Resilient Acquisition: Unlocking High-Velocity Learning with Model-Based Engineering to Deliver Capability to the Fleet Faster

by

Travis J. Rapp

B.S.E., Civil and Environmental Engineering, Duke University, 2011

Submitted to the Department of Mechanical Engineering and Sloan School of Management in Partial Fulfillment of the Requirements for the Degrees of

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June 2019

Signature redacted

Signature of Author ....
Department of Mechanical Engineering
MIT Sloan School of Management
May 2, 2019

Signature redacted

Certified by ....
Steven Spear
Senior Lecturer, MIT Sloan School of Management
Thesis Supervisor

Signature redacted

Certified by ....
Daniel Frey
Professor of Mechanical Engineering
Thesis Supervisor

Signature redacted

Accepted by..
Joan S. Rubin
Executive Director
MIT System Design and Management

Signature redacted

Accepted by..
Nicolas Hadjiconstantinou
Professor of Mechanical Engineering
Chair, Mechanical Engineering Committee on Graduate Studies

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Abstract

As the nation's security needs call for a growing naval fleet, the public-private industrial base for construction and weapon system acquisition will be stressed to perform at a high level of operational excellence. While reaching the required fleet size is a major challenge, ships are the delivery vehicles for complex weapons systems whose design and production is equally critical to deliver capability that the Fleet needs. Underperformance in defense acquisitions is found to be caused by complexity, uncertainty, and risk manifested through poor requirements that are unadaptable to the changing reality of the global security landscape.

This thesis hypothesizes that use of model-based engineering (MBE) will enable the needed efficiency and responsiveness. MBE consists of digital tools motivated by the principles of traceability and high-velocity design iteration that collectively connect requirements to technical specifications in a model-centric format in contrast to the document-based form prevalent today. Given the problem of disengagement between the request for proposal and the finished product, prior case examples of using MBE elsewhere in the defense and industrial establishment show a bridge for the divide between capability requirements and technical realization.

An original process-based shipbuilding production model further demonstrates how understanding effects of component changes affects overall system production. Changes in a ship's required operational capabilities, translated to technical design parameters, are mapped to production steps. The simulated performance is compared across three successive stages of construction when the change is ordered. Results of model simulations demonstrate that similar MBE applications contribute to increased early requirement fidelity, decreases in rework through missed changes, and more rapid design iteration when the models used are properly verified and validated.

Verification and validation (V&V) must be performed in a very specific environment to engender confidence in model usage through a systemic framework. One method of V&V, System Theoretic Process Analysis for Security, is illustrated using an original concept illustration of a Fictional Submarine Strategic Missile. The domain of MBE is expanded to include definition of cybersecurity requirements for a new weapon system to illustrate an iteration of model-based system design. The modeling of these requirements contributes to validated resilience upon delivery, decreasing the likelihood that cyber-physical systems will be forced to rely on time-consuming updates that delay the capability delivery.

Thesis Supervisor: Dr. Steven Spear
Title: Senior Lecturer, MIT Sloan School of Management

Thesis Supervisor: Prof. Daniel Frey
Title: Professor of Mechanical Engineering

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Many others personally lent their time, effort, expertise, and guidance without which this thesis would not have been possible. For the numerous phone calls, site visits, and consultations - thank you for serving as a critical resource in my understanding of production work and illuminating challenges that take place in designing and delivering naval sea systems.

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Key Acronyms

Acronym	Meaning
AIAA	American Institute of Aeronautics and Astronautics
CIWS	Close-In Weapon System
CSDL	The Charles Stark Draper Laboratory, Inc.
CVN	Aircraft Carrier, Nuclear
DDG	Guided Missile Destroyer
DoD	U.S. Department of Defense
DSM	Design Structure Matrix
EGT	Enhanced Ground Testing
ESM	Engineering Systems Matrix
FFG	Guided Missile Fast Frigate
FSSM	Fictional Submarine Strategic Missile
FY	Fiscal Year
HII	Huntington Ingalls Industries
HVL	High-Velocity Learning
IEEE	Institute of Electrical and Electronics Engineers
INCOSE	International Council on Systems Engineering
INSURV	Board of Inspection and Survey
JCIDS	Joint Capabilities Integration and Development System
LCS	Littoral Combat Ship
MBE	Model-Based Engineering
MBSE	Model-Based Systems Engineering
MDAO	Multi-Disciplinary Analysis and Optimization
MSL	MIT Materials Systems Laboratory
NAVAIR	Naval Air Systems Command
NAVSEA	Naval Sea Systems Command
OODA	Observe-Orient-Decide-Act
OPD	Object Process Diagram
OPL	Object Process Language
OPM	Object Process Model
RFP	Request For Proposal
ROC	Required Operational Capability
SBD	Set-Based Design
SSBN	Strategic Ballistic Missile Submarine
SSN	Attack Submarine, Nuclear
SSP	Strategic Systems Program
STPA	System Theoretic Process Analysis
STPA-Sec	System Theoretic Process Analysis for Cybersecurity
SWBS	Ship's Work Breakdown Structure
SWS	Strategic Weapon System
SysML	System Modeling Language
T-AH	Hospital Ship
TLYF	Test Like You Fly
USG	United States Government
USN	United States Navy
V&V	Verification and Validation

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Chapter 1

1.0 Introduction

A good Navy is not a provocation to war. It is the surest guaranty of peace.

President Theodore Roosevelt
Second Annual Message to Congress, December 2, 1902

As the clock struck midnight on January 1, 2019, the Fleet of the United States Navy had 287 deployable battle force ships and submarines, with 75 of those assets currently deployed protecting our national interests. Three aircraft carriers were underway projecting Naval air power – USS *Carl Vinson* (CVN 70) in the Pacific Ocean, USS *John C. Stennis* (CVN 74) in vicinity of the Middle East, and USS *George H.W. Bush* (CVN 77) in the Atlantic Ocean. Additionally, three amphibious assault ships (*Essex*, *Boxer*, and *Kearsarge*) were globally positioned at sea standing ready to support the U.S. Marine Corps ashore. Under the surface of the ocean, the *Ohio*-Class ballistic missile submarine force was at sea providing the maritime triad leg of the U.S. military's strategic deterrence capability, at sea, on patrol, just like every day since 1960 [1].

The figures above are presented to contextualize the numerous and diverse missions asked of the Navy by the nation and its allies. These missions evolve continually as the security environment changes. As the nature of conflict shifts, so do the requirements – ranging from capability to technical specification – levied on naval forces. Though they may change, as long as water covers 70% of the earth, sea power will remain centrally important in safeguarding U.S. national interests.

1.1 Navy the Nation Needs

It shall be the policy of the United States to have available, ***as soon as practicable****, not fewer than 355 battle force ships, comprised of the optimal mix of platforms, with funding subject to the availability of appropriations or other funds.*

Section 1025 of the FY2018 National Defense Authorization Act, H.R. 2810/P.L. 115-91

As the United States draws down land wars in the Middle East, the nation continues to rely on naval presence diplomacy as an effective way of showing power. Consider the humanitarian crisis in South America – the U.S. Navy's most direct response was to send a flagship of the fleet, the USNS *Comfort* (T-AH 19), the Atlantic Ocean-based hospital ship, to establish presence of our national interest and support our allies. As the nature of warfare changes and near-peer competition rises, having more ships in more places presents as an attractive option for policy makers to respond to events across the world. The Navy must be able to offer the full breadth and depth of options.

As the nation's security needs call for a growing naval fleet, the public-private industrial base for construction and maintenance will be stressed to perform at a high level of operational excellence. With capacity increase in a nascent state, U.S. domestic shipbuilders face the prospect of understanding the complete scope of how to implement large-scale continuous improvement to maintain speed, cost, and capacity in new construction to add new hulls to the fleet better faster than can be expected now. The Congressional Research Service reports that "Navy shipbuilding rates could not be increased steeply across the board overnight… Over a period of a few to several years, with investment and management attention, Navy shipbuilding could ramp up to higher rates for achieving a 355-ship fleet over a period of 20 to 30 years" [2].

The challenge does not stop with shipbuilding. At the heart of naval vessels lies their combat and weapon systems that provide lethality as the value proposition of a combatant. These systems are designed and produced to maintain pace with both platform production rate and evolution of the threats they are designed to face.

1.2 Imperative of Global Competition

It has been decades since we last competed for sea control, sea lines of communication, access to world markets, and diplomatic partnerships. Much has changed since we last competed. ***We will adapt to this reality and respond with urgency****.*

U.S. Navy strategy document, *A Design for Maintaining Maritime Superiority 2.0*, December 2018 [3]

With a return to "great power competition," the Navy must now respond to near-peer global powers with forces that should adapt faster than potential future adversaries [3]. The Chinese People's Liberation Army (Navy), or PLA(N), appears to be executing the design-build process well with a much greater mix and production rate of combatant surface vessels in classes similar to the ones that the U.S. Navy is currently struggling with acquiring [4].

These are far from "paper tigers." As the PLA(N) fleet structure demonstrates, they are investing in high-end surface, subsurface, and aircraft carrier classes on the same technological level as the newest offerings from U.S. and allied navies [5]. With a more diverse fleet architecture (as measured by different combatant classes) than the United States Navy, Chinese progress in naval construction may indicate an adaptable production process that accommodate shifting requirements for diverse ship types that respond to modern threats.

Although numerous other instances of Chinese and other near-peer potential adversaries adapting production volume and mix to respond to U.S. Navy capabilities exist in open source literature, their progress can be summarized by designs that evolve continuously, modernize at an increasing rate, and are well adapted to the capabilities of other nations [4]. Even without precisely identifying which tools and techniques are used, it is evident that their acquisition process is resilient enough to adapt and robust enough to produce a world-class industrial product.

1.3 Resilient Acquisition

The types of ships and capabilities procured over this 30-year timespan will evolve with technology and threat advances. Protecting the baseline acquisition profiles provides long-term foundational stability for thoughtful, agile modernization, and a clearer forecast of when to evolve to the next ship design.

Hon. James F. Geurts, Assistant Secretary of the Navy, Research, Development & Acquisition
Testimony to House Armed Services Committee, April 12, 2018

At its core, defense acquisition functions as a closed loop pictured in Figure 1 [6]. Like the automated ship self-defense Close-In-Weapons-System (CIWS), whose integrated radar continuously tracks a target and compensates with a corrected firing trajectory, we must adjust our designs and system mix to remain relevant to the needs presented to our forces.

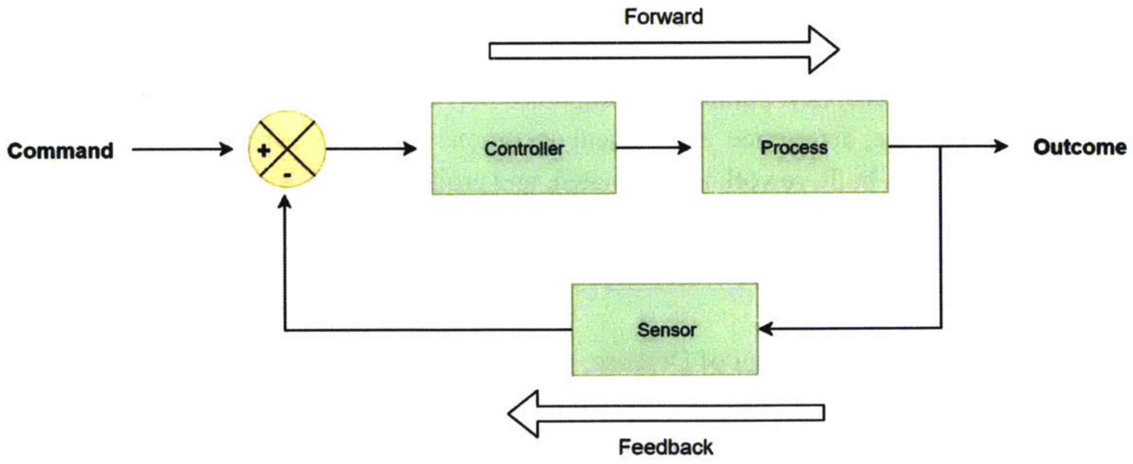
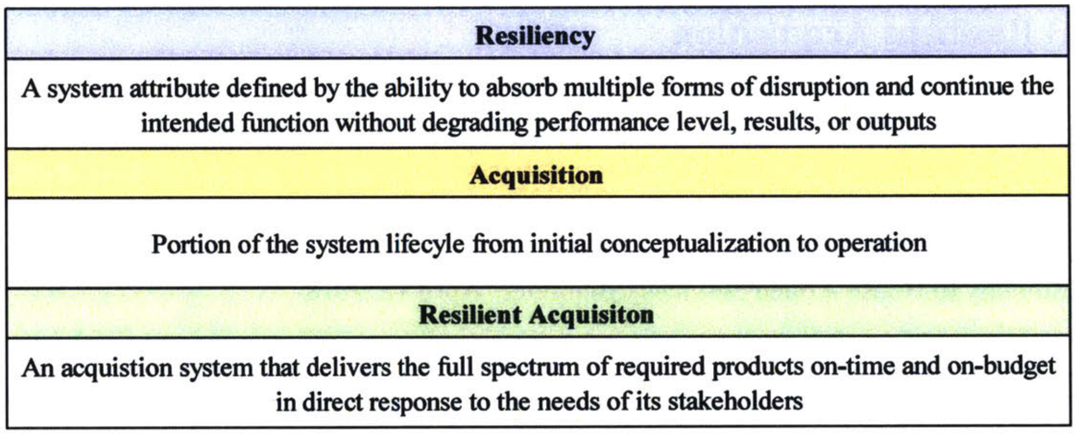


Figure 1: Simple closed loop controller diagram

Resilience measures the degree to which a system can recover quickly from a major disruption while regaining or exceeding its original level of performance [7], [8]. With monolithic projects that have unparalleled bureaucratic momentum behind them, large acquisition projects can hardly adapt once they begin the design phase toward a specific set of requirements which is too late. Is it a problem that exists wholly within the realm of production or throughout the acquisition process? Figure 2 defines the core terms that underpins the solutions that this thesis seeks to identify.



Resiliency
A system attribute defined by the ability to absorb multiple forms of disruption and continue the intended function without degrading performance level, results, or outputs
Acquisition
Portion of the system lifecyle from initial conceptualization to operation
Resilient Acquisiton
An acquistion system that delivers the full spectrum of required products on-time and on-budget in direct response to the needs of its stakeholders

Figure 2: "Resiliency" and "Acquisition" combined and defined

1.4 Model-Based Engineering in Focus

With the Navy challenged by how it conceptualizes, designs, produces, and activates ships and weapons systems, new paradigms should be adopted to ensure that global mission requirements of presence, deterrence, and tactical operations are met. With a better connection of what we need to what is built, rework is eliminated, and production levels can be increased to meet the needs of the Fleet of the future. What this thesis contends is that full adoption of the Model Based Engineering (MBE) enterprise contributes significantly toward yielding the results needed.

Outside the U.S. Department of Defense, private sector design and build efforts are realizing these exact returns from investment in the model-based enterprise [9]. In areas in which projects typically underperformed, adoption of the digital models that capture interface effects have a causal and measurable effect on the outcome. This thesis will attempt to espouse some of the most general and fundamental aspects of MBE rather than suggest a tool that is likely only suited for a single specific application.

1.5 High-Velocity Learning Line of Effort

The U.S. Navy has been tasked with equipping the Fleet with technological advancements – an enormously complex challenge handling largely new designs and not simply iterative elaboration on existing designs. The service's record has been one of underperformance relative to need, cost and, especially, time. In alignment with a core Chief of Naval Operations "Design for Maintaining Maritime Superiority" principle, the lens through which the analysis will be conducted will be using the "High-Velocity" methodology of rapid iteration and problem seeking/solving [3], [10].

Sections in this thesis follow a pattern of systematic discovery beginning with a background, question, hypothesis, then a test method [10]. Tangible examples used in documentation of this practice address concerns that this might be applicable to a certain setting. Diversity of the success stories of following these simple global principles can convince someone else to carry this out in practice.

Combining a model-based engineering and high-velocity learning approach yields a rapid-refresh cycle along with deliberate technical connections as shown in Figure 3. This approach allows planners to take the changing world, requirements, and inputs and interpret them into something that designers use to produce the correct product sooner and more reliably. Delivering capability to the Fleet faster results from the ability to overdeliver on value while simultaneously conserving effort.

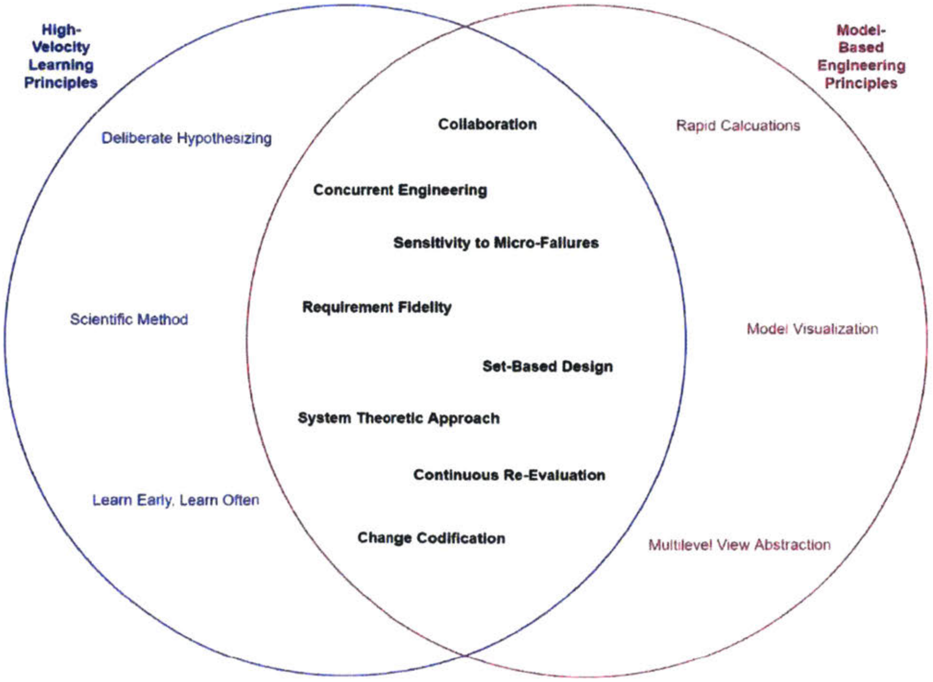


Figure 3: High-Velocity Learning and Model-Based Engineering common principles [10], [11]

1.6 Thesis Outline: Chain of Causality

The level of production that U.S. Navy systems require is difficult to achieve using today's design and specification methods. Subsequent chapters provide an overview of what MBE provides by longitudinally comparing different use cases for the technology, motivations, and results for organizations that have elected to incorporate this set of tools into their design repertoire. With multiple progressive phases of questioning and exploration, a continuous chain of causality represents the method of arriving at the conclusions of this thesis. In addition to the background phases, two representative novel case studies are explored through the creation of models to uncover background on production delays during the fabrication of a representative naval systems – both in shipbuilding and weapons systems development. Every section starts with a question that each section is aimed to answer.

In lieu of "deep diving" on a single aspect or enabling characteristic of Model Based Engineering, I have elected to present an array of options on the use of modeling in the design and production of complex systems. With a rapidly evolving uncertain future motivating the core of this study, opening the aperture as wide as possible ensures that a functionality that applies to a given situation is explored.

Chapter 2: Production Underperformance – Why? Observation of sub-standard performance raises a simple question of why – generally explained by experts and in literature as a disconnect between the physical requirements, the way in which designers manifest those requirements in the mechanical techniques of design, and the way in which we model the physical world. We will first establish that this is a plausible hypothesis by deepening an understanding of contributors to inefficiencies and rework in design and production. By observing attempts made at connecting requirements with physical products, we will draw a conclusion on the current state of the art. This section then concludes with a hypothesis that Model Based Systems Engineering can be applied as a partial solution to correct these systemic design shortfalls.

Chapter 3: Model-Based Engineering – Focus on System Production. What is the Model-Based Engineering in theory and practice? The proposition of this thesis is that the disconnect can be resolved using model-based systems engineering and design to enable faster, less expensive, and modernized "conceptualize – design – build – deliver" sequencing.

Chapter 4: Mind the Gap – Models Connect *Needs* with *Reality*. Given the problem of disengagement between the request for proposal and the finished product, how can MBE help the Navy's disconnect? Would better aligning the contract and design process to manufacture and production accelerate throughput in the shipyard? Multiple case studies contribute to a demonstration of Model Based Engineering bridging the divide between requirements and realty. External case studies will provide proof-of-concept including commercial CubeSats, military aerospace, ballistic missile guidance and navigation, and industrial plant machinery design.

Additionally, we will investigate how a nascent design framework being adopted for ship design, Set-Based Design (SBD), successfully leverages the model-based enterprise.

Chapter 5: Case Study – Shipbuilding Production Model. This application will demonstrate and seek to validate the claims in a naval construction environment by showing how the connection of required operational capabilities to technical specifications and processes yield appreciable results. Providing systematic connection of required operational capabilities to technical specifications enables key decision makers to understand requirement implications to producibility, cost, and schedule. Codification of requirement changes ensures that they propagate more effectively through production iterations.

Chapter 6: Towards the Final Hurdle – Model Verification and Validation. Models will not be useful if we are not confident. While tracing and modeling requirements – are we sure that we are asking for the right things through multiple levels? The System Theoretic Process Analysis (STPA) is presented for identifying system safety and validated operation.

Chapter 7: Concept Illustration – Weapon System Cybersecurity. The final points will be presented in this thesis through a concept illustration of the use of MBE to create requirements and technical detail in one of the most dynamic domains – cybersecurity requirements. With adversaries evolving on a minute-by-minute basis in this domain, adapting to different threats must likewise happen on a continuous basis. Foundational Model Based Engineering paradigms (DSM, OPM) contribute to verification, validation, safety, and confidence in the model's representation of the physical world. Product resiliency can be shown as enhanced through reducing uncertainty in future requirements by taking systematic approach to safety through security (STPA-Sec).

1.7 Starting Point

Policy makers have determined that the U.S Navy fleet should reach 355 ships "as soon as practicable," however the Navy struggles to maintain a total strength of 280. What can we do to get better delivery speed, quality, and cost?

Introduction Summary
The United States needs a 355-ship Navy to contend with the modern nature of warfare and highly capable global adversaries
Model-Based Engineering (MBE) digital tools may help to close the time gap by offering resilient design architectures to adapt to requirement changes
High Velocity Learning methodology approaches enhance the effectiveness of the MBE tools through rapid iterations on solving production problems

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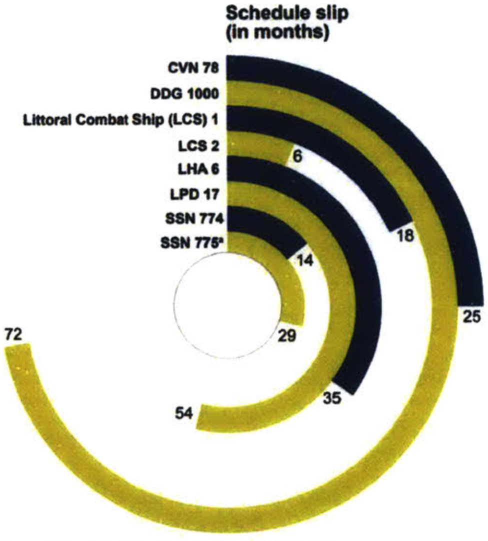
Chapter 2

2.0 Production Underperformance – Why?

Seventeen years and fourteen billion dollars of the taxpayers' money to design and build one armored vehicle…

From *The Pentagon Wars*, (fictional) HBO Movie
1998

In the modern era, developing complex weapons systems has become a multi-decade process. Lead hulls of combatant ship classes are, without exception, delivered to the Navy late and over budget. Figure 4 graphically displays the schedule slip for first-of-class delivery with schedule underperformance of up to two years [12]. Additional examples of shipbuilding projects or weapon system deliveries underperforming in terms of schedule and budget seem routine when reported [13].



Source: GAO analysis of Navy documentation. | GAO-18-238SP

Figure 4: Delivery delay in the lead hull of most recent eight ship classes [12]

The purpose of this section is to go through specific case details and interviews to narrow to a small set of specific problems that will be addressed in this thesis. While researching, I spoke with experts in the field of complex systems design, construction, and acquisition. I always led with a simple question that was general enough to investigate the root cause of delay and mismanaged delivery – how do you ensure that what you are "building" is correct? How is it that complex system acquisition professionals ensure that the systems currently under construction – with funds obligated and progress made on the production line – *will be able to satisfy* the requirements of the customer?

Strong experiential evidence suggests that unclear specifications and change management are primarily to blame for delays in delivering the ships that the Navy needs [12]–[15]. Although this research could never aim to uncover the full scope of acquisition complications over multiple decades, citing key contributing factors can begin to expose why acquisition performance has failed to meet the high expectations of the American people.

If complex systems, no matter whether they originate as government or civilian projects in any domain, face some of the same challenges in acquisition and deployments, we can learn from the full breadth of interdisciplinary experience. This chapter details characteristics of complex systems that make their production difficult and seek to understand how the problems that face disparate industries are all quite similar in abstract.

In this chapter, we will first examine the enemies of progress which were found to be manifestations of complexity, uncertainty, and risk. Those factors contribute to difficulty in defining requirements for complex systems that are acquired, which are factor in delaying delivery of those systems. Finally, one solution to the collective of problems will be proposed to refine the requirement management process through the use of Model-Based Engineering. An overview of this chapter is shown in Figure 5.

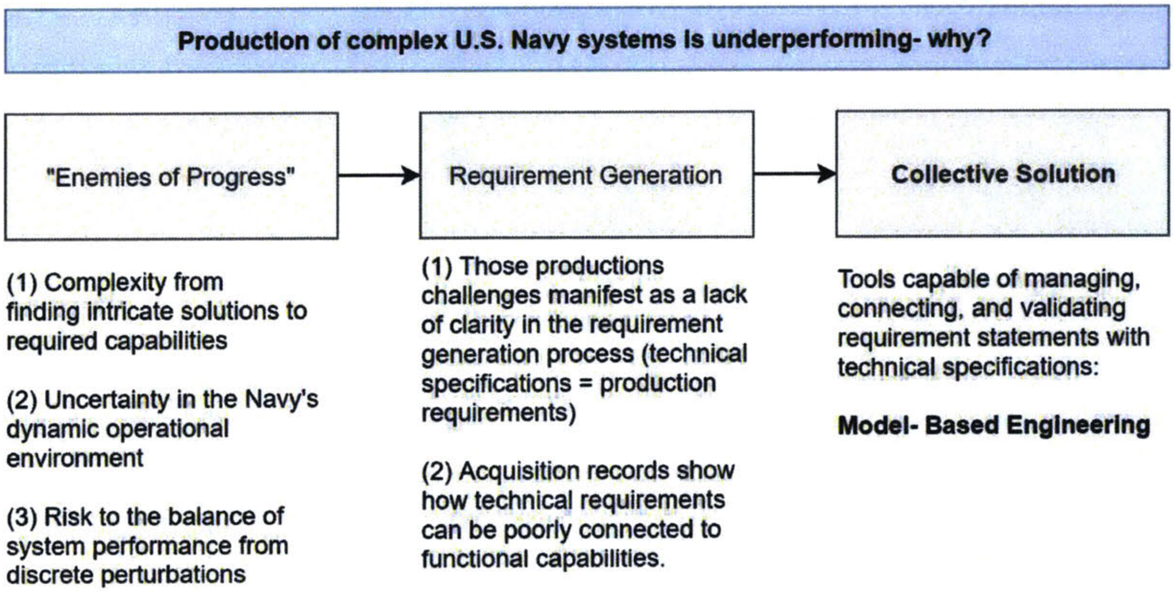


Figure 5: Discovery process flow around production and delivery underperformance

2.1 Enemies of Progress

Examining complex defense system acquisition, what "enemies" does delivery to the end-user face? This question can be approached by investigating factors that slow production of complex systems. This section identifies the enemies as complexity, uncertainty, and risk in design and production which will each be explored further below.

Capturing every reason for delay in a specific project is an unknowable and mostly irrelevant endeavor. Every system is different and the "unknown unknowns" that arise when building future complex systems is outside the realm of possibility for expectation. Therefore, a resilient acquisition system will be one that can respond to unanticipated changes. A system that can respond to *known* challenges is *robust*, while systems *adaptable* to respond to a range of unknown scenarios are *resilient*. Recall the definition of *resiliency* given in Figure 2 as "a system attribute defined by the ability to absorb multiple forms of disruption and continue the intended function without degrading performance level, results, or outputs." Characteristics of these systems are shown in Figure 6 with system examples presented in Table 1.

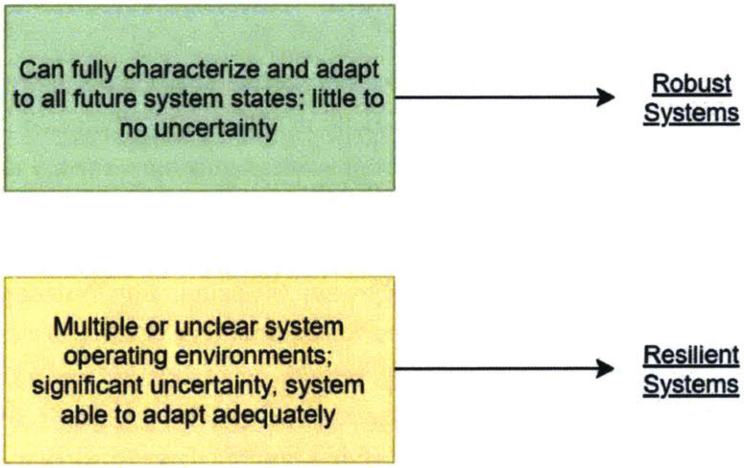


Figure 6: "Robust" vs. "Resilient" system characteristics

If future requirements consisted primarily of having to accommodate a specific change, then the design and build process can be structured to accommodate that specific type of challenge, thereby strengthening robustness. However, known challenges hardly characterize the global security landscape. In cases such as dynamic project environments or uncertain global environments, emphasis should be placed on *holistic resiliency* vice narrow robustness.

