful guidance made this thesis possible. Without their mentorship, very little of this research would have been possible.

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Finally, I want to thank my beautiful wife Amanda for her enduring support, love, and perceptive insights.

1. Problem Background and the DDG 51 Case Study

Over the past 50 years, the cost of U.S. Naval Shipbuilding has grown between 7 to 11% per year, far outpacing inflationary effects during the same timeframe (RAND Corporation 2006). Although the Navy has migrated away from purely weight-based cost estimation methods in the last decade, unpredictable cost growth remains an issue that costs the U.S. taxpayers billions of dollars annually. Background research revealed that cost growth has arisen from two main sources: *customer*-driven factors and *economy*-driven factors, both of which will be explored in depth in Section 2. It was assumed that economy-driven factors in cost growth are of a sufficiently "macro" level to be beyond the reach of Navy policy makers, program managers, and cost estimators to manage or predict. Therefore, the focus narrowed to what was within the Navy's grasp to control: the customer-driven factors, with the Navy functioning as the acquiring agent of ships.

It was discovered that reports on cost growth in U.S. Navy shipbuilding repeatedly returned to the theme of the ever-increasing complexity in modern Naval vessels as a substantial contributor to cost growth. While technological advancement has taken the Navy from relatively simple cannons to highly sophisticated missiles able to obliterate satellites in Low Earth Orbit in the span of a century, the effects on cost growth to build those subsystems has been substantial.

In order to understand and gain traction on the concept of complexity in Naval shipbuilding, it was necessary to determine a method with which to quantify that complexity. Fortunately, MIT doctoral student (at the time of writing) Kaushik Sinha and MIT Professor Olivier de Weck developed an algorithm that did precisely that: quantified structural complexity in a mostly generalizable manner, and although their research focused primarily on software-intensive hardware systems, the equations, algorithms, and logic were modified to suit an application to Naval maritime systems.

As with any algorithm, the quality of the outputs is only as good as the quality of its inputs, so it was determined that a suitable case study needed to meet several requirements:

- Class longevity. A long history of *actual* (vice predicted, parametric, or analogous) costs would help reliably determine what, if any, relation complexity had to cost.
- Proliferation of ships in class. A class with a large number of ships in class would yield more data than a smaller class. It was also hypothesized that any benefits gained from this analysis would positively affect more ships in a larger class.
- Ship class currently in production. There was a desire to choose a class that had not terminated its production run so as to garner at least one or two data points to serve as a predictive measure for the algorithm. The goal for this research was not to merely tell the reader what *was*, but what *could be* in terms of cost growth potential in major subsystems.

Given the diverse set of requirements imposed upon the given ship classes, it was determined that the U.S. DDG 51 *Arleigh Burke*-class and its sister class, the Republic of Korea's KDX *Sejong the Great*-class would be suitable classes of ship for a case study. Both classes have witnessed a production run since the 1980s, with ships populating either three or four individual Flights within class, and are still currently under production in the host country. Although the original desire was to study both ships in their respective shipyards, the R.O.K.'s security concerns precluded the in-depth study of the KDX-class so this led to focusing this study on the system and subsystems within the DDG 51 vessels.

To summarize, the main focus of the research in this study was to examine the concept of the characteristic complexity inherent in various DDG 51 subsystems that drive cost growth and cost uncertainty. It is hypothesized that direct correlations between cost and complexity could drive down cost uncertainty for U.S. Navy policymakers, save the taxpayer large sums of money, and help refine current cost-predictive software tools currently in use by the Navy's cost estimation groups.

1.1 DDG 51 *Arleigh Burke*-class Guided Missile Destroyers: A Case Study

Since the launch of the original DDG 51, the *U.S.S. Arleigh Burke*, in 1985, variants of the DDG 51 concept have garnered international popularity as highly capable, multi-mission platforms featuring the powerful AEGIS radar system (FAS Military Network 2013). While the U.S. concept will be discussed in further detail later, several other countries such as Japan, Spain, Norway, and Australia either have or will have employed variations of AEGIS-capable destroyers. A brief discussion of the aforementioned KDX-class and the Korean shipyard environment is included in Appendix D.

Selecting a vessel of comparable complexity between the U.S. shipyards and the R.O.K. shipyards facilitates a more relevant benchmarking study by comparing "apples to apples" versus comparing a shipyard producing relatively high complexity vessels such as naval combatants versus a shipyard producing relatively low complexity vessels such as container ships.

The DDG 51 class is the U.S.'s "jack of all trades" guided missile destroyer, and while it was originally designed to combat and defend against Soviet-era threats, the employment of the highly sophisticated AEGIS air defense system has allowed the craft to evolve into several different modern mission areas. These combat capabilities include anti-air, anti-submarine, anti-surface, strike operations, and ballistic missile defense (FAS Military Network 2013). A representative multi-view of the ship is shown in Figure 1.

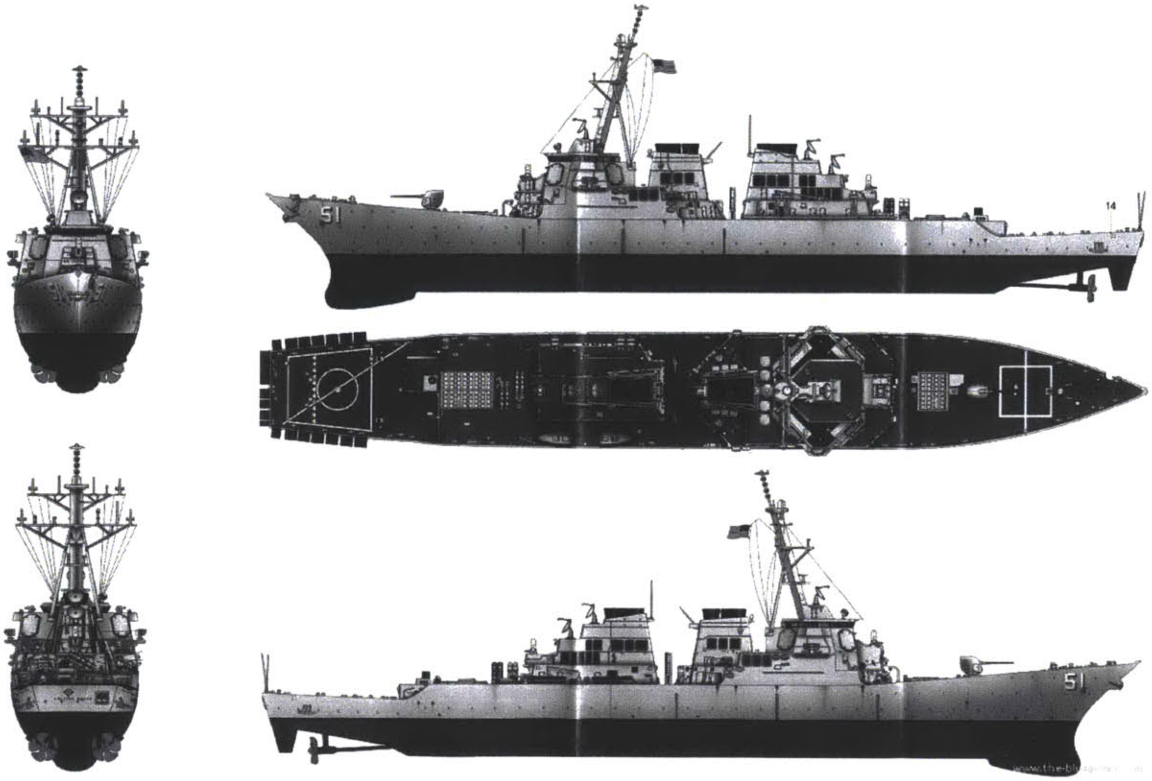

Figure 1: DDG 51 *Arleigh Burke* Guided Missile Destroyer (USS DDG 51 Arleigh Burke Destroyer 2009)

At the time of writing, three flights of the DDG 51 class are currently at sea, and requirement evolution is underway on a fourth flight. In June 2013, the Navy announced that two contracts were awarded to Bath Iron Works (BIW) and Huntington Ingalls Industries (HII) for continued construction of the Flight IIA and eventual construction of Flight III currently under requirements development. As shown in Table 1 and Figure 2, Flight III is expected to begin construction in FY 2016 and will likely provide increased capability via an increase in power and cooling to accommodate replacing the AEGIS AN/AEGIS radar with the Air and Missile Defense Radar (AMDR). (NAVSEA Office of Corporate Communication 2013) (Captain Mark Vandroff, Program Manager, DDG 51 Shipbuilding Program 2012)

The DDG 51 class evolution is shown in Figure 2 where hull numbers starting with the original *Arleigh Burke* and progressing up through the proposed Flight III vessels are mapped to their respective fiscal years and builders.

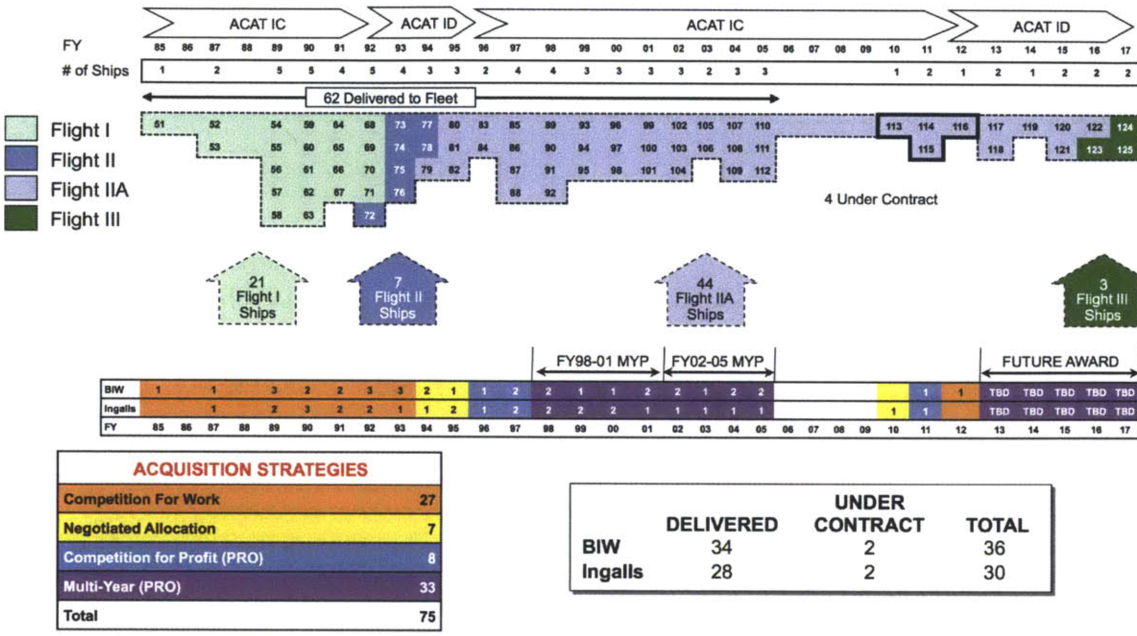

Figure 2: DDG 51 Class Evolution by Flight (Captain Mark Vandroff, DDG 51 Program 2013)

Table 1: DDG 51 Class Evolution by Flight. Numbers in italics represent projected figures based on current data. (NAVSEA Shipbuilding Support Office 2013)

Flight Number	Hulls	Launch Periods	Lightship Weight
I	51 – 71	1989 - 1996	6691 – 6827 tons
II	72 – 78	1996 - 1997	6805 – 6824 tons
IIA	79 – *122*	1998 - *2015*	7134 – *7134* tons
III	*123+*	*2016+*	No Data

1.2 Production in the Innovation Economy (PIE) Study

In 2011, the Massachusetts Institute of Technology (MIT) commissioned the PIE study, and its "overarching goal is to shed light on how America's great strengths in innovation can be scaled up into new productive capabilities. The goal is to develop recommendations for transforming America's production capabilities in an era of increased global competition." (MIT 2011) The Assistant Secretary of the Navy for Research, Development, and Acquisition (ASN(RD&A)) further funded the study to add a standalone module to address US shipbuilding.

There are five parts in the Technical Statement of Work (SOW) of the shipbuilding module of the PIE study.

1. Innovation in Bidding and Contracting
2. Project Management and Rework Dynamics
3. National and International Benchmarking of U.S. Shipbuilding Performance
4. Supply Chain Management and Supplier Base
5. Prospects for U.S. Commercial Shipbuilding

This thesis research was conducted in part for SOW task two and three.

On directives received from the ASN(RD&A)'s office, "the scope of the study is the shipbuilding industry, holding other stakeholders as part of the boundary conditions. The scope includes the linkage between the contractor and USN through the program lifecycle." The study seeks to answer two overarching questions:

- Can the U.S. government be doing more to put more pressure on the prime contractors and suppliers to get better cost performance and innovation?
- Furthermore, why is the escalation in shipbuilding costs greater than general inflation?

2. Literature Review

The literature review focused on two main topics: first, a review of the cost growth problem within the field of Naval shipbuilding, and secondly, an examination of Kaushik Sinha and Olivier de Weck's research into structural complexity quantification will be reviewed for later application to ships and shipboard systems.

The overall topic of complexity was broken into three dimensions: technical, organizational, and strategic complexity (Hoffman and Kohut 2012) as shown in Table 2.

Table 2: Dimensions of Project Complexity (Hoffman and Kohut 2012)

Technical	Organizational	Strategic
Number and type of interfaces	Number and variety of partners (industry, international, academia/research)	Number and diversity of stakeholders
Technology development Requirements	Distributed/virtual team; decentralized authority	Socio-political context
Interdependencies among technologies (tight coupling vs. loose)	Horizontal project organization	Funding sources and processes

For complex, technical projects fully understanding the interfaces and interdependencies in a given system or subsystem are crucial to success. George Low, the legendary leader of NASA's Apollo program, knew this was a key to Apollo's success. He noted that only 100 wires linked the Saturn rocket to the Apollo spacecraft. "The main point is that a single man can fully understand this interface and can cope with all the effects of a change on either side of the interface. If there had been 10 times as many wires, it probably would have taken a hundred (or a thousand?) times as many people to handle the interface," he wrote." (Hoffman and Kohut 2012) A similar interface philosophy applied to Navy projects such as Littoral Combat Ship could not only yield a decrease in cost, but also an increase in operational tempo due to decreased time in port between mission module swaps.

Methods presented in Section 2.2 and applied in Section 4 focused on the technical dimension of complexity, but as Table 2 implies, the concept of complexity has a far greater diversity of roots than simply the technical aspect alone. While the algorithms and quantification of complexity focused on the technical aspect, Section 5 attempted to unify these dimensions, with the principal results from the algorithm logic, into actionable points for cost savings for the U.S. taxpayer.

2.1 Cost Growth

Over the past 50 years, the cost of US naval shipbuilding has increased between 7 to 11% annually, while the average inflation from 1913 to 2013 has been approximately 3.22% (Inflation Data 2013). Given the current environment of fiscal austerity imposed upon government spending, the ever-increasing cost of has ships has resulted in subsequently squeezed naval shipbuilding budgets. A 2006 RAND Corporation study based on Congressional Budget Office (CBO) data points out that a hypothetical boost of $2 billion to $12 billion dollars would "only help the Navy achieve a fleet of 260 ships by the year 2035 rather than the nearly 290 it now has." (RAND Corporation 2006) At the time of writing in 2013, the current US Navy fleet size of commissioned ships has been reduced to 250 ships (NAVSEA Shipbuilding Support Office 2013).

While many factors contribute to ship cost growth, those factors can be attributed to two broad categories: *economy*-driven factors and *customer*-driven factors. Economy-driven factors include items such as equipment, labor rates, and material costs, and the 2006 RAND study found that the cost growth in those rates tracked closely with overall U.S. inflation rates. These economy-driven factors were responsible for a 3.41%[1] cost increase between fiscal years 1961 and 2002 (RAND Corporation 2006), which leaves the remaining 2.5 to 6.5% of cost growth attributable to customer-driven factors.

[1] 3.41% was the average inflation in the U.S. between 1960 and 2009 (Inflation Data 2013).

Customer-driven cost increases were grouped into three subcategories with their associated percentage cost increase between DD 2 in FY 61 and DDG 51 in FY 2002 (RAND Corporation 2006):

- **Characteristic Complexity (2.1%)**
- Standards, Regulations, and Requirements (2.0%)
- Procurement Rates (0.3%)

The magnitude of cost growth for different ships is shown in Figure 1 from a 2005 GAO report.

COST GROWTH IN U.S. NAVY WARSHIPS					
Initial and Current Budget Request ($ millions)					
Case Study Ship	Initial	Current	Difference (%)	Projected Additional Cost Growth	Total Cost Growth (%)[a]
DDG 91	$ 917	$ 997	$ 80 (8.7%)	$ 28-32	$ 110 (12.0%)
DDG 92	925	979	55 (5.4%)	9-10	65 (7.0%)
CVN 76	4,266	4,600	334 (7.8%)	4	338 (7.9%)
CVN 77	4,975	5,024	49 (1.0%)	485-637	610 (12.3%)
LPD 17	954	1,758	804 (84.2%)	112-197	959 (100.5%)
LPD 18	762	1,011	249 (32.6%)	102-136	368 (48.3%)
SSN 774	3,260	3,682	422 (12.9%)	(-54)-(-40)	375 (11.5%)
SSN 775	2,192	2,504	312 (14.2%)	103-219	473 (21.6%)
Total	**$ 18,251**	**$ 20,556**	**$ 2,305 (12.6%)**	**$ 789-1,195**	**$ 3,298 (18.1%)**
[a] Total cost growth was calculated using the current budget request plus the midpoint of the additional cost growth.					
Source: *Improved Management Practices Could Help Minimize Cost Growth in Navy Shipbuilding Programs*, GAO Report, February 2005.					

Figure 3: Cost Growth in US Navy Warships (GAO 2005)

Although the 2006 RAND study was the only report discussed in this paper, several GAO reports, program briefings, and third-party maritime consultants have cited complexity as being a primary driver in cost growth. The end result of the cost growth research determined that there is an inextricable link between complexity and cost growth, and the fact that this complexity is a customer-driven factor warrants a discussion to answer the questions of how do we as the U.S. Navy gain traction and understanding on the concept of complexity and refine our cost estimation techniques to capture the notion of complexity? What complexity-based mitigation factors, if any, are necessary to drive down cost growth and better assess what the final price tag would be? This research sought to not to reduce the cost of shipbuilding itself, but to gain a better definitive understanding of how complexity drives cost in an effort to shrink the gap between projected and actual costs.

2.2 Structural Complexity

To gain a hold on the concept of complexity and provide a quantitative baseline with which to compare different systems, this research focused on work published by Sinha and de Weck, 2013 at MIT. This work served as the numerical basis for the analysis of the DDG 51 class, which will occur in Section 4. The method for quantifying structural complexity was selected as a basis for analysis due to its generalizability of application in engineering systems. Sinha and de Weck, 2013 validated their method for a large (and thus generalizable) range of systems including those of high complexity such as a satellite, aircraft engines, and those systems of low complexity, such as a hair dryer.

Structural complexity was described in functional form via the following simple relation:

$$\text{Structural Complexity, } C = C_1 + C_2C_3$$

- C_1 represented the "sum of complexities of individual components alone (local effect) and does not involve architectural information." (Sinha and de Weck 2013). This term was directly associated with activities related to component engineering. If a system was completely disassembled and all the components (hardware and software) spread out on a hypothetical flat plane, this term would represent the sum of all the individual component complexities.

  To capture the multi-faceted nature of component complexity C_1, Sinha and de Weck sought to aggregate the factors in a way where each particular dimension of C_1 could be analyzed, quantified, and then subsequently rolled up into the parent C_1 figure using an algorithm that normalizes the terms and then sums them. This initial aggregation of factors is defined in an $n \times 1$ array called the X-vector. Sinha and de Weck, 2013 initially proposed the terms within the X-vector (Sinha and de Weck 2013) as shown below, but that vector has been adapted for this DDG-51 class-oriented case study. In Sinha and de Weck's original work, $C_1(X^{(i)})$ was primarily adapted for applications in Cyber-Physical Systems and thus several terms were substituted for more maritime-suitable counterparts.

$$X^{(i)} = \begin{bmatrix} x_1^{(i)} \\ x_2^{(i)} \\ x_3^{(i)} \\ x_4^{(i)} \\ x_5^{(i)} \\ x_6^{(i)} \\ x_7^{(i)} \\ x_8^{(i)} \end{bmatrix} = \begin{bmatrix} x_1^{(i)} = f(Performance\ Tolerance) \\ x_2^{(i)} = f(Performance\ Level) \\ x_3^{(i)} = f(Component\ Size) \\ x_4^{(i)} = f(Amount\ of\ Coupled\ Disciplines) \\ x_5^{(i)} = f(Amount\ of\ Variables) \\ x_6^{(i)} = f(TRL) \\ x_7^{(i)} = f(Heritage\ Knowledge) \\ x_8^{(i)} = f(Heritage\ Reuse) \end{bmatrix}$$

For the purposes of this research, the X-vector is defined as follows:

- X_1 – Measure of performance tolerance. Systems and subsystems with smaller tolerances in performance garner a higher X_1 rating than those that do not. For example, a missile tasked to strike a 1 square meter target would have a higher value for X_1 than another missile tasked to strike a 10 square meter target.
- X_2 – Performance level. What is the performance level expected of the system or subsystem? It is posed that performance correlates with complexity in the same way that an Italian supercar is more complex than an old pickup truck.
- X_3 – Component "size" indicator. How big is the system? X_3 captures the complexity of size; for example, it is proposed that an office building is more complex than an average single residential house.
- X_4 – Number of coupled disciplines involved. How many different fields are coming together to produce this product? A purely mechanical interface is most likely less complex than an electrical to mechanical interface, and X_4

captures the degree to which varied disciplines must come together in a product.

- X_5 – Number of variables involved.
- X_6 – Reliability. The concept of reliability in the X_6 factor has been adapted in this study via the use of DoD's Technology Readiness Level. X_6 is a function of the top of the TRL scale divided by the unit's actual assessed TRL. TRL and the DoD definition of TRL will be discussed in further detail below.

For US systems acquired by the Department of Defense, relative technological development is quantified through the use of the Technology Readiness Level (TRL) System. Fielded, mature systems are rated at a 9, and technologies that only exist in theory and rely on new concepts from science are rated at a TRL of 1. The TRL spans discretely (vice a continuum) from 1 to 9 because of the nonlinear financial and schedule impacts not captured by a purely linear continuum.

$$x_6 = \frac{TRL_{max}}{TRL_i}$$

The concept of TRL and each item's specific relation to x_6 will be explained in greater detail later.

- X_7 – Existing knowledge of operating principle. This metric examines to what degree the technology under question is "new" technology. Is the component under analysis a product of old and theoretically well-understood knowledge or is the subsystem under question relatively novel? As understanding increases, X_7 decreases. For example, the mechanical workings of a bicycle could appear quite complex to the uninitiated, but to a veteran racer or bicycle mechanic the bicycle is a comparatively simple machine due to their degree of existing or prior knowledge of the principles involved.

- X_8 – Extent of reuse/heritage indicator. Similarly to X_7, an increase in heritage reuse, would signify a decrease in X_8 for similar reasons.

C_1 was the summation of its parts (in this case, the X-vector), scaled for commonality to a range between 0 and 10. Although it is possible to weight the component terms of C_1 such that some terms are more important than others, there did not appear to be an objective initial reason to do so.

$$C_1 = \sum_{i=1}^{n=8} x_i$$

- The second term C_2 represents the number and complexity of each pair-wise interaction. C_2 comprises the "interfaces" term and is related to the design and management of interfaces between the individual components described in C_1.

  To calculate C_2 each α components' pairwise interface is defined by a certain β value comprised of two nonzero α values and their coefficient characteristic for that type of interface. Two complex components that interface directly are more likely to have a complex interface compared to a single complex component interfacing with a simple component or two simple components interfacing with each other directly.

$$\beta_{ij} = f_{ij}\alpha_i\alpha_j \;\; where\; \alpha_i, \alpha_j \;\neq 0$$

  Again, for n components and m interactions,

$$C_2 = \sum_{i=1}^{n}\sum_{j=1}^{m} \beta_{ij}A_{ij}$$

- C_3 represents the global effect produced by the effect of architecture or arrangement on the interfaces in a specific topology. This topological complexity term is based upon the product's architecture and is related to the required System Integration efforts.

One of the key contributors to complexity is the internal architectural complexity of the system, and on the physical level that complexity is manifested through the interconnectedness of the system or subsystem. That internal complexity is captured through the use of the Design Structure Matrix (DSM). Figure 4 represents three structural examples of increasing topological complexity. From left to right, these structures represent a centralized/bus architecture, a hierarchical architecture, and a distributed architecture. The degree of interconnectedness of the nodes is the chief differentiating factor leading to increased complexity in the C_3 variable.

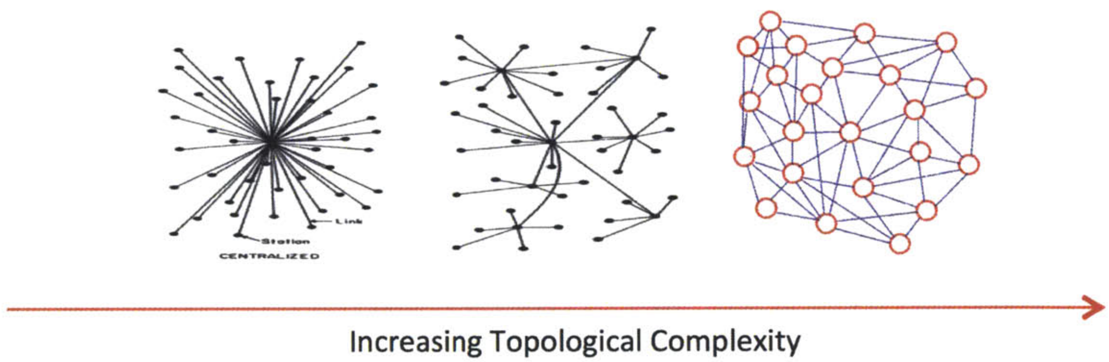

Figure 4: Topological Complexity

Measurement of the topological complexity in the ship's identified subsystem is captured via matrix energy. A property of matrix energy is that it is invariant to isomorphic transformations of the matrix, which makes it a suitable method for measuring the interconnectedness of the subsystem (Horn and Johnson 1994). The final topological complexity metric is defined by the energy of that adjacency matrix $A \in M_{nxn}$.