Table 1: Robust versus Resilient system state examples

System State or Requirement	**Robust or Resilient response?**
Concrete column must support a static load of 30,000 pounds and a live load of 50,000 pounds	**Robust**
Charter aircraft; available for long-haul cargo transport or passenger services	**Resilient**
TD Garden: Boston, MA - hosting professional basketball, hockey, and a Fleetwood Mac concert on consecutive days in March 2019	**Resilient**
Washington State Ferry M/V *Tacoma* capable of carrying 200+ vehicles and 2500 passengers on 35-min. Seattle-Bainbridge Island commuter route	**Robust**
MIT Cogeneration Power Plant with dual-generating modes: 21-MW gas turbine generator and recovery steam generator	**Resilient**

TD Garden 29-31 March 2019: https://www.tdgarden.com/calendar

Washington State DOT: https://www.wsdot.wa.gov/ferries/vesselwatch/vesseldetail.aspx?vessel_id=32

MIT Cogeneration Plant: https://powering.mit.edu/project-faqs/cogeneration

Adopting adjustments specific to past or external projects when previous experience cannot reliably be counted on to provide indication of future challenges or performance has demonstrated a poor return on investment [13]. Causes of progress delay may often not be tangible – for example, a repeated cause of delay in specifications that routinely require excessive manufacturing processes or imprecise measurements. Conversely, the causes are systemic and propagate through sequentially when the acquisition system is used according to its structure. In "Taming the Tigers," Kane and Bartolomei link issues that persist in the defense acquisition world to tigers in the circus ring: requirements, budget, and process structure [14]. The architecture of the defense acquisition system-of-systems requires refreshing principles that guide information consumption, while specifying outputs that can adapt to the environment of increased input and bespoke output.

2.1.1 Complexity

Complexity, when used in this thesis, means something different than the trite catchall used in everyday parlance representing something "not simple or intuitive" [15]. Complex systems have many elements connected via non-linear relationships that exhibit dynamic behavior subject to irregular disturbance and perturbation. With no steady state, the system is in a perpetual transition or adaptive state.

Complex systems contrast with those that are only *complicated* through the interactions of their constituent components. A basic example of a system that is complicated but not complex is a mechanical watch with components shown in Figure 7. The watch has innumerable components each of which takes skill and expertise to assemble, but each relationship between components is well understood to micro-second precision [16]. Contrast the mechanical timepiece with a complex naval warship, where even first-order effects of changing a single component such as a pump or structural member are not apparent even to experienced operators.

Figure 7: Complicated, but not complex – Grand Seiko Spring Drive watch components [16]

The complex systems produced to deliver capability to the U.S. Navy Fleet are, as General Stanley McChrystal states in his book *Team of Teams*, much more "restrictive, technical, and baffling" and can be defined as a system with an almost incomprehensible density of internal linkages that cause the behavior of the system to fluctuate unpredictably [15]. Clearly, complexity has a purpose considering gains in overall functionality over time – such as the progression seen in passenger aircraft, digital technology, and automobiles over the last three decades. This is also readily apparent by observing innumerable components that form vast networks of systems-of-systems inside and aboard naval assets. These include the weapons systems and the hull, mechanical, and electrical components that keep the ship moving forward and either afloat or submerged. With boundaries between large-scale technology systems blurred, the interfaces are increasingly hard to identify and manage. As interconnectedness increases, challenges for operation are created through opportunity to create a conflict at the interface or handoff [10].

Complexity increases naturally as design and technology advances. Older, more basic system functions accomplished a "single purpose and with a clear mission in mind" and now single systems perform myriad task sets [8]. With component technologies evolving rapidly, failing to anticipate the effect that complexity has on the overall system-of-systems can mismatch design and production capability [8].

Complexity is built every day. Some of it defies what was previously thought as physically possible and some of it is routine – biological, cyber, and physical systems in every engineering domain. Challenges that arise from system complexity include integration and connectivity, interface maturity, influence of new components or environment, and system readiness [17].

Quantifying how complexity of a system can be accomplished through first categorization of how sub-system elements are connected, and proceeding to uncover metrics relevant to features of how the system operates [18]. In doing so, Sinha suggests that a relevant general complexity metric must always account for the unique connectivity structure of the system under analysis [18]. Since the structure of element connections is an attribute of the system, this limits comparisons of complexity between different systems to merely an academic effort with limited application in practice. This inhomogeneity from system to system discourages shared approaches to handling complexity as an emergent system attribute and contributes to its deleterious effect on efficient production progress.

2.1.2 Uncertainty

Uncertainty applied to complex systems creates variability when observing first order interactions, and to a much greater degree. subsequent higher order effects. While not a direct result of complexity, the effects of uncertainty are exacerbated by complexity.

Regarding the "Navy the Nation Needs" goal of 355 ship fleet, Secretary of the Navy Richard Spencer admitted at his confirmation hearing before the Senate Armed Services Committee that he "can't tell what the construct of that would be, sitting here today" [19]. His comments further specified uncertainty over whether the future fleet might include a mix of manned and unmanned systems to be designed and acquired in the future. With his suggestions that the "355-Ship Fleet" might be of a different mix than just 355 ships and submarines, significant uncertainty will exist in the requirements that are levied upon the assets of the future fleet.

Naval warfare systems couple uncertainty with urgency – but the design of complex naval systems is far from the only place where that is the case. With a focus on engineering the designs of the future, what major systemic issues when addressed enable the urgency of delivery?

Different types of uncertainty emerge depending on the design stage and interaction of system elements. The effect they have on a project can be a key contribution to project delays [20]. Figure 8 shows different types of uncertainty, with highlights for the most important factors that affect the production of complex defense systems. The uncertainty environment is depicted as highly inter-related among highly *non-linear* systems considered in this thesis. Potential system boundaries can be drawn around the bins of uncertainty types to correspond to the level of analysis performed. Typically, when analyzing a complex engineering system, only the "Product Context" bin may be considered endogenous to the scope of analysis.

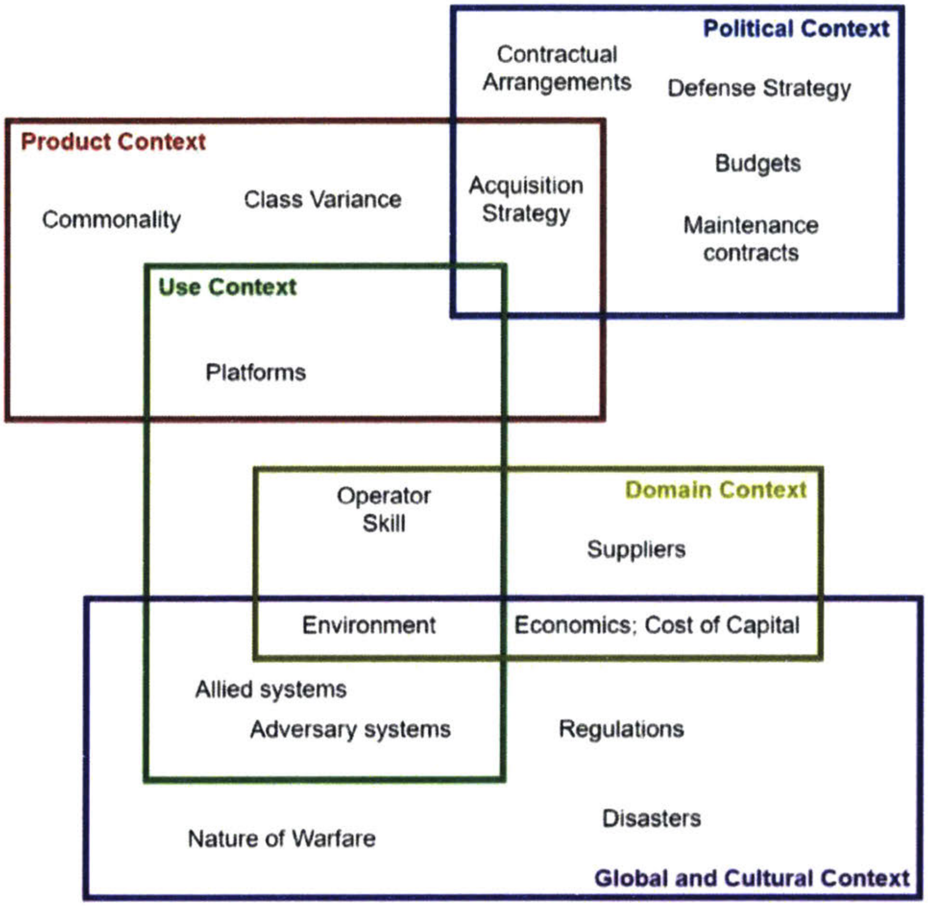


Figure 8: Complex defense system uncertainty map, figure adapted by author from [20]

Uncertainty comes from the product being produced. This includes elements of the technical design of the system produced as innovative in its own field (maybe, a technological breakthrough or novel functionality). Some automakers have made class certainty, known as platforming part of their core business strategy in reducing uncertainty arising from product to product [21]. From chassis commonality to sharing parts and pieces, automakers have been able to leverage classes of products to their advantages for years, while the Navy – despite shorter "class" production runs – limits the learning curve when the acquisition model changes the ship class at every individual iteration. The approach of ship class "block buys" is a variation on the platforming concept and will be further explored subsequently in the context of present-day Littoral Combat Ship production [22].

Uncertainty is also derived from the political environment that the system is acquired in. Uncertainty in future needs of the Navy is investigated deeper and enumerated in Appendix A: Uncertainty in U.S. Navy Force Structure Assessment. Uncertainty in acquiring smaller-scale systems can be observed in shifting strategy as priorities advantage particular sets of products such as new types of weapons systems manufactured by limited sources [21].

Uncertainty through use context comes from changes in how the product will be used in the future. Use context can also be taken as equivalent to the operational environment of a product [20]. This system exogenous uncertainty classification should be closely monitored as a major environmental shift has the potential to render a system under development irrelevant before production begins – as will be illustrated later by the *Zumwalt*-Class (DDG-1000) in Figure 10 and Figure 10.

A system's domain of operation creates another classification of uncertainty. From a commercial perspective the domain could be the industrial sector or market occupied. For large-scale defense systems the domain may extend to the physical description of type of battlefield such as maritime, aerospace, land, or cyber. Trends in these markets or battlespaces carry significant uncertainty tied to the demand and innovation that might exist unique to the domain. For example, planners may choose to account for a higher degree of uncertainty when designing systems that operate in the cyber domain which is experiencing more nascent development than a more well-explored domain such as land-warfare or consumer products markets with a slower changing demand profile [20].

Global and cultural uncertainty also plays a role in development of complex defense systems. It is not elementary to consider the ways in which an uncertain, dynamic global environment can affect the system even outside the categories explored previously. These cultural context elements range from indirect political actions of a foreign actor that can change the actions of an entire group of people or a culture to legislation that can slow or speed a development cycle. Macro-level cultural forces translate into concrete micro-level uncertainties in complex systems.

When realization of uncertainty requires redesign, flexibility enables a smooth transition in which a system can be adapted to an alternative function or external system interface, or augmented measure of performance (i.e. the need to simply make a component stronger with the same functional requirements) [8].

2.1.3 Risk

Systems face risk associated with seemingly normal operation according to their specifications that can cause an unsafe or unintended result [23]. Uncertainty differs from risks which have a set of future predictable outcomes. While precisely predicting risk may be impossible, examples such as anomalous accidents like dry dock failures and flooding occur in the real-world [15]. Should we have designed an acquisition-build system to accommodate casualties in dry dock flooding? What changes to the systems-of-systems would have been necessary for that? Clearly, these are rhetorical questions serving to suggest that different sets of precautions are necessary to adapt a system for such events than to architect a systemic solution resilient to risk.

Mitigation of risk effects means that designers and builders must respond to future changes that are difficult to anticipate. How will this system ensure that the production principles that engender crisis recovery emerge autonomously? Reacting to unforeseeable risk events must happen as second nature by an organization using a resilient design and development procedure so that when an unforeseeable event occurs, disruption and cascading delay do not result.

Suppliers to Japanese automobile manufacturer Toyota have been well-versed in developing reliable processes for consistent delivery and production of the intermediate and final products. Even so, they remain subject to similar risks as all businesses; catastrophic events such as fire and flooding are obvious examples, but equally impactful are unforeseeable administrative, engineering, or design challenges.

In one supplier case study, a fire at a critical component manufacturing plant served to demonstrate how planning for resilience mitigates risk. Steve Spear described that through "normal 'High-Velocity' management- creating and delivering an organization's products and processes- are the same as those needed to handle larger disruptions" [10]. The 1997 fire at Toyota supplier Aisin Seiki destroyed the precise machinery to make safety-critical valves threatening to bring automobile production to a halt. The recovery was remarkable; "near normal" production was resumed within a week [10]. Toyota's network of suppliers naturally stepped in to assist their competitor with production in self-organizing fashion. In this case, the organization network willfully structured its development and production in such a way that they were able to deal with an "abnormal situation in a normal way" by demonstrating responsiveness and ability to recovery as resilience [10]. Beyond presenting more evidence of Toyota's mutually supportive supplier network, this case displays more about a system architecture in place before a risk event that allows the organization to use tools and processes to naturally recover smoothly.

In major defense systems, when acquisition is bound by restrictive processes and single-point-of-failure suppliers, is there any possibility that this network of production could sustain a similar magnitude disruption with such resiliency? The industry must next identify the key enabling characteristics to make crisis recovery – if not autonomous, streamlined and natural to adjust to increasing complexity, uncertainty, and risk events.

2.2 Requirement Generation

Recall the closed loop acquisition model proposed in the introduction, Figure 1. This primarily applies to the requirement setting process for modern complex systems – not restricted to only military systems, but any system that operates in a dynamically changing environment. How do we hit moving requirements? With the right control authority, designing ships for production means making them systematically-immune to changes and shifting requirements.

This issue goes beyond a goal of peacetime production increases, because refining the ability to react quickly to wartime conflict driven production changes is equally as critical. Designers must be able to modify existing specifications to adjust to the reality of the conflicts of the present day. For example, conceiving and designing the concept of the Combat Information Center was born of the hard lessons learned during the confusion of Second World War naval engagements. During these battles, naval planners realized that there was value to be had from a space dedicated to information synthesis and the concept of the Combat Information Center (CIC) that serves as the "nerve center" on nearly all modern warships was born [24].

Requirement validation confirms the "right system is being built" [11]. However, determining whether requirements are ever "right" for a weapon system or platform that measures development and lifecycle time in decades is an impossible task due to the factors considered in the preceding sections of complexity, risk, and uncertainty over time. Consider the changes in the fleet architecture from the late-Cold War with 568 battle force ships to the present day levels under 290 [1], [2]. Numbers alone provide no commentary on whether capability requirements are being met – only measuring how profusion of warfare capability either matches or gaps dynamic functions of Navy mission requirements will tell the story.

The systematic process by which platforms are acquired within the U.S. Department of Defense is the Joint Capabilities Integration and Development System [25]. However, as this thesis does not intend perform a comprehensive critique of the acquisition system itself – just the underlying global principles that provide its analytical foundation – a thorough detail of JCIDS will not be covered in this work and can be found in external references via the Defense Acquisition University [26].

In this section, the generation of ambiguous or unvalidated requirements will be addressed, followed by an example record of recent U.S. Navy acquisition programs, and finally investigating opportunities for improvement in how major ship programs reach production and delivery.

2.2.1 Ambiguity

The structure of requirement generation facilitates persistence of ambiguity throughout the process. The product of concept exploration is typically a set of requirements, schedule, and cost estimate to implement the requirements in a ship. The product of preliminary and contract design is the request for proposal (including ship specification and statement of work) for the detail design and construction of the lead ship. The acquisition plan should influence the structure and goals of the Request For Proposal (RFP) which in turn should govern the ship specifications and the work to create the ship specifications. In a hypothetical case, a disconnect between what the Program Office was trying to achieve with the overall RFP and what the Ship Design Manager was trying to achieve in the ship specifications work to counter purposes. This shows the systemic structural elements that contribute to requirement ambiguity.

Connecting Fleet performance requirements to technical specifications more clearly can lead to a better representation of *what the Fleet needs* – requirements – than can be arrived at via traditional document-based methods. Exploring the relationship between design activities in the acquisition strategy illuminates handoff discrepancies that inhibit high-velocity learning [10].

Requirement ambiguity's implication on production feasibility can be a self-imposed issue where politically charged desires call for unrealistic capabilities without knowledge of the technical implications. In the FY2011 budget, the Navy canceled the proposed next generation of Guided-Missile Cruiser, CG(X), after spending $20 million on a study recommending a $7 billion nuclear cruiser [27]. Developing sets of technical specifications and cost estimates from the ambiguous nature as a "next-generation" platform designed for "multi-mission" roles emphasizing the then-nascent mission set of Ballistic Missile Defense and Anti-Air Warfare delivered unsurprising results in the form of a completely unrealistic and unaffordable platform [27]. Scaling these incomprehensible technical goals was guidance from then-Defense Secretary Donald Rumsfeld for "transformational" new systems [28]. In a potentially fortuitous postscript for the American taxpayer and future generations of U.S. Navy leadership responsible for executing the acquisition of such a platform, the sunk costs were accepted and the program was canceled, moving in the direction of a third, expanded, iteration on the venerable *Arleigh Burke*-Class Destroyers [27].

That requirements for platform design suffer from ambiguity has not been lost on the engineers of Naval Sea Systems Command, the directorate charged with design, acquisition, and lifecycle management of ships and submarines in the U.S. Navy. Requirements Evaluation Teams (RET) are a relatively new construct aimed at ensuring that due diligence has been performed on ship and submarine platform requirements before they are released to private industrial partners. In most cases, these ad-hoc committees should accomplish much of this thoughtful connection of ambiguous requirements of capability (such as "verbs" that cannot be designed into a ship, such as speed or combat functionalities) [29]. First established to re-evaluate the *Zumwalt*-Class (DDG-1000, shown in Figure 9) requirements, NAVSEA has continued the practice on major contemporary programs such as Future Frigate, Large Surface Combatant, and Hospital Ship with pending results [29].

Figure 9: Zumwalt-Class Guided Missile Destroyer (DDG-1000) [30]

RETs are a worthwhile pursuit when executed properly and given enough authority to recommend changes to requirements that may push a platform beyond the boundaries of affordability or schedule that the Fleet requires for its capability to be delivered. Otherwise, they may be a lost opportunity and additional hurdle to clear on the long road to final delivery after construction.

2.2.2 Navy Acquisition Program Record

Sometimes a shift in an uncertain global landscape can alter the required capabilities of a weapon system or delivery platform. When requirements are static, point designs are sufficient. This is being robust. Since requirements are not static, systems pending development must be able to adapt or risk leaving the customer holding an expensive product without a useful mission.

Several high-profile naval acquisitions programs – such as the Future Frigate, Large Surface Combatant, and Hospital Ship – are currently in the nascent requirement generation phase at the time of this writing and are therefore unable to be meaningfully or publicly commented on. Drawing upon recent history, however, an example large acquisition program comes from the DDG-1000 *Zumwalt*-Class [30]. The requirements to which the ship class was built have changed along with the global security landscape. As a result, this program can be evidenced as a victim of market and requirement risk. Figure 10 summarizes how the environment can shift and render a design irrelevant.

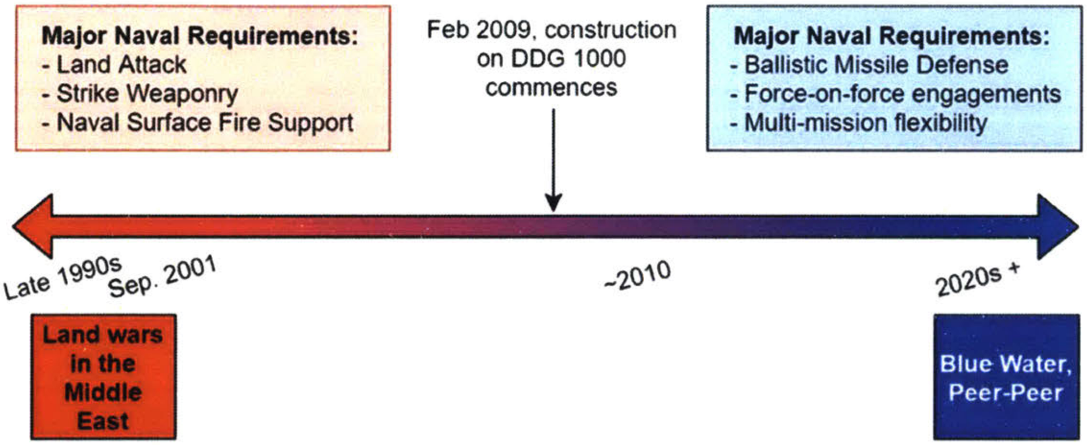


Figure 10: Global security landscape effect on DDG-1000 use context

Recent statements made by U.S. Navy leadership further underscore the requirement ambiguity and the inability to produce, in DDG-1000 Zumwalt-Class, a resilient platform with a warfighting focus [31]. Note the emphasis added in the final sentence, comparing the date cited by Vice Admiral William Merz, responsible for requirement generation across all U.S. Navy systems, with the construction start date in Figure 10.

> *We determined that the best future for that ship is to get it out there with the capability that it has and separate out the Advanced Gun System, leaving everything else in place... [The Zumwalt] is a very capable platform with or without that gun... we will be developing either the round that goes with that gun or what we are going to do with that space if we decide to remove that gun in the future. The ship is doing fine,* ***on track to be operational in 2021*** *in the fleet.* [31]

With the shift in focus for the platform coupled with a design resistant to change given its complexity, operational required capabilities simplified to only an ability to get underway and provide presence. Furthermore, this shift in requirement priority over time has significantly delayed this platform's operational introduction to the fleet while straining thin ship construction budgets. Vice Admiral Merz added that *Zumwalt*'s primary mission set shifted from land-attack to be -

> *... remissioned to a strike platform, whether sea targets or land targets. It takes advantage of its tremendous arsenal of VLS cells. Those VLS cells are larger than any other surface ship VLS cells so that opens up an aperture of more weapons options for that ship.* [31]

Currently, the solution for requirement ambiguity is a resilient weapon system architecture – as Admiral Merz cites, the size and flexibility that the VLS modules provides leaves reason for optimism for future DDG-1000 integration into fleet operations. In the dynamic operational environment anticipated for the U.S. Navy, policy makers must have the management structures in place to adapt to changing environments from the root cause of requirement management before production begins.

2.2.3 Shipyard Production Challenges

Shipyards are relatively open areas in which to observe complex system production and afforded the chance to consult with industry professionals that work with the challenges of delivering capability to the Fleet faster every day. Appendix B: Shipyard Visits summarizes visit information from the sources consulted at nearly all major shipyards producing U.S. Navy warships across the country – however, specific citations below are deliberately generalized for non-attributional purposes. It should be noted that in the paragraphs that follow, the issues presented have been well-documented by Department of the Navy leadership and are only presented in this thesis as evidence for more resilient design-acquisition system tools. Table 2 enumerates some of the challenges faced during shipyard production that are discussed in this section.

Table 2: Shipyard production challenges related to requirement management

Selected requirement-related production challenges in shipyards
Design changes that propagate downstream with complex non-linear effects
Lack of design maturity prior to start of production process
Failure to accurately and comprehensively capture changes – requirements and technical
Variance within supposedly stable class block buys among the same ship class
Changes to a component with unanticipated dependency or interaction with other elements
Performance testing of components or systems with unclear/ambiguous specifications

Challenges in the design phase propagate downstream to shipyard production. It is uncommon for a design to be completed before steel is cut during production. The experience with the Littoral Combat Ship (LCS) production at "Shipyard A" tested this concept with designers hoping to work out details concurrently with construction taking place [32]. Ideally, this could have been a valid strategy had inconsistencies with the first hull and the design matured by the time the next reached the production line. In reality, large changes were made – for example, reduction gears changed, necessitating major support piping configuration changes and an entirely new engine room design [32].

Considering some level of change inevitable despite best efforts to mature the design before production, there are changes that fail to be accurately or completely captured. When work is performed in the shipyard, a field change notice is generated with the details for further incorporation as a drawing attachment until the next integration can be codified [33]. However, without the ability to update drawings on a regular interval, some of the drawings used for production in assembly areas can persist with dozens of annotated changes [33].

> *While getting the LCS into service quickly may have been a worthy goal, the mistakes made and problems encountered in building the ships, and the department's resulting inability to restrain program costs, tell a cautionary tale to all current and future [Department of the Navy] leaders.* [22]

Former U.S. Deputy Secretary of Defense Robert Work's comment references how the acquisition strategy of the ship class in production introduces instability in requirements. In Appendix A: Uncertainty in U.S. Navy Force Structure Assessment, we quantified the uncertainty associated with overall ship-class mix for the Fleet architecture, but what was not explored was the intra-class uncertainty.

One construct intended to reduce the variation between individual hulls of the same class is the concept of the "block buy," as described by Deputy Secretary Work [22]. However, during several events over the course of the class block buy, new information in the form of requirements were levied on the seemingly consistent block buy strategy. Major changes such as the requirements of compliance with shock trial results and swapping point-defense system configurations entered different pieces of equipment mid-way through what should have been a stable block buy period now with an added retrofit change [32].

Components can have unforeseen dependencies on other subsystems within complex systems. One unique feature of the Littoral Combat Ship platform is the feature of adaptable mission modules that were notionally intended to be configured with no dependency on the baseline ship [34]. Although these mission modules are not considered part of the hull, certain features of the package systems are constructed with integral components with the potential to require changes to the baseline class. One theoretical example could be found in the Launch Handling and Recovery (LHR) system which is both part of the mine-hunting mission module and baseline hull equipment [35]. Any potential changes in the operation of the mission module would propagate further into changes to the baseline hull constructions and services that the sub-system would require.

Finally, testing of the product during and after production looms large at all facilities that manage production of complex systems such as shipyards. When a system tested fails to meet the requirement, rework is generated. One of the key facets of delay comes through the testing and acceptance process for certifying Navy ships as ready to enter the Fleet, the process illustrated in Appendix C: Delivery, Test, and Certification Timeline Illustration. As stated in the official Navy instruction for ship delivery and acceptance, "it is essential that the Navy's shipbuilding and modernization programs deliver to the Commander, US Fleet Forces Command ... complete ships, free from contractor and government responsible deficiencies. The ships should be capable of supporting the Navy's mission from the first day of active service" [36].

Putting a system-of-systems through a strenuous test environment before it may face adverse environments in the real world is undoubtedly essential to the process of *design-build-deliver-fight*. Without testing, the *design-build-deliver* component may be finely tuned but when it comes time to the *fight* (or, use of the system in adverse, high stress conditions, not necessarily direct combat) you may find that all your previous efforts invalidated.

In the U.S. Navy, the Board of Inspection and Survey (INSURV) perform acceptance testing to make recommendations to the Chief of Naval Operation on acceptance of an asset [36]. Testing causes rework both justified – when problems that should have been caught during production are found, but also unnecessarily – when the test procedure itself is the issue. As test procedures can be complicated, if they are presented ambiguously, degrees of freedom remain in the system for interpretation and unreliable results over this delivery process. Hypothetically, an operational test of a pump or control system could be ambiguous when using subjective language ("must perform satisfactorily") rather than objective evidence ("must produce pressure of no less than 150 psi"). If the interpretation of test results falls outside of specification, the representative receiving the product has the ability disagrees with those performing the test. The adjudication can persist for long periods of time. Considering the overhead, delay, and cost associated with the test procedure disagreement, this is another component of the time lost in finally delivering the capability to the Fleet [32], [33].

2.2.4 Changing Methods and Documentation

Comparing operations observed between "Shipyard A" and "Shipyard B" – the mix of products and challenges that each site faced were found to be vastly different, yet both continue to contend with the root causes that rest with requirement interpretation and implementation.

"Shipyard B" was observed to be a more mature yard that has been tasked with producing the most mature and arguably least complex designs in the Fleet with primarily Naval Auxiliary vessels [37]. However, as a yard with an active production line for both military and civilian vessels, producing ships of this mix hones skills and positively impacts the readiness of the workforce to interpret the military technical specifications.

Across all the shipyards and production facilities responsible for delivering the correct systems for the Fleet, three principal "enemies of progress" – complexity, uncertainty, and risk – are manifest in the receipt of receipt of requirements from project sponsors that can leave open degrees-of-freedom to deliver problematic solutions behind schedule and over budget. These issues above have been traced to requirements management in ensuring systematic connections between required operational capabilities and validated technical specifications. Migrating static document-based specification to the model environment can facilitate the resilience that the system requires.

2.3 Hypothesis: Collective Solution

Examples with the DDG-1000 and Littoral Combat Ship class production reflect a systemic inability to clearly focus on implementation and delivery of warfighting requirements to the Fleet. For warships such as these, as well as other weapons systems and platforms under development, the ability to fight, survive, and win is precisely the value proposition promised to taxpayers when budget to allocated toward their construction. Without a system that refines and maintains the focus on building ships that meet the high-level operational requirements, we are destined for a Fleet that falls short.

For what form a common solution to managing complexity, uncertainty, and risk in requirements might take, we can derive inspiration from the needs of jet engine manufacturer Pratt and Whitney. In a competitive market with only a small number of large, advanced business rivals, their rewards are large – massive commercial and public sales and service contracts – as is the risk of sunk multi-billion dollar development costs [38]. This case is a microcosm case study of some of the challenges faced by the U.S. Navy, namely a competition between a few powerful near-peer competitors that secretively race to get the newest technology out the door first to their own advantage. In both cases, the desire to bring nascent advances into production strongly contrasts with the engineering challenge of volatility and uncertainty reduction. Without clarity of requirements and design, disorder could prove disastrous. Pratt and Whitney countered these competing forces with a systematic link of requirements of readiness and performance that could be rapidly assessed in both operational and technical validity [39].

Given the problems that the Navy faces in transitioning requirements to reality, what is the systematic solution that this organization can use to ensure that defense systems are produced with realistic expectation to deliver on time and on budget? A 2005 Global Shipbuilding

Industrial Base Benchmarking Study introduces the concept of a "vicious cycle in shipbuilding" which has been updated and expanded in Figure 11 for the production of more general modern complex defense systems [40].

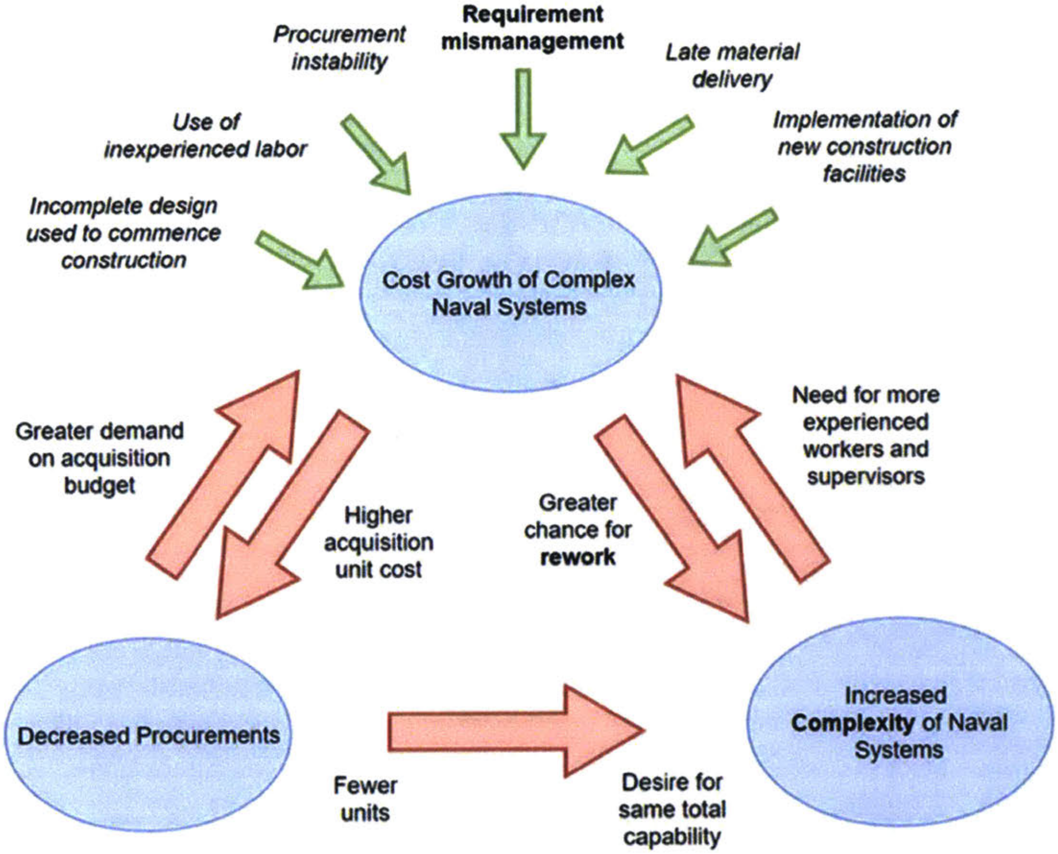


Figure 11: Vicious cycle of acquisitions, figure adapted by author from [40]

To manage systemic underperformance, one must first recognize that being robust simply is not enough. In the Naval acquisitions context, and especially naval vessel construction, we seek the most robust method available to connect requirements to the technical specification with which ships are procured and assembled, and complex weapons systems are built. Evidence presented suggests that more fidelity surrounding the informational handoffs between designers and producers would support better manufacturing, production, and general realization of complex systems. One way in which interface maturity is advanced is using Model Based Engineering (MBE). The hypothesis statement is simple: that MBE system engineering design tools will be helpful in enabling design-for-manufacturing-and-assembly and mission fulfillment. As the product needs (requirements) change, the use of digitally shared models represents the most resilient measure of designing complex systems.

Expected results achieved by using MBE are baselined on the performance of companies that also produce complex systems. The test in this thesis is to find out what model-based systems engineering/design enables. Connecting requirements to specifications may help to ensure that only the minimum amount of complexity required makes it into the final system, making the design elegant and producible. Modeling methods allow production of the right output faster, enabling designers to respond to changing needs. The following sections will investigate to what extent this is the case and provide examples of systematic approaches to ensuring the right products are built on the right schedule for the Fleet.

Underperformance Summary
Major Naval acquisition programs routinely escalate in cost and fall behind delivery schedules
Complexity, uncertainty, and risk are the principal enemies of progress that make production of these systems according to a predicable schedule very difficult
Ambiguous requirements fail to account for these phenomena through missed connection with technical specifications
Model Based Engineering (MBE) is hypothesized as a solution to the collective manifestations of underperformance explored in this chapter

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Chapter 3

3.0 Model-Based Engineering: Focus on System Production

This chapter details a set of common definitions and background on the applications of Model-Based Engineering (MBE) and Model-Based Systems Engineering (MBSE). This context will support this body of research intending to elucidate *if and how* MBSE may be useful in increasing throughput and Fleet availability of U.S. Navy new construction battle force ships and major complex weapons systems. First, we will explore a general background of systems engineering as a discipline and establish coherent and consistent definitions. Next, systems engineering will be expanded upon to explain the concept of the emerging field of Model Based Systems Engineering, what it does and does not incorporate, while again establishing consistency and clarity in definition, before finally introducing some of the theoretical goals of systems engineering modeling.

Exploring applications of Model-Based Systems Engineering within the domains of naval sea system acquisition and weapons development will further support digitization directives from the U.S. Department of Defense [41]. This thesis does not aim to provide a comprehensive overview of the practice of MBSE, nor exploring general use in the various components and steps in ship design, but rather focuses on the aspects and global principles of MBSE that are applicable to the goal of increasing production rates and Fleet capability.

3.1 Systems Engineering

Modern complex systems have many interacting parts that behave non-linearly and are difficult to succinctly characterize. The engineering that goes into them often defies a single engineering domain. Where in the past, a system could be built using only mechanical design principles, for example, today it takes almost every type of engineer to work together for a highly technically demanding feat of engineering. An interdisciplinary approach distinguishes systems engineering from traditional engineering disciplines with a focus that the INCOSE Systems Engineering handbooks suggests "enable[s] realization of successful systems" [11].

Systems engineering's customer-centric approach seeks to draw out required functionality early, a uniquely results-oriented aspect of this discipline as compared to other engineering fields. As the concept is matured and the design developed, the practice of systems engineering proceeds through validation of the system to develop a holistic picture of operations, performance, and support.

Systems engineering is often represented using a "V-Model" to define steps commonly associated across the lifecycle stages in most general projects with an example shown in Figure 12 [25]. Consideration of the unique aspects associated with the stages in lifecycle and adopting its methodical guidance is core to the practice of systems engineering. The "V-Model" is recursive and can be either applied from project start to project finish or at intermediate points in time to advance design from one phase to another.

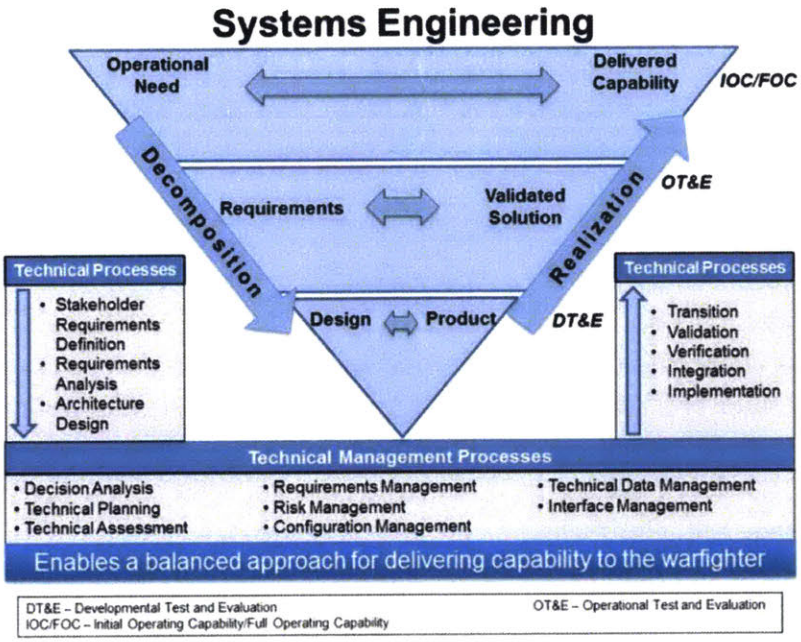


Figure 12: Systems engineering and associated processes [25]

3.1.1 Document Based Artifacts

Components of the systems engineering design process, termed artifacts, traditionally are described through different means. Methods of describing artifacts are traditionally are through the user's natural spoken language or graphical sketches and drawings [42]. These then typically get aggregated in "documents" with names such as "Requirements Document", "Drawing Package", or a "Technical Data Package" [42]. Ideally, a document should contain all information needed to build and operate system. Artifacts can be tailored specifically to a project or more "solution-neutral" in nature.

3.2 Models Used in Systems Engineering

A "model" as used in this thesis is a simplified version of a concept, phenomenon, relationship, structure, or system [8]. This abstraction can be graphical, mathematical, or physical depending on the use case, level of detail required, or the intended audience. By eliminating unnecessary components that do not materially affect the system, a model abstracts reality to facilitate rapid understanding, decision making, and testing "what-if" scenarios by predicting events or changes through control adjustment.

Some literature sources use the terminology of "Model Based Engineering" (MBE) and "Model Based Systems Engineering" (MBSE) interchangeably. While similar, these are two different concepts that imply different levels of generality of focus. Model-Based Engineering is an approach to engineering that uses models as an integral part of the technical baseline that includes the requirements, analysis, design, implementation, and verification of a capability, system, and/or product throughout the acquisition lifecycle. For the purposes of this thesis, MBE will be used as a more general, encompassing practice that includes, as a subset, MBSE.

Simply and generally, MBSE is a model centric method of engineering a system in which the design of the *system* is entirely based on models [42]. With the operative word being *system* – models encapsulate all supporting documentations, requirements, contractual obligations, and traceability of stakeholder needs. INCOSE narrows MBSE to become the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases [43]. The focus is placed on interactions between components, sub-systems, or between entirely different systems themselves, systems-of-systems (SoS).

3.2.1 Types of Models

The type of model is dictated by the specific application or scope of intended usage [44]. This research briefly identifies three major categories of systems engineering models in wide usage: requirements, visualization, and simulation. A model might have the capability to function as an example of each of these groups through different views or types of user interface [45], [46].

Requirement models. Specification of system requirements that dictate system structure by assigning technical, functional, and operational attributes to the elements can be taken as a model of requirements. Principally useful in the conceptualization phase, taking a "breadth-first" approach ensures that the scope of the system is well understood and serves to guide the follow-on technical analyses [47].

Visualization models. Advanced interfaces can display a three-dimensional or detailed interactive view of a physical system [48]. These models blend the data archival capability of digital documentation with graphical display and spatial deconfliction. When elements of the system can be traced to requirements, spatial system elements are linked with metadata regarding their function [49].

Simulation models. These models take the realities of the physical world – mechanics and physics – and computationally recreate them in a computing environment [50]. Because of the specific technical nature and application of these simulation software, their usage is not explored further in this thesis, although the utility they provide in giving design engineering the high-velocity iteration capability is acknowledged.

3.2.2 Language and Methodology Examples

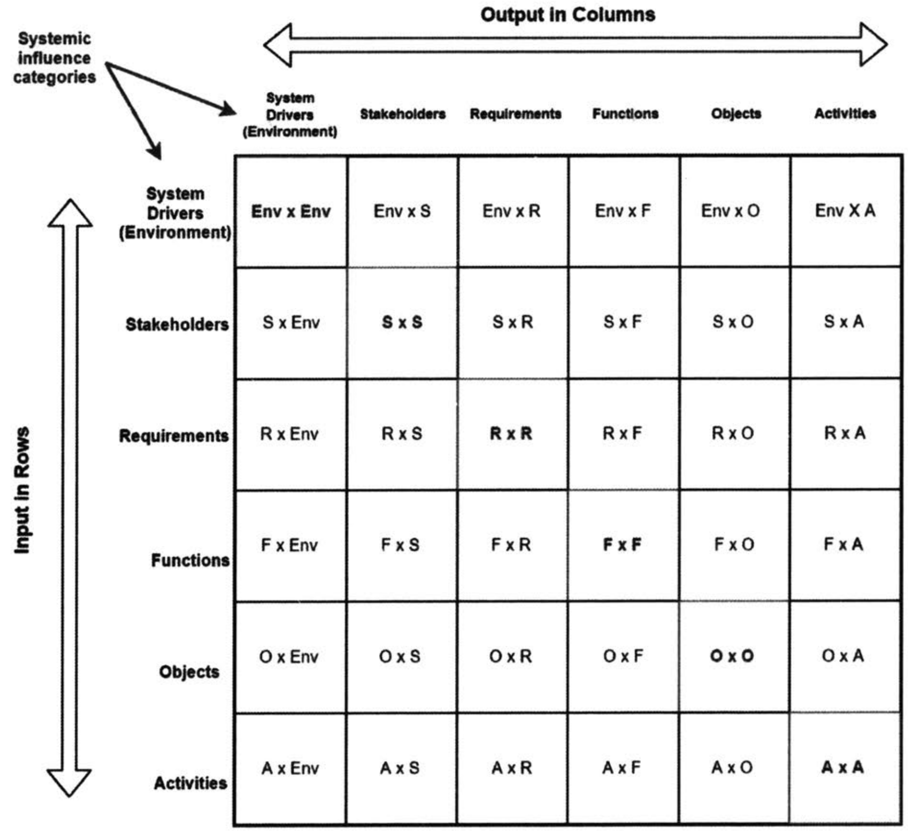
Numerous and pervasive commercial, open source, and academic platforms exist for creating models for systems engineering or simulation. In this thesis, primarily focusing on requirement specificity and fidelity, three examples of modeling languages or methodologies are highlighted for their adaptability and market penetration/usage both in the private and public sectors. For additional information, background, and further use tutorial on the examples provided below, refer to the source texts and international engineering standards cited below. This review is not intended to be an exhaustive listing of the advantages, disadvantages, and features of these modeling language examples; however, note the specific utility that each provides and the featured applications.

*System Modeling Langu*age (SysML) is the engine behind most of what is traditionally considered MBSE in private industrial, academic, and defense applications [41]. Hernandez, et al. characterizes SysML as a "general-purpose graphical modeling language for specifying, analyzing, designing, and verifying complex systems that may include hardware, software, information, personnel, procedures, and facilities" [51]. Applications in which SysML delivers the most value include requirement generation, specification, and traceability, as well as structuring the constraints on the behavior of different elements of a system. The case study featured in Chapter 5 of the requirement traceability, component dependence, and process-based cost model feature aspects of the System Modeling Language, although SysML software was not explicitly utilized.

Object Process Methodology (OPM) is an emerging language, recently codified into ISO Standard 19450 and adopted for use in many different applications to achieve the ends of complex system modeling [52], [53]. Starting with the function and type of system being modeled, the OPM language creates Object Process Diagrams (OPDs) that are capable of embedding complex relationships between "Objects" and "Processes" [53]. In a single view, an engineer can analyze vast amounts of information regarding the nature of system element interactions and the degree of interconnectedness and even derive a sense of the complexity.

OPDs are featured extensively in the Chapter 7 concept illustration of the use of model-based engineering to elucidate cybersecurity requirements for a "Fictional Submarine Strategic Missile."

Design Structure Matrices (DSM) are comparisons between groups of elements to show the interactions and architecture of the system either within a single group or within multiple groups of objects and/or processes [54]. An extension of the DSM concept has been proposed as an Engineering Systems Matrix (ESM) for more complex multi-group interaction architecture maps [8]. System Drivers, or Environment, as shown in Figure 13 are typically exogenous to the system in consideration, but map directly to elements inside the system boundary such as Stakeholders who delineate Objectives of the system and oversee the Functions, Objects, and Activities that provide the purpose and satisfy requirements of the system [8]. Both models explored in Chapters 5 and 7 make extensive use of the Design Structure Matrix tool construct to illustrate modeling system component dependencies.



	System Drivers (Environment)	Stakeholders	Requirements	Functions	Objects	Activities
System Drivers (Environment)	**Env x Env**	Env x S	Env x R	Env x F	Env x O	Env X A
Stakeholders	S x Env	**S x S**	S x R	S x F	S x O	S x A
Requirements	R x Env	R x S	**R x R**	R x F	R x O	R x A
Functions	F x Env	F x S	F x R	**F x F**	F x O	F x A
Objects	O x Env	O x S	O x R	O x F	**O x O**	O x A
Activities	A x Env	A x S	A x R	A x F	A x O	**A x A**

Figure 13: Engineering System Matrix, figure adapted by author from [8]

3.3 Goals of Modeling

System design, acquisition, and maintenance are accomplished through a disparate group of stakeholders across different organizations and might have widely varying motivations. Models seek to coalesce these competing factors in maintaining as close to a single source of information as the enterprise is willing to maintain regarding a complex system. Table 3 and Table 4 summarize the targeted purposes and lifecycle process in which a model-based engineering environment would serve for enabling operational excellence in complex system production.

Table 3: Modeling purpose, adapted by author from [11]

Modeling Purpose	Description
Characterizing an existing system	Concise capture of existing system architecture and design. Information facilitates use, training, and maintenance by displaying attributes of the system.
Mission and system concept evaluation	Applied early in the system lifecycle, models can synthesize and evaluate alternative mission and system concepts – defining mission, added value, or exploring tradespace
System architecture design and requirements flow-down	Display flow of mission and system requirements down to system elements. Different models may address different aspects of design or perform alternative technical analyses.
Systems integration and verification	Integration of hardware and software, potential for automated requirement verification and testing
Training	Simulating various aspects of the systems allows safe, cost-effective, and rapid iterations of stakeholder interaction/education
Knowledge capture and system design evolution	Provides effective, robust, and organized knowledge capture modes that support reuse and evolution following emergence of alternative system attributes, new stakeholders, and technologies.

Table 4: Lifecycle processes and modeling utility, adapted by author from [11]

Lifecycle Process	Modeling Utility
Mission analysis	Descriptive utility of the model ensure that the correct problems are addressed effectively
Requirements traceability	For the physical system itself as well as stakeholders, model can justify requirements and record technical implications to avoid mis-specification
Architecture definition	Candidate options evaluated, enabling evaluation of architecture performance and sub-system interface
Design definition	Adjust parameters for optimization, evaluate consequences, and update system model with real-world or as-built data as fidelity is refined
Verification and validation	Simulate system operational environment with data as an input for computation of critical parameters that monitor simulation fidelity
Operations	Simulations reflect behavior and operations in advance of execution for cost and time savings during planning, validation, or training
Decommissioning	Living document with updates to record changes that reflect real-time status at decommissioning

Connecting different groups of stakeholders promotes complexity management through a robust awareness of system status and elements [44]. Since modeling smooths the communication flow between stakeholder groups, Figure 14 enumerates some of the products contained in a digital model and their hypothetical interactions.

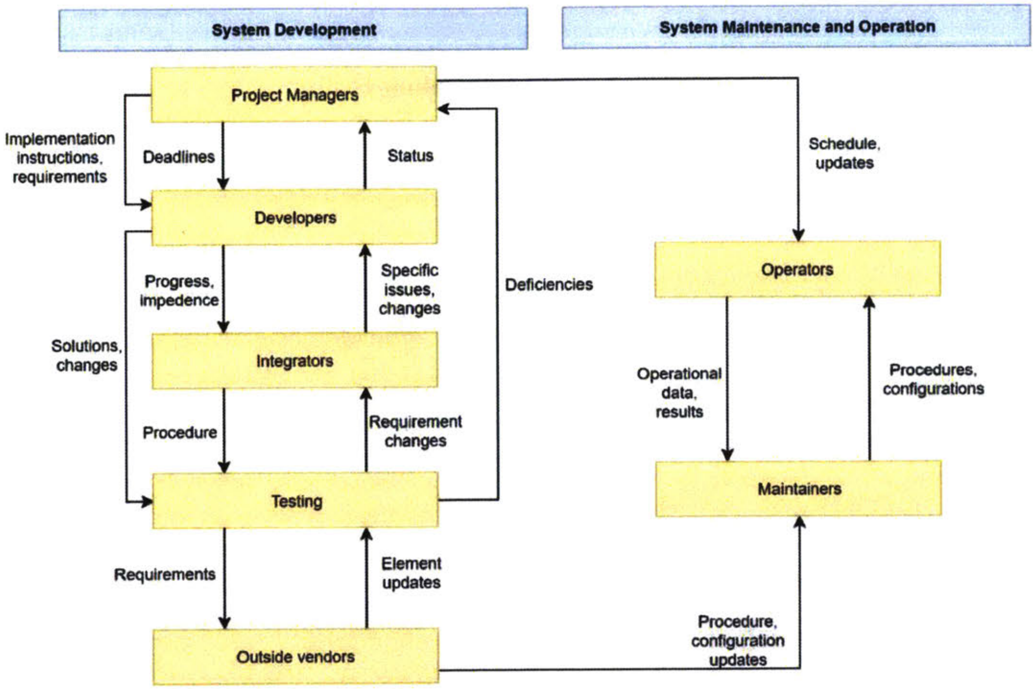


Figure 14: Stakeholder control structure with system information for modeling

A system model enables the ability to "ask questions," or query a computational representation of the "real world." This allows a designer to obtain information such as performance or capability in advance of committing the resource of prototype construction or operation. Early accuracy in constructing a model informs stakeholders of system requirement implications or system behavior in the face of change and uncertainty [55].

Model-Based Engineering Summary

Systems Engineering is uniquely results-oriented among the engineering disciplines and seeks to draw out required functionality of a system and its interfaces early

A "model" is a simplified version of a concept, phenomenon, relationship, structure, or system that can contain systems engineering artifacts

System modeling has a range of improvements to system design activities such as integration of components, requirements traceability, and visualization

Chapter 4

4.0 Mind the Gap: Models Connect *Needs* with ***Reality***

Systems engineering techniques themselves contribute to disaster because they are all paper techniques and there are only "two" instead of "N" dimensions available.

Robert Frosch, Asst. Sec. of the Navy for Research, Development and Acquisition (1966-1973)
1969 Speech to IEEE International Convention [56]

Studying alternate sector approaches to similar problems facing naval acquisitions can give insight to Model-Based Engineering (MBE) usage. Across industries that practice complex system management, common project attributes and a model-centric approach make their study applicable to potential future applications in Naval system production. A diverse set of case studies approach problems with significant positive progress underway in expanding Model Based Engineering. Each example includes the gap analysis between industry problems, and USN problems to deliver additional context into potential model-based solutions.

The case studies that follow demonstrate an industrial application both outside and inside the defense sector to validate the hypothesis of a model-centric solution to system production underperformance. One of the unique aspects of this study is its ability as an academic endeavor to "reach outside the lifelines" of experience within the U.S. shipbuilding base and leverage information flow of lessons learned from civilian endeavors that seek to design, prototype, and produce complex systems that serve a wide variety of purposes. Examining how different teams approached their problems with MBE show why they chose the approach, what tools were used, and what results they achieved that were demonstrably attributable to their use of MBE. One common thread through these case studies is that the application of Model Based Engineering, broadly defined, enabled their work to be completed faster and with fewer defects.

4.1 Small Commercial Cube Satellites

With increased space launch availability, smaller organizations such as start-up companies and university groups pursue the design, manufacture, and operation/observation of small "micro" satellites referred to as "CubeSats." An INCOSE working group explored designing demonstrators of this technology using a MBSE environment to produce artifacts such as mission definitions, use cases and associated requirements, and system behaviors [57]. To date, the development of CubeSats has been largely "intuition" based with over half of the systems subjected to a complete failure [57]. Models that serve as a single-source-of-truth with a collection of the total body of design data were proposed as a step toward formalizing quality assurance in the design and production process.

This application uses an eight-step MBSE approach for defining the behaviors of the CubeSats as shown in Table 5. Definition of system behaviors starts with formalizing the mission requirements relationship with the use case of the satellite. The mission requirements are used to create a representation of the functional architecture with input/output flows captured directly from the use case model in an activity diagram.

Table 5: CubeSat MBSE use case/implementation blueprint [57]

Step 1	Analyze mission requirements to identify enterprise-level use cases
Step 2	Define the relationship between mission requirements and enterprise-level use cases
Step 3	Capture the use cases identified in **Step 1** inside selected systems engineering model
Step 4	Develop use case descriptions
Step 5	Capture the use case descriptions in the model
Step 6	Model the use case scenarios
Step 7	Link the activities to the use cases
Step 8	Continue decomposing the activities

The approach used by this INCOSE team followed generalized system development procedures to refine a specific set of repeatable steps. Furthermore, the steps do not necessitate a specific tool and only draw on the principles of model-based systems engineering that all tools possess. This enables the measures to be easily parlayed into other systems engineering methodologies for systems under development across multiple domains. Although this study did not consider them, the same methodology could be applied to non-functional and interface behaviors.

The engineers from the CubeSat study cite benefits of conversion to a MBSE approach for requirement and functionality development including enhanced team communications, deliberate system requirements that reduce development risk and improve quality, and intra-team lesson/knowledge transfer [57]. Applied with rigor and precision, MBSE enabled quality and productivity improvement and therefore lower risk in this complex space system development process as Table 6 summarizes.

Table 6: CubeSat Case Study gap analysis

CubeSat Case Study Issue	Naval Systems Engineering Design Issue	Common Solution Approach
Traceability; "intuition-based" design	Requirement have little to no link to technical specifications	MBSE architecture traces requirements to functionality
Generalizability; non-standard computing environment	Different users have multiple tools used for their specific domain	Methodology not dependent on any specific tool and exposes common complex system attributes
Performance; High Failure Rate	Part obsolescence and low TRL components contribute to systemic failure	Use case and requirement definition approach extensible to interface requirements of piece-parts
Recursive; system behaviors necessitate layers of decomposition	Requires many iterations of engineering and changes that cause rework	Models can be recursively adjusted across the mission hierarchy with higher-level outputs as lower-level inputs

4.2 Naval Air Systems Command

Conceptualizing, designing, and producing military aircraft systems – Naval Air Systems Command (NAVAIR) shares a similar challenge as organizations charged with design of ships and shipboard systems. NAVAIR commissioned a formal MBSE study to consider technical feasibility to "radically transform systems engineering through Model-Centric Engineering to rapidly deliver the needed capabilities to the warfighter for Large-Scale Air Vehicle Systems" [58]. Extending the academic study to production, NAVAIR seeks to be among the first in the DoD to bring the benefits of a model-based engineering environment to meet the reality of complex system design [59].

The use of a Model-Based Systems Engineering approach in this case study has enabled the employment of a multidisciplinary design, analysis, and optimization (MDAO) approach for computation of tradeoffs and optimum design points. Use of these methods requires a design environment capable of simultaneously considering a breadth of simulation and computational artifacts inside a holistic MBE environment [58]. Table 7 covers the objectives of migration towards this holistic MBE approach.

The end-state vision includes design resilience to small changes in components or requirements by providing an accurate and clear picture of the effect on the overall aircraft. An example given in the study was as external sensors change, the model would be able to forecast the effect on key performance parameters of aircraft aerodynamics or radar observability which were previously designs maintained in document-based format separately [59].

Table 7: NAVAIR Case Study gap analysis [58], [59]

NAVAIR Case Study Issue	Naval Systems Engineering Design Issue	Common Solution Approach
Multi-disciplinary Optimization; Definition of UAS capability in designs enabled by workflow analysis	Similar capabilities such as fuel economies, range, and speeds produce a comparable workflow across different designs	Integrated multidisciplinary optimization enabled by model-based specifications
Change Management; Input and output parameter inter-relationships	Effects of element additions not well understood regarding interactions and emergent behaviors	With a single element change, models capable of generating "thousands" of engineering solutions to identify the optimal
Tradespace exploration; Design of Experiments (DoE)	Sensitivity analysis of component or input changes often obscured by complexity	Exploitation of previous model runs that leverage prior attempt data for use in early-phase design under new mission capability requirements

Based on the results of that study, NAVAIR publicly reiterated an intention to move toward model-based system engineering representation of their requirements and specifications. Commander, Naval Air Systems Command, Vice Admiral Paul Grosklags, as reported in the proceedings of the U.S. Naval Institute, stated at the 2017 National Defense Industrial Association's Systems Engineering Conference [59]:

I've got a model of my threat; I've got a model of my blue forces; I've got environmental models, whether I'm operating in an [electromagnetic warfare] spectrum or I'm operating in the acoustic spectrum under the water; it's all done with models.

NAVAIR further contends that extension of the model-centric environment to the production contractors may also create benefit to reduce [59]:

[writing] a 500- page specification with 20,000 shall-statements, and we give it to industry and go, here, [design] this. We don't give them the threat models, we don't give them the blue force models, we don't give them that system of systems family model we just built. We give them a 500-page document with 20,000 shall-statements.

4.3 Weapon System Guidance and Navigation

During a recent routine technical refresh period, the guidance system of the U.S. Navy's Strategic Weapon System undertook a major upgrade. The technical challenge that a guidance system on a strategic missiles must overcome is described by MIT Lincoln Lab technical staff member Paul Zarchan [60].

Strategic ballistic missiles are different from tactical guided missiles because they travel much longer distances and are designed to intercept stationary targets whose location is known precisely... In this type of strategic application, precise instrumentation is necessary so that the interceptor can steer to the correct position and velocity states at the end of the boost phase. With the correct states the missile will be able to glide ballistically, without further corrective maneuvers, toward the target.

Although the specific technical documentation regarding this case study is distribution limited, we can explore some of the techniques, motivations, and benefits that the Charles Stark Draper Laboratory (CSDL) realized during the evolution of their development of the Life Extension for the Guidance sub-system. Based on exceptional cost of pad-launching ballistic missiles, a principal government constraint was placed on physical demonstrations [9]. Therefore, testing required a digital based design capable of validating the design iterations before convergence on the final product that would reach physical production. With the early knowledge that the engineers would need a proprietary model-based environment, they first developed the computing infrastructure necessary for the simulation analysis. Chapter 6 will explore the further verification and validation that was central to the success of these models.

Table 8: Draper Guidance MBE Case Study gap analysis

Draper Case Study Issue	Naval Systems Engineering Design Issue	Common Solution Approach
Testing; Difficult to physically launch validation flights	Expensive prototypes, difficult to scale and replicate	Model-centric testing environments that faithfully replicate operation
Integration; Design of a sub-system with complex interfaces	High-risk collection of many systems-of-systems whose functionalities are dependent for total system operational success	Computing technology allows the developer to maintain common cognizance over tools used in product design

4.4 Industrial Materials Plant Machinery

The aerospace and defense sectors are not the only areas in which benefits of modularity and flexibility in design are realized. The field of industrial plant machinery design must also contend with individualization in requirements and dynamic societal changes that affect product configuration [61]. Equipment used in the processes of mining, refinement and shipping has been identified for long term gains through implementation of modularity and flexibility in overall plant configuration. Figure 15 summarizes the problem and systems faced in modularizing mineral processing plant machinery. The intended approach of application of MBSE to industrial plant machinery consists of five steps summarized in Table 9.