The concept of matrix (or graph) energy was introduced by Ivan Gutman in 1978 as an aid for modeling the π-electron energy of molecules. Gutman "formulated the π-electron energy of certain molecules as the sum of the absolute values of the eigenvalues of the adjacency matrix of a chemical graph associated with the molecular bonds." (diStefano and Davis 2009)

In each identified subsystem, Λ is the set of connected nodes in the DSM A_{ij}. (Sinha and de Weck 2013)

$$A_{ij} = \begin{cases} 1, & \forall[(i,j)|(i \neq j) \text{ and } (i,j) \in \Lambda] \\ 0, & otherwise \end{cases}$$

The energy is given as follows based on Gutman's method and the standard eigenvalue equation (diStefano and Davis 2009):

$$E(A_{ij}) = \sum_{i=1}^{n} |\lambda_i|; \quad A - \lambda I = 0$$

Unidirectional interfaces only.

One of the chief limitations of the relatively simple summation of the absolute value of the eigenvalues is its lack of generalizability in undirected interfaces. In engineered systems, an undirected interface can be thought of as one in which data can flow multiple directions. For a physical system such as a welded joint, the system is directed, and with that system, the summation of eigenvalues would be sufficient, but in order to make this analysis as generalizable as possible, especially in regards to the analysis of advanced sensors and weaponry, the *summation of singular values* via a singular value decomposition will be used in the calculation of C_3.

$$E(A_{ij}) = \sum_{i=1}^{n} \sigma_i; \quad A - \lambda I = 0$$

Graph energy for Adjacency matrix A_{ij}, containing a binary representation of generalizable, omnidirectional/undirected interfaces.

For the examples given below, A_1 would have an adjacency matrix represented by the following relatively sparse matrix given that only the central node has connections to the others, while A_2 has a slightly higher degree of connectivity among the nodes:

$$A_1 = \begin{bmatrix} 0 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}; \; A_2 = \begin{bmatrix} 0 & 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 1 & 0 & 0 \\ 1 & 0 & \vdots & 0 & 0 & 1 & 1 \\ 0 & 1 & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & 1 & 0 & \vdots & \vdots & \vdots & \vdots \\ \vdots & 0 & 1 & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix}$$

From this equation one can calculate that $\lambda_1 = -2.45$ and $\lambda_2 = 2.45$ (all other eigenvalues are 0) so $E(A_1) = 4.9$. Following the same method, one can calculate the notional $E(A_2)$ value is 6.83 ($\lambda_1 = -2$, $\lambda_2 = 2$, $\lambda_3 = -1.41$, $\lambda_4 = 1.41$, $\lambda_{5\text{-}7} = 0$) which is indicative of A_2 being the more topographically complex structure by its exhibition of a higher degree of inter-connectedness as shown in Figure 5, even though both structures A_1 and A_2 have the same number of nodes and edges, respectively.

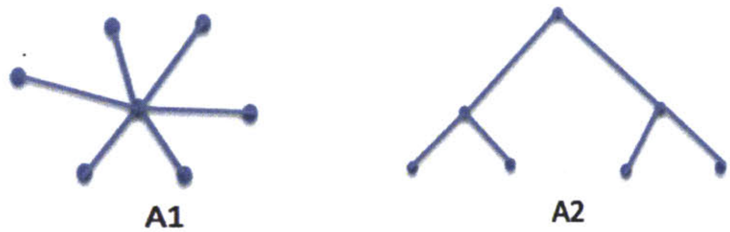

Figure 5: Matrix Energy Nodal Structure Example

$E(A) = \sum_{i=1}^{n} \sigma_i$, where σ_i represents the i^{th} singular value

C_3 was equal to the matrix energy expressed from above times a normalization factor γ based on the number of components.

$$C_3 = \gamma E(A), \gamma = 1/n$$

In summary, structural complexity can be quantified via the integration of the discussed terms into the original equation for each subsystem targeted for analysis.

$$\boldsymbol{C(n, m, A) = \sum_{i=1}^{n} x_i + \left[\sum_{i=1}^{n} \sum_{j=1}^{m} \beta_{ij} A_{ij}\right] \gamma E(A)}$$

As an illustrative example, Sinha and de Weck, 2013 showed that this analysis applied to two different jet engine architectures, "namely a dual spool direct-drive turbofan (e.g. new architecture) and a geared turbofan engine (e.g., new architecture)". After consulting with experts to collect data regarding interface complexity, it was determined structural complexity was underestimated by 43% since originally only the amount of connections and pair-wise interfaces were considered. This resulted in a real 40% increase in complexity when only 28% was predicted thus contributing to an increase in development cost over the previous turbofan engine's predecessor.

3. Information and Data Collection

All information and data collection efforts were seeking to answer the two main constructs that comprise the main premise of this study:

1. Complexity: The number of elements and interdependencies in the ship's architecture contributes to the ship's overall complexity.
2. Technical Risk: As a program management tool, technical risk is a key indicator of a program's self-assessed vulnerabilities. Those areas typically lie in areas of high complexity where the technology or employment of that technology is least understood. For example, a program with a requirement to employ a new radar will most likely assess that radar at a higher technical risk level than another shipboard system such as the hull.

This information is summarized in Figure 6.

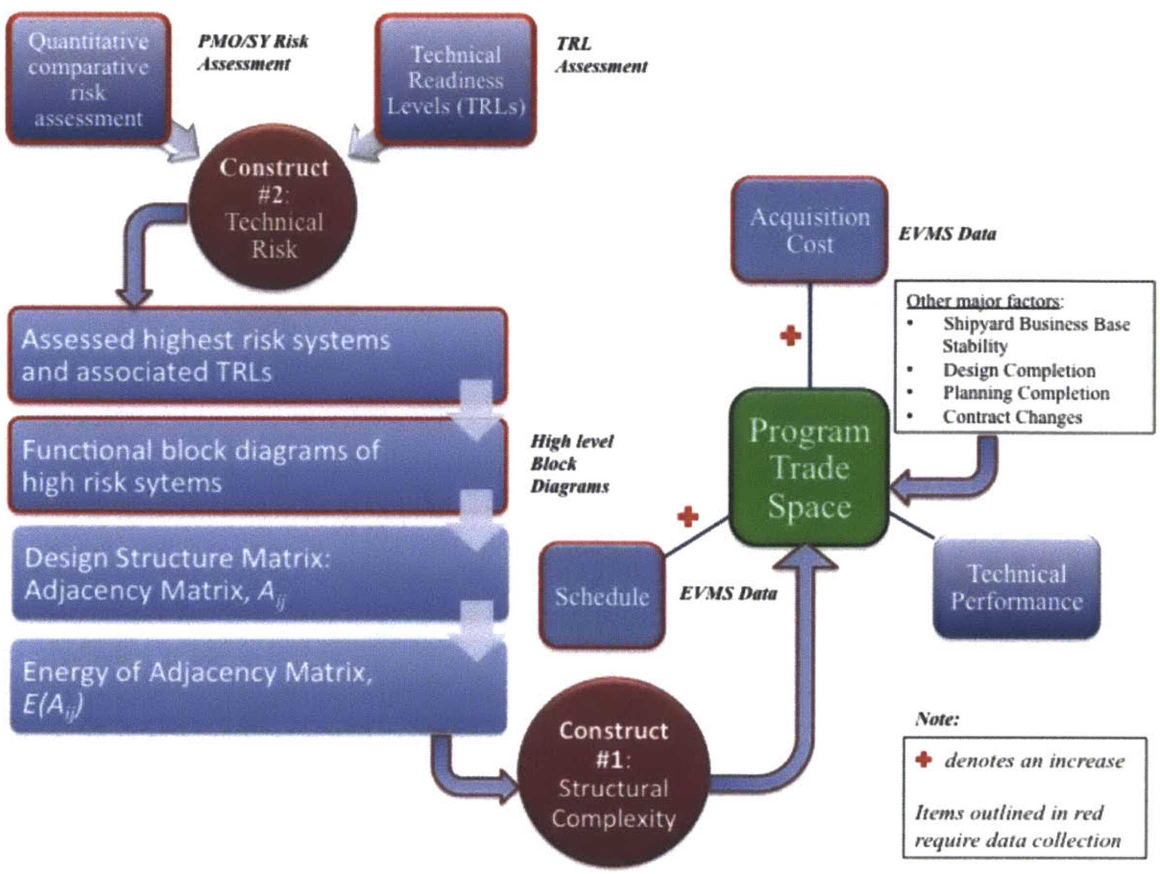

Figure 6: Research, Constructs, and Data Flow

3.1 Data Collection: Interviews

Interviews were conducted throughout the research at several different venues: organized shipyard tours, conferences, and appointments. A summary of the interviews, meetings, and travel conducted in support of this research is included in Appendix A. As the research progressed, the nature of the interviews evolved from seeking contextual and background information to seeking pertinent data and best practice information.

At the beginning of the research, the interviews and meetings helped refine and define what the course of the research would eventually be, and as the study progressed, the interviews became increasingly focused on data mining and gathering specific, targeted information on the subsystems under analysis. Of note, through the interviews with the Technical Director of PMS 400D[2], a set of high-risk subsystems, their associated risk levels, and their functional block diagrams or drawings were obtained. This information fed directly into the logic and algorithms applied for analysis in Section 4.

3.2 Data Collection

Through the interviews with the Technical Director of PMS 400D, the three highest risk systems were identified as the AMDR, MRG, and the MCS. All of the particulars on why these subsystems were selected and their associated assessments are described in further detail in Appendix A. Following the methods described by Sinha and de Weck, 2013 in Section 2.3, the remaining data collection steps were to:

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[2] The Technical Director of PMS [Program Management (Ships)] 400D is the lead technical government authority for HM&E (Hull, Mechanical, and Electrical) items in the DDG 51 program. Other systems such as Air Missile Defense Radar (AMDR) and AEGIS are developed by other entities outside of PMS 400D. The DDG 51 government/contractor team then integrates those developed systems into the DDG 51 design.

- Assign values via expert assessment and field research for the X-vector leading to the determination of C_1.
- Gather the expert interface complexity assessment, β leading to the determination of C_2.
- Collect the subsystem functional block diagram leading to the sequential determine of A_{ij}, E(A), γ, and C_3 as described above.

3.2.1 Component Complexity Metric, X_i

The x_i metric aggregates a complexity valuation for each subsystem based upon eight factors shown in vector X for each subsystem under analysis. It should be noted that the X-vector as it is presented was modified and adapted for the DDG 51-oriented case study and is thus different from what was proposed in Sinha and de Weck's original work.

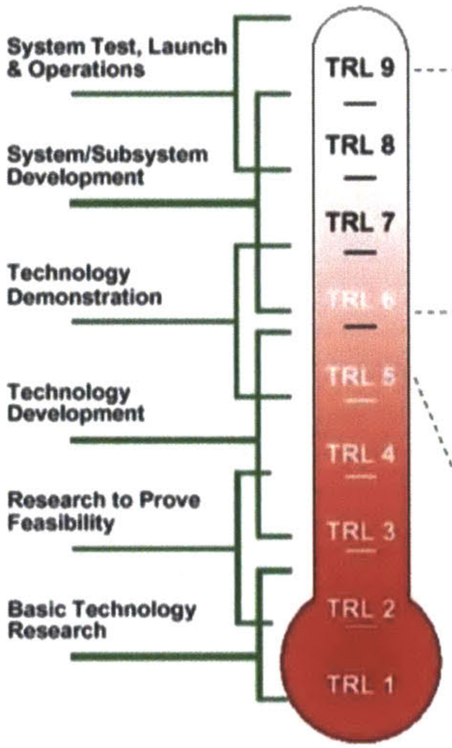
$$X^{(i)} = \begin{bmatrix} x_1^{(i)} \\ x_2^{(i)} \\ x_3^{(i)} \\ x_4^{(i)} \\ x_5^{(i)} \\ x_6^{(i)} \\ x_7^{(i)} \\ x_8^{(i)} \end{bmatrix} = \begin{bmatrix} x_1^{(i)} = f(Performance\ Tolerance) \\ x_2^{(i)} = f(Performance\ Level) \\ x_3^{(i)} = f(Component\ Size) \\ x_4^{(i)} = f(Amount\ of\ Coupled\ Disciplines) \\ x_5^{(i)} = f(Amount\ of\ Variables) \\ x_6^{(i)} = f(TRL) \\ x_7^{(i)} = f(Heritage\ Knowledge) \\ x_8^{(i)} = f(Heritage\ Reuse) \end{bmatrix}; \quad C_1 = f(X^{(i)}) = \sum_1^8 x_j$$

The X vector[3] was determined through a combination of expert assessments and other supporting research.

Given the ambiguity and DoD-centric nature of TRL, an expanded discussion is required of TRL and its effect on the X_6 variable. As an adaptation to DoD acquisition, the component reliability indicator, X_6 was a function of the subsystem's TRL. Each factor will be discussed in detail later, but TRLs were assessed based on

[3] Expanded definitions for each x_i term were provided in Section 2.2.

information from the interview with the PMS 400D Technical Director coupled with an integer-level corroboration per the DoD definitions for TRL. That information was mapped to the TRL level definitions provided in Figure 7 below.



DoD Expanded Definition

TRL 9 - Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation (OT&E). Examples include using the system under operational mission conditions.
Subsystem: AEGIS and MRG_{GE}

TRL 6 - Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment.
Subsystem: MCS

TRL 5 - Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment. Examples include "high-fidelity" laboratory integration of components.
Subsystem: AMDR and MRG_{PGC}

Figure 7: TRL Level Definitions (NASA 2004) **and Expanded Definitions** (ASD R&E 2011)

Each subsystem's TRL was assessed based on the capability of the manufacturer producing that subsystem. For example, General Electric has historically produced the highly precise MRG for the DDG 51 class. When the Flight IIA line was restarted, GE announced that they would no longer be producing the MRG so a contract was let to provide the MRG as GFE for the continuation of the Flight IIA class. Philadelphia Gear Company (PGC) won the contract. When GE sent PGC the drawings for the MRG, PGC discovered that there was missing information in the technical drawings, and that some NRE and learning would exist until that knowledge gap between GE and PGC was closed. In terms of TRL, an item that was TRL 9 for GE was a TRL 5 for PGC (Hellman 2013). According to DoD definitions (ASD R&E 2011):

- **TRL 5** - Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment. Examples include "high-fidelity" laboratory integration of components.
- **TRL 6** - Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment.
- **TRL 9** - Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation (OT&E). Examples include using the system under operational mission conditions.

$$x_6 = \frac{TRL_{max}}{TRL_i}$$

Where $\Re(\text{TRL}) \in [1,9]$ and TRL_i is each subsystem's assessed TRL based on the DoD standard definitions. Table 3 summarizes each subsystem's TRL and corresponding x_i value.

Table 3: Subsystem Risk and x_6 Values

Subsystem	TRL_i	x_6
AEGIS AN/AEGIS	9	1.0
Air and Missile Defense Radar (AMDR)	5	1.8
Main Reduction Gear (MRG_{GE})	9	1.0
MRG_{PGC}	5	1.8
Machinery Control System (MCS)	6	1.5

For reference, the X-vector definition is provided once more:

$$X^{(i)} = \begin{bmatrix} x_1^{(i)} = f(Performance\ Tolerance) \\ x_2^{(i)} = f(Performance\ Level) \\ x_3^{(i)} = f(Component\ Size) \\ x_4^{(i)} = f(Amount\ of\ Coupled\ Disciplines) \\ x_5^{(i)} = f(Amount\ of\ Variables) \\ x_6^{(i)} = f(TRL) \\ x_7^{(i)} = f(Heritage\ Knowledge) \\ x_8^{(i)} = f(Heritage\ Reuse) \end{bmatrix}; \quad C_1 = f(X^{(i)}) = \sum x_j$$

The X-vector summary is shown in Table 4.

Table 4: X-Vector Summary (Normalized [0,10] Value in Parenthesis) for a possible total Component Complexity score of 80

Component Complexity	AEGIS	AMDR	MCS	MRG (GE)	MRG (PGC)
X_1	9	9	6	10	10
X_2	9	10	3	3	3
X_3	7	7	3	2	2
X_4	35 (10)	35 (10)	12 (3.4)	1 (0.1)	1 (0.1)
X_5	35 (10)	35 (10)	31 (8.9)	27 (7.7)	27 (7.7)
X_6	2.0	2.8	2.5	2.0	2.8
X_7	10	3	4	6	8
X_8	10	4	3	5	9
ΣX_i	**67**	**55.8**	**36.8**	**31.8**	**42.6**

3.2.2 Interface Complexity Assessment, β

The Technical Director of PMS 400D also provided the assessment for interface complexity as described in Section 2.3. The director was asked to assess the interface complexity between 0 and 1 with 1 being the most complex interface one would see onboard a ship. An example of an interface that would garner a rating of 1 would be an interface with thousands of wires of varying voltages and frequencies. On the other end of the spectrum, an interface with a 0 rating would be quite simple, such as two plates bolted together. "If there were multiple types of connections between two components (say, load-transfer, material flow and control action flow), it would have a high β value since it would be more 'complex' to achieve/design this connection compared to a simpler load-transfer connection. For large, engineered complex systems, it appears that β_{ij} in [0,1] is a good initial estimate." (Sinha and de Weck 2013)

Unfortunately due to governmental classification issues, it was impossible to assess each subsystem component's interface at a sufficient level of detail to assign β_{ij} values for each interace within the subsystem. Detailed information on important subsystems such as AEGIS and AMDR are (justifiably) closely guarded secrets. Therefore, a simplying assumption had to be made in order to obtain reasonable values for β_{ij}. It was determined that expert assessment, via the Technical Director for PMS 400D, would suffice to estimate the aggregated subsytem's interface complexity β, and that overarching β value would serve as the "rolled up" value for all the component interfaces within the subsystem. While a realistic subsystem would most likely have interfaces of varying complexity, the assumption is that a qualified subject matter expert could estimate the overall average interface complexity. If the Navy chose to implement complexity-based cost estimation as shown in this study, this simplifying assumption could be immediately lifted to populate the β_{ij} matrix without the constraints imposed by security concerns.

Table 5 below summarizes the findings for β_{ij} for the three critical DDG 51 subsystems ranked via the PMS 400D interview and data collection process. These values were assumed to be the *averaged* value of all component interfaces contained within the subsystem, an assumption necessary because of the lack of visibility the researcher had into Navy subsystems because of the unclassified nature for which this study is intended.

Table 5: Subsystem Interface Complexity, β_{ij} (Hellman 2013)

Subsystem	Interface Complexity, β_{ij}
AEGIS AN/AEGIS	0.9
Air and Missile Defense Radar (AMDR)	1.0
Main Reduction Gear (MRG)	0.3
Machinery Control System (MCS)	0.8

3.2.3 Functional Block Diagrams and Schematics

Functional block diagrams were needed to create adjacency matrix models of the system from which the matrix energy could be derived per the methods laid out in Section 2.3. *Functional* block diagrams were chosen instead of *physical* block diagrams due to a subsystem's complexity being a matter of function more than parts. A subsystem could be comprised of a great number of parts while remaining relatively simple, while a different subsystem could be comprised of relatively few parts while being substantially more complex.

These diagrams led to a numerical result for C_3 in the complexity equation.

AMDR and AEGIS

AMDR is slated to be the successor to the highly successful and prolific heritage AEGIS program. On October 10th, 2013, Raytheon was awarded a $385+ million CPIF (Cost Plus Incentive Fee) contract for the "engineering and modeling development phase design, development, integration, test, and delivery of Air and Missile Defense S-Band Radar (AMDR-S)." (Raytheon 2013). At the time of writing, AMDR-S and AMDR-X (X-band capable AMDR) will reportedly fall under separate contracts, and henceforth all references to AMDR will refer to AMDR-S.

Because of the classified and contractually sensitive nature of AMDR, unclassified, publically distributable data was scarce. To overcome this obstacle, the AEGIS (AMDR's immediate predecessor) was used as a case study to illustrate the complexity inherent in large multi-mission shipboard radars such as AEGIS and AMDR. In terms of power and cooling, AMDR will require substantially more of both; the current 200-ton cooling plant will be scaled up to a 300-ton plant that will provide cooling for the AMDR plus margin (Hellman 2013). Initially, the Flight III variant is slated to have a 14-foot AMDR that is the maximum size the DDG 51 deckhouse can accommodate, but eventually ship designs will be required to include the 20-foot AMDR to combat future ballistic missile threats.

A *k-factor* was required to quantitatively link AMDR to AEGIS in terms of complexity: $\text{Complexity}_{\text{AMDR}} = k\ \text{Complexity}_{\text{AEGIS}}$.

To determine a reliable *k* factor, the key differences between AMDR and the traditional AEGIS radars must be examined. While AMDR has an expanded mission set over the less capable AEGIS predecessor, simply counting the missions would not necessarily yield a reliable *k* factor (based on a percent increase of missions) due to the fact that several missions are duplicated between the older AEGIS and the new AMDR. Combining the qualitative interview assessment of increased AMDR complexity from PMS 400D with RAND Corporation's concept (RAND Corporation 2006) of power density (i.e., the ratio of power generation capacity to lightship weight), an *electrical power density*-based k-factor was selected. Power density yields a more reliable metric than just power because more power does not always yield more complexity. An old "muscle" car boasts more power than a modern luxury sedan, yet the modern luxury sedan has orders of magnitude more complexity than the old high-powered muscle car when one considers all the advanced technologies and software intrinsic to the new luxury vehicle. To compare power densities, one must consider the ship as a whole, and to facilitate the most reasonable "apples to apples" comparison, the DDG 51 Flight IIA, as the representative for the AEGIS case, and DDG 51 Flight III, as representative of the AMDR case, was selected. The differences between the ships in terms of length and non-radar centric power draws are minimal; chief differences lie within the radar subsystems and the substantial power requirements of those radar subsystems. A k-factor was determined for AMDR using the definition and comparison equations presented below.

$$\rho_{Pwr} \stackrel{\text{def}}{=} \frac{Power\ Capacity}{Lightship\ Weight}$$

$$k_{AMDR} = \frac{\rho_{Pwr,Flt.III}}{\rho_{Pwr,Flt.IIA}} = \frac{12.0\ MW/9{,}600\ LT}{7.5\ MW/9{,}100\ LT} = 1.52$$

Based on the observed power density increase, a k-factor of 1.52 was selected as the value estimated to yield the closest representation of the relative complexity increase in AMDR over AEGIS, for which there is substantially more unclassified and publishable data. Given that the k-factor functions as a coefficient adjunct to the C_2C_3 portion of the complexity equation, any change in k yields a strictly linear change in net complexity so as more complexity-oriented data becomes publicly available, k_{AMDR} can be dialed-in to a more accurate value. The relationships between k-factor and variations in Flight III's weight or power are shown in Figure 8. Variations are shown with respect to Flight III only; values for Flight IIA were held constant.

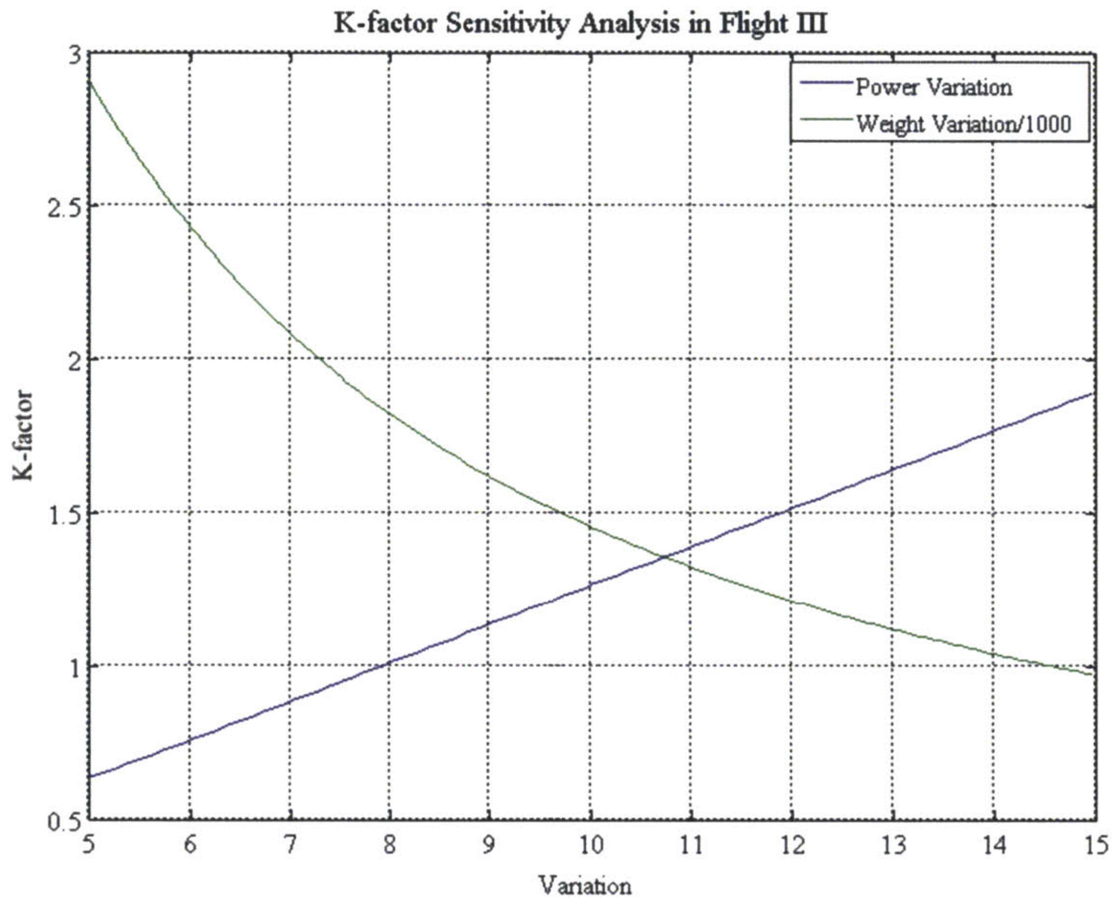


Figure 8: Sensitivity Analysis for AMDR K-Factor

At the time of writing only cost estimates exist for ships that will include AMDR, namely Flight III and beyond. The only actual costs that exist for AMDR are those in the Research, Development, Test, and Acquisition (RDT&E) funds category so AMDR will be used for predictive cost measures while AEGIS will be used for methodology validation using existing costs.