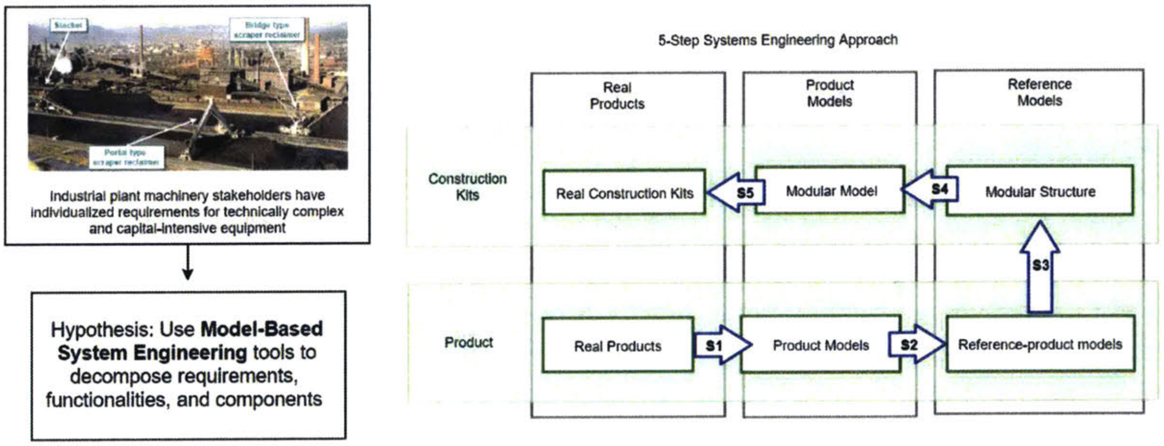


Figure 15: Industrial plant machinery MBSE application, figures adapted by author from [61]

Table 9: Five step process used in modularity motivated MBSE exploration [59]

Step 1 (S1)	Existing products and documentation analyzed with corresponding product models created
Step 2 (S2)	Levels of abstraction in the product models created, elements transferred to a common reference product model
Step 3 (S3)	Iterative adaption and enlargement of the reference product model. When combined with further product reference models, enables the ability to create a cross-product reference model
Step 4 (S4)	Existing product models and cross-product reference models creates a structural description of all possible characteristics for one or more products and now describes the total "construction kit"
Step 5 (S5)	Implementation of construction kit from model specifications

The case contends that development of modular products is necessary to contend with their business environment and adoption of a MBSE design approach would be uniquely suited for the needs of their industry. Systems models using a generic SysML tool framework deliver consistent management over the entire scope of product development information by delivering multiple levels of view abstraction [61]. Due to the limitations in scale and scope of individual cognition, abstracting views allows engineers the ability to absorb interdependencies at a manageable level [6]. The authors of the case contend that a matrix-based representation method contains a large number of characteristics of dependency between elements, an approach that will be leveraged in the subsequent case studies of Chapters 5 and 7 [61].

The analysis team concluded their study by presenting their MBSE model to the industry sponsor to identify standardization possibilities in the portfolio of heavy mineral processing equipment, specifically the portal-type reclaimer [61]. The reconfiguration suggested a requirements model developed through the steps in Figure 15 and Table 9 to yield a result of a consistent construction specification for the industry sponsor organization [61].

With a product development cycle highly characterized by system element interdependencies and design iterations, use of models as performed in this study offer assurance of internal consistency and analytic deduction quantitative relationships where required as summarized in Table 10.

Table 10: Industrial Case Study gap analysis

Industrial Case Study	Naval Systems Engineering Design Issue	Common Solution Approach
Modularity and Flexibility; addresses individuality in requirements	Imperative to be able to change components as requirements call for configuration updates	Product and cross-product models capture interface dependencies
Temporal uncertainty; elements developed today for delivery years later	Details of component sub-systems – often "Government Furnished Equipment" – are not provided to platform designers	MBSE provides common basis for product developers to communicate, enabling consistent representation

4.5 Israeli Defense Force "Iron Dome"

The "Iron Dome" system was developed to provide ballistic missile defensive capability over Israeli cities vulnerable to small-scale terrorist rocket attacks [62]. As threats in this environment adapt to defensive measures taken around their target, stakeholders charged with the systems that provide safeguard face questions of how best to transition concepts quickly to production. This case study holds the Object Process Methodology, discussed earlier in Chapter 3, as an example of a model-based systems engineering framework possessing the fidelity and abstraction to foster the level of rapid evolution that this system requires [62]. The authors of this study argue that configuration management and "cross-functional impact tracking" remains a significant issue among many models in which inputs are dynamic and dependent upon uncertain actors such as terrorist organizations and unstable nation states. Many other MBSE tools such as UML-based SysML tools present user interface difficulties in keeping them up to date. The authors further assert that use of OPM-based tools "unifies the system's functional requirements specification and evolutionary dimensions within a single, overarching, holistic model" [62].

Recalling that an OPM model captures structural, functional, dependency, and behavioral system attributes within one unified view, it was chosen to model the weapon system to provide complexity management and simplicity [52]. The concept of an "Evolving System Model" aligns developers along the idea that model remains aligned with the current perception of the system at all times – an alternate frame of the "single-source-of-truth" concept [60]. The ballistic missile defense system modeled in their study is hypothetical but modeled closely from open-source information on the Iron Dome system. Modeling of the system begins by defining the first-level decomposition of the system components to determine a high-level structure. Functionalities are assigned to each sub-system as shown in Figure 16.

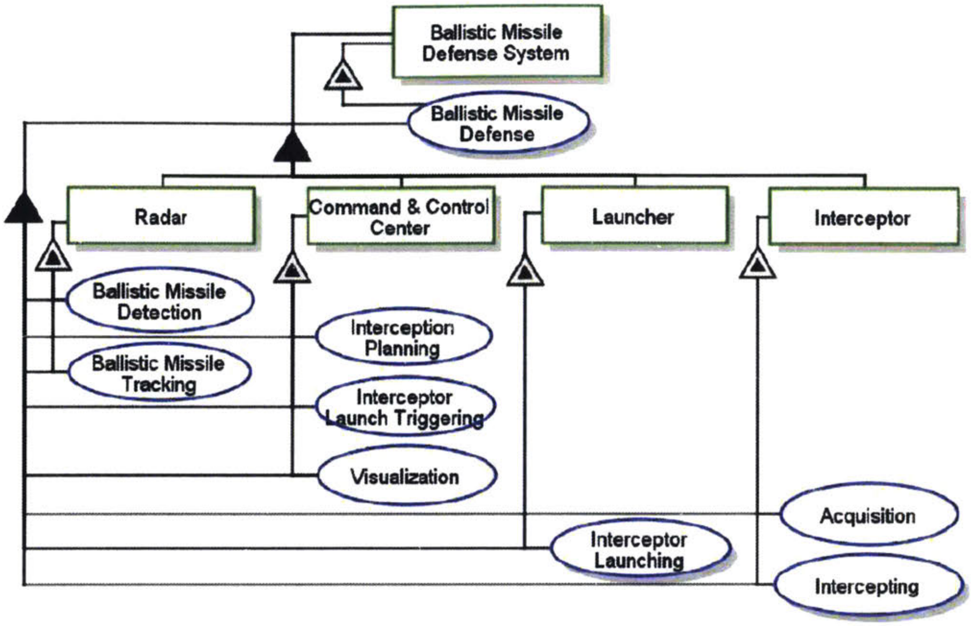


Figure 16: Structural-functional top-level view of a ballistic missile defense system, from [62]

The view from Figure 16 is paired with models of a sample operational scenario modeled by a process that shows system and constituent element functions [62]. With OPM, fidelity can be added to each "object" and "process" in the model to create a holistic system with virtually unlimited functionality in simulation. This modeling technique then easily enables the evolutionary aspects required of a system model regarded to be the "single-source of truth." OPM formalizes the distinction in the model between structural and functional components of the system and operation while providing usable model views that retain valuable layers of information. A summary of the approach detailed in this case study is contained in Table 11.

Table 11: Iron Dome Case Study gap analysis

Iron Dome Case Study	Naval Systems Engineering Design Issue	Common Solution Approach
Production agility; adversaries adapt faster than defensive systems can be fielded	Model language proves too cumbersome for most concept level work on large scale complex systems	OPM provides a way to transition quickly from concept-level study to production through bi-modal graphical and textual information presentation
Holistic model; capable of retaining information on the structural and functional aspects of the system	Managing structural and simulation models in parallel can be difficult to ensure that the latest updates to partition and interface to provide valid simulation outputs	OPM unifies the views of structure and operation to a single view giving the user the ability to seamlessly alternate between update of both sets of system attributes
Complexity management; integration across sub-systems contributes to larger scale in specifying the requirements of a system	"Commercial" systems with a decreased refresh rate contribute to obsolescence and the need for integration among the combat and mobility sub-systems inflates the amount of element interaction [63]	Unification of the static-dynamic views at various level of detail within Object Process Methodology alleviates system complexity and simplifies its management

4.6 Set Based Design Framework

Set Based Design (SBD) presents an inherently resilient approach to the development of complex systems, possessing unique features that allow us to adapt to changing requirements [64]. In MIT Department of Mechanical Engineering course 2.703: Principles of Naval Ship design, rigorous application of Set Based Design was applied on a ship design project from August – December 2017 [65].

Hull Form Exploration was an application particularly well suited for Set Based Design with computationally intensive design parameters such as propulsion powering and resistance. Restructuring the ship design process to more strongly leverage MBSE tools helped to alleviate this specific issue by codifying the system dynamic factors altered by changing a single parameter. The model of requirements could be linked to performance parameters to indicate a change in requirement performance when one aspect of the software model is changed.

Collaborative engineering plays a central role inside the Set Based Shipbuilding environment making use of "model-based design, integration, and verification tools, [and] collaborative engineering environments" [66]. Use of digital modeling tools allows for rapid search of alternatives that may be "dominated" or "undominated" across multiple measures of effectiveness. Figure 17 illustrates a sample analysis view during a set-based design procedure of baseline ship hullform selection. Software can rapidly deliver performance analyses of many variants at a time to enable comparison across measures of effectiveness to establish dominance criteria across multiple phases of down-selection.

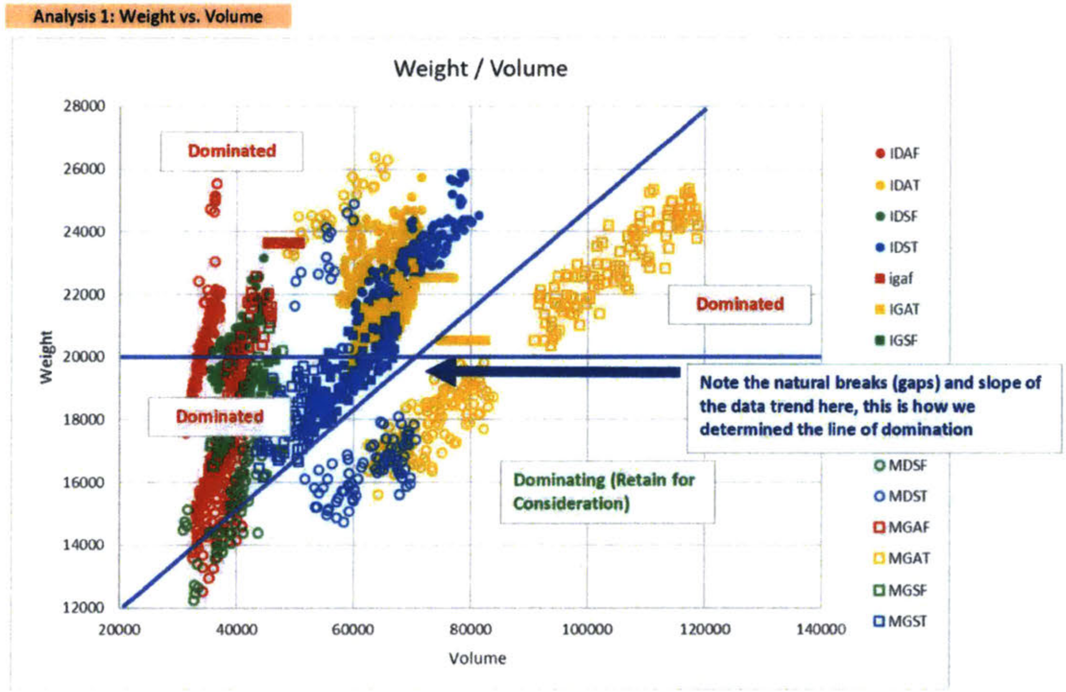


Figure 17: Set Based Design analysis comparing variants of a medium-surface combatant [65]

When designing multiple interdependent elements, communication is observed to naturally enhance the quality of the design process [10], [15], [38]. Set Based Design promotes communication through comparison of the correlation between performance parameters that span multiple engineering domains. Model-based environments that aid in the generation of quantitative data help to reduce the effect of inherently-biased overall measures of effectiveness by promoting the usage of data filters.

Table 12 presents a comparison of how model-based engineering principles enables the procedure of set-based design demonstrating a key symbiotic relationship between a deliberate embrace of high-velocity learning modeling technologies and a set-based engineering approach.

Table 12: Set and Model-Based Engineering, table adapted by author from [67]

Function	Set-Based Approach	"High-Velocity" Model Based Engineering
Search: How should solutions be found?	Define feasible design space, then remove options with documentable inferior solutions	Facilitating rapid experimentation within the design space
Communication: Which ideas are communicated to others?	Communicate sets of possibilities that remain after application of Pareto-style dominance	Digital technology is adaptive; fits the people and processes that are already in place
Integration: How should the system be integrated?	Look for intersections in the sub-system space that meet holistic system-of-system requirements	Focus on informational handoffs as operational design improvement points
Selection: How is the best idea identified?	Design in parallel on each alternative until down-selection. Look for low-cost, rapid tests to prove either infeasibility or dominance.	Simultaneous consideration of multiple variants at a time without inherent parameter bias with early elimination rounds
Optimization: How should the design be optimized?	Paradigm shift to pursue repeatable elimination of dominated alternatives over "optimization"	"See-swarm-solve" iteration patterns made possible via digitization of specification and automated analysis
Specification: How should you constrain others with respect to your own subsystem design?	Use minimum control specifications to allow optimization and mutual adjustment.	Partners both upstream and downstream in the design process compare a suitably large set of alternatives with mutually agreeable dominance criteria
Decision risk control: How should one minimize the risk of "going down the wrong path?"	Establish feasibility before commitment. Pursue high-risk and conservative options in parallel. Seek solutions robust to physical, market, and design variation (i.e. resilient).	Digital tools retain designs concurrently to enable the practice of retaining many designs and applying constraints/requirements simultaneously versus taking a single variant through the "design spiral"
Rework risk control: How to minimize damage and control unreliable communications?	Stay strictly within sets once committed. Manage uncertainty at process gates.	Finding faults sooner rather by mutual and quantitative validation than later mitigates the cost and schedule penalty

4.7 Takeaways: Principles for Complex Systems Acquisition

Development Speed. Considering the mercurial nature of the global security environment, military planners and engineers will not be able to anticipate future needs and must find products able to reach the market faster and more efficiently. Speed throughout development comes from adapting to changing requirements to solve problems with high velocity, and the process is slowed with waste and rework when the wrong features are constructed into the system [68].

Unified Language. A major problem in the realm of military shipbuilding is that for systems engineers, multiple stakeholders speak using a differing vernacular, with disparate languages of engineers relevant to ship design and building [69]. The case studies demonstrated how modeling can be used to help improve communication flow through different phases of design. MBSE uses its cross-disciplinary nature to enable analytical functions, to develop models of a system including, for example, geometry, structure, electrical distribution network, information support network, propulsion sub-system, and hull hydrodynamics [62], [65].

Concept visualization. By visualizing how components come together, we can avoid as much of the ad hoc engineering that occurs when components are assembled without routing specification [32]. Complexity must be viewed from different levels and angles to get a full grasp on what is contained inside. Model-Based Engineering enables the "helicopter" functionality of ease of movement around a system that provides for the cycle between looking holistically and then deep again, with ease that is required to fully understand the breadth of the system issues and individual component interaction [8]. By easily switching between views at high level and those with more detailed granularity, MBSE provides a venue for the process of abstraction as part of the strategy to deal with complex systems.

Integration hub. MBSE does not end with conversion of specifications and interface control documents to a model-centric format. System architecture models provide a hub for data integration and transformation across the product lifecycle. Since we are focusing on the manufacturing and speeding up of production, the ability to link analysis through the systems model to provide insight into the "why" behind architectural level decisions to promote thoughtful change management practices [44].

Set Based Design and collaborative engineering. Making use of "design, integration, and verification tools, [and] collaborative engineering environments," models enable the ideal collaboration environment that Set Based Design leverages [66]. Raising the level of design abstraction in a model-based engineering environment, more people can add their perspective and enhance the collaborative environment with more participation in real time on a digital constantly updating product. Set Based Design further identifies faults in the design earlier in the process through the retention of the full set of the feasible design tradespace before they become more expensive [38].

Our acquisition strategy can shift from document based to model based to theoretically enable different practices conducive to increasing throughput in our nation's shipyards. Potential examples of such practices include contract structure, management operational processes, or engineering design-based changes. These will allow shipbuilders to better understand their scope of work and execute the construction more efficiently and cleanly, decrease the average turn-around-time for construction project and average throughput capacity.

With a better understanding of the ship design process, incorporation of improvement practices will become easier. Using MBSE grants such a flexibility to designers. In addition to helping identify the priority of ship design tool development activities, this design process model is now being used alongside traditional planning processes in the planning for near-term ship design projects [70]. The two novel cases studies of shipbuilding and weapons development in the subsequent chapters will use these principles throughout the model process as a test to the hypothesis of their productivity conducive effects.

MBE Case Study Summary
In commercial projects, MBE can be observed to facilitate traceability and rapid recursive design iterations to improve quality and rate of production
Other sectors of the defense enterprise have pioneered MBE to manage complexity and control changes within a specification
MBE can also enable a key process family called Set Based Design rooted in collaborative engineering, alternative optimization, and risk control
These case studies demonstrate a breadth of application with micro-lessons in each application that can be applied to the Naval construction establishment

Chapter 5

5.0 Case Study: Shipbuilding Production Model

For decades, constructing large scale complex systems has proven to be a difficult endeavor for the Navy. Significant underperformance has manifested itself in delayed deliveries, failed testing, and skyrocketing acquisition costs (see Figure 4 regarding delivery delay and [12] regarding cost overruns). Stakeholders involved in the design and production of complex naval systems cite highly variable and poorly defined requirements as a key contributor to delays due to rework, as investigated in Chapter 2.

One hypothesis is that requirements traceability on a system-wide scale will more clearly link operational capabilities with the technical methods that make them feasible. We have demonstrated that companies or organizations involved in manufacturing of complex systems seek out model-based digital solutions with increasing frequency to earn faster returns on their technology development investment when compared with alternative methods of handing complexity in production.

This case study focuses on the design of the next generation hospital ship for the U.S. Navy as investigated as part of a final capstone design project for the MIT Naval Construction and Engineering Program [71]. A model rendering of the final design results is shown in Figure 18. The design team was responsible for generating requirements to design the ship based on input from the U.S. Navy Bureau of Medicine, the officers and crew of the current hospital ship USNS *Mercy* (T-AH 19), and other sources within the Navy Medicine enterprise.

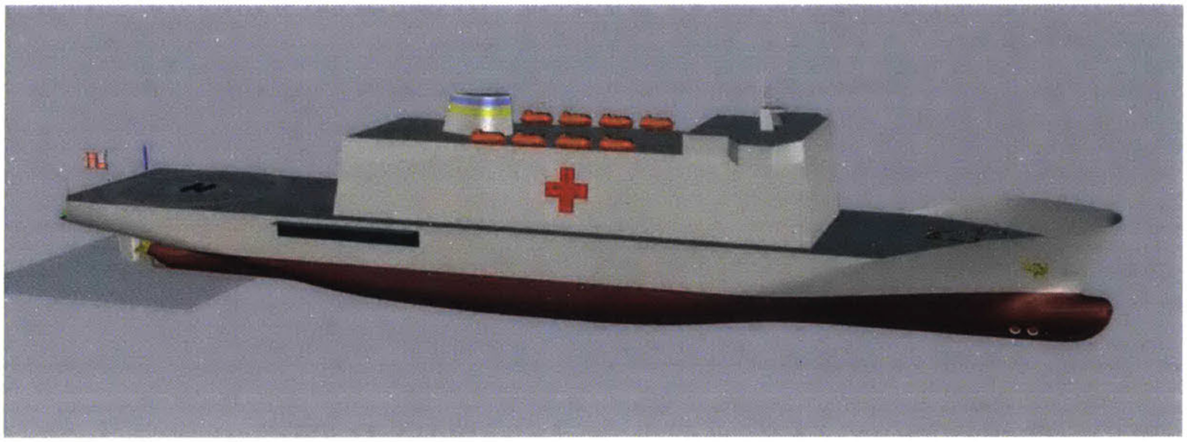
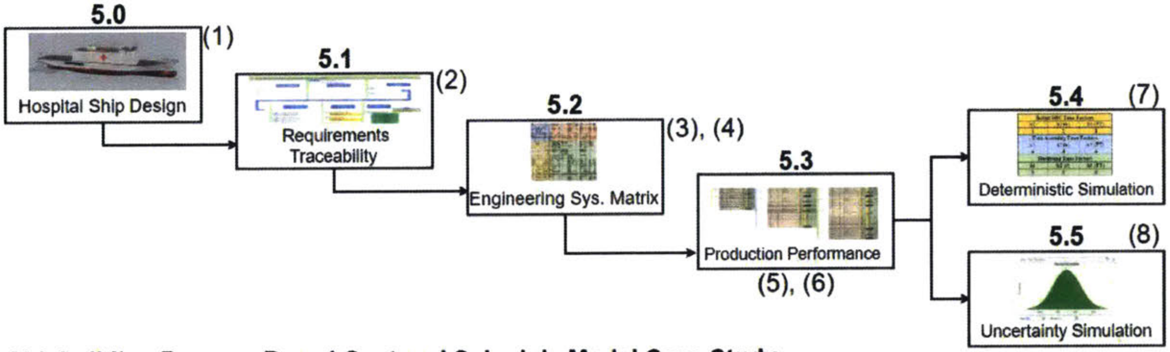


Figure 18: Design rendering of Next Generation Hospital Ship (T-AH 21) [71]

During the concept design, the team received project information from sponsors spread across several disciplines, highlighting the need for a systematic method to capture stakeholder needs and codify them into requirements useful to engineers. As the design evolved and additional stakeholder and engineering knowledge was added to the project, the systematic solution was also able to capture conceptual changes and translate into technical specifications.

This application to the hospital ship design examines different topics and questions that model-based systems engineering usage presents in the practical sense of production. What are the implications of having information that connects required operational capabilities of the past to a future reality in production? What form can a resilient acquisition architecture take to address the uncertainty of an evolving battlespace? This case, summarized in Figure 19, suggests a framework that addresses these questions through virtual representations of reality used to solve real work physical problems of design and construction.



Shipbuilding Process-Based Cost and Schedule Model Case Study

(1) Case study focuses on developing requirements and evaluating change during the production of a new class of U.S. Naval Hospital Ship

(2) Required Operational Capabilities (ROC) decomposed multiple levels into aspects of technical design and component systems usable in engineering design

(3) Relationship between requirements and system components (SWBS groups) is defined and quantified in an Engineering Systems Matrix

(4) Changes in requirements or components will generate a list of affected elements used in a process-based production cost model by deriving affected components from the change

(5) Production performance is modeled through approximating quantity of sub-tasks derived from system elements affected by a change in a requirement

(6) Labor hours measured through linear combination of sub-tasks with coefficients that correspond to the stage of construction that the ship is in when the change is ordered

(7) Production process-based cost model simulations are compared using deterministic inputs

(8) The addition of uncertainty distributions for inputs are compared using Crystal Ball software for comparison with the deterministic outputs

Figure 19: Shipbuilding production process model chapter workflow

5.1 Hospital Ship Requirements Model

5.1.1 Required Operational Capabilities

A complex system is designed to satisfy a functional purpose – to accomplish a required operational capability (ROC). These ROCs are often abstract, and they can be – skilled engineers should be able to handle a seemingly vague sponsor need. The trouble is that ROCs, often imprecise, are almost never requested in units or parameters that are suitable for a design space exploration. For example, when a sponsor asks for twelve operating rooms and accommodation for one thousand passengers, it is difficult to size the electric and auxiliary plant from those figures alone. Nominally, ships or other complex systems are built to cover a deficiency in capability or capacity in a force structure. This discrepancy could be performance of a function or new action incapable using the current equipment such as the need for a ship that can get from San Diego to Japan in a certain number of days, or a new submarine with certain performance characteristics that allow us to counteract our adversary's position better. Requirements can be traceable both upstream and downstream of their statement generation [72]. Starting with required operational capabilities, a requirement map connects capabilities to design specifications and technical elements of the proposed construction of the hospital ship.

Likewise, starting with "required medical capability" does not yield parameters useful to design or select any particular set of equipment. This case study uses a systems engineering model to map *functional* requirements the Hospital Ship to *technical* requirements capable of directly linking to model-based specifications in production. This connection facilitates a resilient *conceptualize-design-build* sequence by linking a ROC seamlessly with its technical design parameters.

Each of the top-level requirements track to more detailed technical specifications that have documented traceability to the lowest level using a derived requirements tracking program [73]. Tangible multi-dimensional traceability of requirements enables stakeholders to observe the relationship between need, concept, design elements, and a final technical implementation of the system. A model of the connections can show in real time the effects of a dynamic requirement environment and allows consideration of a change on a technical basis.

Required Operational Capabilities applicable for the design of this case study's hospital ship are shown in Figure D-1 in Appendix D: Requirement and Component Interaction.

5.1.2 Requirements Model

This thesis proposes that a systemic connection should start as early as possible in the acquisition cycle so that technical specifications can adapt to potential rapid requirement shift. As explored in Chapter 2 with the *Zumwalt*-Class (DDG-1000) – the acquisition problems that the program suffered from did not result from making poor engineering decisions and system choices; the true problem was found in the inflexible requirements that failed to adapt to a changing warfighting concept.

This model replicates the informational handoff between capability needs and technical solutions where, in practice, disconnects have been shown to plague the production of complex systems in requirement translation [38]. Figure 20 represents the structure of the dynamic model that handles changing upstream parameters by altering the design-level requirements.

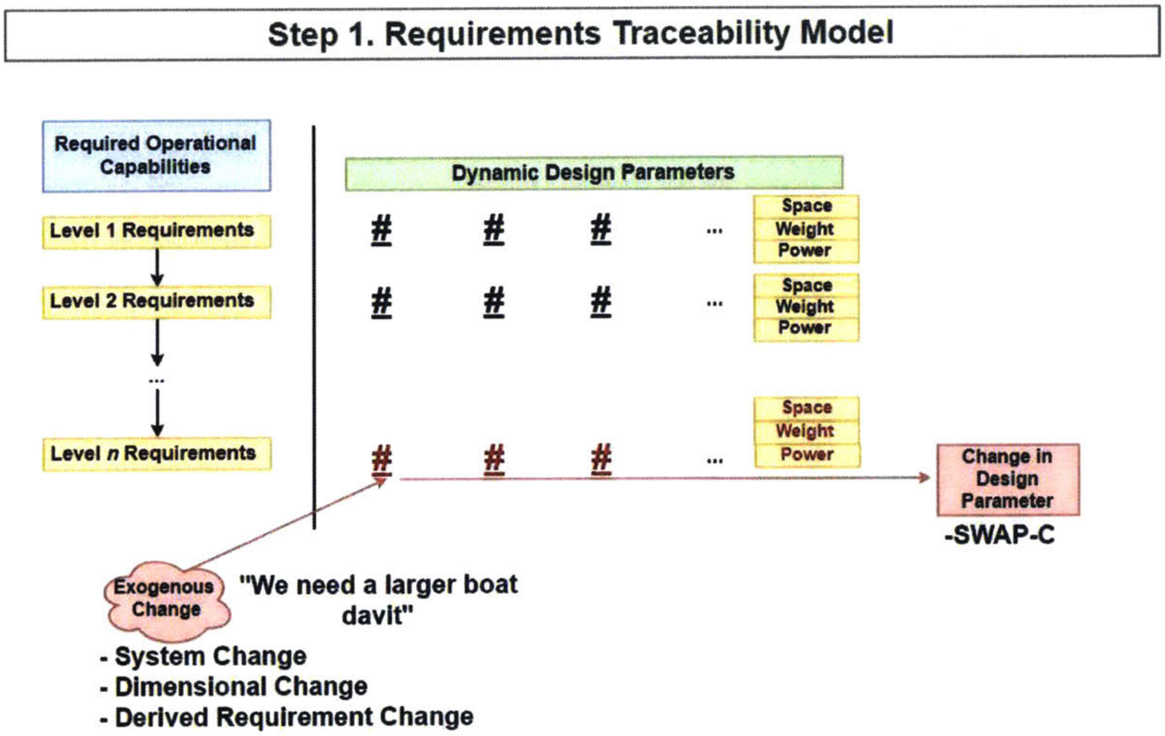


Figure 20: Production Model Step 1 - Requirements Traceability

No matter how complex the traceability tool becomes, this case study's spreadsheet of requirements traceability alone will not change the course of any major acquisition program. These programs face multi-dimensional issues that call for designs inherently adaptable to the world that they are delivered into. However, a more resilient connection of requirements to technical specifications coupled with proper high-velocity review and refresh cycles delivers a solution to address issues of program requirement fidelity. Since "model-based" tools struggle to be captured in this "document-based" thesis, only limited sample views are contained below. In Figure 21, by constructing the engineering background of technical derivation of required operational capability, we gain insight into what changes in capability could mean for the design parameters of the ship. Although the model does not yet extend into the detailed design phase, this parameter model can highlight specific consideration areas to focus a design effort.

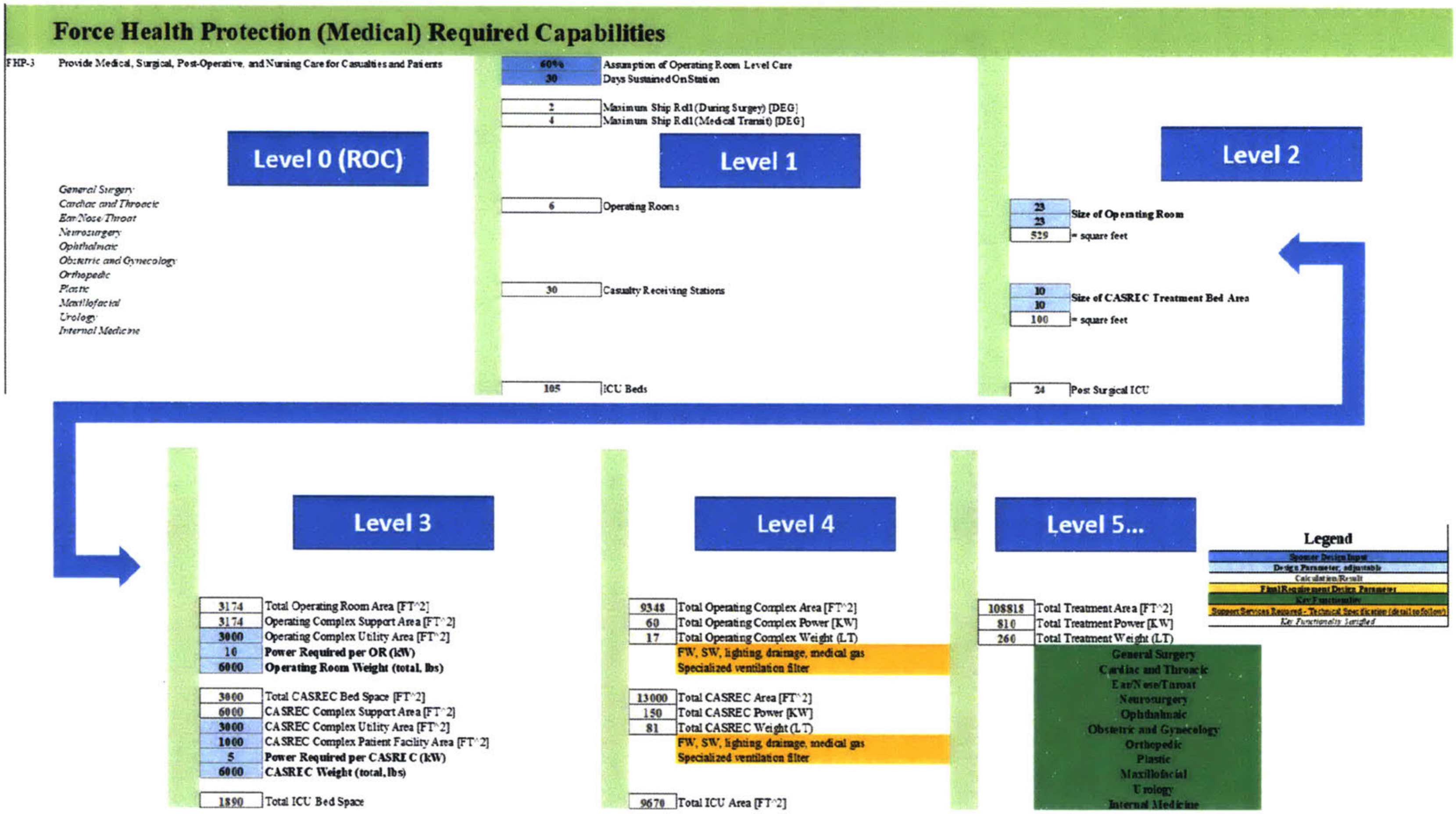


Figure 21: Functionality of requirements traceability model

5.2 Engineering System Design Structure Matrix

An approach closely related to network analysis to directly investigate interactions between individual system elements in a matrix is the Design Structure Matrix (DSM) and its extension as discussed in Chapter 3, the Engineering Systems Matrix (ESM). The "ESM" term will be used in this chapter to denote the full model of requirement and component interactions explained below. In constructing the ESM for this case study, each element of the physical world relates to a stated operational requirement. The idea of a ESM can be extended to compare the links or element connections between boundary external "system drivers" and elements that a systems engineer would concern herself with such as stakeholders, requirements, and components of an engineering system [8].

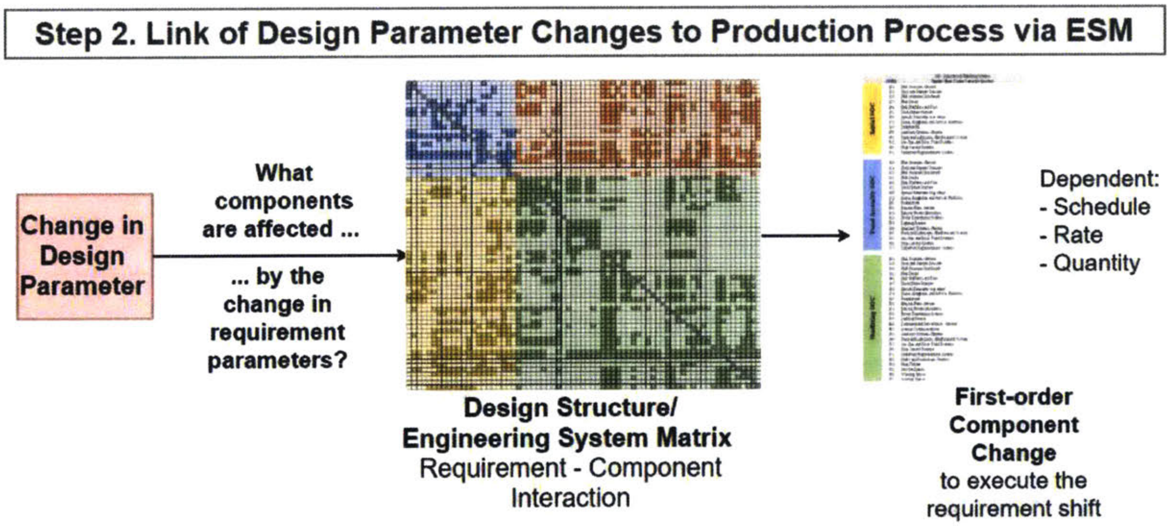
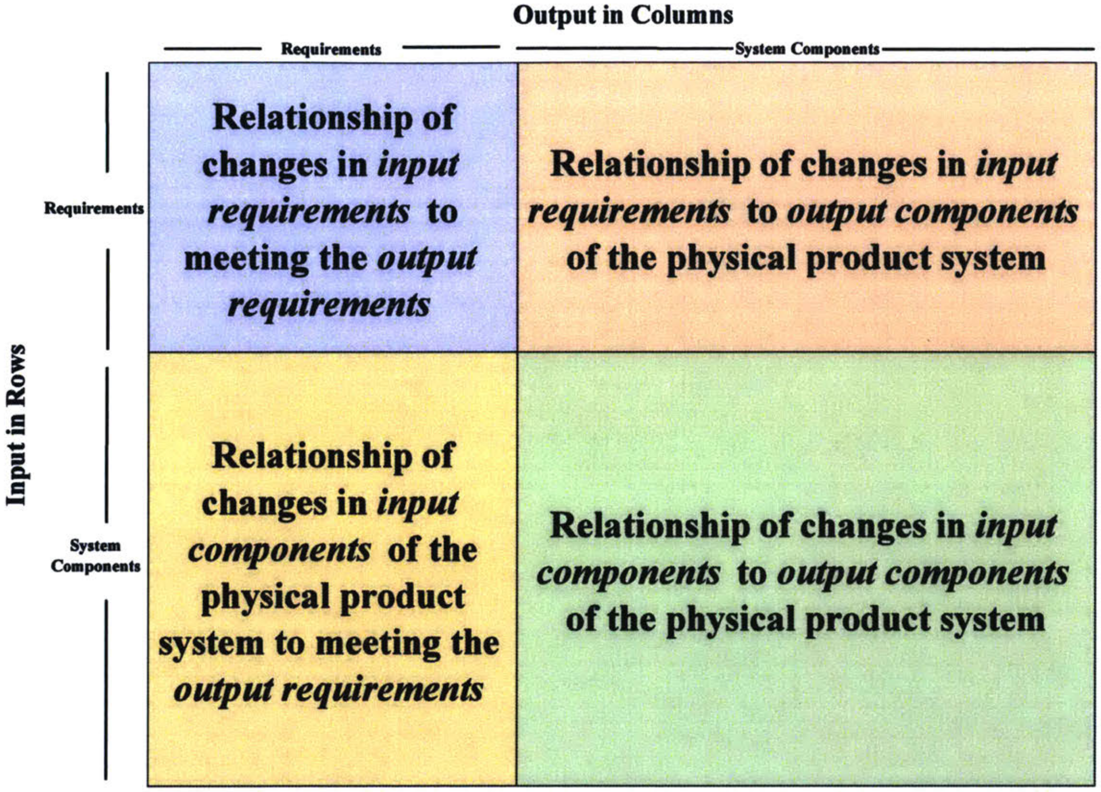


Figure 22: Production Model Step 2 – Component Interactions

The goal and structure of this portion of the shipbuilding model is shown in Figure 22. A meta-model ESM that shows the following relationships as displayed in Figure 23 with a blank template with more detailed listing of the input and output entries listed in Appendix D: Requirement and Component Interaction. This component of the model starts with an ESM that displays elements of interconnectedness between elements of the system and the requirements of the components. This yields four individual DSMs (the four quadrants in Figure 23) which can illuminate a single design relationship between requirements and system elements.



Output in Columns

Input in Rows

	Requirements	System Components
Requirements	**Relationship of changes in *input requirements* to meeting the *output requirements***	**Relationship of changes in *input requirements* to *output components* of the physical product system**
System Components	**Relationship of changes in *input components* of the physical product system to meeting the *output requirements***	**Relationship of changes in *input components* to *output components* of the physical product system**

Figure 23: Engineering System Matrix (ESM) model connecting ROC to System Components

Depending on the scope of the model, the dependency matrix can represent information to any level of fidelity. Even at a high level, as demonstrated in this case study, we can reap clear design benefits. Figure 24 shows how each of the physical design elements are connected to operational requirements by highlighting which physical components are mapped to satisfying requirements. If a component is "orphaned" – defined here as not connected with satisfying an operational requirement – then close consideration of its inclusion in the final design must be made. Likewise, the ESM shows which groups of physical elements depend on other groups to give an idea of the degree to which aspects of design may depend on others. For example, in Figure 24, the 200-SWBS component group representing the propulsion sub-system is observed to be highly dependent on aspects of the physical hull structure of the ship. The ESM would assist an engineer in determining how changes in the hull structure sub-system, potentially to hull size and shape from which powering and resistance requirements are derived according to the speed capability level, may impact the propulsion sub-system.

Each node reflects the quantitative nature of the dependency involved in changing the row-variable to the corresponding first-order change in the column variable, either "proportional", "inversely proportional", or "variable" denoted by the nodes marked with **P**, **I**, or **V** respectively in Figure 24 and Figure 25.

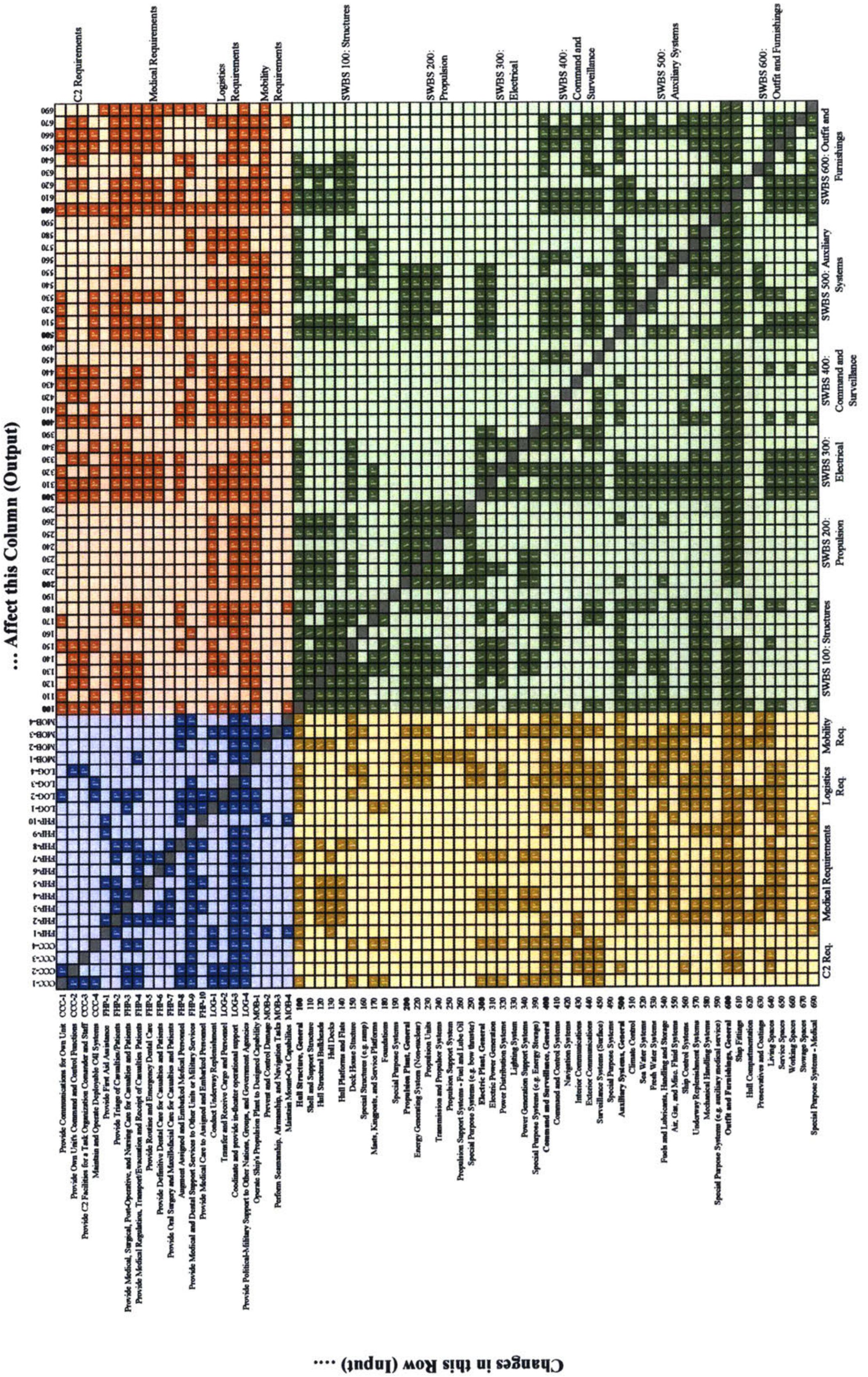
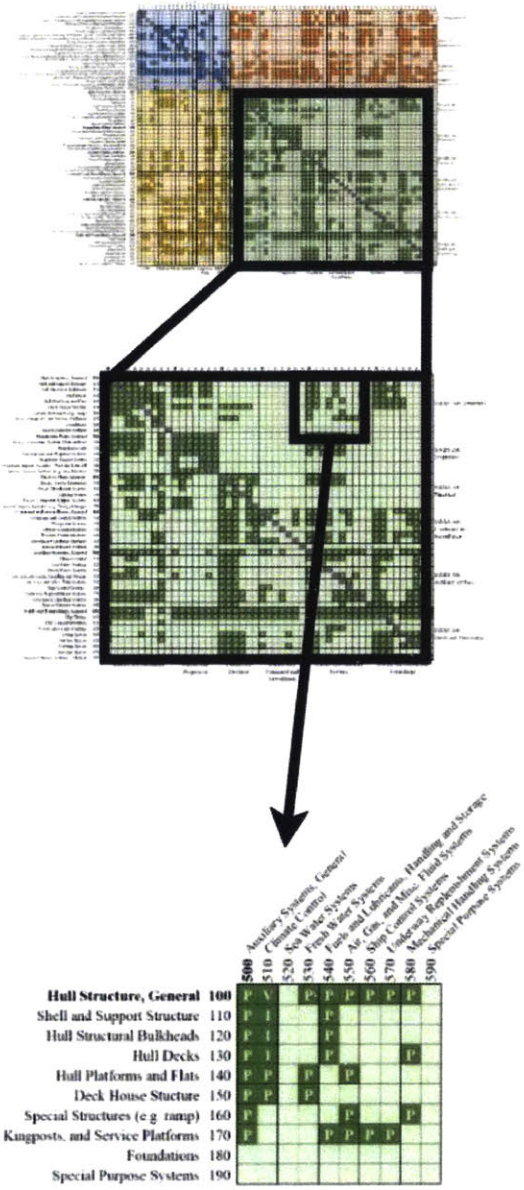


Figure 24: Hospital Ship Requirement and Component-group Engineering System Matrix



Engineering System Matrix

The overall Engineering System Matrix (ESM) shows the full relationship between requirements and components in the system. To model how a change in one component affects other components, focus on the lower-right quadrant

Component-Component Design Structure Matrix

This DSM shows relationships between different sets of component groups. For this illustration, focus on the sub-set with structural components as row inputs and auxiliary components as column outputs

Component Group Comparison

This sub-set of a DSM illustrates how changes in structural components (100-SWBS group) affects auxiliary components (500-group)

	500 Auxiliary Systems, General	510 Climate Control	520 Sea Water Systems	530 Fresh Water Systems	540 Fuels and Lubricants, Handling and Storage	550 Air, Gas, and Misc. Fluid Systems	560 Ship Control Systems	570 Underway Replenishment Systems	580 Mechanical Handling Systems	590 Special Purpose Systems
Hull Structure, General 100	P	V		P	P	P	P	P	P	
Shell and Support Structure 110	P	I			P					
Hull Structural Bulkheads 120	P	I			P					
Hull Decks 130	P	I			P				P	
Hull Platforms and Flats 140	P	P		P		P				
Deck House Stucture 150	P	P		P						
Special Structures (e g ramp) 160	P					P			P	
Masts, Kingposts, and Service Platforms 170	P				P	P	P	P		
Foundations 180										
Special Purpose Systems 190										

P = change in "row" component **proportional** to "column" component

I = change in "row" component **inversely proportional** to "column" component

V = change in "row" component **varies** in relation to "column" component

Figure 25: Using the Requirement-Component Engineering System Matrix

5.3 Production Performance Model

The concept of modeling production performance draws from the discipline of systems engineering through its focus on the emergence of interactions among groups of individually independent actions. Examining the overall system performance model rather than performance of an individual component more accurately predicts requirement effects on production delivery. In this section, a list of production processes associated with a capability requirement translates to cost and schedule effects using a process-based labor model.

5.3.1 Production Processes

Figure 26 summarizes the third step in the process-based simulation of the technical implications of a requirement change.

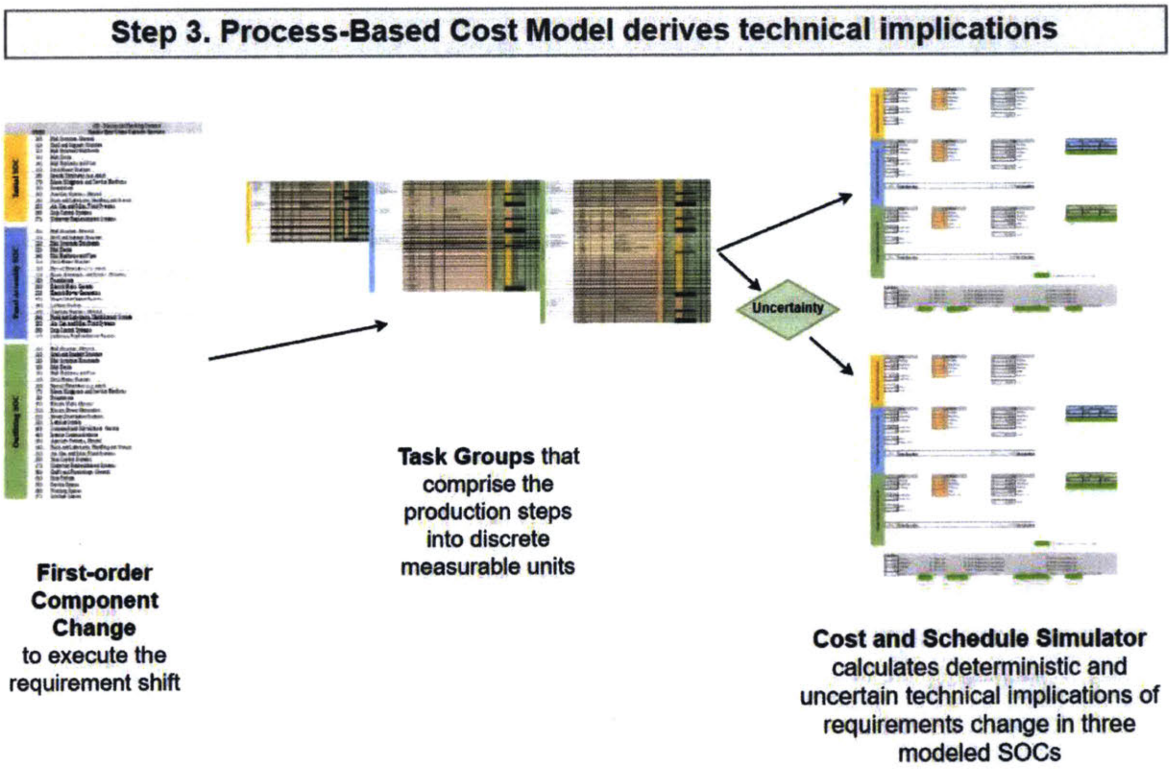


Figure 26: Production Model Step 3 – Process Based Cost Model determines results

Many of the process sets contained in the model come from research performed by the MIT Material Systems Laboratory, who observed and recorded the shipbuilding process at Huntington Ingalls Industries Shipbuilding (HII) [74]. The lab's previous model was configured to simulate the production process through the Unit Assembly stage of ship construction [75].

The rates of work recorded by the MIT team were protected as proprietary information of HII and as such, the data was not accessible for the creation of this model. This limitation does not detract from this model's functionality as this construct only aims to serve as a case study or proof for how the requirements can be connected to the technical specifications in a systematic fashion.

A selection of the shipbuilding processes modeled in this simulation is contained in Appendix E: Shipbuilding Processes and Rate Coefficients. This model incorporates activities for which empirical data was not measured by the MSL team since many outfitting processes are not replicated before the Unit Assembly stage of construction [75]. For the production processes of painting, lagging, removing interferences, pipe bending, and pipe fitting, rates and sub-process steps were based on past repair experiences and alternative shipyard observation and were quantitatively approximated using Rate Coefficients in the Simulator Tool [37].

5.3.2 Rate Coefficients and Simulator Tool

Coefficients to scale production process rates are used to determine production times throughout the different stages of construction modeled in the "Cost and Schedule Simulator" third step shown in Figure 26. This process model uses a linear combination of scaled quantities to determine the magnitude of labor hours required for a process. With empirical data for only the Unit Assembly stage, an approximation for usable data at more advanced stages of construction applies a multiplier, or a Rate Coefficient, to account for the additional challenge associated with production in late stages of construction such as higher assembly density and difficult weld angles.

Some earlier stages of construction assemble components of the vessel while the block is inverted from its eventual orientation. Once the inverted block is returned to the ship shape and all the welds now overhead, even skilled welding professional lengthen their rate of welding per unit of length [35]. As such, the further a system progresses into construction, it can be generally assumed that slower process rates will occur at every step of production [76].

To emphasize the integrity of proprietary rate and performance data contained in the model from HII, this analysis limits coefficient manipulation to those in the generalized equation for total time for a task group and not the specific rates for sub-process actions (e.g., specific welding, fitting, lifting, etc. rates are not used or approximated in this model).

Total time for a shipbuilding production process, T_i is taken as a function of the coefficients $\kappa_{1,i}$, $\kappa_{2,i}$, and $\kappa_{3,i}$ for task group i as shown in the equation below. These coefficients respectively refer to the summed total of the non-scaled, length-scaled, and quantity-scaled rate factors of the task group i. The scaling accounts for only labor costs to execute the change and not material costs needed (i.e. lost costs to accounted for the old equipment removed and the replacement equipment installed).

$$T_i = \kappa_{1,i} + \kappa_{2,i}[\text{Quantity}_i] + \kappa_{3,i}[\text{Length}_i]$$

Set up cost for equipment in each task step is accounted for in the coefficient of constant (fixed) time, $\kappa_{1,i}$. Quantity based time-costs (such as crane lifts) are contained in the $\kappa_{2,i}$ and the sub-processes scaled by length (such as weld actions) $\kappa_{3,i}$. Appendix E: Shipbuilding Processes and Rate Coefficients contains a table of subprocesses and their associated rate coefficients. The rate coefficients were the sum of each of the sub-processes in each scaling category. Since shipyard as-built data was deliberately obscured in the model, sample generalized rounded coefficients were used to illustrate the functionality of the model.

The final step in the model is to calculate the resulting effect on cost and schedule for the selected processes in the Schedule and Cost Simulator. The user interface for this part of the model is shown in Appendix G: Cost and Schedule Simulator Views. In this model, the resulting time sums across all three change phases are calculated and the rate coefficients can be adjusted to correspond to rate differences between the stages of constructions. Labor rates are computed using estimates of total compensation, overhead, equipment amortization, and consumable usage for each type of shipbuilding process modeled to calculate change labor cost from total amount of labor time.

5.3.3 Requirement Change Simulation Scenario

Running a simulation begins with selecting the requirement change scenario of testing interest. Due to the dual functionality (component/requirement) of the ESM, the change could either be to a *component* group to two-digit SWBS fidelity – X-X-0 Group, such as the 580 Group, representing the mechanical handling systems component group, or to a *requirement* from the Required Operational Capability list, such as the FHP-3 requirement to provide medical, surgical, and nursing care.

The choice of change scenario to simulate was motivated by selecting a system well-integrated with the rest of the ship as a critical component but might not have as many formalized connections to other sub-systems and components as to make the simulation too large in scope (such as modeling a change in hull-shape or size). An ideal example came from simulating a change in type of small-boat loading crane and davit, an example of which is shown in Figure 27. This problem is representative of the types of problems that shipbuilders might face in requirements change and downstream second order effects.

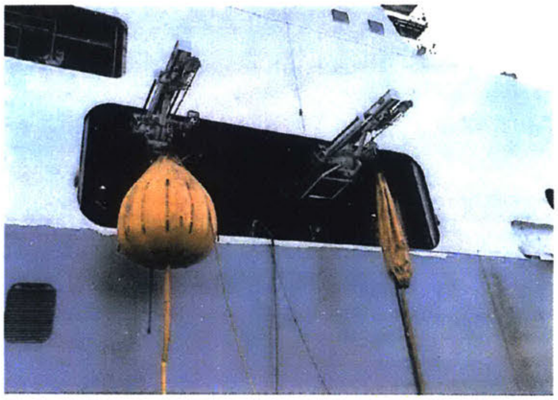


Figure 27: Example commercial boat davit in a testing configuration [71]

Note that the boat davits on the proposed ship design in Figure 28 are positioned lower to the waterline and inside the hull skin of the ship. This factor influences the nature of the work required to execute a change once the ship structure is assembled.

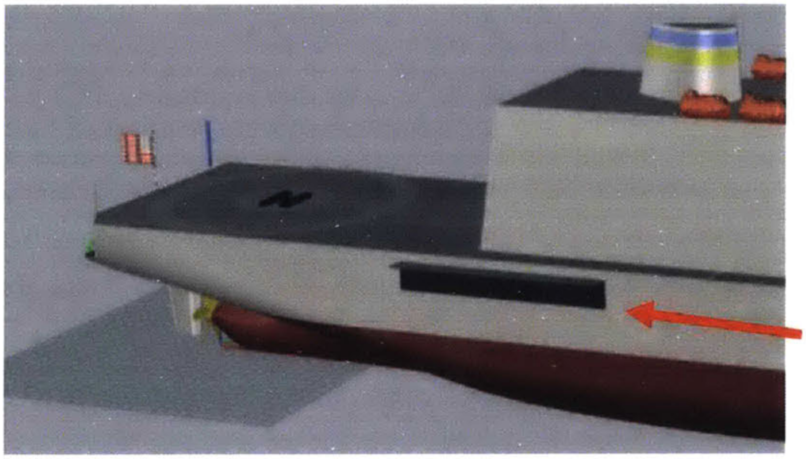


Figure 28: Location of requirement change – proposed upgrade to boat transfer davit [71]

5.4 Simulate Deterministic Output

To summarize the model described to this point, the requirements traceability model connects the required operational capabilities to technical design parameters, the ESM/DSM captures the interactions among the components and requirements of the system, and a process-based schedule and cost model simulates time and cost to perform certain tasks in the shipyard. Combining the functionalities of these model components, we can select a representative requirement change, determine its effect on changing design parameters, other components, and simulate the effort in budget and time required to execute this change in the production process.

The model and simulations can additionally account for how the shipbuilding process changes as production progresses. Shipbuilders refer to the progression through the production process according to the Stage of Construction (SOC) in which the vessel is in [76]. Although the progression of ship construction varies between individual shipyards, a sample sequence is contained in Table 13 [35], [37], [76].

Table 13: Naval ship construction stages of construction [37], [76]

SOC 1	Fabrication: initial cutting of steel
SOC 2	Sub-assembly, or panel assembly: welding structure onto initial steel pieces
SOC 3	Unit Assembly: sub-assemblies welded together to form units or blocks
SOC 4	Blast and Paint: complete installation of heavy equipment and coat the block
SOC 5	Grand Block: units and blocks come together to form Grand Blocks
SOC 6	Block Erection: "Grand Blocks" welded together in the dock and most equipment installed
SOC 7	Final Outfitting: ship launched, and final equipment install
SOC 8	Testing: conducted waterborne

Figure 29: Stage of Construction color legend used in the production model

Although the construction stages can be discretized to many steps as shown in Table 13, this model will consider only three for simplicity. The earliest stage represents the pre-construction phase. Next, an intermediate phase is represented by the Unit Assembly stage. Finally, the waterborne outfitting phase, Final Outfitting is the most advanced stage represented in the model. The model representations below utilize the color legend shown in Figure 29.

As the components of the ship progress through the assembly sequence, the effects that a change will have as it is applied later in production have a three-layered effect – (a) more components will be affected during later stages of construction, (b) quantities of the individual tasks will increase, and (c) the speed or rate that the tasks will be performed will slow later in the process [33], [35], [37], [76].

For example, producing a design whose technical details are completed from the initial stage of construction, a certain activity may require approximately 10 ft of overhead welding and fabrication of 50 ft worth of custom field run pipe spooling. For a change at a point mid-way through the production process, these quantities may increase while also adding quantities of interference removal or other activities that are now associated with the SOC that the vessel is now in. Finally, when executing this change at the end of the construction process, once the vessel is launched, there may be more welds, an increasing amount of interference removal, and even more activities such as extra painting and rework.

5.4.1 Simulation Round 1- Changes to Affected Components

Figure 30 shows how dependency between the components increases as the project advances to later SOCs. This section of the ESM represents a component-component interaction map, the relationship shown by the lower right quadrant of the ESM from Figure 23. Note that in later stages of construction a change in a specific sub-system will affect an increased number of other related sub-systems, following a hypothetical progression in ship assembly.

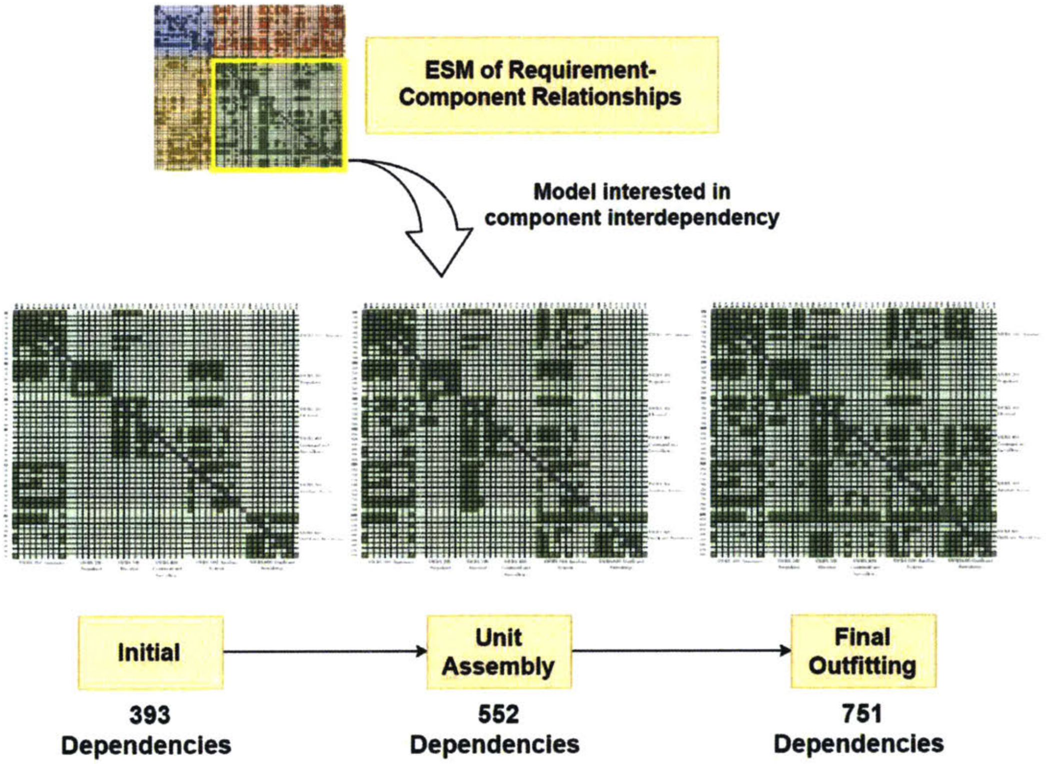


Figure 30: ESM dependency changes throughout successive construction changes

A generalized list of shipbuilding production processes from a sample combatant construction project (an Integrated Master Schedule in industry parlance) provided structure for the process tasks that were selected to correspond to change work for each group of affected ship sub-systems [77]. Full views of the tasks selected to execute a SWBS 580-Group requirement change are contained in Appendix F: Simulation of Shipbuilding Processes for SWBS Group 580 Requirement Change.