Figure 9 below shows the functional block diagram for the AEGIS radar.

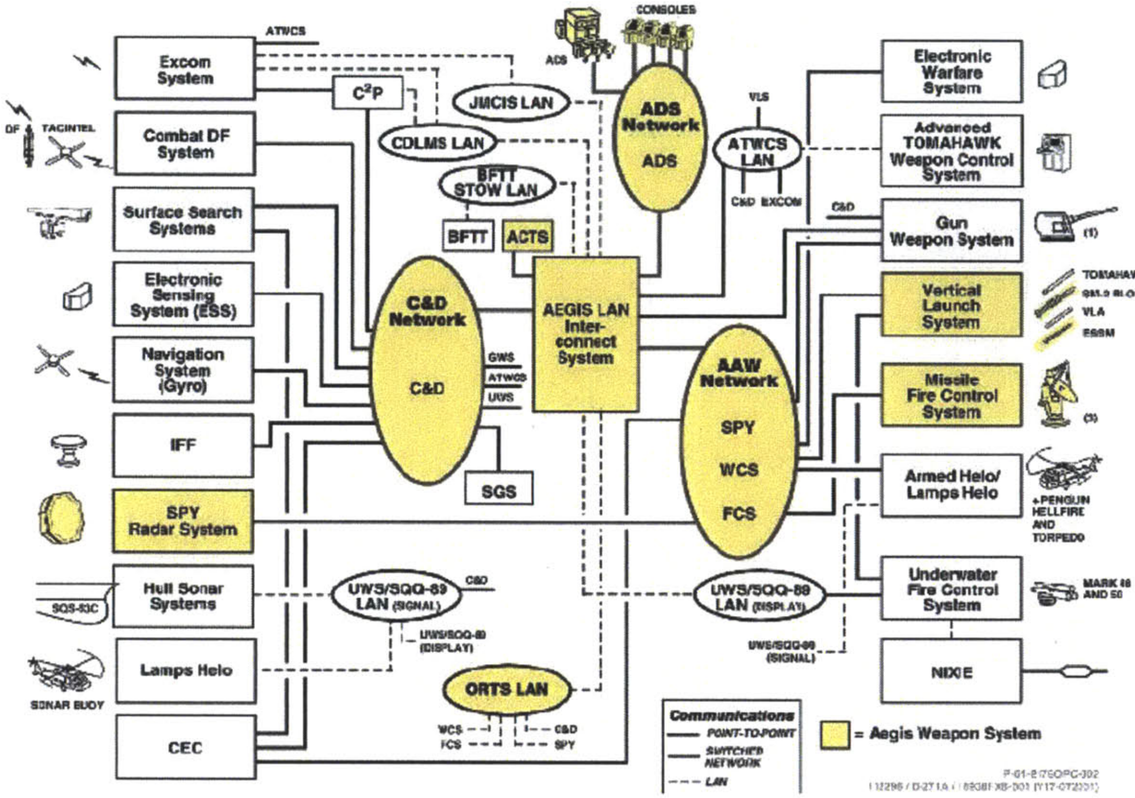


Figure 9: AEGIS Subsystem (Global Security 2011) - Unclassified

Figure 9 above was translated via functional interfaces to the symmetrical adjacency matrix shown below in Table 6.

Correspondingly, the energy of the adjacency matrix is associated with the eigenvalues per the equation discussed in Section 2.2:

$$E(A_{ij}) = \sum_{i=1}^{n} \sigma_i; \quad A - \lambda I = 0$$

It follows that:

Table 6: Adjacency Matrix, A_{AEGIS}

	Excom	Combat DF	Surface Search Sys.	ESS	Navigation Sys. (Gyro)	IFF	SPY Radar System	Hull Sonar System	LAMPS Helo	CEC	UWS/SQQ-69 LAN (Signal)	ORTS LAN	UWS/SQQ-69 LAN (Disp.)	NIXIE	Underwater Fire Control Sys.	Armed Helo	Missile Fire Control Sys.	Vertical Launch Sys.	Gun Weapon Sys.	Adv. TOMAHAWK Weapon Cntrl.	Electronic Warfare Sys.	AAW Network	ATWCS LAN	ADS Network	ADS	JMCIS LAN	C2P	CDLMS LAN	BFTT STOW LAN	BFTT	ACTS	C&D Network	SGS	AEGIS LAN Interconnect Sys.
Excom	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	1	0	0	0	0	0	0
Combat DF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Surface Search Sys.	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
ESS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Navigation Sys. (Gyro)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
IFF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
SPY Radar System	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Hull Sonar System	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LAMPS Helo	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CEC	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0
UWS/SQQ-69 LAN (Signal)	0	0	0	0	0	0	0	1	1	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
ORTS LAN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0	1	0	0
UWS/SQQ-69 LAN (Disp.)	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
NIXIE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Underwater Fire Control Sys.	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Armed Helo	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Missile Fire Control Sys.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Vertical Launch Sys.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	1	0	0
Gun Weapon Sys.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	1
Adv. TOMAHAWK Weapon Cntrl.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Electronic Warfare Sys.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
AAW Network	0	0	0	0	0	1	0	0	1	0	2	0	0	0	1	1	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1
ATWCS LAN	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ADS Network	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1
ADS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
JMCIS LAN	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
C2P	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0
CDLMS LAN	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
BFTT STOW LAN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1
BFTT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
ACTS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
C&D Network	0	1	1	1	1	1	0	0	0	1	1	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1
SGS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
AEGIS LAN Interconnect Sys.	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	1	0	1	0	1	0	1	1	0	1	1	0	0

$$\sigma_{AEGIS,n=1:34} = [4.835; 4.366; 2.790; \ldots 0]; E(A_{AEGIS}) = \sum_{i=1}^{n} \sigma_{AEGIS} = 37.33$$

Because there are 35 individual units (one of which has a double connection as reflected in the adjacency matrix A_{AEGIS}), $\gamma = 1/35 = 0.029$ and $C_3 = \gamma\, E(A_{AEGIS}) = 0.988$.

Machinery Control System (MCS)

The MCS "provides a centralized means of monitoring and controlling the main propulsion plant, electric plant, and auxiliary systems" (Cairns 2011) onboard the DDG 51 class. Like the AEGIS and AMDR subsystems, MCS's complexity is derived from the amount of interfaces, the complexity of those interfaces, and the complexity of the software/data contained within the system. MCS must manage over 2,000 independent signals, which has subsequent ramifications in terms of the amount of code and wiring involved in fielding the MCS subsystem. Further downstream, the system operators and warfighters must manage that complexity in terms of troubleshooting errors. Finding a loose wire in an electronics rack with 2,000 wires coming out of the back is a non-trivial task to the operator.

MCS touches several vital systems such the power generation subsystems and electrical distribution subsystems onboard the DDG 51, and because of MCS's central role, efforts have been taken to ensure its continued operation during a wartime scenario where the host ship sustains damage. These efforts have resulted in the development of the zonal electrical distribution system (ZEDS) that provides reliable power to vital loads via redundancy and the compartmentalization of the electrical system into survivable zones. As a result, MCS (as shown in Figure 10) is further complicated in reality by the survivability requirements of the ship, but due to the unquantifiable nature of the effect of ZEDS, MCS complexity calculations were calculated based solely on the high level block diagram provided by NAVSEA's PMS 400D.

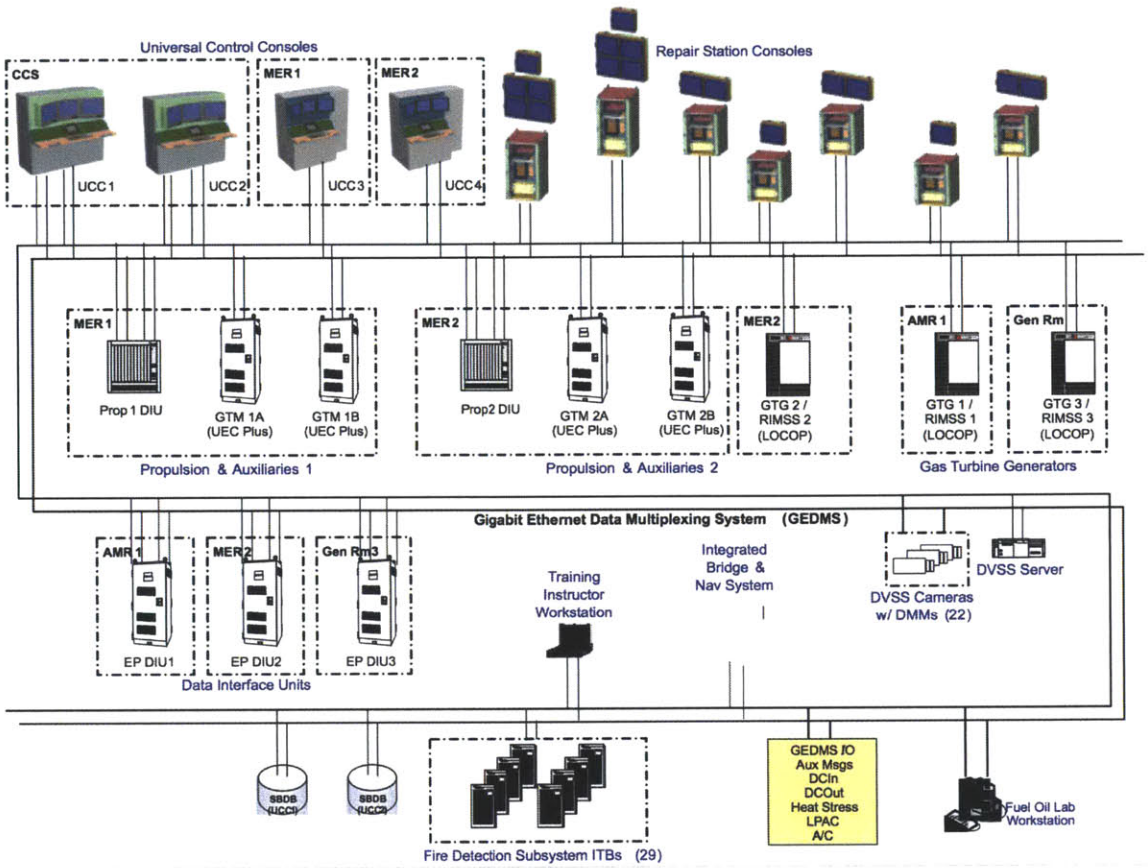


Figure 10: Machinery Control System (Hellman 2013) - Unclassified

The system adjacency matrix for MCS is shown in Table 7.

	UCC 1	UCC 2	UCC 3	UCC 4	Repair Station Console (1)	Repair Station Console (2)	Repair Station Console (3)	Repair Station Console (4)	Repair Station Console (5)	Repair Station Console (6)	Prop 1 DIU	GTM 1A (UEC Plus)	GTM 1B (UEC Plus)	Prop 2 DIU	GTM 2A (UEC Plus)	GTM 2B (UEC Plus)	GTG 1/RIMSS 1 (LOCOP)	GTG 2/RIMSS 2 (LOCOP)	GTG 3/RIMSS 3 (LOCOP)	EP DIU 1	EP DIU 2	EP DIU 3	Int. Bridge & Navy. System	DVSS Cameras w/ DMMs	DVSS Server	SBDB (UCC1)	SBDB (UCC2)	Fire Dectection Subsystem ITBs	GEDMS IO, Aux, DC	Fuel Oil Lab Workstation	Main MCS BUS
UCC 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
UCC 2	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
UCC 3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
UCC 4	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1
Repair Station Console (1)	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
Repair Station Console (2)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
Repair Station Console (3)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
Repair Station Console (4)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
Repair Station Console (5)	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	1
Repair Station Console (6)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
Prop 1 DIU	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
GTM 1A (UEC Plus)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
GTM 1B (UEC Plus)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
Prop 2 DIU	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1
GTM 2A (UEC Plus)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	1
GTM 2B (UEC Plus)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
GTG 1/RIMSS 1 (LOCOP)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
GTG 2/RIMSS 2 (LOCOP)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
GTG 3/RIMSS 3 (LOCOP)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
EP DIU 1	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	1
EP DIU 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
EP DIU 3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
Int. Bridge & Navy. System	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	0	0	1
DVSS Cameras w/ DMMs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
DVSS Server	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
SBDB (UCC1)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
SBDB (UCC2)	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1
Fire Dectection Subsystem ITBs	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	1
GEDMS IO, Aux, DC	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1
Fuel Oil Lab Workstation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Main MCS BUS	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0

Table 7: Binary Adjacency Matrix, A_{MCS}

The figure and table show a subsystem that exhibits a high number of connections, but the connections all lead to and from a central bus that composes the core of the MCS.

Because of the bus configuration of MCS, the adjacency matrix A_{MCS} has only two nonzero eigenvalues in the 31 unit length vector: $\sigma_1 = 5.48$ and $\sigma_2 = 5.48$.

$$E(A_{MCS}) = \sum_{i=1}^{n} \sigma_{MCS} = 10.96$$

$$C_{3\_MCS} = \gamma E(A_{MCS}) = 0.322$$

Recall that the C_3 component of the complexity equation for AEGIS was 0.988 showing that based on configuration alone, AEGIS was approximately three times more complex than MCS, which was consistent with the *qualitative* complexity assessments conducted at NAVSEA and PMS 400D.

Main Reduction Gear

A reduction gear is a device used for slowing the rotational input speed to a desired rotational output speed. In the DDG 51 class, the Main Reduction Gear (MRG) reduces the 3600-RPM produced by the LM-2500 gas turbines to approximately 168-RPM (at full power and 100% pitch) at the propeller shaft (Halpin 2007).

While the MRG is a highly complex and complicated subsystem, it is not complicated in the same manner as the AEGIS, AMDR, or MCS – namely the MRG lacks the software-intensiveness that characterize those subsystems' core capabilities. The MRG is a mechanical entity, but two factors have combined to make the MRG a suitable subsystem for analysis in terms of complexity: extremely high precision requirements in terms of position/alignment and a recent change in contractors that has effectively lowered a heritage piece of equipment's effective TRL as discussed in Section 2.2. Recall that the contractor factor boosted component complexity term x_6/TRL-factor by roughly 1/3 just by changing from GE who possessed complete drawings, corporate knowledge, and a well developed learning curve, to a new company who although possessing the technical capability to produce MRGs did not possess those traits that led to a high *effective* TRL for GE.

PMS 400D provided an unclassified schematic of DDG 106's port MRG for analysis, and it shown below in Figure 11.

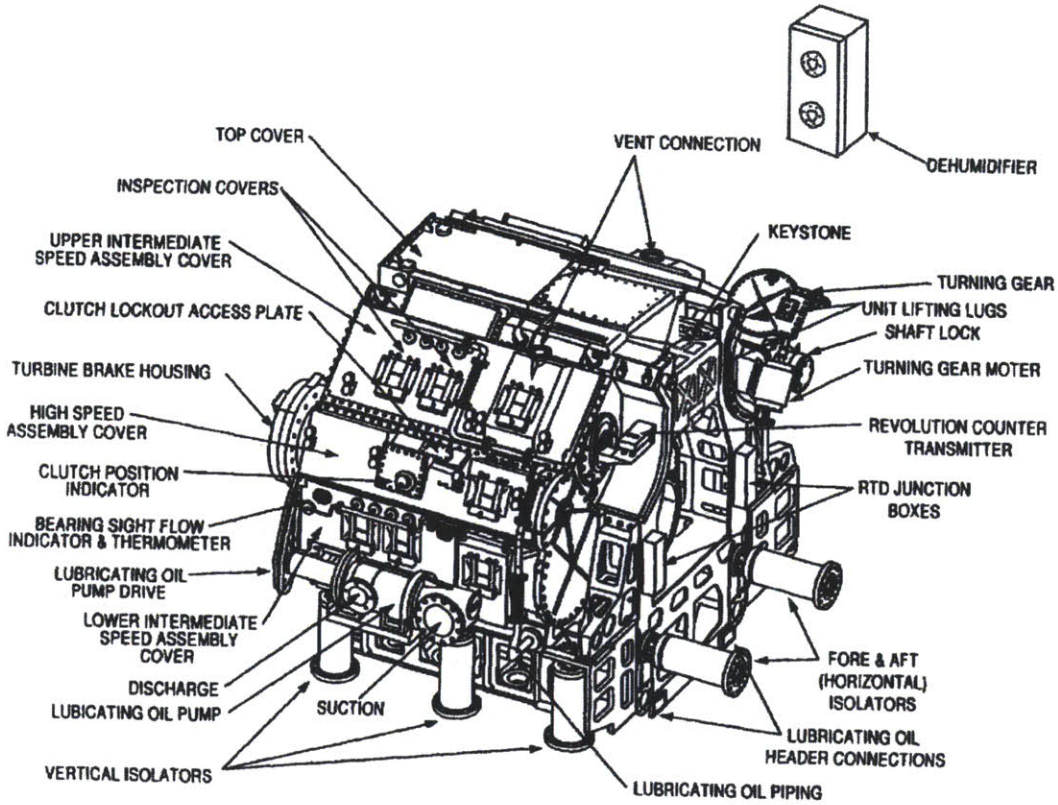


Figure 11: DDG 106 Propulsion Reduction Gear Arrangement, Port Gear, Isometric View (Hellman 2013) **- Unclassified**

Following the same method as employed on the AEGIS and MCS subsystems, the adjacency matrix for the MRG is shown below in Table 8.

Table 8: Binary Adjacency Matrix, A_{MRG}

	Top Cover	Vent Connection	Dehumidifier	Keystone	Turning Gear	Unit Lifting Lugs	Shaft Lock	Turning Gear Motor	Revolution Counter Transmitter	RTD Junction Boxes	Fore & Aft (Horizontal Isolators)	Lubricating Oil Header X-tions	Lubricating Oil Piping	Suction	Vertical Isolators	Lubricating Oil Pump	Discharge	Lower Intermediate Speed Ass.	Lubricating Oil Pump Drive	Bearing Sight Flow Ind. & Therm.	Clutch Position Indicator	High Speed Assembly Cover	Turbine Brake Housing	Clutch Lockout Access Plate	Upper Intermediate Speed Ass.	Inspection Covers	Main Assembly
Top Cover	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Vent Connection	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
Dehumidifier	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Keystone	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Turning Gear	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Unit Lifting Lugs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
Shaft Lock	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Turning Gear Motor	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Revolution Counter Transmitter	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
RTD Junction Boxes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
Fore & Aft (Horizontal Isolators)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4
Lubricating Oil Header X-tions	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
Lubricating Oil Piping	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Suction	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Vertical Isolators	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6
Lubricating Oil Pump	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Discharge	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Lower Intermediate Speed Ass.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1
Lubricating Oil Pump Drive	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Bearing Sight Flow Ind. & Therm.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Clutch Position Indicator	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
High Speed Assembly Cover	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1
Turbine Brake Housing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Clutch Lockout Access Plate	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Upper Intermediate Speed Ass.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2
Inspection Covers	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0
Main Assembly	1	2	0	1	0	2	1	1	1	2	4	2	1	1	6	1	1	1	0	1	0	1	1	1	2	0	0

σ_{MRG} was comprised of five paired nonzero eigenvalues ($\sigma_{6\text{-}22} = 0$):

$$\sigma_{MRG} = [\pm 9.29, \pm 1.95, \pm 1.00, \pm 1.00, \pm 0.98]$$

$$E(A_{MRG}) = \sum_{i=1}^{n} \sigma_{MRG} = 28.44$$

As a result,

$$C_{3\_MRG} = \gamma E(A_{MRG}) = 0.836$$

In the following section, these values for C_3 will be compared against values for C_1, C_2, and C_{total} for the three highest complexity systems assessed by NAVSEA.

4. Ship Subsystem Complexity

The subsystem data collected, formatted, and initially analyzed in Section 3 was synthesized and underwent final analysis in Section 4 using the logic, methods, and algorithms discussed previously.

4.1 AMDR/AEGIS, MCS, and MRG

Table 9 reflects the collection summary of data from Section 3 for synthesized and prepared for analysis in Section 4. Mathwork's MATLAB software was used for matrix calculations. The code[4] is attached in Appendix B.

In this thesis, complexity is determined via the overarching and governing equation for each subsystem:

$$C_{final} = C_1 + C_2 C_3$$

Or more specifically, the expanded equation is:

$$\boldsymbol{C_{final}} = \sum_{i=1}^{n} \boldsymbol{x_i} + \left[\sum_{i=1}^{n} \sum_{j=1}^{m} \boldsymbol{\beta_{ij} A_{ij}} \right] \boldsymbol{\gamma E(A)}$$

From the data analyzed in Section 3 using Sinha and de Weck, 2013's methodology, Table 9 summarizes the results. Note that the total complexity numbers report are unitless and that the complexity of the different systems can be compared against each other, but not necessarily against other classes of systems (such as jet engines) since those other systems may have been assessed using different normalization factors for α and β, among others.

[4] The author can provide a digital version of the code in the form of MATLAB's native m-file upon request from interested parties.

Table 9: Complexity Component Results

Variable	MCS	MRG (GE)	MRG (PGC)	AEGIS	AMDR
$C_1 = \sum_{i=1}^{n} x_i$	36.8	31.8	42.8	67.0	55.8
β_i	0.8	0.3	0.3	0.9	1.0
$C_2 = \sum_{i=1}^{n}\sum_{j=1}^{m} \beta_{ij}A_{ij}$	48.0	23.4	23.4	82.8	92.0*[5]
$C_3 = \gamma E(A)$	0.353	1.053	1.053	1.098	1.327*
k-factor	1.00	1.00	1.00	1.00	**1.33**
C_{final}	**53.8**	**56.4**	**67.2**	**157.91**	**190.1**

5* AMDR values without objective quantitative substantiation were filled by the AEGIS baseline values and corrected with the k-factors per the methodology discussed in Section 3. The k-factor was integrated via $C_{Final\text{-}AMDR} = k^*C_{final'}$

Graphically, one can see in Figure 12 that AMDR was projected to be the most complex system on board DDG 51 Flight III (and arguably in the U.S. Navy). AMDR's numerical complexity terms revealed that the relatively low component complexity C_1, complexity of the interfaces β_{ij} and C_2, and the arrangement of those interfaces C_3 all contribute to the complexity of the subsystem PMS 400D had deemed "as complex as it gets."