The model first measures the effect that the extra component interdependency has on additional work processes. By holding the quantity and rate of work performed among each task common to the three stages of construction constant while varying only the addition of tasks themselves, the effect of increased interdependency in the form of additional production processes is measured. Figure 31 shows the task additions in the three different phases that the model simulates with the cost and schedule results summarized in Appendix G: Cost and Schedule Simulator Views.

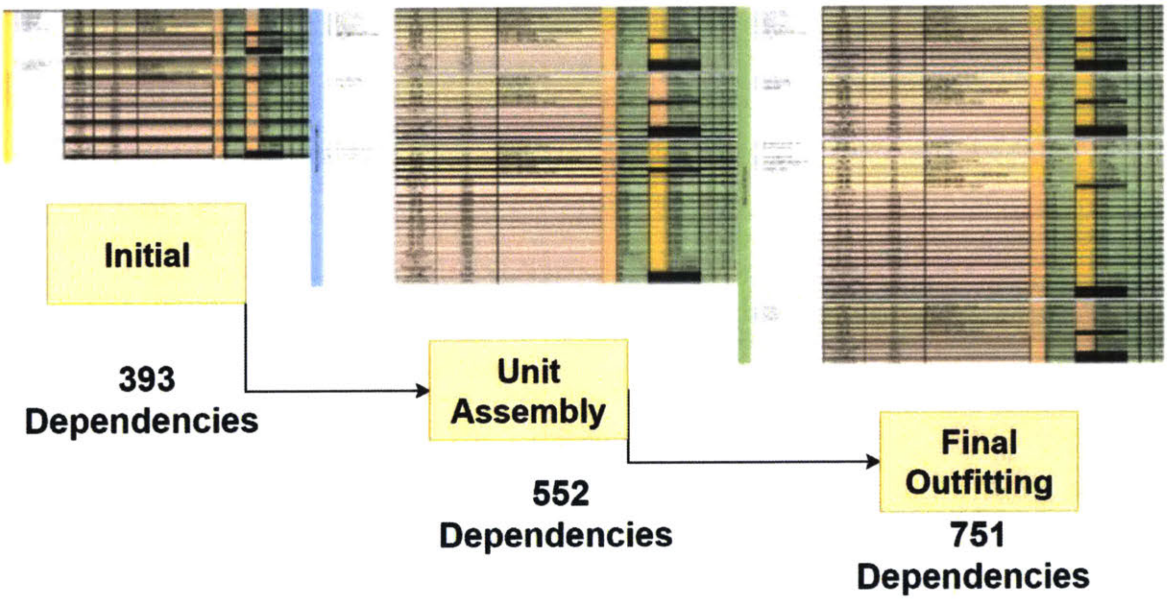
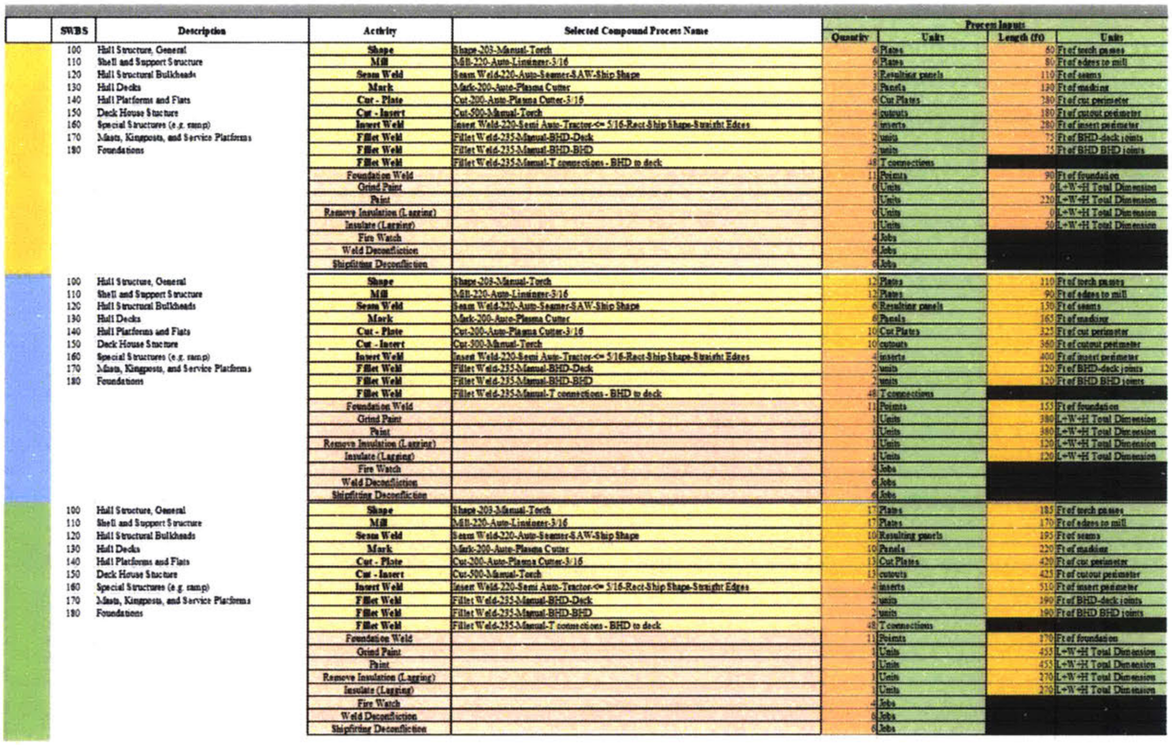


Figure 31: Simulation Rd. 1 –accounts only for increase in tasks to execute requirements change during three successive stages of construction

5.4.2 Simulation Round 2- Addition of Task Quantity Increases

In addition to extra tasks that accompany changes during later stages of construction, the model next accounts for an increase in the quantity of each task performed. For example, the total quantity of plate and pipe cutting required increases during later stages of construction accounting for interference removal to facilitate equipment installation in a higher density area.

Figure 32 shows the same task structure as used in the previous section, along with highlighted quantity increases in successive stages of construction for the selection SWBS Group with the cost and schedule results summarized in Appendix G: Cost and Schedule Simulator Views.



	SWBS	Description	Activity	Selected Compound Process Name	Process Inputs			
					Quantity	Units	Length (ft)	Units
🟨	100	Hull Structure, General	Shape	Shape-203-Manual-Torch	6	Plates	60	Ft of torch passes
	110	Shell and Support Structure	Mill	Mill-220-Auto-Linsinger-3/16	6	Plates	80	Ft of edges to mill
	120	Hull Structural Bulkheads	Seam Weld	Seam Weld-220-Auto-Seamer-SAW-Ship Shape	3	Resulting panels	110	Ft of seams
	130	Hull Decks	Mark	Mark-200-Auto-Plasma Cutter	3	Panels	130	Ft of marking
	140	Hull Platforms and Flats	Cut - Plate	Cut-200-Auto-Plasma Cutter-3/16	6	Cut Plates	280	Ft of cut perimeter
	150	Deck House Stucture	Cut - Insert	Cut-500-Manual-Torch	4	cutouts	180	Ft of cutout perimeter
	160	Special Structures (e.g. ramp)	Insert Weld	Insert Weld-220-Semi Auto-Tractor-<= 5/16-Rect-Ship Shape-Straight Edges	4	inserts	280	Ft of insert perimeter
	170	Masts, Kingposts, and Service Platforms	Fillet Weld	Fillet Weld-235-Manual-BHD-Deck	2	units	75	Ft of BHD-deck joints
	180	Foundations	Fillet Weld	Fillet Weld-235-Manual-BHD-BHD	2	units	75	Ft of BHD BHD joints
			Fillet Weld	Fillet Weld-235-Manual-T connections - BHD to deck	48	T connections		
			Foundation Weld		11	Points	90	Ft of foundation
			Grind Paint		0	Units	0	L+W+H Total Dimension
			Paint		1	Units	220	L+W+H Total Dimension
			Remove Insulation (Lagging)		0	Units	0	L+W+H Total Dimension
			Insulate (Lagging)		1	Units	50	L+W+H Total Dimension
			Fire Watch		4	Jobs		
			Weld Deconfliction		6	Jobs		
			Shipfitting Deconfliction		6	Jobs		
🟦	100	Hull Structure, General	Shape	Shape-203-Manual-Torch	12	Plates	110	Ft of torch passes
	110	Shell and Support Structure	Mill	Mill-220-Auto-Linsinger-3/16	12	Plates	90	Ft of edges to mill
	120	Hull Structural Bulkheads	Seam Weld	Seam Weld-220-Auto-Seamer-SAW-Ship Shape	6	Resulting panels	150	Ft of seams
	130	Hull Decks	Mark	Mark-200-Auto-Plasma Cutter	6	Panels	165	Ft of marking
	140	Hull Platforms and Flats	Cut - Plate	Cut-200-Auto-Plasma Cutter-3/16	10	Cut Plates	325	Ft of cut perimeter
	150	Deck House Stucture	Cut - Insert	Cut-500-Manual-Torch	10	cutouts	360	Ft of cutout perimeter
	160	Special Structures (e.g. ramp)	Insert Weld	Insert Weld-220-Semi Auto-Tractor-<= 5/16-Rect-Ship Shape-Straight Edges	4	inserts	400	Ft of insert perimeter
	170	Masts, Kingposts, and Service Platforms	Fillet Weld	Fillet Weld-235-Manual-BHD-Deck	2	units	120	Ft of BHD-deck joints
	180	Foundations	Fillet Weld	Fillet Weld-235-Manual-BHD-BHD	2	units	120	Ft of BHD BHD joints
			Fillet Weld	Fillet Weld-235-Manual-T connections - BHD to deck	48	T connections		
			Foundation Weld		11	Points	155	Ft of foundation
			Grind Paint		1	Units	380	L+W+H Total Dimension
			Paint		1	Units	380	L+W+H Total Dimension
			Remove Insulation (Lagging)		1	Units	120	L+W+H Total Dimension
			Insulate (Lagging)		1	Units	120	L+W+H Total Dimension
			Fire Watch		4	Jobs		
			Weld Deconfliction		6	Jobs		
			Shipfitting Deconfliction		6	Jobs		
🟩	100	Hull Structure, General	Shape	Shape-203-Manual-Torch	17	Plates	185	Ft of torch passes
	110	Shell and Support Structure	Mill	Mill-220-Auto-Linsinger-3/16	17	Plates	170	Ft of edges to mill
	120	Hull Structural Bulkheads	Seam Weld	Seam Weld-220-Auto-Seamer-SAW-Ship Shape	10	Resulting panels	195	Ft of seams
	130	Hull Decks	Mark	Mark-200-Auto-Plasma Cutter	10	Panels	220	Ft of marking
	140	Hull Platforms and Flats	Cut - Plate	Cut-200-Auto-Plasma Cutter-3/16	13	Cut Plates	420	Ft of cut perimeter
	150	Deck House Stucture	Cut - Insert	Cut-500-Manual-Torch	13	cutouts	425	Ft of cutout perimeter
	160	Special Structures (e.g. ramp)	Insert Weld	Insert Weld-220-Semi Auto-Tractor-<= 5/16-Rect-Ship Shape-Straight Edges	4	inserts	510	Ft of insert perimeter
	170	Masts, Kingposts, and Service Platforms	Fillet Weld	Fillet Weld-235-Manual-BHD-Deck	2	units	390	Ft of BHD-deck joints
	180	Foundations	Fillet Weld	Fillet Weld-235-Manual-BHD-BHD	2	units	390	Ft of BHD BHD joints
			Fillet Weld	Fillet Weld-235-Manual-T connections - BHD to deck	48	T connections		
			Foundation Weld		11	Points	170	Ft of foundation
			Grind Paint		1	Units	455	L+W+H Total Dimension
			Paint		1	Units	455	L+W+H Total Dimension
			Remove Insulation (Lagging)		1	Units	270	L+W+H Total Dimension
			Insulate (Lagging)		1	Units	270	L+W+H Total Dimension
			Fire Watch		4	Jobs		
			Weld Deconfliction		6	Jobs		
			Shipfitting Deconfliction		6	Jobs		

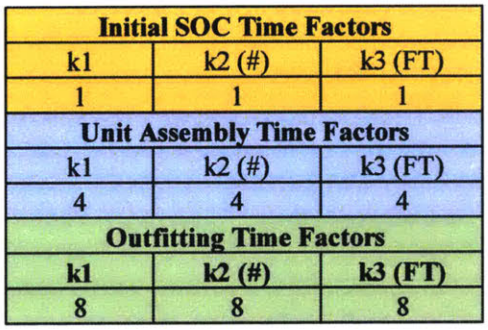
Figure 32: Simulation Rd. 2 – changes in task quantities (SWBS 100-Group changes shown)

5.4.3 Simulation Round 3 – Rate Coefficient Variation

Finally, we examined changes in rate coefficients to account for the fact that certain work tasks take longer when they are performed during later stages of construction. For example, a weld task completed during the panel assembly stage could be done in a more ergonomically feasible position with the extra space afforded at that stage of construction. However, once the block is inverted and in its final position on the ship, this weld may be in an overhead position requiring a more difficult posture and therefore slower weld rate. Beyond welding, this model accounts for the increased complexity of other processes as well such as coatings and shipfitting that happen at much slower rates as the project reaches advanced stages of construction [35], [37], [76].

Identical task structure and quantities as used in the previous section were used to simulate results of applying the third layer with the rate coefficient variation modeled as shown in Figure 33. The final cost and schedule results that account for increased component interdependency, higher work quantity, and adjusted rate coefficients are summarized in Appendix G: Cost and Schedule Simulator Views.

Figure 33 quantifies the heuristic that we used to illustrate the data, stylized as "1-4-8" is a simple statement that performing a *one*-manhour task scheduled during initial design to be completed during panel assembly would take approximately *four* times as long after the unit assembly stage of construction, and *eight* times as long after the ship has been launched and is waterborne [76]. Although this heuristic is meant to be extremely informal, for the purposes of the model it serves as a useful rate coefficient estimate.



Initial SOC Time Factors		
k1	k2 (#)	k3 (FT)
1	1	1
Unit Assembly Time Factors		
k1	k2 (#)	k3 (FT)
4	4	4
Outfitting Time Factors		
k1	k2 (#)	k3 (FT)
8	8	8

Figure 33: Simulation Rd. 3 – variation in work rate across three stages of construction (example figures shown illustrating a basic "1-4-8" rate heuristic)

5.4.4 Deterministic Comparison

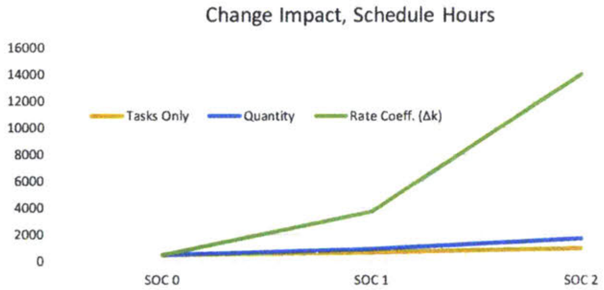
While the precise quantification of comparisons will change with details of the change specification and specific shipyard performance, the important conclusion that this model reaches is a facilitation of real-time comparison of the sensitivity of parameter update and adjustment. Although exactly predicting cost and schedule implications for a change would far exceed the scope of the research– this model provides direction for formulating the connection between requirements and technical specifications.

Adapting this model to a true production scenario could be achieved through observation and input of production process quantities and rates. Additionally, this model can be extended to account for other costs to the shipyard such as opportunity costs to other projects for the use of equipment that would have otherwise been allotted elsewhere. However, this model seeks to eliminate some naivety around requirement change costs or delays. Considering additional complexity in construction, increased quantity within the individual tasks, and slower production rates creates a complex relationship that a model-based environment begins to capture. Figure 34 and Figure 35 summarize the schedule and cost impact, respectively, of the proposed

requirement change by calculating total cost, cost increase factor, and a time increase factor. Note that when all three layers are applied – the additional production tasks, quantities and the construction stage-adjusted work rates, the overall schedule and cost effects significantly exceeds the heuristic of "1-4-8" that we applied as an approximation.

Schedule Impact

	Tasks Only	Quantity	Rate Coeff. (Δ_k)
SOC 0	467.49	467.49	467.49
SOC 1	661.49	929.27	3717.08
SOC 2	1005.54	1753.275	14026.2



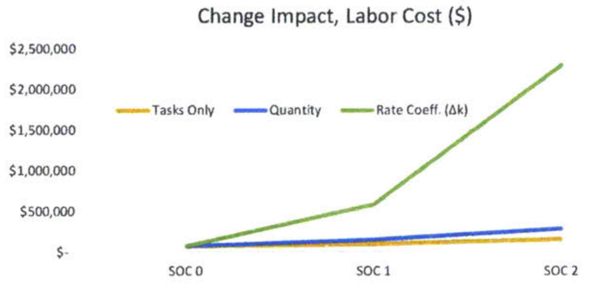
Schedule Variation Factors

	Tasks Only	Quantity	Rate Coeff. (Δ_k)
SOC 0	1.0	1.0	1.0
SOC 1	1.4	2.0	8.0
SOC 2	2.2	3.8	30.0

Figure 34: Impact of requirement change on schedule, summary

Cost Impact

	Tasks Only	Quantity	Rate Coeff. (Δ_k)
SOC 0	$ 66,457	$ 66,457	$ 66,457
SOC 1	$ 99,121	$ 147,094	$ 588,378
SOC 2	$ 158,021	$ 286,809	$ 2,294,472



Cost of Change Variation Factors

	Tasks Only	Quantity	Rate Coeff. (Δ_k)
SOC 0	1.00	1.00	1.00
SOC 1	1.49	2.21	8.85
SOC 2	2.38	4.32	34.53

Figure 35: Impact of requirement change on labor costs, summary

This model demonstrates that heuristics such as "1-4-8" used in a complex manufacturing process fails to account for the reality of the complex component interactions. The data summaries in Figure 34 and Figure 35 uncover the degree to which a total amount of work as part of a total requirements or component change is part of a non-linear dependency structure that further complicates the calculation of effect on delivery schedule or overall budget. These deterministic results show how changes made early in the production process can have near-exponential returns on schedule and cost. Changes made late in the production process often increase effects on the schedule and cost by upwards of 30 times for a specific change. Connecting requirements to technical specifications uncovers nonlinear effects of the complex ship building process.

5.5 Uncertainty and Sensitivity Analysis

The above analyses were presented using deterministic data – data that a model architect "claims" to know with certainty and exactness. However, this is clearly not the case. Uncertainty was discussed in Chapter 2 – in the real world there are infinite variables that are subjected to an uncertain distribution. This section aims to demonstrate the variance in simulation results obtained when ascribing a level of uncertainty to a parameter when compared with the misconception of certainty obtained through deterministic results.

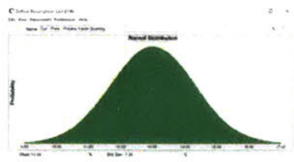
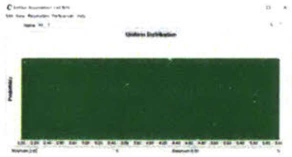
5.5.1 Application of Uncertainty to Production Model

The production model described to this point inputs thousands of individual parameters to measure the schedule and cost performance of labor involved in executing a requirement change at three different construction stages. This portion of the experiment suggests a method to establish real-world performance bounds on outcomes while providing a framework for simulations to measure sensitivity of individual parameters. Like the requirement-component interaction ESM in Section 5.2, multiple iterations of this simulation can demonstrate which parameters may have the greatest individual effect on outcomes through non-linear connectivity to the rest of the system.

To evaluate the effect that uncertain parameters have on the model, we identified variables and the general distribution of the parameters. This simulation assigns stochastic distributions to the quantities of sub-process tasks and rate coefficients in the Performance Model component (as described in Section 5.3). Monte Carlo simulations with 1,000 iterations were performed using the Oracle Crystal Ball ® software in a spreadsheet interface [78].

As shown in Table 14, quantities of production process steps (Section 5.3.1) were modeled using a normal distribution assuming a mean of the initial design estimate and 10% standard deviation around the mean ($\sigma = 0.10\mu$). The normal distribution was chosen to represent the continuous quantities around a mean for processes such as weld amount length or quantity of structural members affected that behave similarly in variance to natural phenomena [79]. Rate coefficients (Section 5.3.2) were modeled using a continuous uniform distribution centered around the "1-4-8" scaling heuristic to reflect equal likelihood of the range that work rates vary around an initial estimate [79]. The functionality of the Crystal Ball software allows for real-time updating of each individual uncertainty distribution to reflect updates gathered regarding their assumptions.

Table 14: Uncertainty Parameters

Uncertain Design Parameter	**Crystal Ball Assumption**	**Uncertainty Distribution**
Production Process Quantity	*Normally distributed* μ = Initial Design Estimate $\sigma = (0.10)\ \mu$	
Rate Coefficients $\kappa_{1,i}$, $\kappa_{2,i}$, and $\kappa_{3,i}$	*Uniformly distributed* μ = Initial Design Estimate Min = $(0.5)\ \mu$ Max = $(2)\ \mu$	

Monte Carlo simulations yielded uncertainty information in Figure 36 with Table 15 as a comparison of the deterministic results with the range of results obtained through accounting for an initial level of uncertainty in the selected parameters. The resulting Crystal Ball forecast reports containing uncertainty trial data are contained in Appendix H: Uncertainty Forecasts.

Table 15: Deterministic and uncertain simulation comparison

	Model Output	**Deterministic Parameter Result**	**Uncertain Parameter Min/Max**
Unit Assy.	Time Factor	8.0	4.2 / 11.8
	Cost	$590,000	$308,000 / $870,000
	Cost Factor	8.85	4.6 / 13.3
Final Assy.	Time Factor	30.0	22.7 / 37.8
	Cost	$2,300,000	$1.7 M / $2.9 M
	Cost Factor	34.53	25.8 / 44.0

The plot of Monte Carlo simulation results demonstrates the wide range of potential outcomes from variable inputs through a complex system using uncertain parameters. The histogram of the Monte Carlo results in Figure 36 generally feature two peaks representing a bi-modal distribution to account for the interactions of all uncertain parameters. Even with models that require manual input to capture uncertainty for the stochastic simulation, this risk and uncertainty yields large variation among the results.

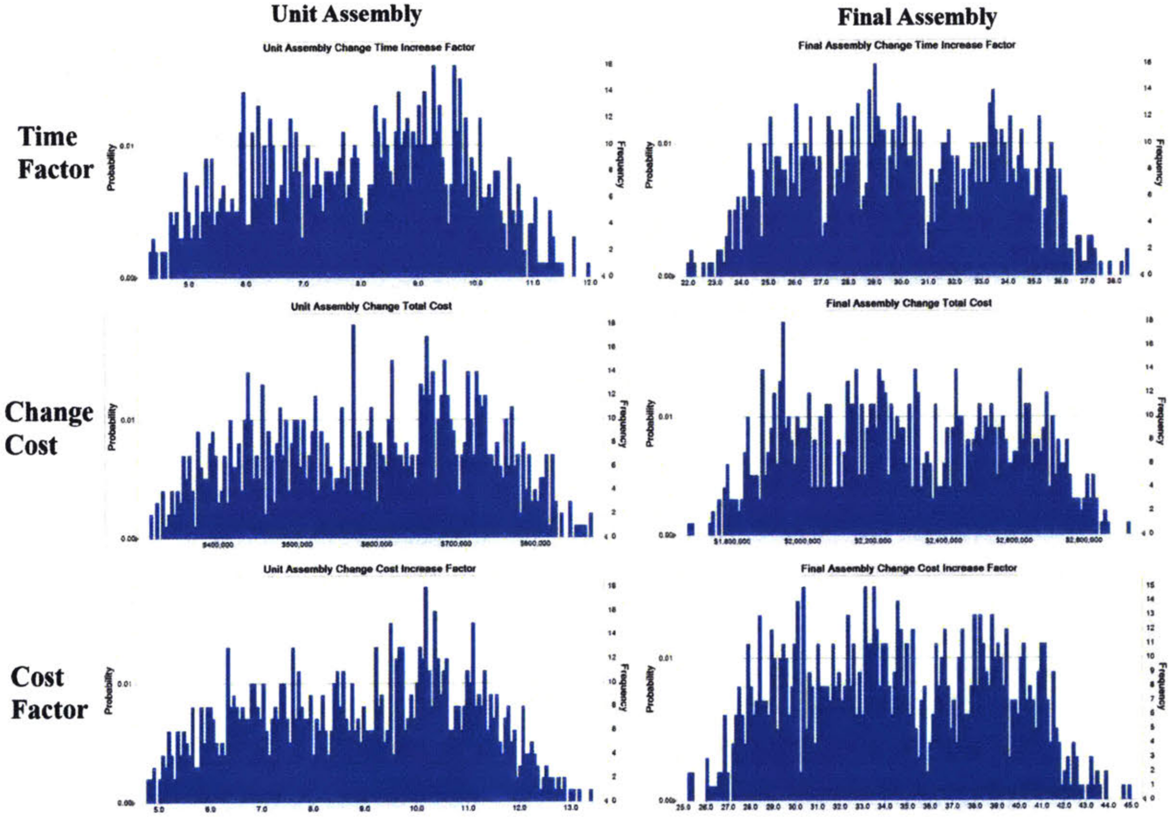


Figure 36: Uncertainty simulations- cost and schedule impacts for advanced stage changes

5.5.2 Uncertainty Observations

Qualitatively, uncertainty accentuates the compound effects of multiple non-linear elements in the model. When each process task is considered individually, it may ascribe to a handy heuristic such as "1-4-8" mentioned earlier. However, this section highlights how uncertainty distributions over some variables produce pronounced effects in the results of system production time and cost. Due to the complex non-linear dependencies inside a model such as the process-based cost model featured here, we can see that implementation of all the tasks required to execute a change in component or requirement can far exceed the single-task time scale factor.

Although it is well understood that making changes late in the design-build process can be problematic for meeting schedules and budgets, what is not well understood are the system dynamic factors that contribute to exactly how much effect this might have. What this case study model demonstrates is a new conception of a model that can be used to capture these effects. Although not based on a real-world specification, operational observations and actual as-built dimensions can be inputted to deliver actual actionable results.

The case studies presented in Chapter 4 demonstrated that a robust requirements traceability can make the system design much more resilient to variation through visualizing the effect of a dynamic environment. Implementing uncertainty analysis tools in a dynamic design model can enable engineers to visualize the technical implications of potential parameter distributions or ranges without having to perform time-consuming manual recalculation.

5.6 Final Case Study Test Results

The models and simulations created for this case study have the structure and potential to be updated with shipyard, requirement, and specification details to become useful in predicting production performance. For the purposes of this thesis, this case serves to demonstrate three principles enabled by adopting model-based engineering practices in the production of complex systems.

5.6.1 Smarter Requirements

Connecting requirements to technical specifications can have significant implications for the design of complex sea systems. This model demonstrates issues encountered in industries and sectors that deal with complex requirements and even more complex production/delivery. Groups responsible for proposing requirements must have a systematic way for understanding how their decisions are affecting design, production, cost, and schedule overall. The structure used in this case study recreates a change scenario in order to understand the effects on technical specifications. Future iterations of this type of model could incorporate a connection to 3D design tools to better visualize the requirements process. Research in the field of economics suggests that "expert" informed decision makers are significantly more likely to make what could be considered economically rational choices of a less expensive product than one of comparable performance but a higher price [80]. This thesis contends that requirement planners can set *more informed requirements earlier* with a clear and systematic connection of capability to technical specifications.

Understanding the requirements that the Fleet will be held to can be captured in models of this nature. Often, build specifications are not written according to Fleet requirements, and when the ship goes through the Navy's Acceptance Trials (see Appendix C: Delivery, Test, and

Certification Timeline Illustration) the testing community (possibly, the Board of Inspection and Survey for major ship system) finds problems with construction result. However, the shipbuilder has performed according to contract requirements. Fleet requirements were not part of the build – an issue that expressly capturing requirements in model-based format can address through traceability.

5.6.2 Change Codification

Codifying changes more effectively saves significant construction budget while eliminating the schedule slip associated with repeatedly missing the mark on requirements definition. This model construct may serve to eliminate rework by ensuring that changes that are eventually proposed remain connected to the technical specifications that they inform. One of the most consistently cited problems facing efficient production of complex naval systems is not capturing and adequately ensuring that the lessons learned from the previous system build are incorporated into the drawings and the planning sequence. In the shipbuilding domain, failing to properly document changes on a ship drawing often results in drawings with dozens of engineering changes waiting to be implemented. When production activities bypass the changes and assemble according to out-of-date documentation, failing to codify the change creates rework [32], [33], [35].

5.6.3 Right System, First Time

Model-Based Engineering, even in simple application, enables a leverage of High-Velocity Learning. Improvement and innovation demonstrably result from iteration through the most-rapidly achievable method [10]. MBE connects the research and development contributing to requirements generation with production operations downstream in a collaborative, instantly updating environment. Models allow planners and designers to add data as it becomes available, change uncertainty data as the environment and business cases change, and present a comprehensive display of known information regarding a process in a common format. If a process is not modeled, that should be a sign that the model is not updated, and there is more information to be learned about the system's production rather than a mark against the modeling approach's validity. Collecting information in a systematic fashion as organized in this case study can be a start to presenting engineers and decision makers with the information needed to make an informed complex system design.

Rework is easier to discover when the ship is operational but early insight can be gained through a valid requirement and technical process model. Prior to official testing and operation is an ideal phase to utilize requirements models to "red-team" system design issues [3], [38]. Migration of model-based engineering beyond the concept development phase and into technical requirements of the production process serves to build the system as it is needed in operation.

5.7 Model Verification and Validation

Validation confirms that each system level as built or as it will be built satisfies the stakeholder's stated needs involving the buyer or third parties [2]. Cost estimates of major naval platform procurement actions can be optimized to conform to the tool used to calculate cost figures. With weight-based cost models, platform designs can gravitate toward an "optimal" lower weight and higher density configuration without substantial regard in the concept phase of design-for-manufacturing or producibility [81]. A validated process-based model has the potential to capture the real-world nuances present in shipyard production processes.

The challenge of model verification and validation is one of the key limiting factors of Model Based Engineering. Overcoming this hurdle can contribute to the credibility that the designer can use to justify the reduction of hard-product-prototyping, test, and design with a heavier cost-saving through reliance on the model. What steps would be required to verify and validate the model as it is used here to provide the kind of information that would be useful to the end of connecting required functionalities with technical specifications?

Shipbuilding Production Model Summary
Smarter Requirements: connecting requirements to technical specifications can have significant implications for the design of complex sea systems
Change Codification: capturing change effectively eliminating budget and schedule slip associated with repeatedly missing requirements definition
Right System, First Time: model-based engineering solutions allow speed and efficacy in iteration on technical design of complex system
Model tools must be thoroughly validated to allow users and designers to confidently expand usability in accurate reflection of real-world processes

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Chapter 6

6.0 Towards the Final Hurdle: Model Verification and Validation

Confidence shared is better than confidence only in yourself

Coach Mike Krzyzewski

In the preceding chapters, we first established that the U.S. Navy Fleet was suffering from underperformance in shipbuilding and system acquisition. One of the principal reasons continually cited was the disconnect between operational requirements and the "as-built" technical specifications. Many of the global principles enabled by Model-Based Engineering (MBE) deliver the high-velocity solution that aids in reasserting operational excellence in system production. However, as the shipbuilding requirement traceability and process-based cost model case study showed, the model-based solution can only be as useful as the confidence that we can place in the model's fidelity. Solving for this limitation of model output confidence is called Verification and Validation (V&V). Taking a closer look at this practice will be the first iteration at closing that gap between model creation and a useful, validated, output.

How do companies verify and validate the assumptions that form the analytical basis of their modeling decisions? This chapter will explore the standards and processes in place to verify performance of models in high-complexity and high-uncertainty environments. To validate the technical models, effort must be made to align the model with an accurate reflection of the total environment of operation to yield a result that also accurately reproduces the physical world. Practical application and V&V standards together provide the backbone for a validation architecture that, for the first time, will connect the needs of the future Fleet with the technical reality possible for production. Providing a consolidated data source for specifications will lead to confidence in production and validation that the right systems are created to support the needs of the Fleet.

6.1 Test Like You Fly

Space systems can be among the most delicate and complex structures in production with often little to no opportunity to "pad test." Since most are single-use, engineers get only one shot to prove their worth when all the components come together to travel exo-atmosphere. Well-developed verification and validation programs in this field have been created by the American Institute of Aeronautics and Astronautics and International Council on Systems Engineering with an approach that seeks to identify the smallest errors at every level of system development in requirements, analysis, design, and test procedures [73], [82], [83].

Verification and Validation is critical for ship and weapons systems to first verify that the right system is built [83]. Once production and operational stages are underway, standardized management processes "enforce the 'system-is-built-right' verification approach" as early as possible and at the lowest level of system development [73]. The phrase "Test Like You Fly" (TLYF) is used in the aerospace sector to reflect the emphasis that this community must place on valid test procedures that accurately reflect real-world operational conditions [73], [82], [84]. Adopting similar principles would be benefit naval *sea* systems, as well, with parallel risks in system use and test in an environment even more volatile and inhospitable than space – the maritime domain.

Often, taking a TLYF approach will dictate inclusion of the worst-case scenario of anticipated conditions to ensure robustness against the anticipated conditions [84]. Testing a model with operationally relevant characteristics further extends to realistic equipment configurations. Examples of mission characteristics include environmental and component sequencing, rhythm, people, processes, and procedures present during production [73]. Considering the example of the shipbuilding process from the Chapter 5 case study, a process model must be validated against the full end-to-end production line configuration, using accurately tracked timing and sequence, incorporating cognizance of environmental considerations (e.g., budgeting schedule slip due to winter weather during ship production at Bath Iron Works, Maine or hurricane threats at Ingalls Shipyard in Pascagoula, Mississippi), and operational acuity of the labor force and production equipment.

Taking "Test Like You Fly" literally, a further example of this comes from the Enhanced Ground Testing program by the Charles Stark Draper Laboratory for verification and validation of the MBE design of Inertial Measurement Units for guidance and navigation systems [85].

> *Each time a guided missile system is flight tested, the missile is destroyed—at the cost of millions of dollars. Demonstrating that the system will perform accurately and reliably demands realistic and rigorous verification and validation programs. The challenge is to maintain testing rigor using more affordable methods.* [85]

As realistic V&V was a central priority, Draper created the process of Enhanced Ground Testing (EGT) to address the priority of affordability while maintaining the utmost test fidelity. To replicate the "trajectory, thermal, vibration, shock and linear acceleration profiles from Draper's predictive models", engineers implemented non-destructive test procedures involving the use of military jets, centrifuges and other dynamic test platforms [85]. Figure 37 displays a photograph of the test setup. In doing so, the MBE products of the design process for that specific component (see case study in Section 4.3) were verified and validated with test conditions that replicated those of designed operation.

Figure 37: Enhanced Ground Testing (EGT) validation of guidance components [85]

6.2 Exhaustive Tracing

Often system designers are given measures of performance that are not simple to immediately capture in a requirement. If the Navy needs a ship that travels at a maximum speed of 45 knots, engineers know how to design that – because it is a straightforward process to choose a hullform and select engines that both fit inside the envelope and produce enough horsepower to overcome the hydrodynamic resistance produced by the hullform selected.

However, much more frequently encountered are nebulous required capabilities, as displayed in the first level of decomposition in the Chapter 5 shipbuilding model. Although they may not be immediately quantifiable, they are also not vague. The intent of a requirement request is clear when the operational commander asks for capability such as a long-range strike bomber or a ballistic missile incapable of being detected by enemy radar. However, the lack of formal connection between qualitative operational needs and engineering practice contributes to functional requirement misinterpretation. Subsequent performance of the V&V process will generate an engineering change request if the need is determined not to be met.

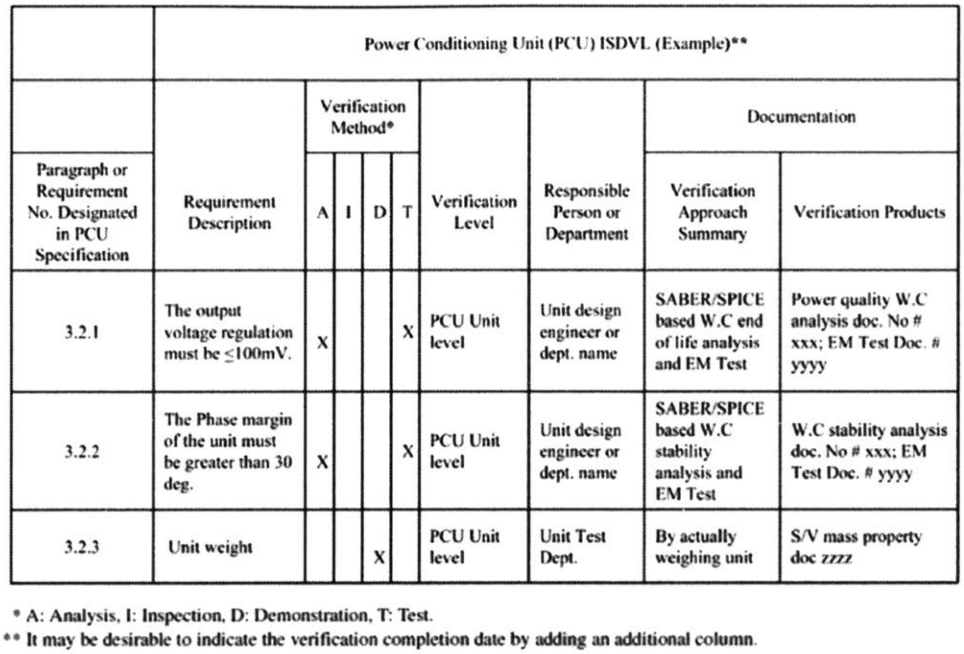
Strictly validating requirements can be used to ensure that the "right system is being built" and both the American Institute of Aeronautics and Astronautics and International Council on Systems Engineering cover several artifacts used in practice to document the satisfaction or correct interpretation of a requirement and are summarized in Appendix I: Verification and Validation Artifacts [73], [83].

Models require confirmation of their validity in many different environments with consistent approaches among all builders of naval ship and weapon systems, such as the six-step process outlined by the AIAA in Table 16. This distributed process can follow the model of space systems that come from similarly distributed sources across the aerospace and defense community. Additionally, software programs can be utilized to analytically verify the comprehensive nature and completeness of a model regarding requirement consistency. Examples of software designed to perform analysis-of-models can be found in Monterey Phoenix software family from the Naval Postgraduate School [86].

Table 16: Standardized Modular Verification Management Process

AIAA-Standardized Modular Verification Management Process [73]
[VM-1] Requirement flow down and establishment of specification
[VM-2] Verification cross reference matrix
[VM-3] Integration and test
[VM-4] Individual specification dedicated verification ledger
[VM-5] Sell-Off/Consent-To-Ship
[VM-6] Verification related risk management

More generally, note that the first step in the AIAA-Standard verification management process in Table 16 starts with a similar approach to requirements decomposition as exhibited in the traceability model of the prior chapter. A formalized method can be used to ensure that every requirement can be traced to a documented method of verification [84]. Although presented in a document-based form, Figure 38 shows the structure that a model can take in which requirements traceability is linked to management of V&V processes.



	Power Conditioning Unit (PCU) ISDVL (Example)**								
		Verification Method*						Documentation	
Paragraph or Requirement No. Designated in PCU Specification	Requirement Description	A	I	D	T	Verification Level	Responsible Person or Department	Verification Approach Summary	Verification Products
3.2.1	The output voltage regulation must be ≤100mV.	X			X	PCU Unit level	Unit design engineer or dept. name	SABER/SPICE based W.C end of life analysis and EM Test	Power quality W.C analysis doc. No # xxx; EM Test Doc. # yyyy
3.2.2	The Phase margin of the unit must be greater than 30 deg.	X			X	PCU Unit level	Unit design engineer or dept. name	SABER/SPICE based W.C stability analysis and EM Test	W.C stability analysis doc. No # xxx; EM Test Doc. # yyyy
3.2.3	Unit weight			X		PCU Unit level	Unit Test Dept.	By actually weighing unit	S/V mass property doc zzzz

* A: Analysis, I: Inspection, D: Demonstration, T: Test.

** It may be desirable to indicate the verification completion date by adding an additional column.

Figure 38: Individual Specification Dedicated Verification Ledger [82]

6.3 Verification and Validation During Design

V&V in practice ensures that systems satisfy design requirements, which circles back to a question of safety in operation and design. Various methods for system safety have been discussed, as in Professor Nancy Leveson's *Engineering a Safer World* [23]. A systems thinking-based approach to system safety, as discussed below, expands beyond a V&V review to address hazards and elucidate requirements for the whole process to produce a system that can meet the mission.

6.3.1 System Theoretic Process Analysis

Ensuring the safety of a high priority system parallels verification and validation of performance. Most will have catastrophic or adverse failure modes that must be designed out in a systematic manner. However, these adverse events can also result when the system performs as designed. For example, consider the aircraft lithium-ion battery failures of 2013 [87]. The environmental control system was designed to remove smoke through a cooling duct but was unable to perform any controlling actions due to the designed inactivation response in the event of battery failure. The environmental control system suffered no *systemic failures* as it behaved as intended according to the design requirements implemented but resulted in highly adverse conditions – a smoke filled passenger cabin [87].

Systematic safety analyses seek to remove a measure of uncertainty. The uncertainty is removed by desired system behaviors that can be made inherent attributes of the system. Verifying system safety during the design phase means that this process must be *continuous* and *dynamic*. Reactive safety analysis will succeed only at identifying an issue either much too late in the design or production process or, worse, after a failure or catastrophic event (as distinct from a system failure) which may not have occurred in a catastrophic event. Experience proves that swifter cycle times of learning from systematic discovering delivers operational excellence throughout the development lifecycle, extending beyond mistakes during production [10].

System Theoretic Process Analysis (STPA) identifies conditions as a result of systemic attributes that might develop into a hazardous situation throughout operation. STPA can be performed during the acquisition process before the product is physically delivered [87]. There are two principal steps in this type of analysis.

First, seek out the potential for inadequate system control contributing to an unintended system state. Establishing a unique system control structure is the systems engineering foundation of this analysis. The control structure, diagrams, and models of increasing fidelity can be used to identify weak spots and recommend changes that enhance the resiliency of the system in question. This encapsulates steps 1) and 2) in Figure 39 [87].

Second, apply a critical examination to the system emergent features to identify how the actions identified in the first step could occur. From the root cause, new requirements and behavior constraints can be established for elements of the system such as stakeholders, physical or equipment components, sensors, or operators. Concluding the STPA process is conducted in steps 3) and 4) in Figure 39 [87].

In the next chapter, we will use a concept illustration of a fictional weapon system demonstrating an application of extending a full application of STPA to the domain of cybersecurity during the design lifecycle phase. This illustration will show that the process is widely applicable to determining how systemic behaviors can result in failures across multiple domains as shown in Figure 39.

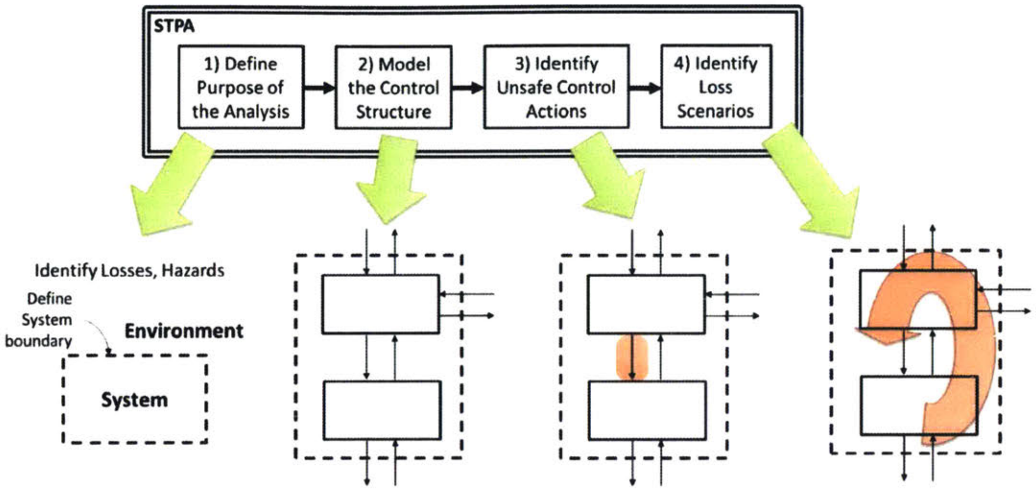


Figure 39: Overview of STPA method [87]

6.4 Execution Roadmap

In order to use a model for any practical purposes beyond the academic setting, the information that it provides needs to be firmly based on the physical reality. Although we often cannot be confident that past behaviors can be used directly to predict future outcomes, we must pursue a path for developing system models that can accurately capture system behaviors and enable resilient designs that will have high likelihood of achieving mission success under uncertain and adverse operating environments.

This chapter presented frameworks and mindsets useful in ensuring that models are verified and validated with the requirements of the system. As we saw, verification and validation can also be used from a design standpoint, and not simply as a reactive impediment to the development cycle. The concept illustration in the subsequent chapter introduces the application of this process for the structure of cross-functional cyber-physical requirements.

Verification and Validation Summary
Multiple approaches to V&V demonstrate that requirements and relationships are represented accurately and instill confidence in an MBE approach
"Test Like You Fly" from the aerospace sector ensures that a model replicates the operational conditions faithfully to exhaustively capture all possible outcomes
System Theoretic Process Analysis (STPA) provides a framework to systematically assesses the safety and operational stability using models during acquisition

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Chapter 7

7.0 Concept Illustration: Weapon System Cybersecurity

We had to explore and break ground in... the adaptation of man to the machine. We were going to bring into existence machines and equipment which the Navy had not seen before and had no experience with.

Vice Admiral William F. "Red" Raborn
U.S. Navy's first Director of Special Projects Division, 1955

Strategic ballistic missile weapon systems were first investigated in Chapter 4 to characterize a successful implementation of Model Based Engineering in streamlining testing and production of the design of the upgraded guidance system [85]. We can extend this analysis to consider sub-systems that comprise a Fictional Submarine Strategic Missile (FSSM) program. The level of surety required by advanced strategic-level weapons systems can only be possible in an environment where critical information can be accessed or shared only by those systems and stakeholders that require it. Tacit threats of a cyber nature have emerged as adversarial actors seek to counter U.S. Naval power both with physical assets and in the cyber battle space.

As with all complex systems, requirements are a multi-domain problem. These takes many forms in the current "Information Age" and touches every industry on the planet. Until this section, this thesis has focused primarily on the representation of requirements and technical specifications of the physical world of complex system construction including aerospace, marine, and defense systems. A preponderance of experiential and empirical evidence demonstrated that requirements in diverse domains can shift rapidly during the system lifecycle. Complex warfighting needs may change with a single event or the incremental passage of time. Nowhere is this uncertainty of requirements starker, more impactful, or has more of a chance to render previous work completely irrelevant than in the field of cybersecurity – the field of protecting the integrity of cyber-physical systems and the critical information assets on which they rely [88].

7.1 Concept Illustration Hypotheses

The three hypotheses that this concept illustration addresses are shown as lines of effort in Figure 40. First, we will establish how principles enabled by Model Based Engineering are domain agnostic. Next, methods of concurrent design, verification, and validation will demonstrate that model-based engineering methods reduce uncertainty effects from future requirements by increasing the integrity of the design of the end-product. Finally, in the case of the FSSM, system requirements dictate a unique and tailored verification and validation sequence to ensure the applicability and usability of our representation of reality in the model. In this concept illustration, that tailored sequence will be the application of STPA extended to the cybersecurity domain. The use of multiple paradigms of system design and analysis in Model Based Engineering contributes to verification, validation, and confidence in the model's representation of the physical world.

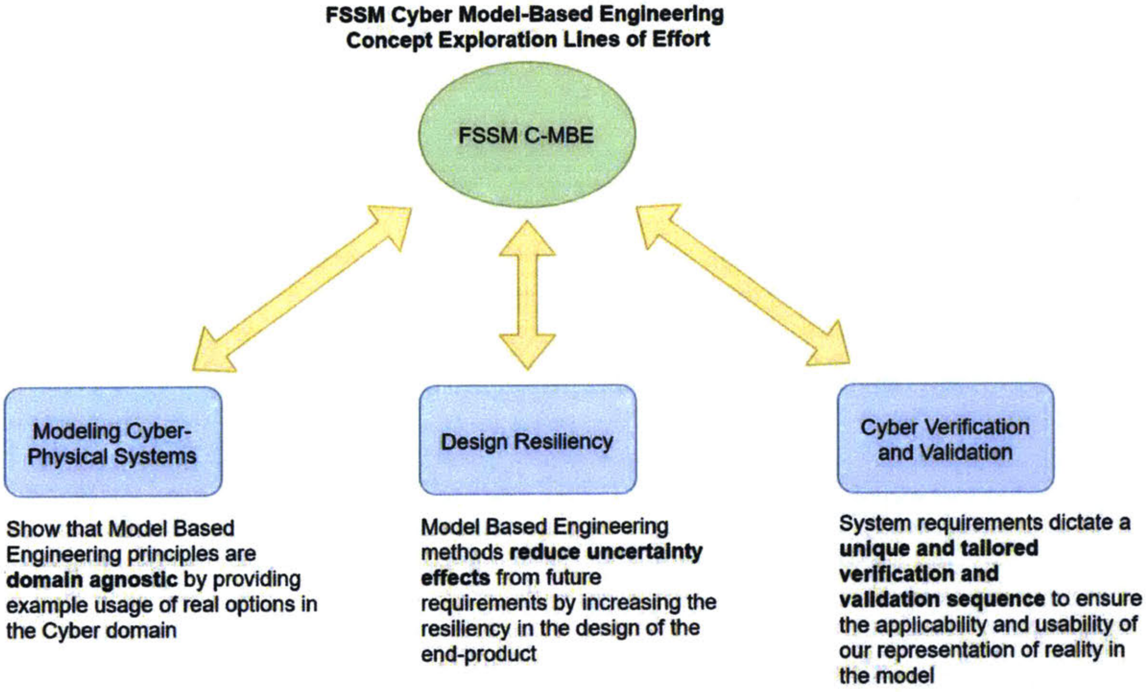
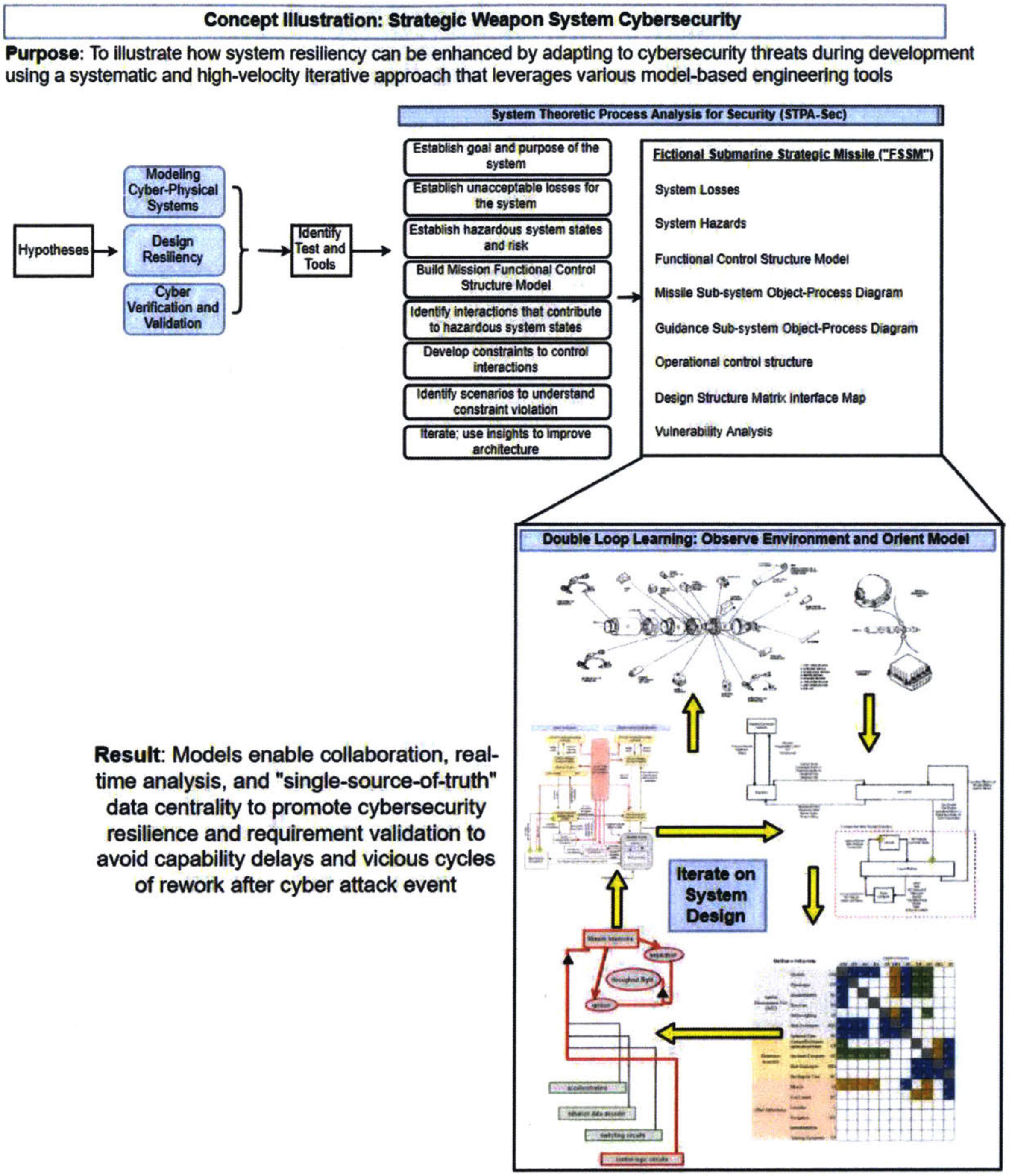


Figure 40: Cyber MBE Concept Illustration lines of effort

This analysis follows the progression shown below in Figure 41. We start by amending the operating definition for resilience used in this thesis for the cyber-physical domain and examine the nature and directionality of threats and general system vulnerabilities. The concept of using MBE in the cyber-physical context to advance a design with validated requirements for resiliency against unknown cybersecurity threats is illustrated by proposing an initial framework for the use of Systems Theoretic Process Analysis for Security (STPA-Sec). STPA-Sec promotes the ability to anticipate, withstand, and recover from a hostile cyber act for a complex system.



Concept Illustration: Strategic Weapon System Cybersecurity

Purpose: To illustrate how system resiliency can be enhanced by adapting to cybersecurity threats during development using a systematic and high-velocity iterative approach that leverages various model-based engineering tools

System Theoretic Process Analysis for Security (STPA-Sec)

- Establish goal and purpose of the system
- Establish unacceptable losses for the system
- Establish hazardous system states and risk
- Build Mission Functional Control Structure Model
- Identify interactions that contribute to hazardous system states
- Develop constraints to control interactions
- Identify scenarios to understand constraint violation
- Iterate; use insights to improve architecture

Fictional Submarine Strategic Missile ("FSSM")

- System Losses
- System Hazards
- Functional Control Structure Model
- Missile Sub-system Object-Process Diagram
- Guidance Sub-system Object-Process Diagram
- Operational control structure
- Design Structure Matrix Interface Map
- Vulnerability Analysis

Double Loop Learning: Observe Environment and Orient Model

Result: Models enable collaboration, real-time analysis, and "single-source-of-truth" data centrality to promote cybersecurity resilience and requirement validation to avoid capability delays and vicious cycles of rework after cyber attack event

Figure 41: Concept illustration process flow summary

7.2 Cybersecurity Resiliency

Recall that we are using the definition of *resiliency* as a system attribute defined by the ability to absorb multiple forms of disruption and continue the intended function without degrading performance level, results, or outputs (Figure 2, Chapter 1). When considering the full spectrum of cyber-physical systems, *cybersecurity resiliency*, as defined in Figure 42, is not to be confused with its application from other domains subjected to purely physical threats. During the development of critical naval cyber-physical sea systems, we measure cybersecurity resiliency as ability to adapt defensive measures to an adversary with an asymmetric offensive capability in the domain of digital information transfer where the barriers to entry often approach zero [88].

Cybersecurity Resiliency
An attribute of a cyber-physical system measured by the ability to absorb changing developments in the cyber-warfare domain and protect critical components from compromise

Figure 42: Cybersecurity Resiliency for complex naval systems, defined

Although the detailed exploration of the nuances of cybersecurity requirement setting is beyond the scope of this thesis; as cyber-physical components permeate our defense systems, it is increasingly applicable to consider how proposed resilient acquisition tools affect the cyber-elements of these systems. Developing measures of performance and effectiveness for cybersecurity resiliency is a matter of ongoing research but must involve the entire system lifecycle starting with concept formulation and protecting information about system attributes before production.

7.2.1 Resilience Throughout System Lifecycle

Resiliency of a design depends on the functional attributes built into, or added to, the system as compared with how well the system model adheres to requirements. After deployment, resilient weapon systems retain the flexibility to adapt to new threats that develop over time. Measuring the "system integrity" is related to the system's ability to adapt resiliently in that it expands to include both preventive features (resistance) and the capacity for recovery from a disruptive event.

The concept and design phases must therefore continue over the entirety of operational life of the system. An abstraction of the system integrity metric that measures the protection of sensitive (or "classified") information called "Classification Integrity" can be held as motivation for developing an adaptive resiliency in the realm of cybersecurity requirements. Figure 43 illustrates how this Classification Integrity may develop over time in the presence of cyber vulnerabilities. The visualization helps to establish the imperative to develop requirements for the Fleet to ensure that what we are designing today will remain relevant in the realm of global security through its deployment over the time scale of operational lifecycle [89].

Figure 43 includes a set of curves for "Classification Integrity" as a function of time. As time advances, we postulate that there is a decreasing likelihood that you can protect the critical aspects of the system from adversarial exposure or breach. As more stakeholders are added to the system – developers, operators, contractors – the curve advances lower, proportional to the amount of information transfer points added to the system. The pressures that time and stakeholder information transfers place on protecting the integrity of the most sensitive elements of the system may be faced for decades, but a single earlier security event compromising the system gives adversaries the remaining operational lifecycle to develop responses before the system reaches its first deployment.

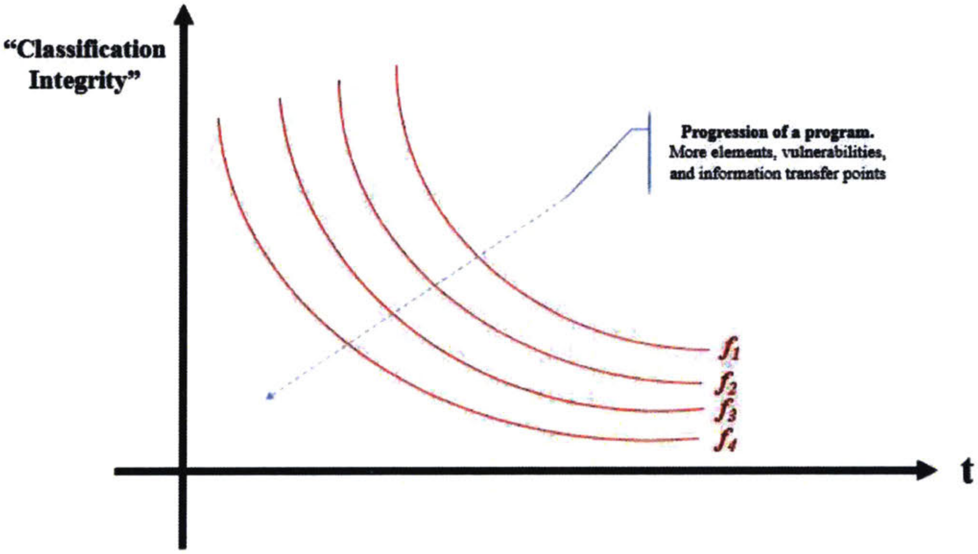


Figure 43: Abstraction of "Classification Integrity" metric vs. time

7.2.2 Threat of the Unknown

Marriott learned during the investigation that there had been unauthorized access to the Starwood network ***since 2014****...* [90]

Details on civil cybersecurity cases, such as the 2018 Marriott data breach mentioned in the quote above, demonstrate examples of how, unlike kinetic or material vulnerabilities, unknown cyber breaches can persist, exacting damage for several years before being detected.