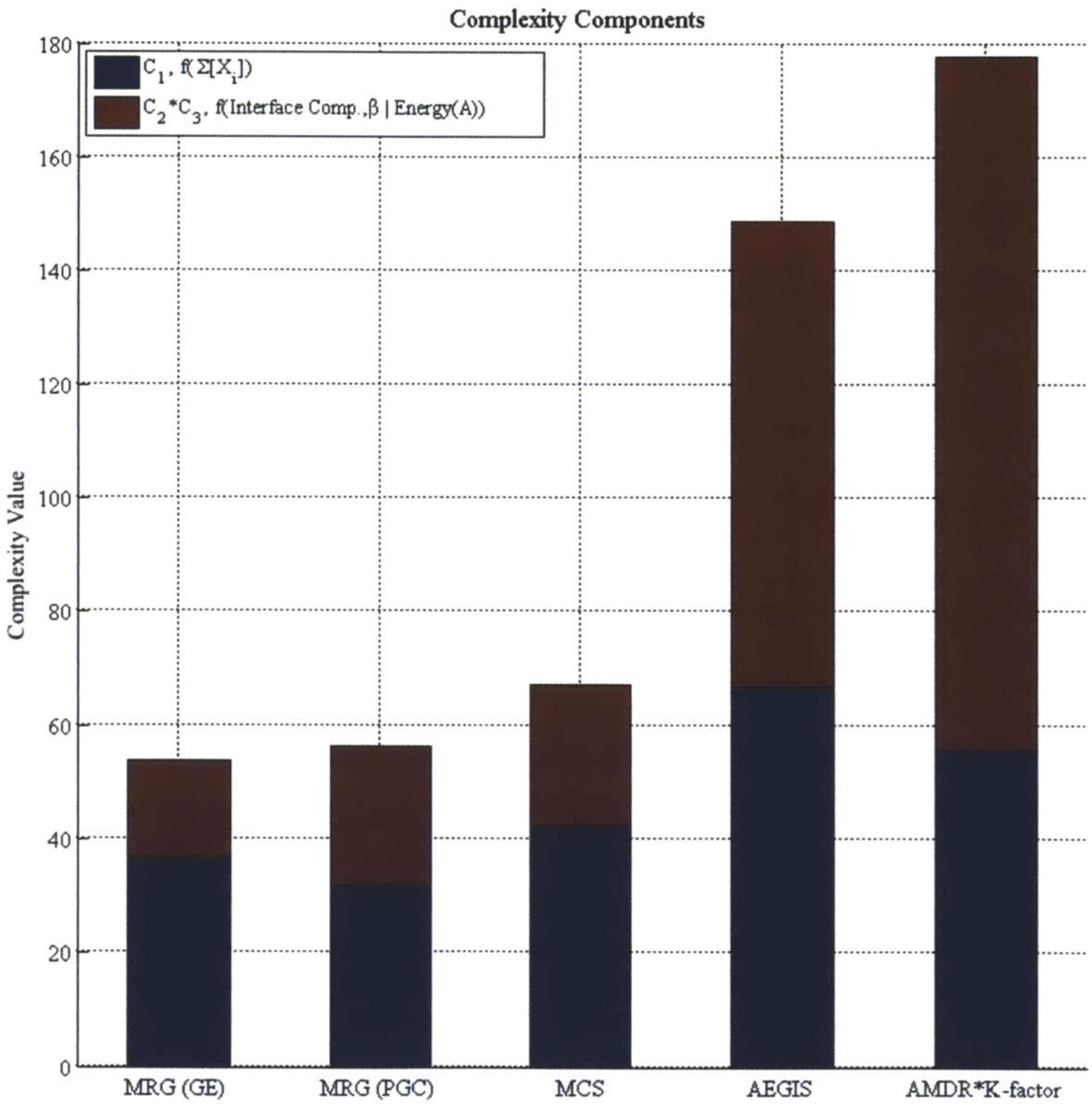


Figure 12: Complexity Component Breakout

For the lower complexity systems like the MRG and MCS, C_1 (component complexity) dominated, while for the higher complexity radar system, C_1 played a more minor role. In the case of AMDR, the C_2C_3 term dominated the net complexity of the subsystem. By observing the sources of complexity within each subsystem one can reasonably deduce that the *interconnections* and *types of connections* within the subsystem can play as large a role as the other intrinsic system properties that have hitherto predominantly been the focus of complexity studies captured in the X-vector. Understanding the relative sources of complexity can also help better allocate resources in the program between technical component specialists and systems engineering.

4.2 Cost Assessment

A cost assessment was conducted to map the subsystems analyzed for complexity to their respective costs.

While many different forms of cost exist (especially within the field of government procurement), cost in this research was defined as either the total contract value as announced by the winning company or the total program cost as reported by GAO reports or publically available, Distribution A NAVSEA program office briefings.

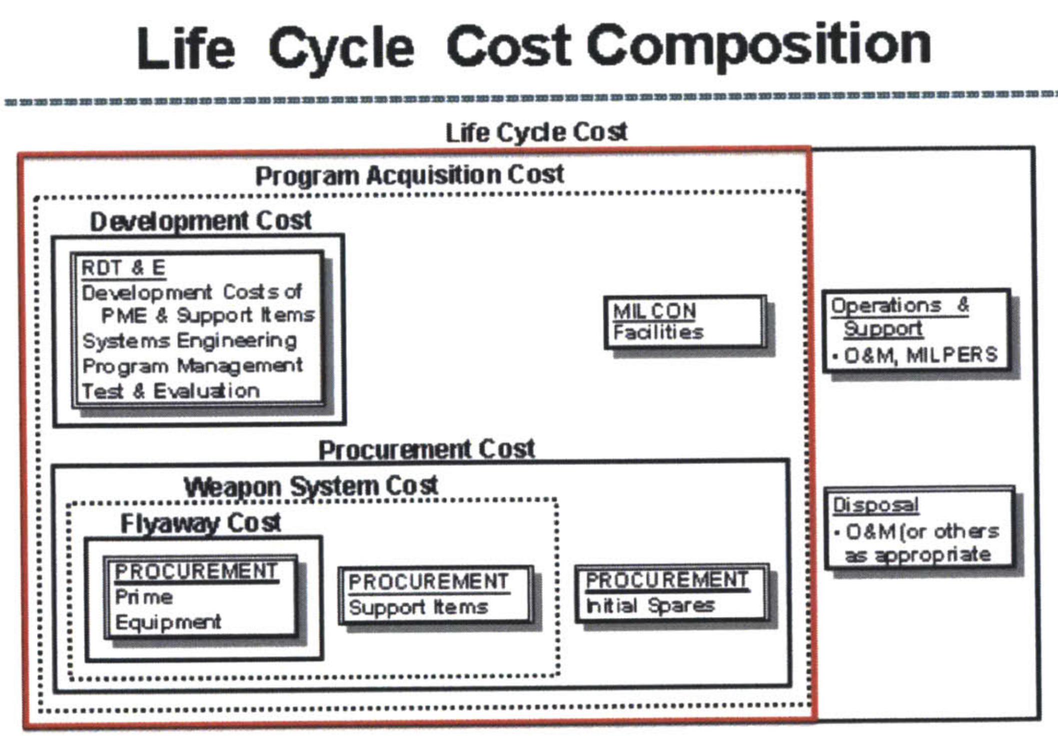


Figure 13: DoD Cost Types and Relationships (DAU 2013)

The costs used in this study are the Program Acquisition Costs outlined in the red box in Figure 13.

4.2.1 MCS Cost Assessment

MCS was originally started as a NAVSEA 05 RDT&E program that was eventually intended to undergo a parallel development effort as a separate NAVSEA 05 contract, but program management and policy makers decided that this route included an unacceptably high risk level in development. To drive down the risk, a new plan was created that made MCS a separate RDT&E Line Item that was added to the lead ship contract (Fortune 2012). The first MCS was awarded as a contract to the shipyard for construction in April of 1985 for approximately \$31M (\$61.1M in FY2013) for the lead unit (GAO 1990), but further research yielded no data on the cost of subsequent units. Given the paucity of openly available cost data, it was necessary to turn to other means of assessing a realistic cost because most acquisitions typically witness a decrease in unit cost as the total number of acquired units increases.

In the Department of Defense, the Learning Curve Theory is used to model "how the cost of a good or service might vary over time…assuming [analysts] were to remove the effects of inflation…" (DAU 2008). The effects of learning have historically been shown to lead to a price decline as manufacturers and producers become more efficient at producing their good or service. This assumes that the configuration of the good being produced remains relatively stable.

The learning curves slope is the percentage value that represents the degree to which learning is occurring as shown by the iterative decrease in unit costs over time. If the production quantity is doubled, the slope represents as a percentage what that next doubled values cost would be. If a notional learning curve has a slope of 80% and a unit has an initial cost of \$100, units 1, 2, 4, and 8 would cost \$100, 80, 64, 51.2, respectively. Table 10 represents typical learning curve slopes by product or trade.

Table 10: Typical Slope Values by Activity (DAU 2008)

Activity	Typical Slope
Aerospace	85%
Shipbuilding	80 - 85%
Electronics	90 - 95%
Machine Tools	75% - 85%
Machining	90 - 95%
Welding	90%
Raw Materials	93 - 96%
Purchased Parts	85 - 88%

Although MCS has many mechanical outputs, MCS itself is primarily a software entity, and thus MCS should logically fall chiefly within the electronics Learning curve family. According to Table 10, the electronics slope ranges vary by 5% within the family, and research published by DAU stated that the variation within that family depends on a number of factors with the most MCS-relevant being:

- Similarity between the new item and an item or items previously produced;
- Duration of time since a similar item was produced;
- Availability of material and components;

Based on the above criterion, a 95% learning curve slope was selected for use in this analysis. This slope value was selected due to the relatively low throughput in MCS delivery, which has historically been between 1-2 ships per year before the DDG production shutdown. A low throughput typically corresponds to a higher learning curve slope, which subsequently entails less cost or time reductions for the customer. This high throughput factor is a major factor in the Korean shipyards' cost performance, despite sometimes building ships that are nearly identical to U.S. vessels and based upon US MILSPEC.

A 95% Learning slope was also chosen as the most conservative value that would reflect the likely possibility that the people who developed this GFE equipment had prior experience developing other MCSs for other classes of ships, such as U.S. Navy auxiliary ships.

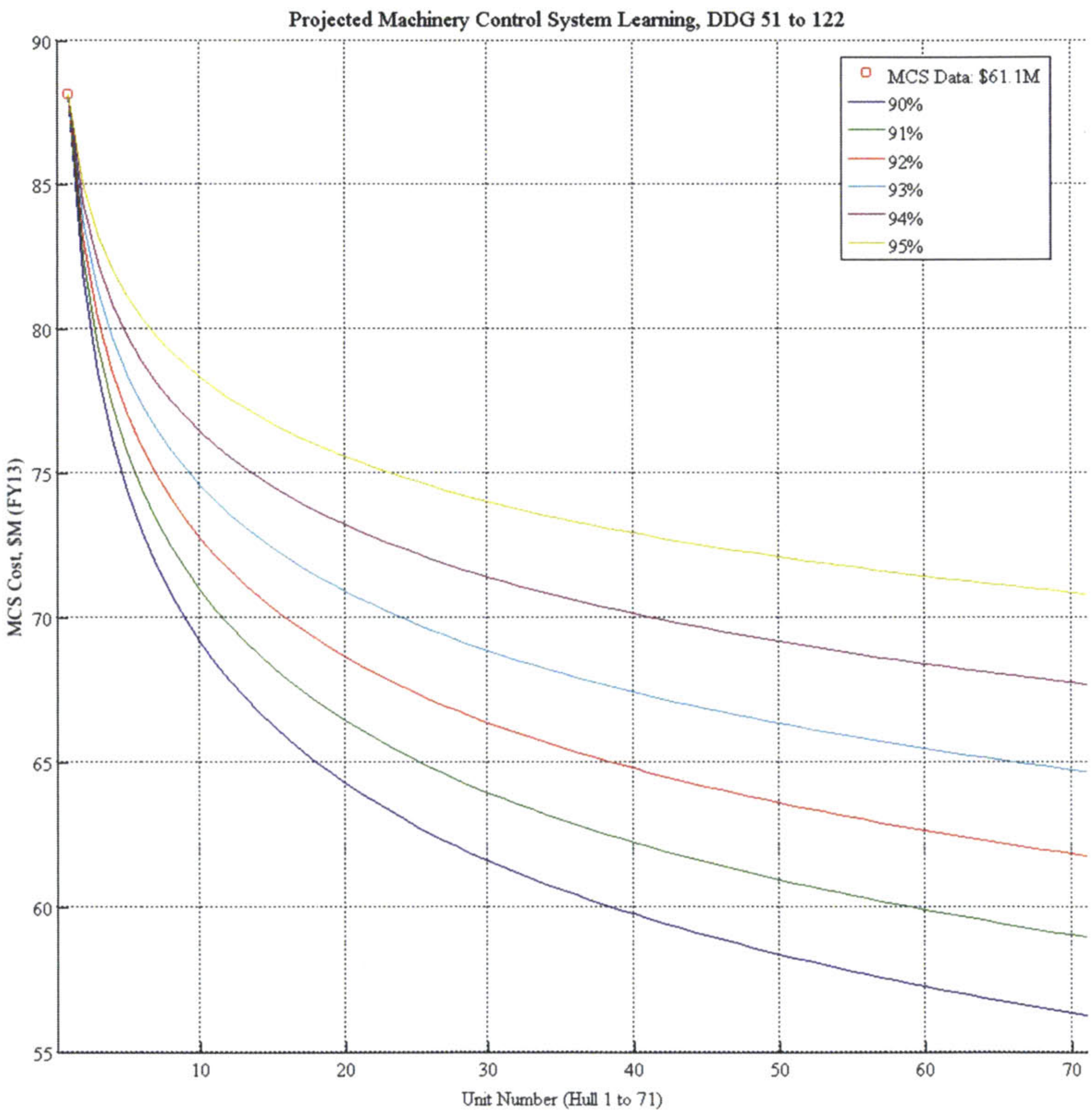


Figure 14: ***Machinery Control System*** **Learning Curve Slopes.** Note: while this curve portrays learning for the MCS subsystem, the system-level curve(s) for the DDG 51 class would be truncated at approximately unit 35 due to the fact that identical hulls are being built at two different yards and thus undergoing two separate learning processes.

The family of curves shown in Figure 14 reflected the substantial cost difference of one percentage point in terms of learning curve slope distributed over 71 MCS units, from the MCS placed onboard DDG 51 (the first of class ship in Flight I) to DDG 122 (slated last-of-class ship for Flight IIA). Given that *m* is learning curve slope and *x* corresponds to MCS unit number, overall cost for the MCS production run is:

$$\int_{x=1}^{x=x_i} Cost_{x_1} x^{\log(m)/\log(2)} \delta x \begin{cases} Cost_{total}(m = 0.90) = 61.5 \dfrac{\$M}{unit}, FY13 \\ Cost_{total}(m = 0.95) = 73.4 \dfrac{\$M}{unit}, FY13 \end{cases}$$

The difference between just five percentage points in learning curve slope translated to approximately \$12 million over the production run for MCS.

4.2.2 MRG Cost Assessment

The MRG produced by GE originally cost \$148M (FY1989, inflated to \$274M in FY2013), and was delivered as GFE for Flight I of the DDG 51 class (GAO 1990). There were a total of 20 ships in Flight I (NAVSEA Shipbuilding Support Office 2013), which resulted in a total of 40 MRGs produced for Flight I.

According to DDG 51 program office data, the contract for the MRG was awarded on June 18th, 2010 to PGC for \$80.2M for three ship sets with implementation starting on DDG 113. The awarded contract was a Firm Fixed Price contract (Captain Mark Vandroff, Program Manager, DDG 51 Shipbuilding Program 2012). As of right now, the contract value is set at \$80.2M to provide MRGs to DDG 113, 114, and 115, but options for additional ships could bring the eventual contract value closer to \$425M (Defense Industry Daily 2012). Given that those options have not materialized at the time of writing, \$80.2M is the assumed contract value for analysis, but it is acknowledged that if the Navy pursues the additional options, there will possibly be potential savings per unit due to the nature of economies of scale and the effects of industrial learning. Eventually PGC's cost per unit will likely approach that of GE.

4.2.3 AEGIS and AMDR Cost Assessment

RCA Gets Contract For 'Aegis'

WASHINGTON (UPI) —The Navy announced Tuesday the award of a $253 million contract for the development of a new antiaircraft missile to be known as "Aegis."

The announcement said the new missile is planned for guided missile ships in the mid-1970's and "is the Navy's answer to the threat of antishipping missiles."

"Ships armed with Aegis will be capable of defending a task force including carriers and other types of ships," the Navy said.

It added: "The new system is designed to destroy small, fast targets in hostile environments."

The contract went to RCA Defense Electronics Products Division.

The Navy said the missile will have electronic scanning radar "able to 'look' in all directions almost instantaneously, and a dual purpose launcher that can fire rocket-propelled anti-submarine weapons as well as antiaircraft missiles.

"The new Aegis radar and related subsystems can aid in guiding friendly aircraft as well as in locating hostile air targets," the Navy said. Other equipment will include a computer for missile guidance and a new device called an "illuminator" that uses radar to improve missile guidance.

Figure 15: RCA's 1969 Contract Initiation

The AEGIS program has a long history dating back to December 24th, 1969 when RCA was awarded the first R&D contract to develop the AEGIS program as shown in Figure 15. Although the program initially kicked off in the 1960s, it was not until 1986 that RCA was able to field the system on the new DDG 51 production line. RCA along with the AEGIS contract was sold several times in the ensuing years, but the original contract value for implementation on all DDGs was valued at \$9.0B in FY1986, which translates to \$18.9B in FY2013 value (State New Service 1986). Since 1986, AEGIS has undergone a series of 12 successive upgrades and modernization efforts to meet and counter ever-evolving threats, and those efforts have come at a cost that was also factored into this assessment. To accurately capture the cost of AEGIS, one must account for the amount of cost that was re-invested into AEGIS for each of the successive upgrades.

Because actual and publishable cost data was unavailable for AEGIS, other software-centric DoD systems with published cost data were analyzed for cost increases as a percentage of original procurement cost. It was determined based on a collection of systems from the Air Force that software-centric upgrades generally cost anywhere between 5-10% of the original procurement cost, where more recent systems tend to have costs at the higher end of the 5-10% range (Knaack 1988). Based on the trends published by Knaack, those trends were extrapolated to the AEGIS upgrades and presented in Table 11.

Table 11: AEGIS Upgrade Series Program Cost[6] Estimation

Baseline	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10	U11	U12	Total
-	5%	5.5%	6%	6.5%	7%	7.5%	8%	8.5%	9%	9.5%	10%	10%	74.7%
\$18.90B	0.95	1.04	1.13	1.23	1.32	1.42	1.51	1.61	1.70	1.80	1.89	1.89	14.13

That 1.747 factor brings the procurement total to \$33.03B. The procurement quantity was set at 71, with hulls from DDG 51 to 122; Hull 123 and beyond constitute Flight III, and Flight III is slated to field the new AMDR.

At the time of writing, the only *actual* costs for AMDR are associated with RDT&E efforts, and the acquisition is currently being split into two separate but concurrent development efforts: one contract which was announced on October 10th, 2013 by Raytheon for the development of the S-band portion of AMDR (AMDR-S) plus the

6 Program cost as defined here subsumes RDT&E and manufacturing costs.

Radar Suite Controller (RSC), and the second portion for X-band radar only (AMDR-X) will be announced at a future date. The initial AMDR-S plus RSC contract was awarded for $1,633M for the Low Rate Initial Production (LRIP) Flight III ships (Space Daily 2013). The inclusion and integration of AMDR-X will significantly increase the cost of the total AMDR package even beyond what is presented here, but any figures associated with AMDR-X and the subsequent integration would only be speculation.

In this research, AMDR's complexity and associated cost is intended to serve as a *predictive* set of values, vice a set of *actual* values are shown on the other subsystems that have previously been discussed in this Section.

5. Results and Analysis

The data collected in Section 4 was analyzed via the MATLAB algorithm coded in Appendix B. A matrix-based calculation tool was selected due to the vector array nature of the input variables previously discussed.

5.1 Aggregated Subsystem Comparison and Analysis

The complexity data was summarized in Section 4.1, and the cost data is summarized in Table 12. This section maps the cost and complexity data derived up to this point in an effort to extract a quantitative relationship between those two variables using the summary figures described in Table 9 and Table 12.

Table 12: Subsystem Cost Summary, in Millions USD

**Cost figures in $M, USD*	MRG_{GE}	MRG_{PGC}	MCS	AEGIS	AMDR-S
Total Program Cost/Contract Value	$274[7]	$80	$5,208	$18,881	$1,633
Total Procurement Quantity	40	6	71	71	3
Cost per Unit	**$6.85**	**$13.4**	**$73.35**	**$265.93**	**$544.3**

Using the summarized data, each subsystem was plotted with cost versus complexity. The results are shown in Figure 16.

The first plot correlation method studied used the power law method as proposed by Sinha and de Weck, 2012, and for comparative purposes, an exponential curve was also fit to the available data to determine if greater trend line fidelity could be obtained. Other

[7] In FY1989 the total value was $148M. That figure has been scaled up to FY2013 dollars, which takes into account inflationary effects.

fits such as various polynomials were also tested, but were not included here due to a relatively low data fidelity. It should be noted that the *type* of curve that fits the data is not as important as the fact that some defined quantitative relationship exists between complexity and cost. And this relationship is non-linear i.e. *cost increases superlinearly with complexity*. The aim of this study to accurately map one variable to the other is to place a flexible and realistic decision-making tool in the hands of Navy leadership.

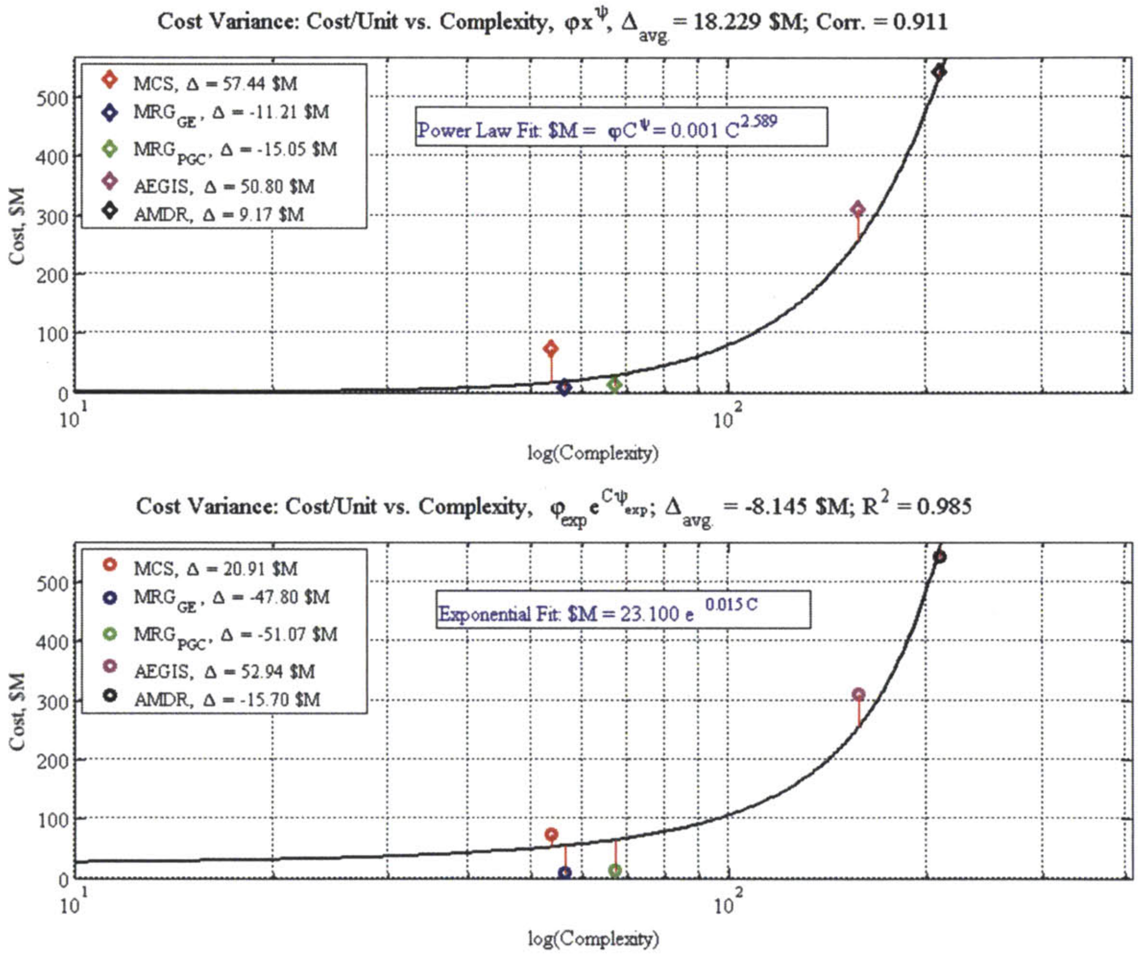


Figure 16: Cost versus Complexity and Cost Variance. Data points represent actual per unit program/contract cost values obtained from company contract announcements and GAO findings. The black trend line represents complexity-oriented cost prediction.

Figure 16 (top) demonstrated the proposed *power law* curve fit to the data, which resulted in a correlation factor[8] of roughly 91.1% while the bottom figure using an *exponential* fit resulted in a much higher correlation factor at 98.5% to this particular given set of data. It is acknowledged that the limited number of data points (N = 5) in this particular study would impede one from drawing any wide-sweeping conclusions, but this study *does* demonstrate a clear trend that cost will scale with complexity in a power-law relationship as proposed by Sinha and de Weck, 2013 or as an exponentially increasing function as this study demonstrates. More data points would determine which curve ultimately fits better to any given set of data, but the fact that a highly correlated relationship exists between acquisition cost and complexity as it is quantified in this study yields potential value in updating or augmenting Navy and DoD cost models with a complexity-based cost estimation module. Traditional shipbuilding cost models are mainly based on displaced volume and/or mass of the hull, however, increasingly what goes into a ship is a bigger driver of cost than the size of the ship itself.

The small red lines in Figure 16 highlight the cost variance of the actual cost data obtained from contract announcement and GAO reports (data points) versus the complexity-based predictions (black line) established via the methods laid out in this thesis.

Exponential cost growth as a function of complexity was determined to be:

$$\$M = 23.1e^{0.015C}$$

This means that a one-unit increase in complexity yields a 1.5% increase in acquisition cost! Increases in complexity have occurred from myriad sources: automation, software-intensive combat systems, and increasingly complex power systems, and this equation

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8 Correlation (vice R^2) was used to determine the power law curve fit's fidelity whereas R^2 was used to determine the fit for the exponential data. The difference was applicability of the two error calculation methods to the curves. Both error calculations were made via MATLAB's internal algorithms.

tells us that those incremental boosts in complexity are responsible for an exponential increase in cost.

It is proposed that the analysis of more subsystems would refine the coefficient values for φ and ψ in both the power law and exponential equations while simultaneously boosting the correlation factor. Although only four subsystems with five separate points are plotted here, a large collection of subsystems with their respective cost data would most likely improve the correlation number from its current value. If one were to imagine a scatterplot of the cost and complexity of all the different systems on board the DDG 51, it is hypothesized based on these results that the cost versus complexity trend would closely follow either a power law or exponential curve. A model based on a larger number of samples would serve as a powerful tool for cost analysts to either refine the current program (PODOC) for cost estimating or possibly supplant it completely in the future.

"Rolling up" complexity, or obtaining a hierarchical quantification of the complexity contained within any given system is a matter of assessing each subsystem's complexity and adding that total complexity to the next higher tier's C_1, component complexity, term. That next higher tier's entire complexity with the summation of the lower tiers parts would then be added to the next level's C_1 and so on, until all the levels are understood and quantified. While the C_1 terms are a function of their components' individual net complexity, C_2 and C_3 remain uniquely independent on that particular tier's interface complexity and topological complexity.

5.2 Sensitivity Analysis

Over the past decade, the Navy has increasingly designed ships to concepts with reduced crew size and increased automation in an effort to reduce overall Life Cycle Cost. DDG 1000 and LCS are examples of recent high profile ship designs exemplifying a reduced crew concept reliant upon relatively high degrees of automation.

In terms of subsystem architecture, an increased degree of automation implies a higher degree of inter-connectedness within a subsystem. More parts of the ship communicate internally with other parts of the ship with minimal reliance upon operator intervention to do so. Although initial operational reports from LCS have indicated that automated systems are requiring nearly as much operator management as their less technically-advanced predecessors on other similarly-sized combatants, the large cost benefits of a reduced crew size mean that automation will likely be improved vice being removed by Navy decision makers.

Assuming a premise of ever-increasing automation driven by the motivation to reduce lifecycle costs, what happens to subsystem complexity and its subsequent cost predictions?

Relatively sparse matrices such as those shown by the bus-and-components architecture characterized by the Machinery Control System in Figure 10 (Section 3.2.3) will most likely have more non-zero values in the currently sparse A_{ij} matrix as ships increasingly move towards networked internal systems.

To more thoroughly understand the effect of inter-connectedness within the subsystem, all factors other than the number of connections were held constant while the number of inter-connections was allowed to vary. The number of connections in the subsystem directly affected the energy of A_{ij}, which subsequently affected λ_{ij}, C_2, and C_3.

The original MCS case study had 32 connections, all of which were piecewise connections from different subsystems to the main bus. To conduct the sensitivity analysis, the number of interconnections was randomly boosted by a series of percentages to study the net effect on complexity. Recall that A_{ij} was insensitive to the *type* of connections, only to the *number and amount* of connections involved. For example, in terms of the complexity algorithm, it does not matter whether a hypothetical Unit A is connected to a notional Unit B or notional Unit C, but the *number* and *type* of connections between those units matter greatly.

Six different notional adjacency matrices were created for MCS with the number of connections varying between each graph. Each of the six different adjacency matrices were created to represent notional increases in automation and were not intended to convey any actual level of functionality in the MCS. Incremental customer-driven boosts in automation were represented by each incremental increase in population of A_{MCS}. The 100% connection increase is shown as an example of increased cross-connections and automation in Table 13.

Table 13: Notional MCS Adjacency Matrix with 100% Increase in Interconnectivity

	UCC 1	UCC 2	UCC 3	UCC 4	Repair Station Console (1)	Repair Station Console (2)	Repair Station Console (3)	Repair Station Console (4)	Repair Station Console (5)	Repair Station Console (6)	Prop 1 DIU	GTM 1A (UEC Plus)	GTM 1B (UEC Plus)	Prop 2 DIU	GTM 2A (UEC Plus)	GTM 2B (UEC Plus)	GTG 1/RIMSS 1 (LOCOP)	GTG 2/RIMSS 2 (LOCOP)	GTG 3/RIMSS 3 (LOCOP)	EP DIU 1	EP DIU 2	EP DIU 3	Int. Bridge & Navy. System	DVSS Cameras w/ DMMs	DVSS Server	SBDB (UCC1)	SBDB (UCC2)	Fire Dectection Subsystem ITBs	GEDMS IO, Aux, DC	Fuel Oil Lab Workstation	Main MCS BUS
UCC 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
UCC 2	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
UCC 3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
UCC 4	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1
Repair Station Console (1)	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
Repair Station Console (2)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
Repair Station Console (3)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
Repair Station Console (4)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
Repair Station Console (5)	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	1
Repair Station Console (6)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
Prop 1 DIU	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
GTM 1A (UEC Plus)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
GTM 1B (UEC Plus)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
Prop 2 DIU	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1
GTM 2A (UEC Plus)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	1
GTM 2B (UEC Plus)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
GTG 1/RIMSS 1 (LOCOP)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
GTG 2/RIMSS 2 (LOCOP)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
GTG 3/RIMSS 3 (LOCOP)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
EP DIU 1	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	1
EP DIU 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
EP DIU 3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
Int. Bridge & Navy. System	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	0	0	1
DVSS Cameras w/ DMMs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
DVSS Server	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
SBDB (UCC1)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
SBDB (UCC2)	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1
Fire Dectection Subsystem ITBs	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	1
GEDMS IO, Aux, DC	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1
Fuel Oil Lab Workstation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Main MCS BUS	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0

Percentage increases in connectivity were selected to determine how C_3 varies with that percentage increase. Using MATLAB and following the same logic as stipulated before, it was discovered that C_3 varies as a third order polynomial with an increase in connectivity as shown in Figure 17. A third order polynomial fit generated a 99.9% R^2

value indicating high correlation between the data and the fitted polynomial. It should be noted that Sinha and de Weck, 2013 predicted that C_3 would vary with *square root* of interconnectivity vice a third-order polynomial, but as with the original data, a larger sample of subsystems would most likely alter the fitted equation. Regardless of whether the fitted equation is a function of the square root, a third order polynomial, or another related equation form, the fact that the customer may face escalating costs through an increase in automation remains a salient and central point to this thesis.

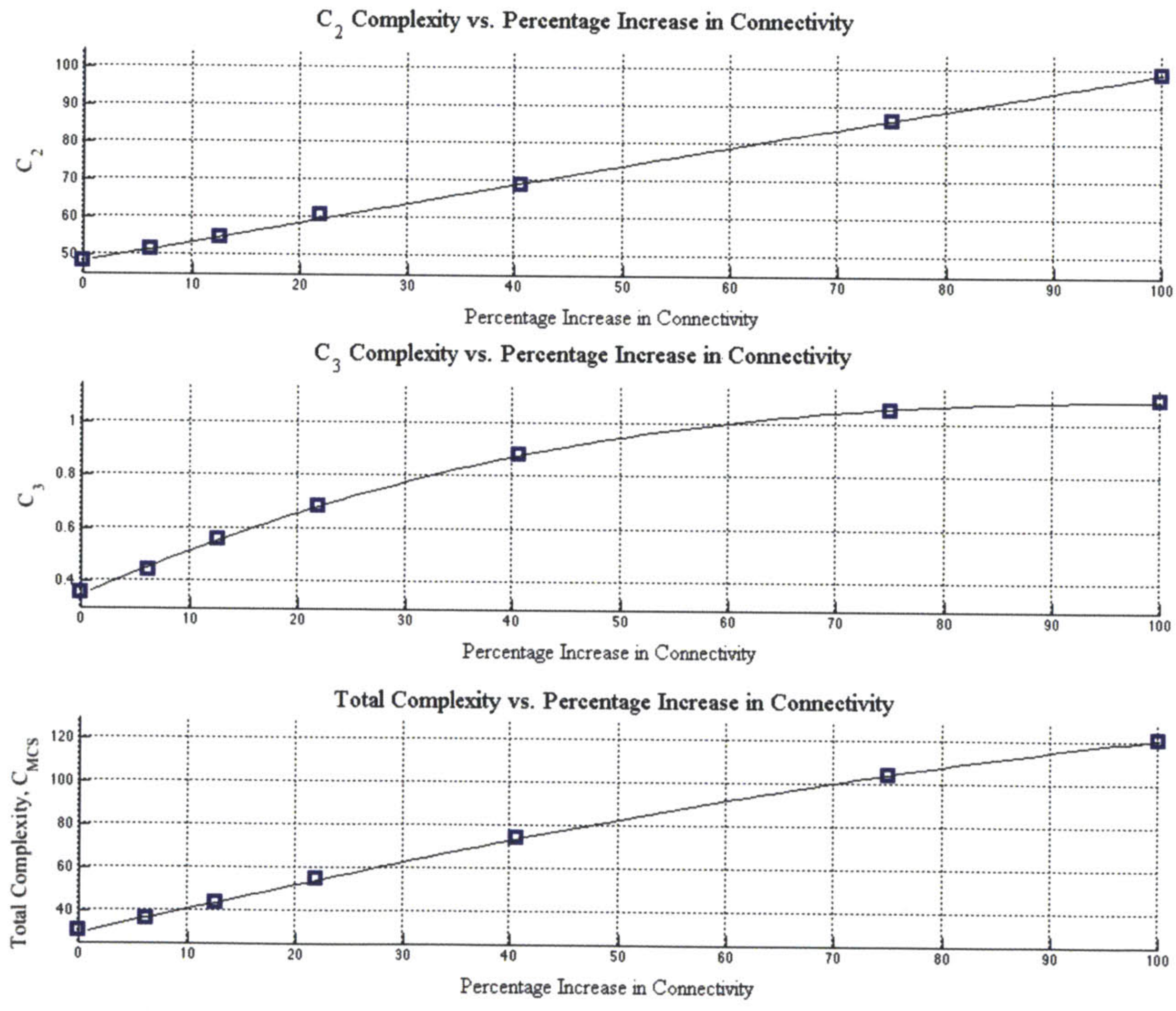

Figure 17: C_3 versus Percentage Increase in Subsystem Interconnectivity

The top graph (C_2) in Figure 17 implies a strict linear relationship between an interconnectivity increase, but the middle figure (C_3) shows that above a certain point, a subsystem's net C_3 complexity will not vary as much as when interconnections are first introduced into the system.

Recalling the equation that led to the calculation of C_2 and C_3 it can be deduced that a linear relationship would be the inevitable product of a term comprised of multiplying the sums:

$$C_{total} = C_1 + C_2 C_3 = \sum_{i=1}^{n} x_i + \left[\sum_{i=1}^{n} \sum_{j=1}^{m} \beta_{ij} A_{ij} \right] \gamma E(A_{ij})$$

However, non-linearity (in the polynomial sense) is introduced into the equation via the matrix energy calculations, which produced the middle C_3 graph shown in Figure 17. The final result is a logical blend of the two given the multiplicative nature of the relationship terms.

For the Navy, this means that the upfront cost of automation that is currently quite expensive will remain so over time as each system gains evermore complexity. Intuitively, this makes sense because a developed and interconnected system will in effect become the new "normal" or the new baseline. Any new augmentations to the subsystem would essentially restart you from the bottom left portion of each graph, and the program would experience complexity costs again.

The Air Force has experienced and will experience complexity-based cost growth, especially in terms of their increasingly prolific and highly in-demand Unmanned Aerial Vehicle (UAV) systems. Policy makers view automation as a key way to not only drive down costs in terms of personnel, but as a way to boost operational effectiveness by reducing bandwidth/latency issues, improving situational awareness, and eliminating (or mitigating) operator error through the removal of information saturation, boredom, and sensitive judgment calls (Hansman and Weibel 2004). Figure 18 below shows DoD's aggressive push for UAV automation, and by recalling that cost also scales superlinearly with complexity (driven by a boost in C_3 here), one can logically deduce that the Air

Force and DoD could have some significant and unintended cost growth in their near future.

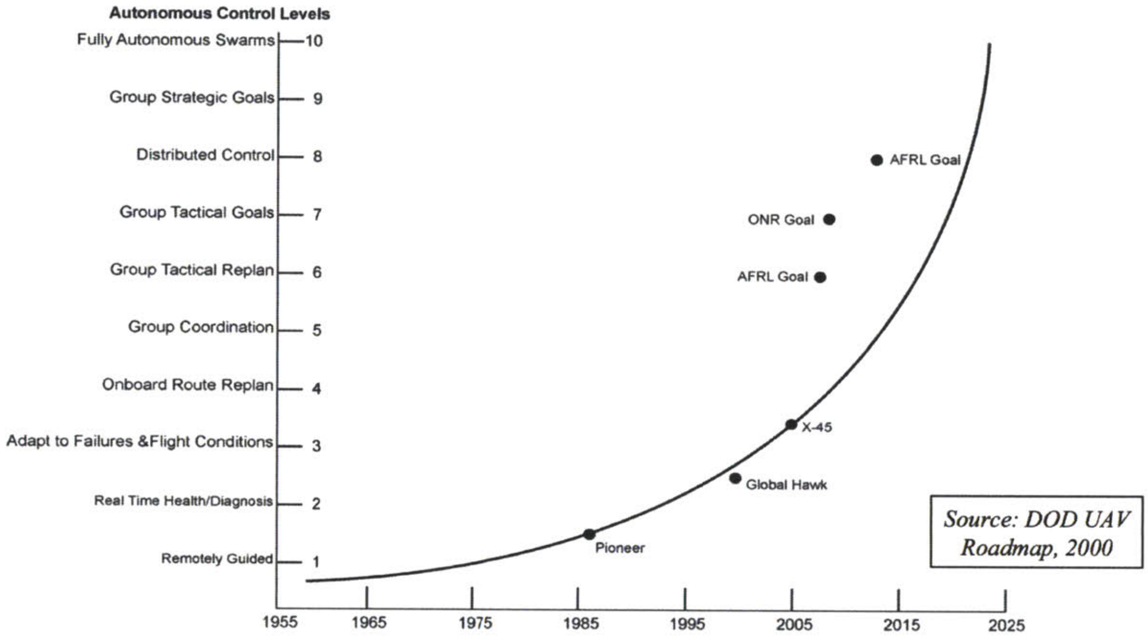

Figure 18: DOD UAV Roadmap

Based on the analysis in the C_3 variable, it stands to reason that system architectures will most likely become increasingly distributed in nature, which means that there will be more nodes with larger numbers of connections. In an engineered system, this concept would be represented by a cost-driven increase in systems with more parts but fewer inter-connections meaning that interfaces would be more manageable. The obvious tradeoff to this concept would be the coinciding boost in System Engineering, Integration, and Test costs that would result from having a larger number of disparate systems interacting in the aggregate.

5.3 Discussion

What does the cost versus complexity trend really mean? Recall that the fitted equation showed exponential cost growth:

$$\$M = 23.100e^{0.015C}$$

If that relationship was broken down to is components via the natural log properties *it is evident that a one-unit increase in complexity would yield a 1.5% increase in cost.*

$$ln(\$M) = ln\ (23.100e^{0.015C})$$

$$ln(\$M) = l\,n(23.100) + 0.015C$$

$$\boxed{ln(\$M) = 23.100 + 0.015C}$$

One could reasonably expect that given the exponential relationship between cost and complexity, a program or customer implementing a complexity-based cost estimation method would set a limit on complexity units in a program, with the validated foreknowledge that complexity is intrinsically linked to cost. From that point, complexity-units would be a quantifiable way of managing risk *and* cost in the program trade-space.

Although DDG 1000 was not analyzed in this thesis, it is reasonable to assume that the plethora of cutting-edge (albeit complex) technology stuffed into DDG 1000 is in large degree responsible for the staggering costs that were witnessed in the development of that vessel. Furthermore, a complexity analysis conducted via this algorithm before construction could possibly have given decision makers and program managers an enhanced degree of insight into the financial path that lay before them. Program managers could weigh the importance of considered subsystems based on complexity, associated cost, and value to the warfighter, and it is hypothesized that some subsystems would be devalued in importance based on that subsystem's complexity value.

Another idea would be to implement what would essentially be a "cap and trade" style complexity-based cost engineering approach to program management, whereby program managers can accept greater complexity on one subsystem while trading off for a decrease in others.

Complexity's exponential relationship highlights the financial danger of falling in love with technology. The Navy is currently producing technologically unmatched vessels to the warfighter, but this research raises the question of whether a handful of technology-laden, multi-mission masterpieces are better than a plethora of diverse, single-mission vessels in a cost-constrained acquisition environment.

Another question to consider is what the Navy's function is going to be in the next war if world events take a tragic turn for the worse? The perennial response is usually some reference to the U.S.'s role in the Far East, where U.S. Forces are being increasingly strategically aligned in what is known as the "Asian Pivot". Although China is one of America's most-valued trading partners and both sides would see all-out war as catastrophic turn of events for both sides, China is frequently mentioned in what-if scenarios. In 2012, a particularly outspoken Chinese admiral in discussion of DDG 1000 frankly opined, "All it would take to sink the high-tech American ship is an armada of explosive-laden fishing boats." (Talmadge 2012) While the discussion of swarm-tactics and responses are the subject of tomes of research, the comment by the Chinese admiral is an eye-opening reminder of the technology-implementation policy contrasts in use by different Navies around the world. Is a swarm of low-technology, single- or dual-mission vessels superior in terms of mission-effectiveness than a handful of vessels that can single-handedly conduct Ballistic Missile Defense, strike an Al-Qaeda or Haqqani camp 1000 miles inland, and conduct anti-submarine warfare (to name a few missions)? A complexity-based cost assessment dictates the cost advantages of a push towards a distributed system architecture, and it seems as though the evolutionary pressure induced by hypothetical world threats are indicative of an additional push in the low-complexity, high-quantity direction as well.

6. Summary and Recommendations

As the sophistication and technology of ships increases, U.S. Navy shipbuilding must be an effective and cost-efficient acquirer of technology-dense one-of-a-kind ships all while meeting significant cost and schedule constraints in a fluctuating demand environment. A drive to provide world-class technology to the U.S. Navy's warfighters necessitates increasingly complex ships, which further augments the non-trivial problem of providing cost effective, on-schedule ships for the American taxpayer. The primary objective of this study was to quantify, assess, and analyze cost predictive complexity-oriented benchmarks in the pre-construction phase of the U.S. Navy's ship acquisition process. This study used commercially available software such as Mathwork's MATLAB software to analyze the numerical cost data and assess the fidelity of the predictive benchmarks to the datasets. The end result was that a consideration of complexity via the methods and algorithms established in this study supported an exponential cost versus complexity relationship to refine the current cost estimation methods and software currently in use in U.S. Navy shipbuilding.

With the addition of more complexity data, it would theoretically be possible to not only present a refined exponential (or power law) cost versus complexity prediction curve, it would also be possible to present the "rolled up" complexity for the ship in its entirety. A validated complexity metric for the entire ship would be a powerful indicator and comparison tool with which to compare ships of various types and classes, as well as their respective costs. Further logical deductions could aid decision-makers in comparing shipyards, akin to the efforts made in the benchmarking studies presented in Appendix E.

6.1 Summary

This study focused on the four main high-risk subsystems identified by PMS 400D on board the DDG 51 Guided Missile Destroyers: the Main Reduction Gear as developed by both General Electric and Philadelphia Gear Company, Machinery Control System, AEGIS radar system, and the new Air and Missile Defense Radar System.

A complexity metric was developed through 10-pronged assessment of each subsystem based on different intrinsic properties of that subsystem and its relative relationship to other subsystems in its technical environment.

Cost was determined via various publicly available, open-source documents including GAO reports and Distribution A Program Office briefings.

It was found through the algorithm developed and applied in this thesis that an exponential fit of cost data yielded a 98.5% correlation to the data. Although a sample size of N = 5 was applied in this research, it is hypothesized based on the initial trends that more data would confirm the exponential cost increase with complexity trend and serve to refine the coefficient values in the final cost versus complexity exponential equation shown in summary Figure 19.

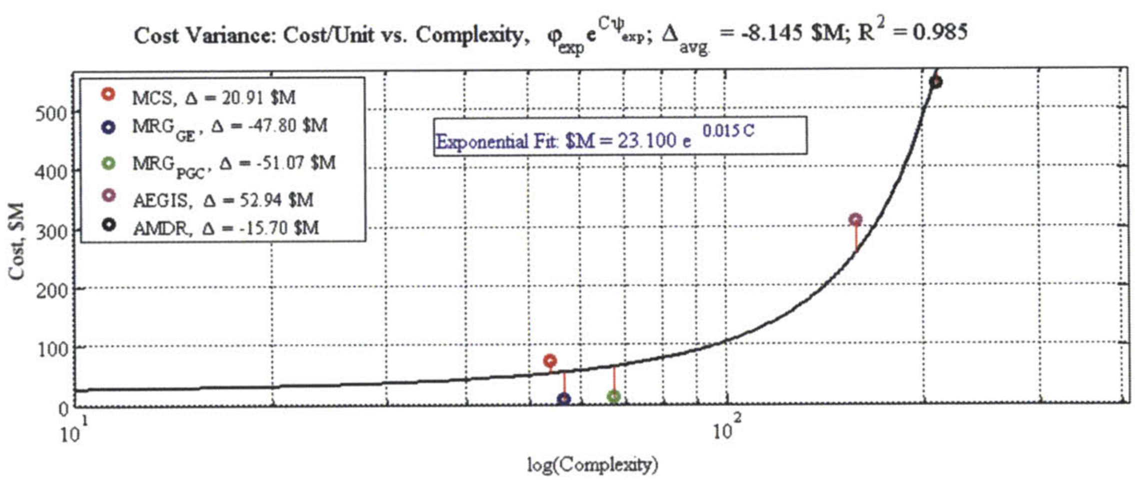

Figure 19: Unit Cost vs. Complexity, Exponential Fit: $\$M = 23.1e^{0.015C}$

In the future, this graph will change, as it is a snapshot in time of a system or subsystem's complexity and cost. Although the evidence reviewed in this study indicates a general trend for subsystems to move up and to the right over time, there are examples where this is not always the case. According to cost justification data produced by NSWC Carderock, RDT&E efforts are currently underway to reduce complexity of the MCS by developing a wireless approach that will concurrently boost the host ship's survivability and reduce the overall construction costs (NSWC Carderock 2008). If and when the new wireless MCS becomes a reality, it will shift to the left, although it remains to be seen whether cost will correspondingly decrease.

6.2 Recommendations

The aim of this study was to examine how complexity affects cost and to leverage that knowledge to refine the Navy's cost estimating abilities for large-scale, complex technical system such as those on board the various flights of the DDG 51 class. Given the premise of that aim, the recommendations are threefold:

1. Stand up a NAVSEA 05C Integrated Product Team (IPT) to create a database of the systems and subsystems that create the most cost vulnerability for any given particular ship program. This database would include classified repositories of the information that was gleaned from open-source data in this document. Each subsystem would have an adjacency matrix verified as being correct (row-by-row) by maintenance personnel, a corresponding interface complexity assessment as concurred upon by the IPT, and a verified X-vector as populated by the previously determined information and assessments.
2. For old systems with *actual* costs, this complexity would be evaluated for cost versus complexity performance and would refine the overall trend-line coefficients for the entire system. For new systems with undetermined costs, the previous data points and their coinciding trend line would be used to make a cost estimation that would be compared with other cost estimations as generated by NAVSEA 05's PODOC software tool. A record of the comparative cost estimation performance would be tabulated.
3. Based upon the performance of this algorithm, this algorithm via a complexity-weighted factor would either augment the conventional cost estimation methods, or if enough fidelity existed in the long-term, complexity-based cost estimation could completely supplant the existing methods. This would involve standing up a cost estimation branch office that maintains, verifies, and gathers new information regarding systems and subsystems under analysis.

6.3 Areas for Further Study

This study sought to refine the Navy's current cost models through the use of a quantification of complexity. What would be the effect of the inclusion of other cost estimation tools such as Compensated Gross Tonnage (CGT) whereby predictions are made based on ship type? It is hypothesized that an algorithm comprised of a blend of complexity and CGT could yield even further gains in the effort to shrink the ever-present cost delta between actual and predicted system costs. Further elaboration on CGT is included in Appendix E.

To further augment the cost prediction accuracy gains made by the inclusion of CGT-based estimation methods, another area of study based on contract structure and the diversity of the industrial base could prove as a useful tool for Navy and DoD policy makers. As Dominic Alvarran pointed out in his research[9] of contracts for SOW part 1 of the Production in the Innovation Economy (PIE) study, the consequences of having only two relatively equal market share competitors (also known as an oligopoly) with one buyer (monopsony) has far reaching consequences characterized by the fact that free market competition is no longer "the main driver of performance [and cost]." (Alvarran 2013) A study into the dynamics of the interplay between the actual *price* the Navy pays, the price the Navy predicts they would pay via cost-estimation algorithms, contract structure, and the number/diversity of market players could yield interesting insights and understanding into the relatively complex DoD acquisition environment.

Roi Guinto's 2014 research into the dynamics of Navy contract competition indicated that when multiple sellers or vendors exist, the Navy could, on average, expect to pay 8% less in terms of total price[10] (with greater than 95% statistical confidence based on T-tests) than when negotiating with one seller alone (Guinto 2014). With multi-year, multi-

[9] More information on how Alvarran's research ties into the Navy contracting process is included in Appendix C.1.

[10] Guinto noted that the 8% savings was generated due to what was termed as "shipyard optimism" and its affect on bid competition levels, vice actual savings on the shipyard's part.

ship contract price points in the multi-billion dollar range, an 8% potential savings is enormous, and being able to home in on an accurate price estimate would be valuable to the taxpayer. Further cost estimation refinement studies based on complexity, CGT, traditional SWBS groups, and competition environment levels would have the potential to yield profound insights and open the door to fundamental change in the Navy cost estimation process.

6.4 Closing Comments

Through the course of research, many valuable lessons learned and shipbuilding wisdom has been accumulated that falls outside the relatively narrow scope of any one particular thesis. In order to promulgate this message, a brief synopsis of these items is recorded here at the close of my research.

- **100% of the new ship design and 100% of construction planning *MUST* be complete prior to the start of construction**. In the world shipbuilding market, the US Navy is absolutely alone in the paradigm of beginning construction before the design and plan are complete. While a concurrent design and build operation (not to be confused with the iterative Design-Build planning technique employed at EB and NASSCO) may slightly minimize upfront costs, the ramifications to total overall cost and schedule due to change orders is enormous, and NASSCO's proprietary data has proven that the Navy simply cannot afford to continue down this path.

For example, Daewoo Shipbuilding (NASSCO's partner in Okpo, South Korea) will *only* share a drawing for review and comments prior to the promised delivery date in order to ensure that no changes will enter the drawing until it has been deemed complete. The systemic nature of a ship means that small, seemingly insignificant changes in one part of the ship can propagate throughout the entire ship touching up to 90% of the ship's drawings.

Completing 100% of the new ship design and 100% of the construction planning prior to the start of construction is the ***"silver bullet"*** *to driving down cost and schedule in US Navy shipbuilding.*

The underlying pressure behind the U.S. Navy's unique and concurrent design and build approach is the significant political pressure applied to the program manager to meet or exceed unreasonable schedule delivery dates (Hugel 2013).

In 2005 the GAO echoed this philosophy by stating that there was a pandemic "lack of design maturity…required to rebuild completed areas of the ship." (Keane 2011)

- **Designing for producibility will drive down cost and improve schedule performance**. A persistent problem in shipbuilding is the tendency of the designers to create drawings and "throw them over the wall" to the production team. EB and NASSCO implement the Design-Build technique whereby a team of designer and a team of manufacturing leads iterate a design for producibility, which minimizes the problems created by the knowledge gaps of their counterparts' respective challenges.

A drawing MUST be signed by the production team lead as evidence of this relationship.

Designing for producibility extends to image based work packages clearly stating in words and pictures tools required to complete the job, sequencing, and overall layout of the construction task at hand. The roots of this effort stem from items purchased at retail stores such as Target® or Ikea® where the end consumer constructs the final product at home via a simple, picture-based pamphlet.

- **Create, sustain, and support a culture of process improvement.** The highest performing shipyards have a robust process improvement *culture* with buy-in from management and the shipyard employees. Dr. Borgschulte Germany's Lürssen shipyard frankly stated "It is all about process improvement" (Borgschulte 2013), and this philosophy is echoed at NASSCO with rotating

“Breakfast Clubs” (early morning meetings) featuring grassroots workshop process improvement efforts. It should be noted that not every effort or idea will generate hundreds of thousands of dollars in savings, but the aggregation of savings of all ideas is a substantial value to the taxpayer.

Bibliography

Allison, Jacob I. *Japan Maritime Self-Defense Force (JMSDF) guided-missle defense destroyer JDS Atago (DDG-177).* USN Photo, USN, 2011.

Alvarran, Dominic. "Realigning Contract Incentives for the Non-Competitive Environment of the US Shipbuilding Industry." Master's and Engineer's Thesis, M.I.T., Cambridge, MA, 2013.

ASD R&E. *Technology Readiness Assessment (TRA).* Guidance, Washington, D.C.: DoD, 2011, 20.

Borgschulte, Klaus. "Challenges in Specialized Shipbuilding." *Presentation.*

Cambridge, MA: Lurssen Shipbuilders, September 5, 2013.

Cairns, John A. "DDG 51 Class Land Based Engineering Site (LBES) - The Vision and the Value." *American Society of Naval Engineers,* 2011.

Captain Mark Vandroff, USN. "DDG 51 Program." 2013.

Captain Mark Vandroff, USN, interview by US Naval Institute. *Program Manager, DDG 51 Shipbuilding Program* www.news.usni.org, (2012).

DAU. *Cost Terms.* 2013.

https://dap.dau.mil/acquipedia/Pages/ArticleDetails.aspx?aid=419dcd24-0e78-4279-a50a-9c122c4f0630 (accessed February 11, 2014).

DAU. *Learning Curves.* Text, Washington, D.C.: DAU, 2008.

Defense Acquisition University. *Depot Level Maintenance.* 2013.

https://acc.dau.mil/depot (accessed June 19, 2013).

Defense Industry Daily. *Adding Arleigh Burkes: H.I.I. Steps Forward for DDG-51 Restart.* June 12, 2012. http://www.defenseindustrydaily.com/adding-arleigh-burkes-northrop-grumman-underway-06007/ (accessed January 7, 2014).

—. "Korea's KDX-III AEGIS Destroyers." *Defense Industry Daily,* April 7, 2013.

Dickseski, Jerri. "America's Largest Military Shipbuilder Begins Operations as a New, Publicly Traded Company under the Name of Huntington Ingalls Industries." News Release, HII, 2011.

diStefano, Christi, and Gary Davis. *Matrix Energy.* Report, University of Massachusetts at Dartmouth, Dartmouth: CSUMS, 2009.

FAS Military Network. *DDG-51 ARLEIGH BURKE-class.* 2013. www.fas.org (accessed June 27, 2013).

FMI, and USD(AT&L). *Globall Shipbuilding Industrial Base Benchmarking Study.* Benchmarking Report, Washington, D.C.: Department of Defense, 2005.

Fortune, Randall. *Give and Take: Program Management Design Engineering.* Presentation, Washington, D.C.: ASNE, 2012.

Galrahn. *AMDR Will Bring Very High Fleet Costs.* November 17, 2011.

http://www.informationdissemination.net/2011/11/amdr-will-bring-very-high-fleet-costs.html (accessed October 18, 2013).

GAO. "Cost and Schedule Problems on the DDG-51 AEGIS Destroyer Program." Report, Washington, D.C., 1990.

GAO. *DEFENSE ACQUISITIONS: Assessments of Selected Weapon Programs.* Report, Washington, DC: GAO, 2013.

GAO. *GAO Report GAO-12-113-05.* Report, GAO, Washington, D.C.: GAO, 2012.

GAO. *Improved Management Practices Could Help Minimize Cost Growth in Navy Shipbuilding Programs.* Report, Washington, D.C.: GAO, 2005.

GAO. *Navy Shipbuilding: Cost and Schedule Problems on the DDG-51 AEGIS Destroyer Program.* Report, Washington, D.C.: GAO, 1990, 60.

GD NASSCO. *MIT Visit.* Report Presentation, San Diego: GD NASSCO, 2013.

General Dynamics. "2012 General Dynamics Annual Report." 2012.

Global Security. *AEGIS Combat System (ACS).* July 7, 2011.

http://www.globalsecurity.org/military/systems/ship/systems/aegis.htm (accessed October 19, 2013).

—. *World-Wide Shipbuilding Industry.* 2010.

www.globalsecurity.org/military/world/shipbuilding.htm (accessed August 7, 2013).

Guinto, Roi. "Navy Contract Gaming - TBD." Thesis, MIT, Cambridge, MA, 2014.

Halpin, Richard. *Propulsion Control the DDG Class: 16 Years of Lessons Learned.* Washington, DC: www.navalengineers.org, 2007.

Hansman, and Weibel. *Human and Automation Integration Considerations for UAV Systems.* Presentation, Cambridge: MIT International Center for Air Transportation, 2004.

Harris, Fred, interview by Aaron Dobson. "Challenges in US Navy Shipbuilding." *President, GD NASSCO San Diego.* San Diego, CA, (August 13, 2013).

Hellman, Todd, interview by Aaron Dobson. *Technical Director, PMS 400D* Washington, DC, (October 9, 2013).

Hoffman, Edward, and Matt Kohut. *NASA's Journey to Project Management Excellence.* Washington, DC: National Aeronautics and Space Administration, 2012.

Horn, and Johnson. *Topics in Matrix Analysis.* Cambridge Press, 1994.

Hugel, Rear Admiral (ret.). "Table Discussions at MIT Shipbuilding Seminar." Cambridge, MA, September 5, 2013.

Inflation Data. 2013. www.inflationdata.com (accessed May 10, 2014).

Inside View. 2013. www.insideview.com (accessed June 18, 2013).

Keane, Bob. *Reducing Total Ownership Cost (TOC): Thinking Outside the Hull.* Presentation, ASNE Day 2011, 2011.

Knaack, Marcelle. *Encyclopedia of USAF Aircraft and Missile Systems.* Offce of Air Force History, 1988.

L-3. *L-3 Maritime.* Announcment, New York: L-3, 2010.

Lockheed Martin Corporation. "Lockheed Martin Awarded Machinery Control System Computer Program Modernization Contract for U.S. Navy Destroyers." News Release, Orlando, FL, 2013.

Marine Insight. *Top 10 Shipbuilding Companies in the World in 2012.* August 14, 2012. www.marineinsight.com (accessed August 7, 2013).

MIT. *Production in the Innovation Economy.* 2011. http://web.mit.edu/pie.
NASA. *NASA Technology Readiness Levels.* December 16, 2004.

http://as.nasa.gov/aboutus/trl-introduction.html (accessed October 17, 2013).

NAVAIR. *DDG-51 Machinery Control System (MCS).* Flyer, Orlando: NAVAIR, 2013.

Naval Technology. *KDX Class Destroyers.* July 31, 2013. www.naval-technology.com.
NAVSEA Office of Corporate Communication. *DDG 51 Multiyear Procurement Contract Awarded.* News Report, www.navy.mil, 2013.

NAVSEA Shipbuilding Support Office. *DDG Class.* 2013. www.nvr.navy.mil (accessed June 28, 2013).

—. *Naval Vessel Register.* 2013. www.nvr.navy.mil (accessed August 7, 2013).
NSWC Carderock. "Exhibit R-2a, RDT&E Project Justification." Budget Line Item Justification, Washington, D.C., 2008.

Orr, Mel. "Republic of Korea (ROK) Navy Destroyer ROKS Sejong the Great (DDG 991)." Sea of Japan: USN, March 6, 2012.

Parker, Katrina. "USS Roosevelt (DDG 80)." Atlantic Ocean: USN, July 13, 2008.

RAND Corporation. *Why Has the Cost of Navy Ships Risen?* Report, Washington, DC: Arena et al., 2006.

Raytheon. *Raytheon awarded US Navy next generation Air and Missile Defense Radar contract.* October 10, 2013. http://finance.yahoo.com/news/raytheon-awarded-us-navy-next-231900443.html (accessed October 18, 2013).

Shapiro, Michael. "Huntington Ingalls to turn Avondale shipyard into a builder of oil and gas equipment." *Daily Press,* February 5, 2013.

Sinha, Kaushik, and Olivier de Weck. "Structural Complexity Quantification for Engineered Complex Systems and Implications on System Architecture and Design." *Proceedings of the International Design Engineering Technical Conference.* Portland, Oregon: American Society of Mechanical Engineers, 2013.

Space Daily. *Space Daily.* October 15, 2013.

http://www.spacedaily.com/reports/Raytheon_Awarded_US_Navy_Next_Generation_Air_And_Missile_Defense_Radar_Contract_999.html (accessed January 7, 2014).

State New Service. "RCA Fights over AEGIS." *The New York Times,* November 30, 1986.

Talmadge, Eric. *US Navy hopes stealth ship answers a rising China.* Yahoo! News. June 4, 2012. http://news.yahoo.com/us-navy-hopes-stealth-ship-answers-rising-china-065329046.html (accessed February 12, 2014).

Thomsen, James E., interview by PIE Study Team. *ASN (RD&A) Office* (2012).

UPI. "RCA Gets Contract for 'Aegis'." *The News and Courier*, December 24, 1969: 12-B.
US Government Accountability Office. *"GAO-13-294SP DEFENSE ACQUISITIONS Assessments of Selected Weapon Programs".* Report, Washington, D.C.: GAO, 2013, 117-8.

USS DDG 51 Arleigh Burke Destroyer. June 2009. www.the-blueprints.com (accessed June 27, 2013).

Appendices

Appendix A: Travel Summary and Interview with Technical Director, PMS 400D

May 2nd, 2013 Interviews (Cambridge, Massachusetts):

- Navy Captain and former Commanding Officer of NSWC Carderock Naval Research Center.
- Navy Commander and submarine operations, construction, and maintenance specialist.

August 12th to August 14th, 2013 (San Diego, California):

- Traveled to National Steel and Shipbuilding Company (NASSCO) - San Diego.
- Interviews conducted with President Fred Harris and support team.

September 16th, 2013 (Washington, D.C.):

- Visited Navy Yard to meet Technical Director for PMS 400D
- Information gathering session

October 9th, 2013 (Washington, D.C.):

- Follow up visit to Navy Yard to meet Technical Director
- Interview with TD

February 20th, 2014 (Crystal City, Virginia):

- Presented initial findings to American Society of Naval Architects at professional society expo.
- Engaged in real-time feedback with industry experts

9 October 2013, 0900 to 1130

1100 New Jersey Avenue SE

Washington, DC 20003

The Technical Director of PMS [Program Management (Ships)] 400D is the lead technical government authority for HM&E (Hull, Mechanical, and Electrical) items in the DDG 51 program. Other systems such as Air Missile Defense Radar (AMDR) and AEGIS are developed by other entities outside of PMS 400D. The DDG 51 government/contractor team then integrates those developed systems into the DDG 51 design.

Questions for Discussion

- What systems/subsystems pose the greatest technical risk to the DDG 51 program?
    - AMDR
        - Significantly more complex and less understood than AEGIS system.
        - Requires more power and cooling than AEGIS. Larger cooling plants will be implemented.
        - System interface complexity assessed to be **1.0** on a 0 to 1 scale, with 1 being the most complex. AMDR is deemed to be "as complex as it gets".
    - Main Reduction Gear (MRG)
        - Most expensive piece of HM&E
        - High number of subcomponents
        - New contractor will have to build new MRG.
            - GE used to manufacture MRG.
            - Philadelphia Gear Company (PGC) now building MRG.
            - Alignment effort is critical and labor intensive.
            - Quieting
        - No EVM on cost performance because it is provided to the ship as Government Furnished Equipment (GFE).
        - System interface complexity assessed to be **0.3** on the 0 to 1 scale previous mentioned.
    - Mission Control System (MCS)
        - High number of interfaces, wiring, and lines of code.
        - Function as information "superhighway".
        - Changes to system often have unintended effects due to the high number of systems that the MCS interfaces with.
        - System interface complexity assessed to be **0.8** on the 0 to 1 scale.
- At what TRL are those systems?

- Why are those systems the most risky?
    - Level of understanding in a new system such as AMDR
    - Number of interfaces
    - Number of components
    - Relative contract value
- In terms of interface complexity and the understanding of those interfaces, how would you rate interface complexity on a scale of 1 to 10? For example, the interface complexity of one board nailed or bolted to another board would be rated at a 1. At the other end of the spectrum, an interface composed of thousands of wires at varying power loads, frequencies, etc. would be a 10.
    - Provided above.

Data Requests

- High level functional block diagram of highest risk systems

Definition of Complexity

Definitions of complexity abound and are generally very different, but many commonalities are observed[11].

- Most complex systems contain a lot of redundancy.
- A complex system consists of many parts.
- There are many relationships/interactions among the parts.
- The complex systems can often be described with a hierarchy; redundant components can be grouped together and considered as integrated units.

Questions and Topics of Discussion

11 Caprace and Rigo, "A real-time assessment of the ship design complexity". 2010

1. Is vessel/system complexity currently a factor used in the creation of a development or acquisition strategy in order to improve probability of a successful outcome? If so, how does it factor into the process? E.g., is it a standalone process or does it integrate into a risk assessment or risk management strategy?
2. What indicators do you use to measure or judge complexity, if any?
3. What classes of surface ships seem to be more complex in terms of technology systems and construction versus others?
4. What onboard ship systems, subsystems, or components stand out as having evolved most quickly in terms of complexity? Are subsystems of differing complexity managed differently based upon that complexity?
5. How does the novelty or newness of a technology and the organization executing the program with that technology affect the overall assessment of complexity and subsequent mitigation strategies? I.e., organizational factors, supply chain complexity, national/international partners, GFE/CFE, human factors, EPA…)
6. What systems that are non-intrinsic to the ship have most increased the "contextual" complexity of the design process?
7. In your experience, how have the *program offices* assessed, planned for, and mitigated the issue of complexity? I.e., Set Based Design/Time-deferred decision-making. What practices are most effective?
8. How have the *shipyards* assessed, planned for, and mitigated the issue of complexity? What practices are most effective?
9. What aspects of the shipyard limit the yard's ability to efficiently construct ever increasingly complex ships?
10. What national or international industries or projects come to mind for those who manage complexity well?

Appendix B: MATLAB Complexity Algorithm, Source Script, and Output

Contents


```
clear all
clc
close all
format shortg

disp('---------------   Aaron Dobson, LT USN    --------------------------')
disp('---- complexity.m: Algorithm to Calculate Structural Complexity ---')
disp('  In support of Naval Engineers Degree and Masters of Science in')
disp('                Engineering Management     ')
disp('-----------------  Submitted May 2014  ----------------------------')
disp('--------- Massachusetts Institute of Technology  ------------------')
disp('   ')
disp('   ')
---------------   Aaron Dobson, LT USN    --------------------------
---- complexity.m: Algorithm to Calculate Structural Complexity ---
  In support of Naval Engineers Degree and Masters of Science in
                Engineering Management
-----------------  Submitted May 2014  ----------------------------
--------- Massachusetts Institute of Technology  ------------------
```

Complexity Algorithm Inputs

```
% X1 = measure of performance tolerance
% X2 = measure of performance level
% X3 = component size indicator
% X4 = # of coupled disciplines involved
% X5 = variables involved
% X6 = TRL factor
% X7 = exisiting knowledge of operating principle
% X8 = extent of reuse/heritage indicator

% X Vector (Alpha -> C1)
X_AEGIS = [9 9 7 10 10 2.0 10 10];
X_AMDR = [9 10 7 10 10 2.8 3 4];
X_MCS = [6 3 3 3.4 8.9 2.5 6 4];
X_MRG_GE = [10 3 2 0.1 7.7 2 4 3];
X_MRG_PGC = [10 3 2 0.1 7.7 2.8 8 9];

% AMDR Complexity K-Factor
LSW3 = 9600; % Lightship weight for Flight III in Long Tons
LSW2 = 9100; % Lightship weight for Flight IIA in Long Tons
PF3 = 12; % Power for Flight III in MW
```

```
PF2 = 7.5; % Power for Flight IIA in MW

k = (PF3/LSW3)/(PF2/LSW2);  % Power Density Comparison (FIII/FIIA)

x = 5:0.05:14.95;
kP = (x./LSW3)/(PF2/LSW2);
x1 = 5000:50:14950;
kLSW = PF3*x1.^-1*(PF2/LSW2)^-1;

figure
plot(x,kP,x1/1000,kLSW)
hold on
legend('Power Variation','Weight Variation/1000')
xlabel('Variation','FontName','Times','FontSize',16);
ylabel('K-factor','FontName','Times','FontSize',16)
title('K-factor Sensitivity Analysis in Flight III','FontName',...
    'Times','FontSize',18)
set(gcf,'color','w')
set(gca,'FontName','Times','FontSize',16)
H = legend('Power Variation','Weight Variation/1000');
set(H,'Location','NorthEast','FontName','Times','FontSize',14)
grid on

% Interface Complexity Assessments (Beta -> C2)
beta_AEGIS = 0.9; % beta defined as interface complexity
beta_AMDR = 1;
beta_MCS = 0.8;
beta_MRG = 0.3;

% Load EXCEL files/Adjacency Matrices (~ -> C3)
A_AEGIS = xlsread('Matrices.xlsx','AEGIS');
A_MCS = xlsread('Matrices.xlsx','MCS');
A_MRG = xlsread('Matrices.xlsx','MRG');

% Subsystem Costs:
% 1-AEGIS, 2-AMDR, 3-MCS, 4-MRG_GE, 5-MRG_PGC
cost(:,1) = [33030*0.666, 1633, 0, 274, 80.2]; % Costs in FY13 $Mil
Q(:,1) = [71, 3, 71, 40, 6]; % Quantity or units

% Learning curve SLOPE percentage for MCS
LC = 0.95; % Set value between [0.90, 0.95]
```

Complexity Calculations

```
% C1 Calculations

X = [X_AEGIS; X_AMDR; X_MCS; X_MRG_GE; X_MRG_PGC];

C1_AEGIS = sum(X_AEGIS);
C1_AMDR = sum(X_AMDR);
C1_MCS = sum(X_MCS);
C1_MRG_GE = sum(X_MRG_GE);
C1_MRG_PGC = sum(X_MRG_PGC);

% C2 Calculations

C2_AEGIS = sum(sum(beta_AEGIS*A_AEGIS));
C2_AMDR = sum(sum(beta_AMDR*A_AEGIS));
C2_MCS = sum(sum(beta_MCS*A_MCS));
C2_MRG = sum(sum(beta_MRG*A_MRG));

% C3 Calculations

E_AEGIS = sum(svd(A_AEGIS));
gamma_AEGIS = 1/length(A_AEGIS);
```

```
C3_AEGIS = gamma_AEGIS*E_AEGIS;

E_MCS = sum(svd(A_MCS));
gamma_MCS = 1/length(A_MCS);
C3_MCS = gamma_MCS*E_MCS;

E_MRG = sum(svd(A_MRG));
gamma_MRG = 1/length(A_MRG);
C3_MRG = gamma_MRG*E_MRG;

% C = C1 + C2*C3 (Net Complexity Calculation)

C_AEGIS = C1_AEGIS + C2_AEGIS*C3_AEGIS;
C_AMDR_k = C1_AMDR + k*C2_AMDR*C3_AEGIS;
C_AMDR = C1_AMDR + C2_AMDR*C3_AEGIS;
C_MCS = C1_MCS + C2_MCS*C3_MCS;
C_MRG_GE = C1_MRG_GE + C2_MRG*C3_MRG;
C_MRG_PGC = C1_MRG_PGC + C2_MRG*C3_MRG;

% AMDR Calculations
C3_AMDR = zeros(101,1); C_AMDR1 = C3_AMDR; k1 = C3_AMDR;
for i = 1:101
    k1(i) = 0.99+i/100;
    eig_AMDR = eig(k1(i)*A_AEGIS);
    E_AMDR = sum(abs(eig_AMDR));
    C3_AMDR(i) = gamma_AEGIS*E_AMDR;
    C_AMDR1(i) = C1_AMDR + C2_AMDR*C3_AMDR(i);
    y1(i) = C_AMDR;
end

% Consolidated matrix with complexity sources in subsystems

C_AEGISx = [C1_AEGIS C2_AEGIS C3_AEGIS]; C(1,:) = C_AEGISx;
C_AMDRx = [C1_AMDR C2_AMDR C3_AMDR(2)*k]; C(2,:) = C_AMDRx;
C_MCSx = [C1_MCS C2_MCS C3_MCS]; C(3,:) = C_MCSx;
C_MRG_GEx = [C1_MRG_GE C2_MRG C3_MRG]; C(4,:) = C_MRG_GEx;
C_MRG_PGCx = [C1_MRG_PGC C2_MRG C3_MRG]; C(5,:) = C_MRG_PGCx;
```

Learning Curves

```
clear i j
SWslope = (90:95)/100;
cost0 = 61.1;
units = 1:71;

cost1 = zeros(6,71); costMCSx = zeros(1,6); costMCS = zeros(1,71);
for i = 1:length(SWslope)
    for j = 1:length(units)
        cost1(i,j) = cost0*j^log(SWslope(i))/log(2);
    end
    costMCSx(i) = trapz(cost1(i,:));

    if SWslope(i) == LC
        costMCS = cost1(i,:);
        cost(3) = trapz(costMCS);
    end
end
```

Cost Correlation - Power Law

```
% Aggregated Matrix

idx1 = 1:5; % 1-AEGIS, 2-AMDR, 3-MCS, 4-MRG_GE, 5-MRG_PGC
Cfinal = [C_AEGIS C_AMDR_k C_MCS C_MRG_GE C_MRG_PGC];
C(:,4) = Cfinal'; C(:,5) = idx1'; C(:,6) = cost; C(:,7) = Q;
[~,index] = sort(C(:,4),'ascend');
CF = C(index,:);
```

```
Cx = [CF(:,1) CF(:,2).*CF(:,3)];

CQ = CF(:,6)./CF(:,7); % Cost/Quantity (Sorted)
comp = CF(:,4); % Complexity (sorted)

figure
% Finds coefficient and exponent in power law
%[slope, intercept] = logfit(comp,CQ,'loglog');
[slope, intercept] = logfit(comp,CQ,'loglog');

psi = slope;
phi = 10^intercept;

x = 0:1:max(comp)+200;
y = phi*x.^psi;

yPSI = zeros(length(x),length(x));
psi_i = 1.3:0.1:1.7;
for i = 1:length(psi_i)
    for j = 1:length(x)
        yPSI(i,j) = phi*j.^psi_i(i);
    end
end

% Correlation of curve fit
ycorr = phi*CQ(1:5).^psi;
R = corrcoef(comp(1:5),ycorr);
```

Cost Deltas - Power Law & Exponential

```
clear i j
delta = zeros(1,5); xtemp = zeros(5,100); ytemp = xtemp; delta2 = delta;
for i = 1:size(CF,1)
    delta(i) = CQ(i) - phi*comp(i)^psi;
    XT(i,:) = comp(i)*ones(1,100);
    YT(i,:) = linspace(CQ(i),phi*comp(i)^psi);
end
```

Cost Correlation - Exponential Fit

```
F = fit(comp,CQ,'exp1');
coeff = coeffvalues(F);
yEx = coeff(1)*exp(coeff(2)*x);
R2 = 0.9846;
[~,~,residuals] = regress(CQ,[ones(length(comp),1),comp],0.05);

clear i
for i = 1:size(CF,1)
    delta2(i) = CQ(i) - coeff(1)*exp(comp(i)*coeff(2));
    YT2(i,:) = linspace(CQ(i),coeff(1)*exp(comp(i)*coeff(2)));
end
```

Algorithm Output/Display

```
disp('C_final for AEGIS:')
disp(C_AEGIS)
disp('  ')
disp('C_final for AMDR, no K-factor:')
disp(C_AMDR)
disp('  ')
disp('C_final for AMDR, with K-factor = 1.33:')
disp(C_AMDR_k)
disp('C_final for MCS:')
disp(C_MCS)
disp('C_final for old GE MRG:')
disp(C_MRG_GE)
disp('  ')
```

```
disp('C_final for new PGC MRG:')
disp(C_MRG_PGC)

figure
hold on
bar(Cx,0.5,'stack');
set(gca, 'XTick',1:5, 'XTickLabel',...
    {'MRG (GE)' 'MRG (PGC)' 'MCS'  'AEGIS' 'AMDR*K-factor'})
grid on
H = legend('C_1, f(\Sigma[X_i])',...
    'C_2*C_3, f(Interface Comp.,\beta | Energy(A))');
set(H,'Location','NorthWest','FontName','Times','FontSize',14)
set(gca,'FontName','Times','FontSize',16)
set(gcf,'color','w')
ylabel('Complexity Value','FontName','Times','FontSize',16)
title('Complexity Components','FontName','Times','FontSize',18)
hold off


% 1-AEGIS, 2-AMDR, 3-MCS, 4-MRG_GE, 5-MRG_PGC

figure
% Power Law Plot
subplot(2,1,1)
semilogx(comp(1),CQ(1),'rd',comp(2),CQ(2),'bd',comp(3),CQ(3),'gd',...
    comp(4),CQ(4),'md',comp(5),CQ(5),'kd','LineWidth',3,'MarkerSize',8)
hold on
semilogx(x,y,'k-','LineWidth',2)
semilogx(XT(1,:),YT(1,:),'r-',XT(2,:),YT(2,:),'r-',XT(3,:),YT(3,:),'r-',...
    XT(4,:),YT(4,:),'r-',XT(5,:),YT(5,:),'r-')
H = legend(sprintf('MCS, \\Delta = %0.2f $M',delta(1)),...
    sprintf('MRG_{GE}, \\Delta = %0.2f $M',delta(2)),...
    sprintf('MRG_{PGC}, \\Delta = %0.2f $M',delta(3)),...
    sprintf('AEGIS, \\Delta = %0.2f $M',delta(4)),...
    sprintf('AMDR, \\Delta = %0.2f $M',delta(5)));
set(H,'Location','NorthWest','FontName','Times','FontSize',14)
STR1 = sprintf('Power Law Fit: $M = \\phi C^{\\psi} = %0.3f C^{%0.3f}',...
    phi,psi);
text(50,200,STR1,'FontName','Times','FontSize',16,'color','m',...
    'BackgroundColor','w','EdgeColor','k')
set(gca,'FontName','Times','FontSize',16)
set(gcf,'color','w')
xlabel('log(Complexity)','FontName','Times','FontSize',16);
ylabel('Cost, $M','FontName','Times','FontSize',16);
axis([10 max(comp)+200 0 max(CQ)+25])
str = sprintf('Cost Variance: Cost/Unit vs. Complexity,\\phi x^{\\psi},
\\Delta_{avg.}= %0.3f $M; Corr. = %0.3f',mean(delta),R(1,2));
title(str,'FontName','Times','FontSize',18)
grid on
hold off

% Exponential Plot

subplot(2,1,2)
semilogx(comp(1),CQ(1),'ro',comp(2),CQ(2),'bo',comp(3),CQ(3),'go',...
    comp(4),CQ(4),'mo',comp(5),CQ(5),'ko',...
    'LineWidth',3,'MarkerSize',8)
hold on
semilogx(x,yEx,'k-','LineWidth',2)
semilogx(XT(1,:),YT2(1,:),'r-',XT(2,:),YT2(2,:),'r-',XT(3,:),...
    YT2(3,:),'r-',XT(4,:),YT2(4,:),'r-',XT(5,:),YT2(5,:),'r-')
semilogx(residuals)
H = legend(sprintf('MCS, \\Delta = %0.2f $M',delta2(1)),...
    sprintf('MRG_{GE}, \\Delta = %0.2f $M',delta2(2)),...
    sprintf('MRG_{PGC}, \\Delta = %0.2f $M',delta2(3)),...
```

```
    sprintf('AEGIS, \\Delta = %0.2f $M',delta2(4)),...
    sprintf('AMDR, \\Delta = %0.2f $M',delta2(5)));
set(H,'Location','NorthWest','FontName','Times','FontSize',14)
set(gca,'FontName','Times','FontSize',16)
set(gcf,'color','w')
STR2 = sprintf('Exponential Fit: $M = %0.3f e^{%0.3f C}',...
    coeff(1),coeff(2));
text(50,200,STR2,'FontName','Times','FontSize',16,'color','m',...
    'BackgroundColor','w','EdgeColor','k')
xlabel('log(Complexity)','FontName','Times','FontSize',16);
ylabel('Cost, $M','FontName','Times','FontSize',16);
axis([10 max(comp)+200 0 max(CQ)+25])
str = sprintf('Cost Variance: Cost/Unit vs. Complexity,
\\phi_{exp}e^{C\\psi_{exp}}; \\Delta_{avg.} = %0.3f $M; R^2 =
%0.3f',mean(delta2),R2);
title(str,'FontName','Times','FontSize',18)
grid on
hold off

figure
hold on
plot(1,cost1(1,1),'ro','MarkerSize',8)
plot(units,cost1)
xlim([0.2 71])
title('Projected Machinery Control System Learning, DDG 51 to 122',...
    'FontName','Times','FontSize',18)
grid on
H = legend('MCS Data: $61.1M','90%','91%','92%','93%','94%','95%');
set(gca,'FontName','Times','FontSize',16)
set(gcf,'color','w')
xlabel('Unit Number (Hull 1 to 71)','FontName','Times','FontSize',16)
ylabel('MCS Cost, $M (FY13)','FontName','Times','FontSize',16)
C_final for AEGIS:
       157.91


C_final for AMDR, no K-factor:
       156.81


C_final for AMDR, with K-factor = 1.33:
       208.99

C_final for MCS:
       53.762

C_final for old GE MRG:
       56.445


C_final for new PGC MRG:
       67.245
```

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Appendix C: U.S. Shipyards

Any discussion of current U.S. naval shipbuilding capabilities must first be predicated on the understanding of the dichotomy that exists between a monopsony (one buyer) and an oligopoly (multiple sellers). In the case of U.S. naval shipbuilding, the U.S. government is the monopsonistic buyer/acquirer, and the two seller conglomerates in the oligopoly are General Dynamics (GD) and Huntington Ingalls Industries (HII). The U.S. Navy's role as an acquiring agent, and both corporations' holdings, portfolio, and subsidiaries will be examined in further detail later.

Functionally, shipyards in the United States performing work related to U.S. Naval vessels can roughly be divided into three categories: those performing only new construction, those performing only repair, modernization, and overhaul (RMO), and those that do both.

A key item affecting cost escalation is that U.S. shipyards must produce with an unstable business base. For example, a shipyard that received a large contract to construct a new class of say, 24 ships could realistically see that contract cut in half (if not more) due to budget constraints and changes in defense needs. While this paradigm allows policy makers greater flexibility in terms of planning and restructuring the force to fit needs, shipyards are hesitant to invest in large scale capital infrastructure improvements if their budget for making a return on that investment is unsure. This lack of reinvestment infrastructure forces work to occur on dated or low-capacity/inefficient equipment.

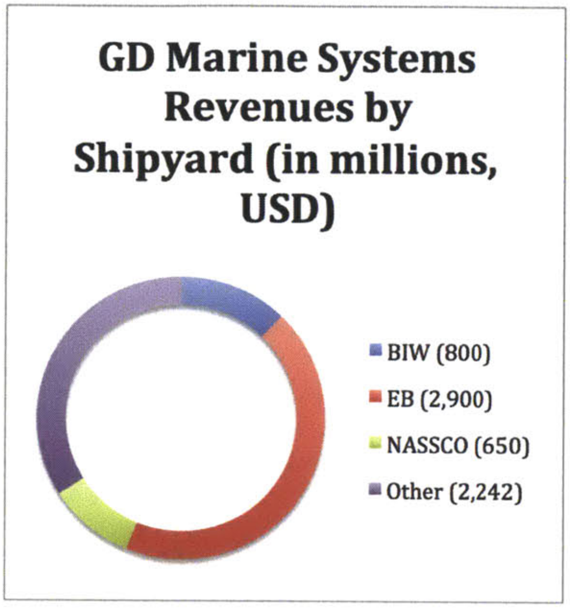
C.1 U.S. New Construction Shipbuilders and Shipyards

GD and HII are the two dominant tier one shipbuilders for U.S. Naval vessels. These two contractor conglomerates and their respective subsidiaries build all surface combatants, support craft, and submarines. The relationship between the contractors and their subsidiaries is shown in Figure 20.

Figure 20: Tier One U.S. Shipbuilders and Their Subsidiaries

GD is a U.S.-based, multinational, Fortune 500 corporation with four main business segments: Aerospace, Combat Systems, Information Technology, and Marine Systems. Of GD's four overarching business sectors, the marine systems segment is the smallest in terms of revenue as shown in Figure 21 (General Dynamics 2012). The GD Marine Systems portfolio consists of:

- Nuclear-powered Submarines (Virginia class and Ohio-class replacement)
- Surface Combatants (DDG51 and DDG1000)
- Auxiliary and Combat Logistics Ships (MLP and T-AKE)
- Commercial Ships (Jones Act ships)
- Design and Engineering Support
- Overhaul, Repair, and Lifecycle Support Services



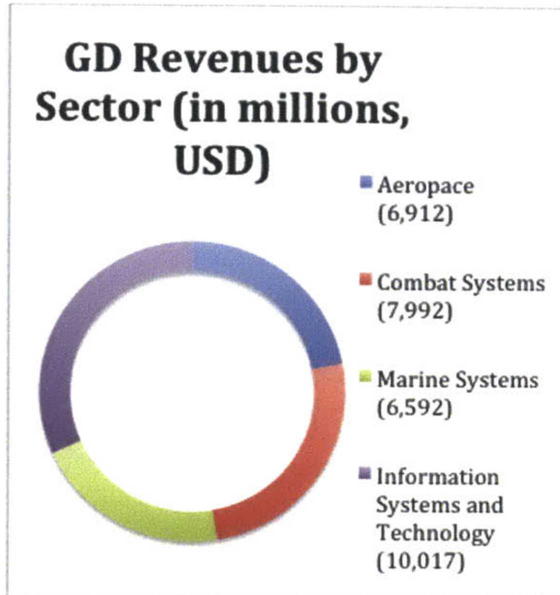


Figure 21: GD Revenues by Shipyard and Sector (Inside View 2013)

Figure 21 reveals that the sum total of GD's subsidiaries engaged in U.S. Naval shipbuilding only accounts for 13.8% of GD's annual revenues.

GD NASSCO (San Diego) is the only US Naval shipbuilder engaged in both naval new construction *and* commercial new construction. Although other yards in Norfolk, Mayport, and Gray fall under the GD NASSCO umbrella, those yards are engaged exclusively in repair work. The relatively small 89-acre San Diego yard is the only one that maintains all three activities (naval new construction, commercial new construction, and repair) in roughly equal parts in terms of long-term average revenue (GD NASSCO 2013).

Huntington Ingalls Industries (HII) was divested from Northrop Grumman (NG) on March 31st, 2011, and the two major shipyards in NG's holdings were subjoined under the new HII umbrella. HII was previously known as Northrop Grumman Shipbuilding (NGSB) (Dickseski 2011). The two shipyards involved were:

- Ingalls Shipbuilding – *Pascagoula, Mississippi*
- Newport News Shipbuilding – *Newport News, Virginia*

Avondale shipyard was also part of NGSB's holdings until July 13, 2010 NGSB announced they would be consolidating Navy shipbuilding to their Pascagoula shipyard. At the time of writing in 2013, Navy shipbuilding is winding down in Avondale, and HII's intent is to migrate Avondale's operations to oil and gas equipment construction (Shapiro 2013). Although Navy shipbuilding is still occurring at Avondale at the time of writing, all analysis going forward will focus on Ingalls Shipbuilding and Newport News Shipbuilding.

Despite only engaging at shipbuilding at two shipyards, HII has captured just over 60% over the U.S. naval shipbuilding market share as shown in Figure 22.

As Dominic Alvarran pointed out in his research of contracts for SOW part 1 of the Production in the Innovation Economy (PIE) study, the consequences of having only two relatively equal market share competitors (previously mentioned oligopoly) with one buyer (monopsony) has far reaching consequences characterized by the fact that free market competition is no longer "the main driver of performance." (Alvarran 2013)

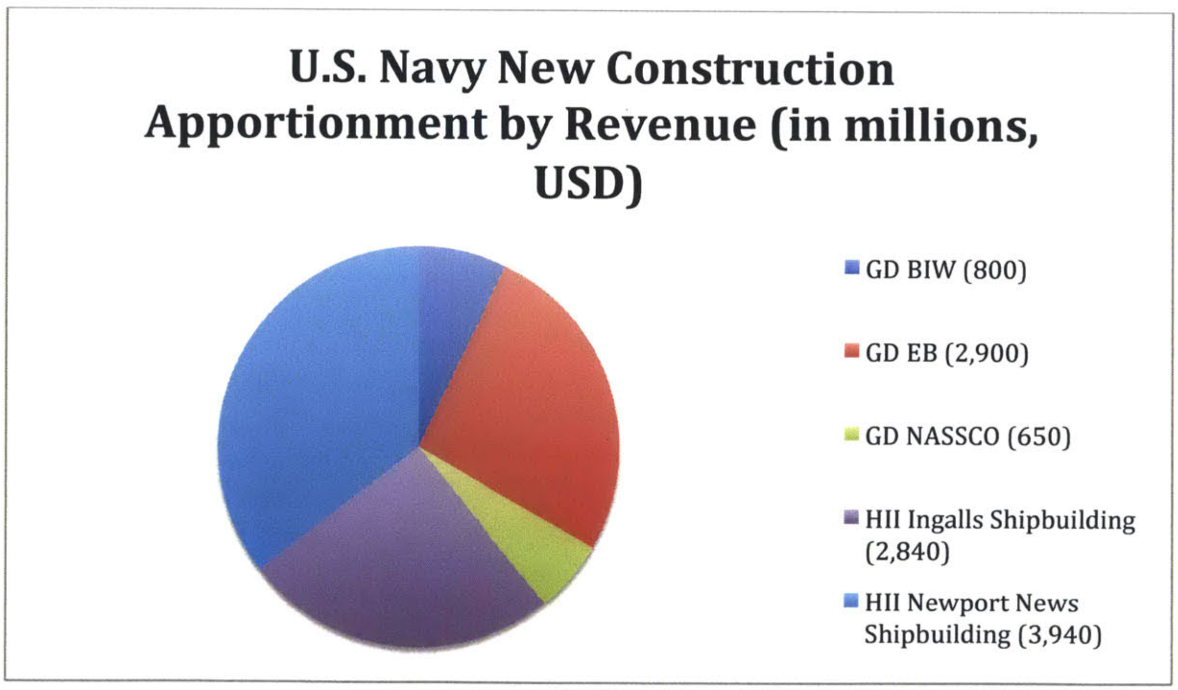


Figure 22: U.S. Navy New Construction Apportionment by Revenue

C.2 U.S. Repair, Modernization, and Overhaul (RMO) Shipyards

While any of the five major new construction yards can perform RMO, the bulk of the U.S. Navy's RMO operations occur at any of the four major public shipyards. As the name implies, public shipyards are publicly owned, Navy-administered shipyards. In America, there are currently four public shipyards:

- Norfolk Naval Shipyard (NNSY) – *Norfolk, Virginia*
- Pearl Harbor Naval Shipyard (PHNSY) – *Pearl Harbor, Hawaii*
- Puget Sound Naval Shipyard (PSNSY) – *Bremerton, Washington*
- Portsmouth Naval Shipyard (PNSY) – *Portsmouth, New Hampshire*

U.S. Navy ship maintenance is divided into three tiers, based on the size and capability of the organization performing maintenance. These large public shipyards conduct Depot or D-level maintenance, which is the largest and most capable of all three maintenance tiers. The other two tiers are Intermediate or I-level maintenance and Organizational or O-level maintenance. For the purposes of this study, only these four D-level maintenance shipyards will be under analysis due to the larger budgets and small number of shipyards. (Defense Acquisition University 2013)

To summarize, Table 14 shows the alignment of tier one, tier two, and public shipyards aligned by the classes of USN ships they either build or conduct RMO for.

Shipyard	Surface Combatants	Aircraft Carriers	Amphibious Assault Vessels	Surface Support Vessels	Ballistic Missile Submarines	Attack Submarines	Civil Ships and/or Platforms	
Norfolk Naval Shipyard *(Norfolk, Virginia)*	•	•	•	•	•	•		Naval Shipyards *(Depot Level Maintenance Yards)*
Pearl Harbor Naval Shipyard *(Pearl Harbor, Hawaii)*	•		•	•		•		
Portsmouth Naval Shipyard[1] *(Portsmouth, New Hampshire)*						•		
Puget Sound Naval Shipyard *(Bremerton, Washington)*	•	•	•	•	•	•		
GD Bath Iron Works[2] *(Bath, Maine)*	⊙							"Big Six" Tier One Shipyards
GD Electric Boat *(Groton, Connecticut)*					⊙	⊙		
HII/Newport News Shipbuilding *(Newport News, Virginia)*		⊙				⊙		
Ingalls Shipbuilding[3] *(Pascagoula, Mississippi)*	⊙		⊙	⊙				
NG Avondale[4] *(Westwego, Louisiana)*			~~⊙~~	~~⊙~~			⊙	
GD NASSCO *(Norfolk, Virginia and San Diego, California)*	•		•	⊙			⊙	
Marinette Marine[5] *(Marinette, Wisconsin)*	o						⊙	Tier Two Shipyards
Austal USA[6] *(Mobile, Alabama)*	⊙			⊙			⊙	

⊙ New Construction and Repair, Modernization, Overhaul
• Repair, Modernization, and Overhaul Only
o New Construction Only

[1] Only Los Angeles and Virginia Class submarines
[2] DDG1000 and DDG51 Only
[3] DDG51, LPD Flt. I and II, LHA, and Coast Guard National Security Cutters
[4] Avondale is set to close in 2013. NG consolidation to Pascagoula, MS.
[5] Naval new construction is limited to Lockheed Martin's odd-numbered LCS variant (LCS1, LCS3, LCS5...)
[6] Austal's new construction limited to JHSV and even-numbered LCS variants (LCS2, LCS4, LCS6...)

Table 14: Tier One, Tier Two, and Public Shipyards vs. Ship Classes and Respective Functional Alignment

Appendix D: R.O.K. Shipyards and the KDX-class

D.1 Republic of Korea (R.O.K.)'s Shipyards

In the post-World War II reconstruction era, Japan regained and expanded their pre-war shipbuilding capabilities, and by the 1970s Korea and China had also entered the market edging out the traditional European and U.S. shipbuilders as shown in Figure 23. In 2012, the US built only 0.1% of all the world's ships above 100 CGT (Harris 2013).

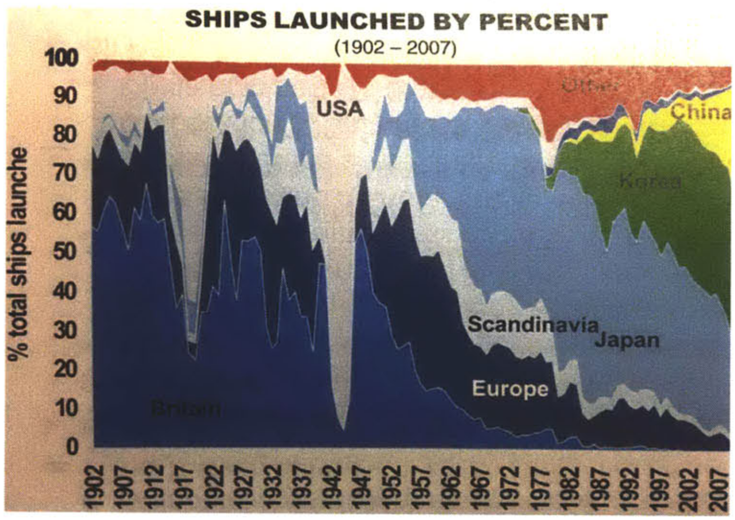


Figure 23: Worldwide Shipbuilding Market Share (Harris 2013)

In the 1970s the Korean government established the shipbuilding industry as a strategic national priority. During this time the government set up an initial shipbuilding cluster around Busan with the associated equipment supplier companies in a conglomerate known as *chaebol*, which initially had significant government ownership. Even to this day, the Korean government is still the majority stakeholder in the Daewoo Shipbuilding (DSME) who subsequently owns 40% of Doosan engine manufacturing. The number one shipyard in the world Hyundai Heavy Industries (HHI), STX shipbuilding, and Samsung shipbuilding all have some degree of government ownership. ROK, Japan, and especially China all receive subsidies from their government. (Harris 2013)

It is a popular misconception that Asian shipbuilding dominates the world market due to cheap labor rates. While many Asian shipyards do have very cheap labor rates, the *throughput* of the yards and the ensuing benefits from that throughput make the difference that has edged out European and US shipbuilding.

In terms of gross tonnage produced, South Korea dominates the world shipbuilding market. According to 2012 data compiled by Marine Insight based on data from the Clarkson World Register, the top four shipbuilders in the world are all based in the ROK (Marine Insight 2012):

1. Hyundai Heavy Industries – Ulsan, South Korea (93,893,700 GT)
2. Daewoo Shipbuilding – Okpo, South Korea (68,284,087 GT)
3. Samsung Heavy Industry – Geoje, South Korea (58,082,349 GT)
4. Hyundai Samho – Samho, South Korea (28,414,515 GT)

For comparison, US shipyards produced approximately 526,000 GT *total* in 2009 (Global Security 2010).

D.2 R.O.K.'s KDX Program

The KDX (Korean Destroyer eXperimental) program was launched in 1998 to defend the coastal waters around the Republic of Korea (ROK) and to transition the ROK Navy (ROKN) to becoming a blue water capable force. As shown in Figure 24, Flight III of the KDX class resembles the U.S.'s DDG 51 Flight IIA class in many aspects in that the KDX-III is designed to be a "multi-purpose destroyer with full air defense, land attack, anti-shipping, and anti-submarine capabilities. It is also being designed with the ability to add tactical ballistic missile defense, [an] important consideration if North Korea is your neighbor." (Defense Industry Daily 2013)

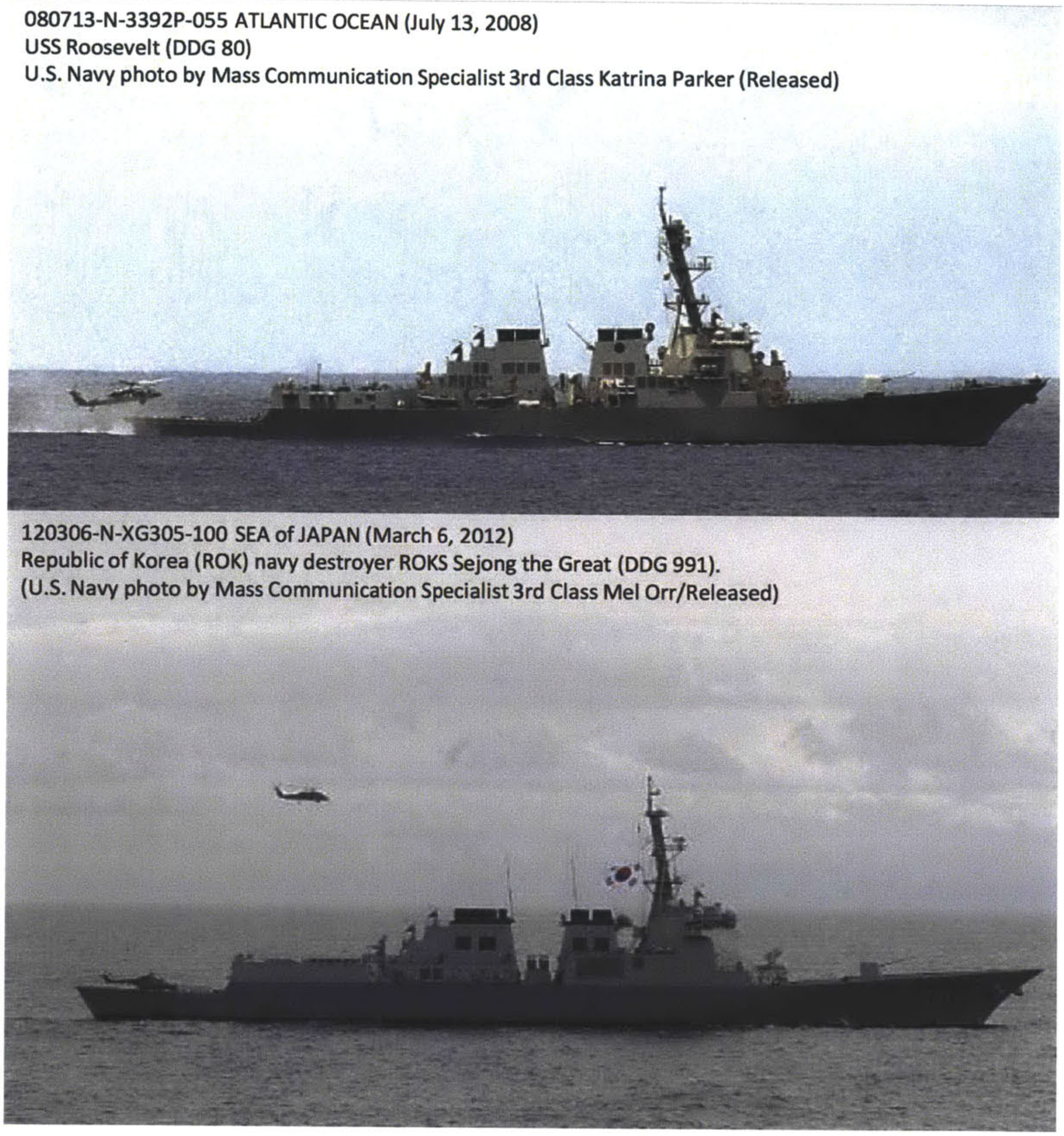


Figure 24: Sejong the Great (DDH 991), lead ship of the KDX-III flight and DDG 80, a DDG 51 class Flight IIA vessel (Parker 2008) (Orr 2012)

As shown in Table 15 construction of the KDX program began exclusively with Daewoo Heavy Industries.

Table 15: KDX Program Summary (Naval Technology 2013)

Flight	Class Name	Ships in Class	Builder(s)	Launch Dates
KDX-I	*Gwanggaeto the Great*	3	DHI	July 1998 to June 2000
KDX-II	*Chungmugong Yi Sun-Shin*	6	DHI and HHI	November 2003 to September 2008
KDX-III	*Sejong the Great*	3	DHI and HHI	December 2008 to August 2012

Appendix E: Benchmarking in Naval Shipbuilding

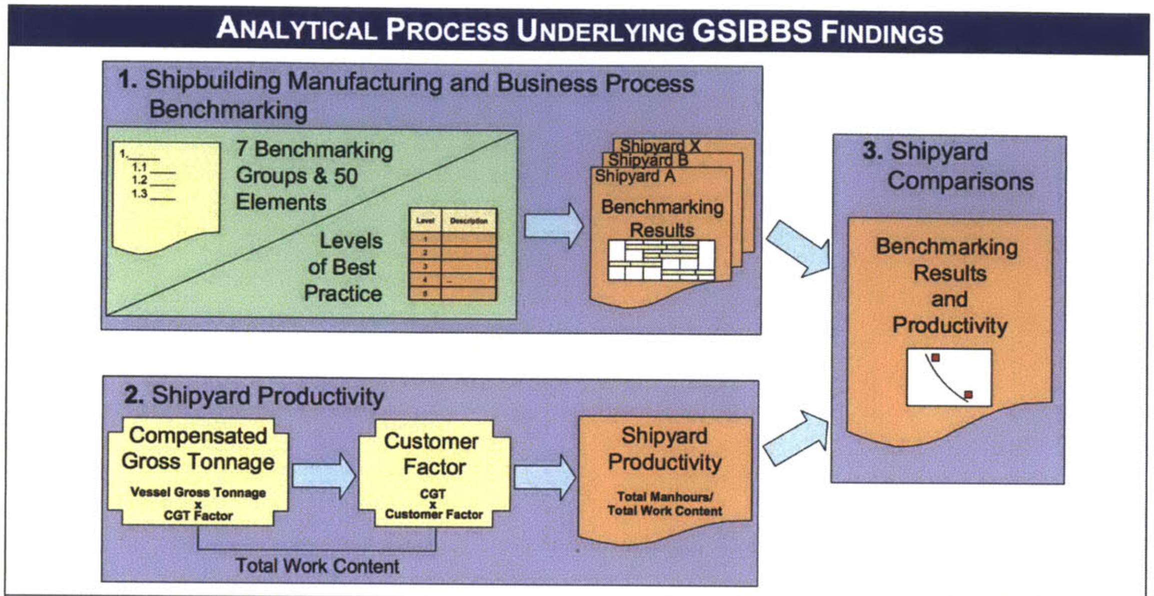
In May 2005 the Department of Defense (DoD) published a report entitled Global Shipbuilding Industrial Base Benchmarking Study (GSIBBS) based on (FMI's) benchmarking techniques and assessments. Although multiple and proprietary editions of this report exist, all information contained in this report is based on the publicly releasable version that can be found at the link contained in the source bibliography. (FMI and USD(AT&L) 2005).

FMI is a small firm based out of London, U.K., and they are considered among the best in the world for benchmarking shipyards. The 2005 GSIBBS report produced in part by FMI is one of the most substantial works to date to address the four concerns listed below that make up the primary objectives of the report.

The GSIBBS report had four primary objectives:

1. Survey current manufacturing and business practices of selected global shipyards, leveraging benchmarking work completed in previous studies.
2. Assess U.S. private shipyards using a standardized benchmarking system. Provide specific site and comparative analysis of each major U.S. shipyard.
3. Compare the U.S. shipbuilding industry against leading international shipyards and identify key opportunities for improvement.
4. Identify DoD, Navy, and industry actions, policies, and contract incentives to implement remedies in the U.S. shipbuilding base.

FMI's benchmarking system "was established in 1975 and has been refined through more than 150 world-wide benchmarking surveys since. This benchmarking system is a widely recognized method of assessing shipyard manufacturing and business practices. The process also includes a normalized measure of shipyard productivity, accounting for disparate ship complexity and varying customer profiles, to further evaluate the effective implementation of manufacturing and business best practices." (FMI and USD(AT&L) 2005). Figure 25 shows the underlying methods used to analyze and compare shipyards.



Source: First Marine International and ODUSD(IP)

Figure 25: Analytical Process Underlying GSIBBS Findings

Step 1:

For each shipyard assessed, FMI and the DoD team evaluated 50 distinct elements within the seven benchmarking groups shown below (FMI and USD(AT&L) 2005).

1. Steelwork Production

1.1. Plate Stockyard and Treatment
1.2. Stiffener Stockyard
1.3. Plate Cutting
1.4. Stiffener Cutting
1.5. Plate and Stiffener Forming
1.6. Minor Assembly
1.7. Sub-assembly
1.8. Flat Unit Assembly
1.9. Curved and 3D Unit Assembly
1.10. Superstructure Unit Assembly
1.11. Outfit Steel

2. Outfit Manufacturing and Storage

2.1. Pipe Shop
2.2. Machine Shop
2.3. Sheet Metal Working
2.4. Electrical
2.5. General Storage and Warehousing
2.6. Storage of Large Heavy Items

3. Pre-erection Activities

3.1. Module Building

3.2. Outfit Parts Marshalling
3.3. Pre-erection Outfitting
3.4. Block Assembly
3.5. Unit and Block Storage
3.6. Materials Handling

4. Ship Construction and Outfitting
4.1. Ship Construction
4.2. Erection and Fairing
4.3. Welding
4.4. Onboard Services
4.5. Staging and Access
4.6. Outfit Installation
4.7. Painting

5. Yard Layout and Environment
5.1. Layout and Material Flow
5.2. General Environment

6. Design, Engineering, and Production Engineering
6.1. Ship Design
6.2. Steelwork Production Information
6.3. Outfit Production Information
6.4. Steelwork Coding System
6.5. Parts Listing Procedure
6.6. Production Engineering
6.7. Design for Production
6.8. Dimensional Accuracy and Quality Control
6.9. Lofting Methods

7. Organization and Operating Systems
7.1. Manpower and Organization of Work
7.2. Master Planning
7.3. Steelwork Scheduling
7.4. Outfit Scheduling
7.5. Production Control
7.6. Stores Control
7.7. Performance and Efficiency Calculations
7.8. Quality Assurance
7.9. Production Management Information Systems

Those elements were given scores from levels 1 to 5 corresponding to the following descriptions (FMI and USD(AT&L) 2005).

Levels of Technology

1 - Reflects shipyard practice of the early 1960s.

2 - Technology employed in the modernized or new shipyards of the late 1960s and early

1970s.

3 - Good shipbuilding practice of the late 1970s. Represented by the new or fully re-developed shipyards of that time in the US, Europe, South Korea, and Japan.

4 - Typical of shipyards that have improved their technology during the 1980s and 1990s, but not up to leading standards.

5 - State-of-the-art technology.

Although the publically distributable version does not include shipyard specific information, results from shipyard specific assessment would follow the notional example in Figure 26.

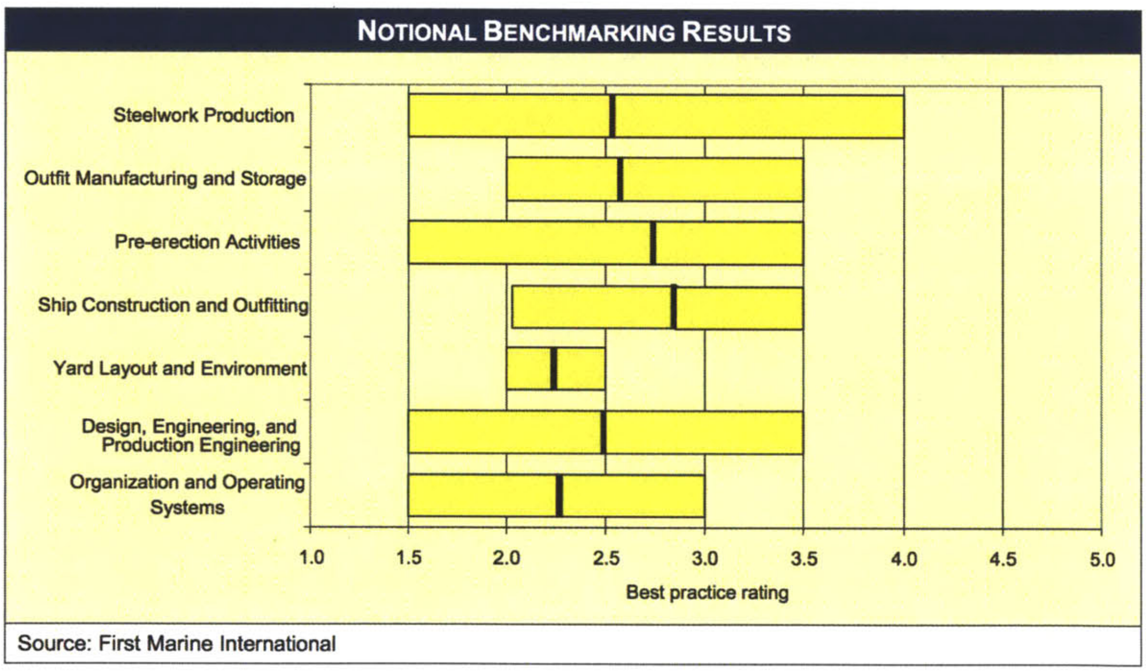


Figure 26: Notional Benchmarking Results

Step 2:

To establish shipyard productivity metrics, some compensation must be made for the level of complexity of the vessels that the shipyard under assessment is producing. The accepted standard for normalizing this complexity is the application of a *Compensated*

Gross Tonnage (CGT) Factor where higher complexity vessels are assigned correspondingly higher CGT Factors.

CGT Factors are determined by "characteristics such as: vessel specifications (combat systems, survivability, shock, etc.), design standards, outfit density, average compartment size, and the complexity of structural arrangements." (FMI and USD(AT&L) 2005)

CGT = Vessel Gross Tonnage x CGT Factor

Figure 27 shows the comparison between a large, relatively less complex bulk carrier and a smaller, denser, higher complexity frigate. The concept of CGT demonstrates that the work content does not necessarily scale with the size or volume of a ship.

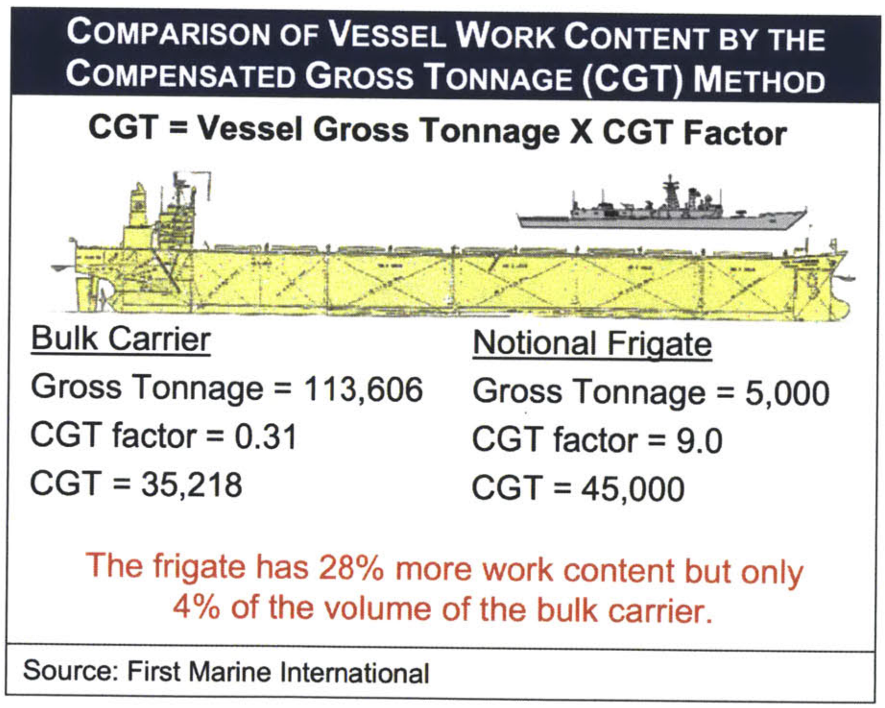


Figure 27: Comparison of Vessel Work Content by the CGT Method

FMI includes a customer factor as an indicator of the amount of influence the customer has on the shipbuilding process as compared to a "normal commercial contract". Further discussion in Section 6 will highlight the reasons *why* this customer factor exists and practical solutions to drive the highly influential customer factor down.

Customer Factors for Various Shipbuilding Customers (FMI and USD(AT&L) 2005)

1.00 Normal Commercial Contract

1.06 Naval auxiliaries for [U.K.'s] Ministry of Defense (MoD) and typical export combatants

1.12 Combatants built for MoD and demanding export customer

Total Work Content = CGT X Customer Factor

By taking into account CGT, the customer factor, and the total work content, productivity at different shipyards can be compared.

Shipyard Productivity = Total Shipyard Man-hours Expended / Total Work Content

As Figure X shows, even in 2005 US significantly lagged the productivity data from the major Asian shipbuilders in the 1990s, and although the report states that the US improved from 3.1 in 2000 to 3.6 in 2005, a significant gap remains between the aggregated international average and the US average.

Step 3:

Results can be aggregated by country to view trends. Figure 28 shows the proper right-and-down progress. Later, it can be seen that the U.S. progressed in a similar manner while still losing market share to their Asian counterparts.

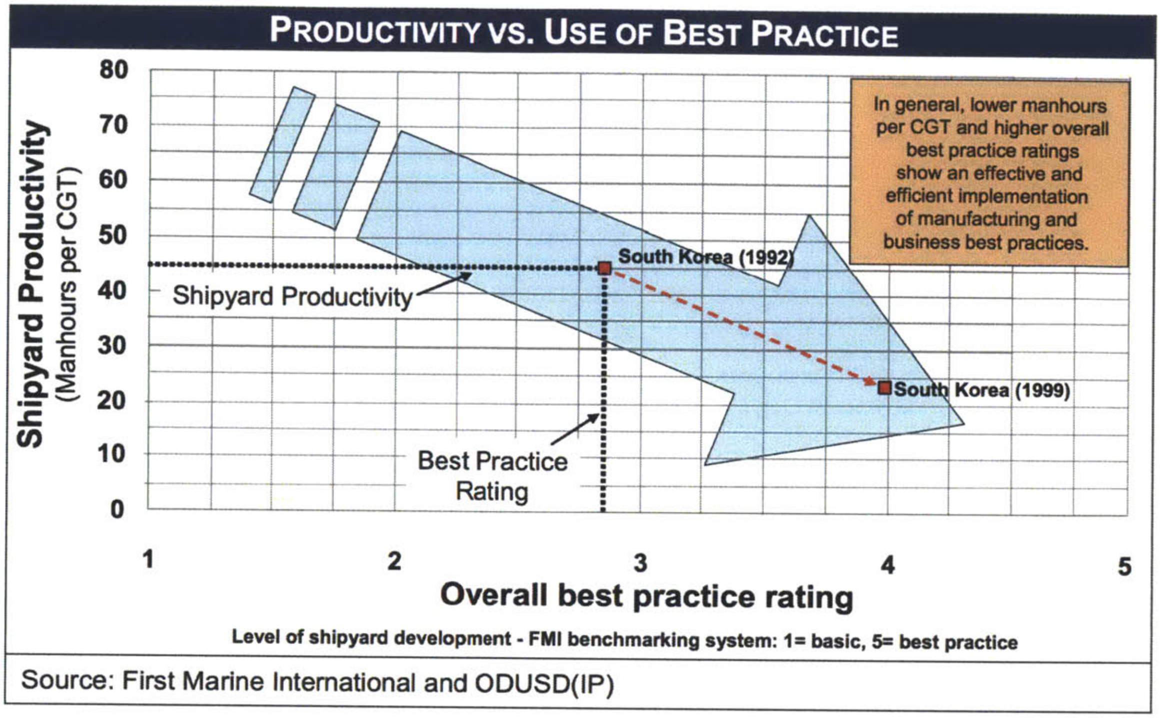


Figure 28: Trends in Productivity vs. Use of Best Practice (South Korea)

The red line denoting naval new construction lags the black line denoting commercial shipbuilding chiefly due to the higher complexity of naval shipbuilding and the increased density of naval ships.

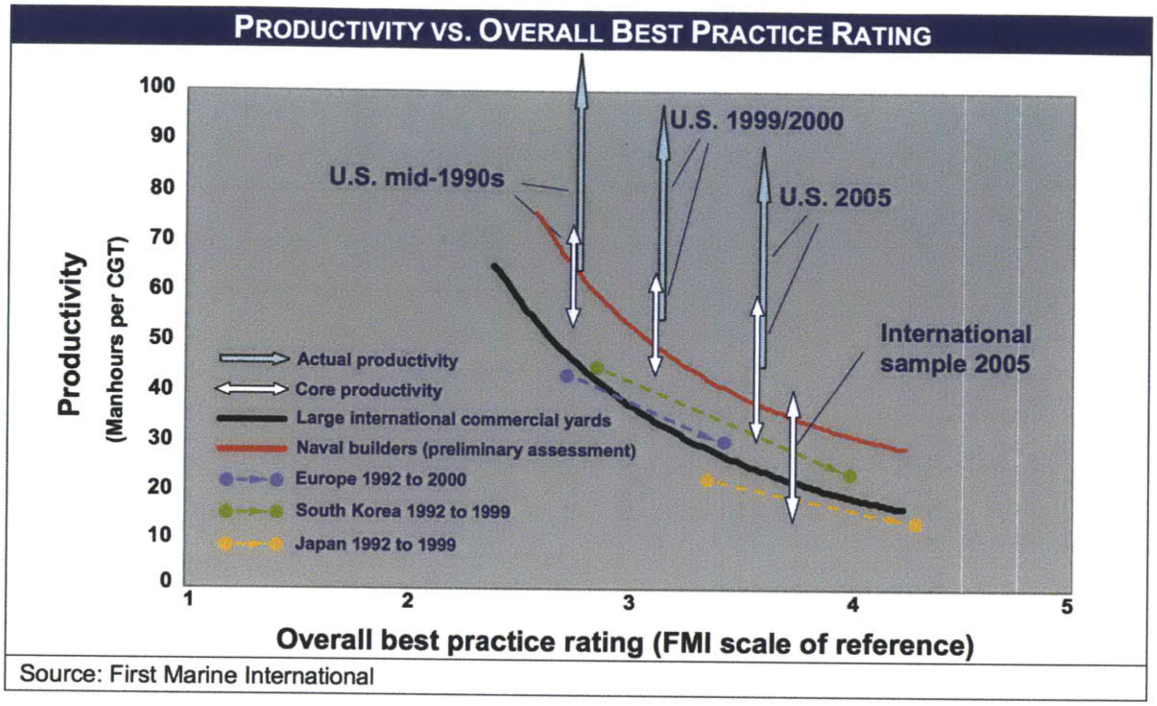


Figure 29: Productivity vs. Overall Best Practice Rating

Individually, the U.S. progressed in all areas as shown in Figure 29. The largest gains were made in Steelwork Production (2.8 to 3.3) and Ship Construction and Outfitting (2.7 to 3.2), and it should be noted that on the 2000 studies both of these areas were considered below average (FMI and USD(AT&L) 2005). GD's NASSCO shipbuilding in San Diego, California invested in a new automated stiffener cutting line and a new panel line in 2003, and investments like these are examples of how the benchmarking categories improved to the extent they did between the years 2000 and 2005.

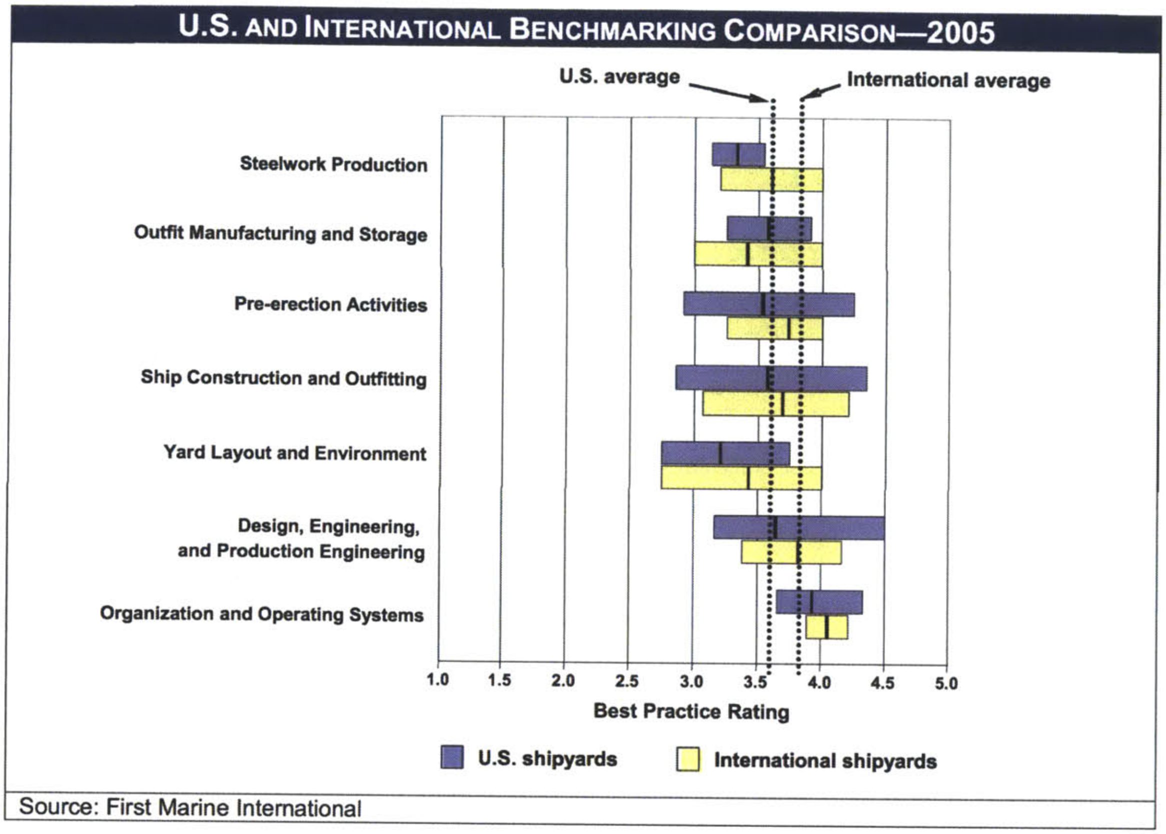


Figure 30: US and International Benchmarking (FMI and USD(AT&L) 2005)

The GSIBBS report concludes with an assessment of the "significant factors undermining US shipyard core productivity". Many of themes discussed in these conclusions from 2005 are still a pervasive negative factor in 2013 as evidenced by interviews with shipbuilding leaders in industry. The conclusions are given in Figure 31.

SIGNIFICANT FACTORS UNDERMINING U.S. SHIPYARD CORE PRODUCTIVITY	
Factor	**Cause**
First-of-class performance drop-off	Start of a new class of vessel often causes a decline in productivity due to: immature and complex designs, ineffective planning, decreased worker efficiency, and lack of production optimization.
Excessive change orders	Immature and complex designs cause numerous and costly change orders to be made during the production process.
Interference between concurrent series	Concurrent ship series often compete for the same constrained resources. When this happens, productivity in both ship series drop.
Introduction of new facilities or processes	When new processes or facilities are employed, productivity declines during the transition process due to employee training, learning, and startup problems.
Workforce variation	Vessel procurement fluctuations necessitate commensurate changes in employment. Ramp-ups/drawdowns contribute to worker inefficiency.
Source: First Marine International	

Figure 31: Significant Factors Undermining U.S. Shipyard Core Productivity

The application of a numerical structural complexity method differs from the concept of CGT described in Appendix D because this method will be applied to systems with the greatest perceived complexity, uncertainty, and technological risk whereas CGT applies to vessels in a more holistic manner. CGT numerically describes a vessel such as a surface combatant as being more technologically complex than an oil tanker principally due to the ratio of outfit weight to lightship weight; structural complexity will describe a certain *subsystem* such as the AEGIS radar or hydraulics as being more structurally complex than another subsystem such as the hull.

Appendix F: Navy Official Security Approval for Release and Unlimited Distribution

Subject: #239-14 Cost Prediction via Quantitative Analysis of Complexity in U.S. Navy Shipbuilding

Date: Wed, 14 May 2014 13:51:45 -0400

The subject material proposed for public release has been reviewed and is returned with the following response.

Statement A: Approved for Release. Distribution is unlimited.

This email serves as the official approval document. The printed materials will be archived and maintained per Navy policy standards.

Deputy Director
NAVSEA Office of Corporate Communications