Not knowing where your systems are vulnerable to breach compounds the risk of an incident via blindness of a security problem, ensuring that you won't address an issue until it is too late – as in the case of corporate security breaches in the news on a regular basis. To defend a cyber-physical system from hostile operations, focus is required on the entirety of the system control structure to include development, production, and operations in addition to the operators and the physical system itself. Figure 44 and Figure 45 illustrate that limiting a cyber defense focus to operators and the physical system itself can limit the focus to the exclusion of other areas of vulnerability.

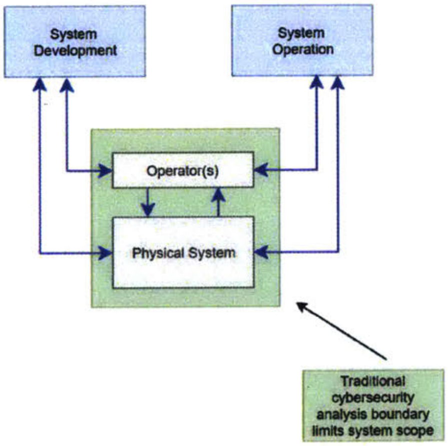


Figure 44: Typical cyber-physical defense control structure

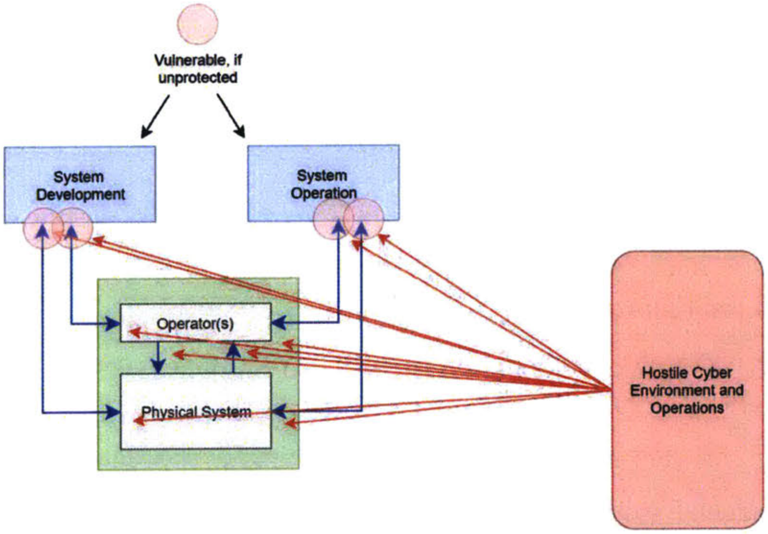


Figure 45: Vulnerabilities in the cyber-physical defense structure

Since the threat is unknown, the adversary's choice of target or attack strategy cannot be used in planning. Therefore, maintaining a standard library of robust measures will not be enough to defend against innumerable, rapidly evolving threats that can come from any direction and at any level in the program or system. Accelerated cycles of developing architecture, as illustrated in Figure 46, inherently hardens the design by re-baselining the situational awareness and penetration strategies of an adversary.

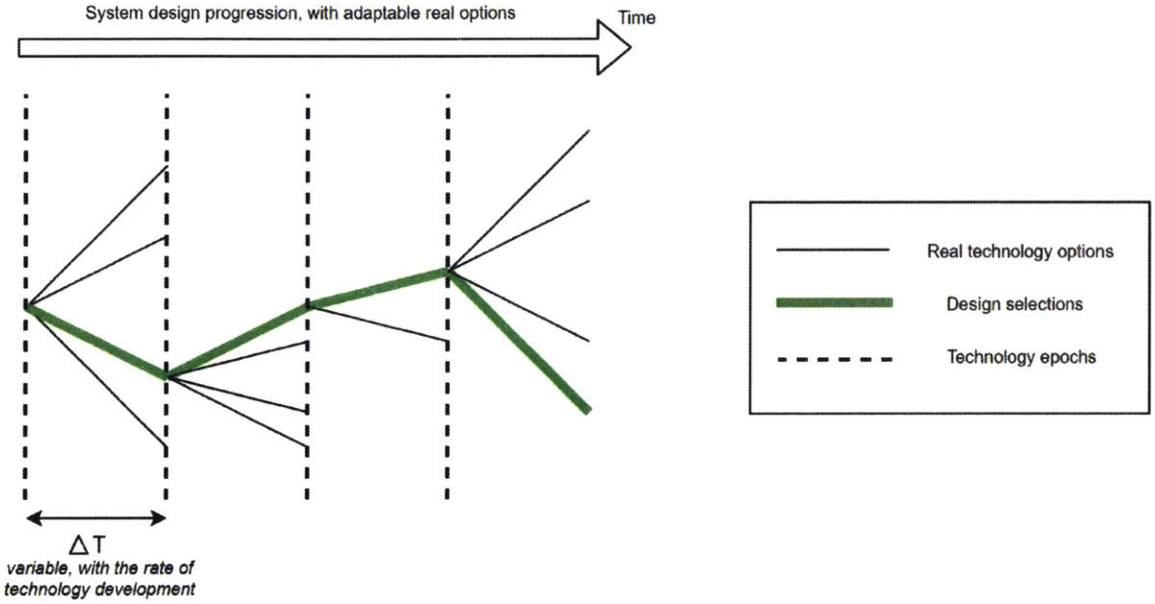


Figure 46: System adaptation using Real Options at technological junctures, or epochs

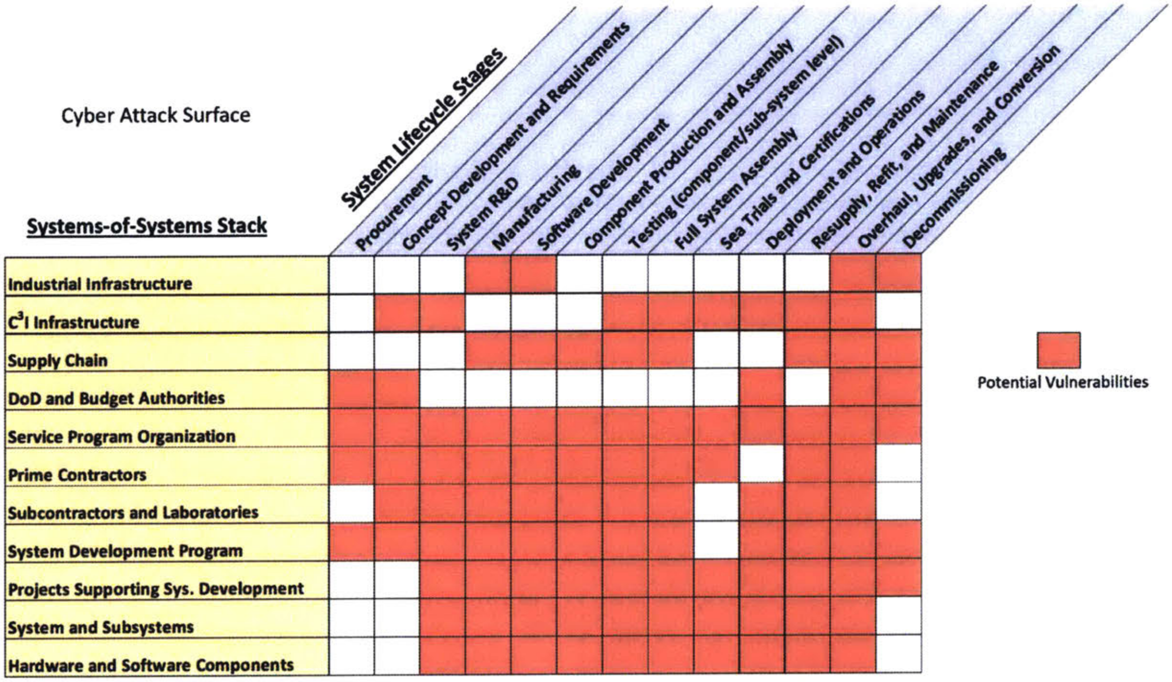
The Real Options framework "bakes-in" an architecture for developing, monitoring, and maintaining cybersecurity relevance throughout the lifecycle of the weapons system development by continually adding advanced features and redesigns [91]. By exercising options on technology and/or architecture improvements at comparatively short intervals (ΔT in Figure 46), the adversary will be forced to re-assess and re-approach attack techniques in response to a resilient and adaptive design architecture [89].

7.2.3 Cyber-Physical MBSE

Cyber-physical systems are characterized in structure by cyber connectivity in every physical component, networks of sensors and actuators, and underlying executable code [92]. Additionally, their behaviors cross multiple domains through the use of computer-based logical controls that have stringent timing parameters and multiple spatial and temporal resolutions [92].

Advanced weapons systems such as the Fictional Submarine Strategic Missile (FSSM) considered in this concept illustration exhibit these defining characteristics. The interface between the cyber and physical domains enables situational awareness, command and control, and the weapon systems capabilities.

A model of a cyber-physical system serves to enhance the resiliency of the system through adaptation in design to threats and requirement evolution. Starting with a reference architecture, designers can create Real Options for extension, added functionality, or robustness. Comparing the "stack" of systems-of-systems with perceptions of how they progress through lifecycle phases can identify potential vulnerabilities over the adversary's cyberattack surface, as shown in Figure 47. Although this DSM is at a generalized level given a relative lack of knowledge about the nature of how cybersecurity threats evolve, one can easily make the extension into higher complexity provided access to complete details of operation, full listing of components, and the nature by which they interact to complete the functionality of the notional weapons system.



Cyber Attack Surface

Systems-of-Systems Stack	System Lifecycle Stages												
	Procurement	Concept Development and Requirements	System R&D	Manufacturing	Software Development	Component Production and Assembly	Testing (component/sub-system level)	Full System Assembly	Sea Trials and Certifications	Deployment and Operations	Resupply, Refit, and Maintenance	Overhaul, Upgrades, and Conversion	Decommissioning
Industrial Infrastructure				🟥	🟥							🟥	🟥
C^3I Infrastructure		🟥	🟥				🟥	🟥	🟥	🟥	🟥	🟥	
Supply Chain				🟥	🟥	🟥	🟥	🟥			🟥	🟥	🟥
DoD and Budget Authorities	🟥	🟥								🟥		🟥	🟥
Service Program Organization	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
Prime Contractors	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥		🟥	🟥	
Subcontractors and Laboratories		🟥	🟥	🟥	🟥	🟥	🟥	🟥		🟥	🟥	🟥	
System Development Program	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥		🟥	🟥	🟥	🟥
Projects Supporting Sys. Development			🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
System and Subsystems			🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	
Hardware and Software Components			🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	

🟥 Potential Vulnerabilities

Figure 47: Notional Cyber Attack Surface, adapted by author with permission from [89]

In a model of a cyber-physical system, information sharing pathways carry an increased significance as they have the potential to present both an informational and physical vulnerability. The organizational structure of a system has an impact on the effectiveness of the dynamics of system discovery critical for resilient adaptation [38]. In a model of both the cyber and physical domains, the interface is often a human-machine interface, a control signal, or an input/output signal. An abstraction provides the perspective that highlights emergent properties or interactions especially relevant in analyzing the measures of performance selected for a system.

Looking at models of the systems engineering aspects of cyber-physical systems, we are left with the motivating question of how to establish a systematic and mechanistic process with which to evaluate the security in the form of *information assurance*. In large-scale or high-impact systems, "system performance" is often synonymous with "system safety." Adaptation of the System Theoretic Process Analysis (STPA) can be made to the realm of cybersecurity to provide a framework for information assurance [93]. The goal of this analysis in a complete form may be to propose an architectural extension to one or all the architectures that might improve resiliency. Upon concluding an integration of this analysis, the models can be used by those with system expertise to identify the vulnerabilities in a single view before an adversary has the chance to exploit them.

7.3 STPA for Security

System information assurance is not a well understood problem. Requirements for cybersecurity are multi-domain in the sense that weapon systems can no longer be procured in a vacuum independent from the platforms that are being designed to accommodate them. Careful consideration of the requirements placed on these payload delivery systems must be made to ensure the right product is reaching the Fleet in the shortest amount of time.

This may be a point of departure for the approach to developing system requirements as compared to "standard" approaches based kinetic threats. How do we create requirements that are responsive to a threat environment that is (a) almost impossible to project beyond an initial deployment timeline for the FSSM under development, (b) evolving much more rapidly than the development of the FSSM, and (c) extends into many levels of the system-of-systems "stack" that supports the development, deployment, and support of the FSSM [89]?

STPA-Sec applies systems theoretic principles to analyze the resiliency of a cyber system by identification of problems before they manifest themselves as cyber vulnerabilities. This process can be applied throughout the lifecycle as information about the system and threat complexities are gathered, studied, and modeled to conduct continual, iterative, and rigorous inquiry that identifies high-level cyber exposures. Continual review and re-assessment throughout the lifecycle and systems engineering "V" process (see Figure 12 in Chapter 3) underpins mission assurance from the process onset. STPA-Sec is a rigorous analysis process designed to prevent unintended operation that results in a system loss by learning from, then controlling, interactions between components. The inquiry framework consists of an eight-step process summarized in Table 17.

Table 17: Eight Steps of Systems Theoretic Process Analysis for Security [93]

Step 1	Establish goal and purpose of the system
Step 2	Establish unacceptable losses for the system
Step 3	Establish the hazardous system states that place system at risk of suffering unacceptable losses
Step 4	Build Mission Functional Control Structure Model
Step 5	Identify the interactions that give rise to the hazardous system states using modified Step 1 Table
Step 6	Develop constraints to control these interactions
Step 7	Identify scenarios to understand how constraints might be violated (given existing architecture) using Step 2 Table
Step 8	Use insights to improve existing architecture

Step 1: Establish the goal and purpose of the system

In performing this initial step, the boundary for the system must be established in order to bound our investigation scope. A complex strategic weapon system has many options for boundaries that range from the individual micro-component to the national command authority. A system boundary limits scope and suggests a level of detail that might be able to be reached. While setting a wide system boundary may be advisable for a large-scope study aiming to capture the system dynamic effects of many elements, doing so may limit the fidelity able to be achieved. Considering too narrow of a focus may cause externally emergent details that affect a system to be missed.

It is important to note that the models and descriptions in the concept illustration shown below through the steps of STPA-Sec are purposefully not complete. Although they are derived from a historical weapon system configuration in order to illustrate a potential representative system architecture, considerable further analysis would be necessary to identify vulnerabilities in a real-world system architecture [94]. They are illustrated to demonstrate an example of how a model-based configuration design and display can be used to determine systemic vulnerabilities and set corresponding requirements.

The representative FSSM could be comprised of several sub-systems as shown in Figure 48, including Missile, Guidance, Launcher, Fire Control, Navigation, Instrumentation and Training Equipment [94]. The Missile and Guidance sub-systems of the FSSM Weapon System were selected to perform this concept illustration, and highlighted in the object-process diagram of the weapon system (Figure 48) and the physical component diagrams of Figure 49 and Figure 50, respectively. For more information on the Object Process Methodology, refer to Chapter 3, the source texts by Dori, *Model-Based Systems Engineering with OPM and SysML*, and existing international standards, ISO 19450 [52], [53].

The goal and purpose of these two sub-systems are based on representative open-source weapon system technology [94]. The Missile sub-system of FSSM could be " an inertially guided, three-stage, solid-propellant missile with maneuverable post-boost vehicle which is separated to independently deploy reentry bodies", while the Guidance sub-system could "employ a stellar-inertial guidance concept allowing the missile to accurately reach a point and velocity on the trajectory where reentry bodies are released and will free-fall to their targets" [94].

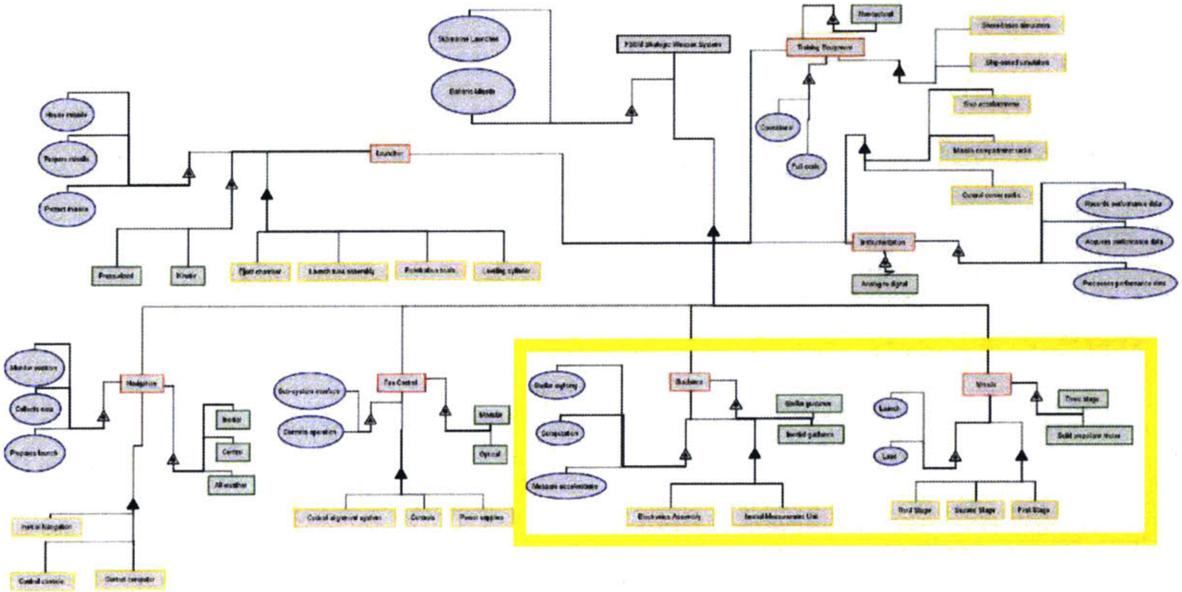


Figure 48: OPD of the overall FSSM Weapon System with Missile and Guidance sub-systems highlighted

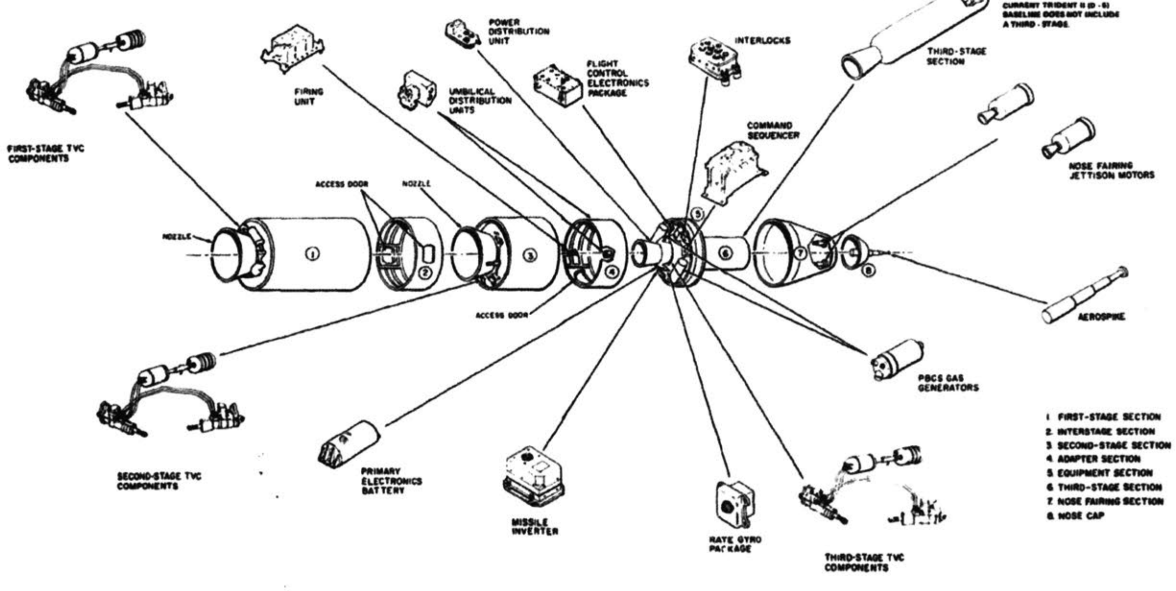


Figure 49: Missile Subsystem basis for analysis, from public domain source [94]

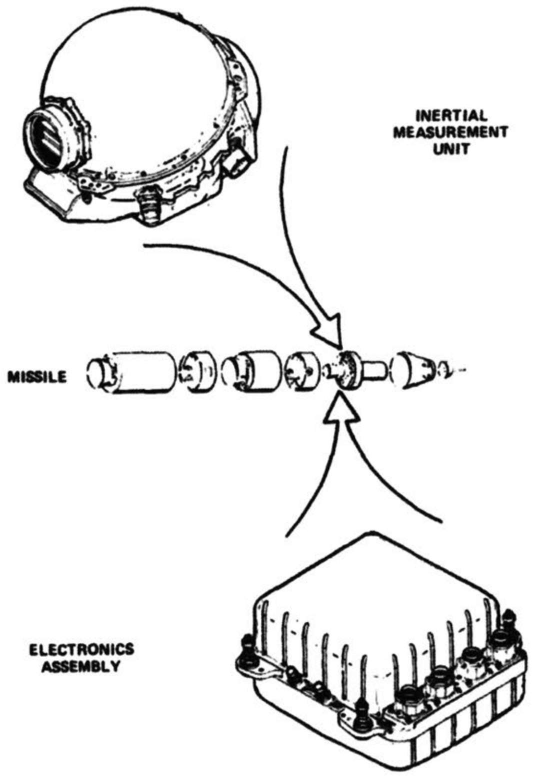


Figure 50: Guidance Subsystem basis for analysis, from public domain source [94]

Step 2: Establish unacceptable losses of the system

In establishing unacceptable losses, we can look at the mission critical failure states as defined by the AIAA, including conditions resulting in mission failure (see Table 18) [73]. Loss Type 1 indicates a systemic failure that results in lost functionality without redundancy to provide the ability to continue the mission. This could include the physical loss of a component or the failure to transfer information where required. In Loss Type 2, equipment performs outside the ranges of specification limits defined for mission assurance – potentially, reduction in measured speed, range, or accuracy. Although not an immediate loss, Loss Type 3 conditions reduce the mean time between failures to a point below the mission duration, therefore probabilistically predicting a mission failure. Finally, the transient condition with a Loss Type 4 event creates a repetitive condition whose compound effect results in a loss of mission performance.

Table 18: Mission-critical failure states, adapted by author from [73]

Loss Type	Description
1	Failure leading to inability to meet/achieve mission objective (e.g., payload or weapon bus is no longer capable of supporting the mission objectives)
2	Inability to meet minimum performance specifications for primary mission
3	Degrading condition whose trend indicates a loss of mission before mean mission duration (MMD) or design life
4	Repetitive transient condition(s) that, uncorrected, would lead to an unacceptable loss of mission performance, data comma or services (e.g., weapon fault in flight with mean time to fault much less than mean time to recover).

The system can experience physical losses in the system itself or its delivery platform. However, for the purposes of this concept illustration, while we acknowledge these system losses and their grave consequences, unacceptable losses at this iteration will be confined to those of a cyber nature.

Cyber-related losses consist of system vulnerability exploitations by an adversary. Since we are limiting our system boundary to the Missile and Guidance sub-systems, these will be specific breaches of the cyber-physical interface of their components. Recall the "Classification

Integrity" metric introduced in Figure 43. Infiltration by an adversary counts as a major system loss since information regarding this weapon system is considered integral to its efficacy. Four unacceptable losses are listed in Table 19 to provide the context of types of potential loss events for the subsequent steps of the STPA-Sec methodology.

Table 19: STPA-Sec Step 2 - Unacceptable Losses

L1	Physical failure of aeronautical or propulsion component on the Missile
L2	Loss of test data transmitted to monitoring station by the Missile
L3	Position incorrectly recognized or recorded with low-fidelity by Guidance
L4	Guidance fails to receive data from Fire Control or fails to transmit to sensors/actuators

Step 3: Establish the hazardous system states that place system at risk of suffering unacceptable losses

A cyber-attack surface (Figure 47) provides the map of potential vulnerability points in a system where attacks can be anticipated. A cyber-attack vulnerability profile is informed by models of the physical world through identifying the nodes of information flow, i.e. handoff points – that are most at risk of causing a catastrophic loss event of the type listed in Table 19.

Three major issues that face complex defense systems from a cybersecurity standpoint are (a) the reliance on commercially available COTS technologies, (b) unreliable or unsecure supply chains, and (c) system complexity that obfuscates the systemic vulnerabilities [95]. These major issues are categorized as system hazards enumerated in Table 20.

Table 20: STPA-SEC Step 3 - System Hazards

H1	Commercial off the shelf technologies with exploitable vulnerabilities
H2	Complex supply chain could be breached without being able to track the source
H3	System complexity obscures where vulnerabilities exist, or missed information transfer

Step 4: Build Mission Functional Control Structure Model

The Missile and Guidance subsystems are elements of the FSSM platform in the notional model of the entire Mission Functional Control Structure shown in Figure 51.

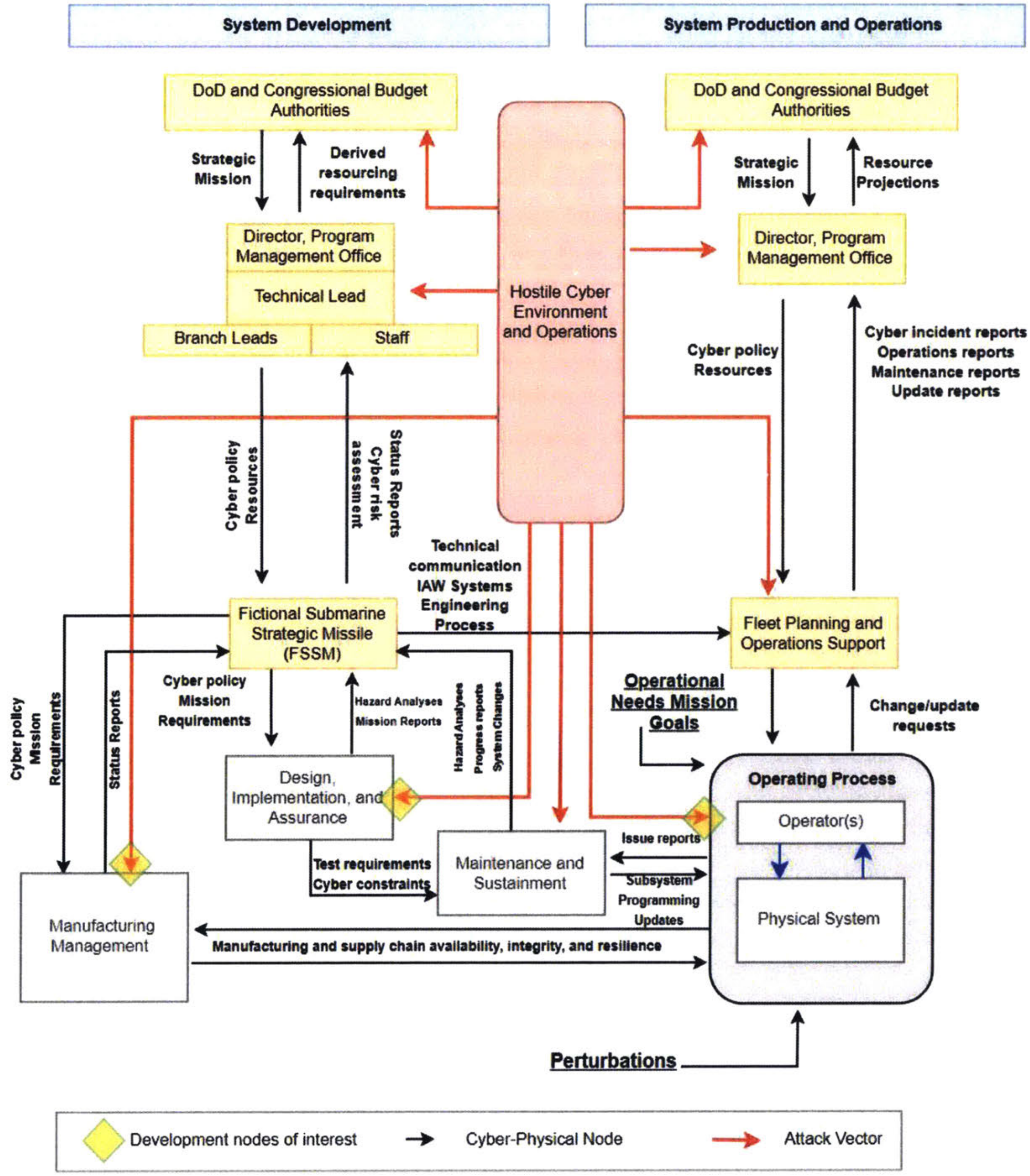


Figure 51: FSSM Control Structure with system acquisition, development and operations engagements, adapted with permission from [89]

The interaction descriptions on the figure are entry points where an STPA-Sec process can be developed around the details of interaction. Figure 51 also shows how the FSSM system-of-systems is exposed to cyber threats across the entire domain of its development, operations, and control. The preponderance of cyber readiness measures focuses on physical system design and operations but often overlooks information handoffs that may provide breach opportunities [96]. Each of the connectors, whether physical or cyber component, represents a potential source of vulnerability that can be analyzed with STPA-Sec. When focused on a single node, the STPA-Sec procedure can be applied recursively to the microcosm problem in the node to reach conclusions regarding the holistic system.

Specific functional control structure models of the Missile and Guidance subsystems are built as Object Process Diagrams (OPDs) shown in Figure 52 and Figure 53. These diagrams are not intended to represent an actual system, but are derived from historical configurations of past weapon models [94]. The methodology used in this STPA-Sec stage is the Object Process Methodology (OPM). OPM provides a useful object and process differentiation for the use of this methodology in STPA-Sec analysis. Objects retain the characteristic of "essence" which can be either physical or informational while a process has an "origin" which can be either environmental or systemic [97].

The types of connectors and shapes of objects and processes characterize the interactions of the system elements. When looking at the full view we can search for single points of failure or critical components for system functionality. OPDs of a system architecture display a single holistic view of a system. This presents a demonstrated advantage over methodologies that require multiple views to uncover the information contained in the model [62].

Each object and process modeled for these two sub-systems has been assigned the appropriate designator to inform the types of interactions and their controllability. This also aids in contextualization of information and component flow through the system to further identify vulnerabilities or possible points of failure of a certain "arm" of the system. If a process or object can be considered both *environmental* and *systemic* – usually a physical element – then the default categorization is *systemic* because we can consider the environmental "element" to be a component (property/object) of the greater system.

As mentioned above, the models shown below are purposefully not complete and require considerable further analysis to identify vulnerabilities in the system architecture. They are illustrated to demonstrate an example of how a model-based configuration display can be used to proceed through the steps of this analysis.

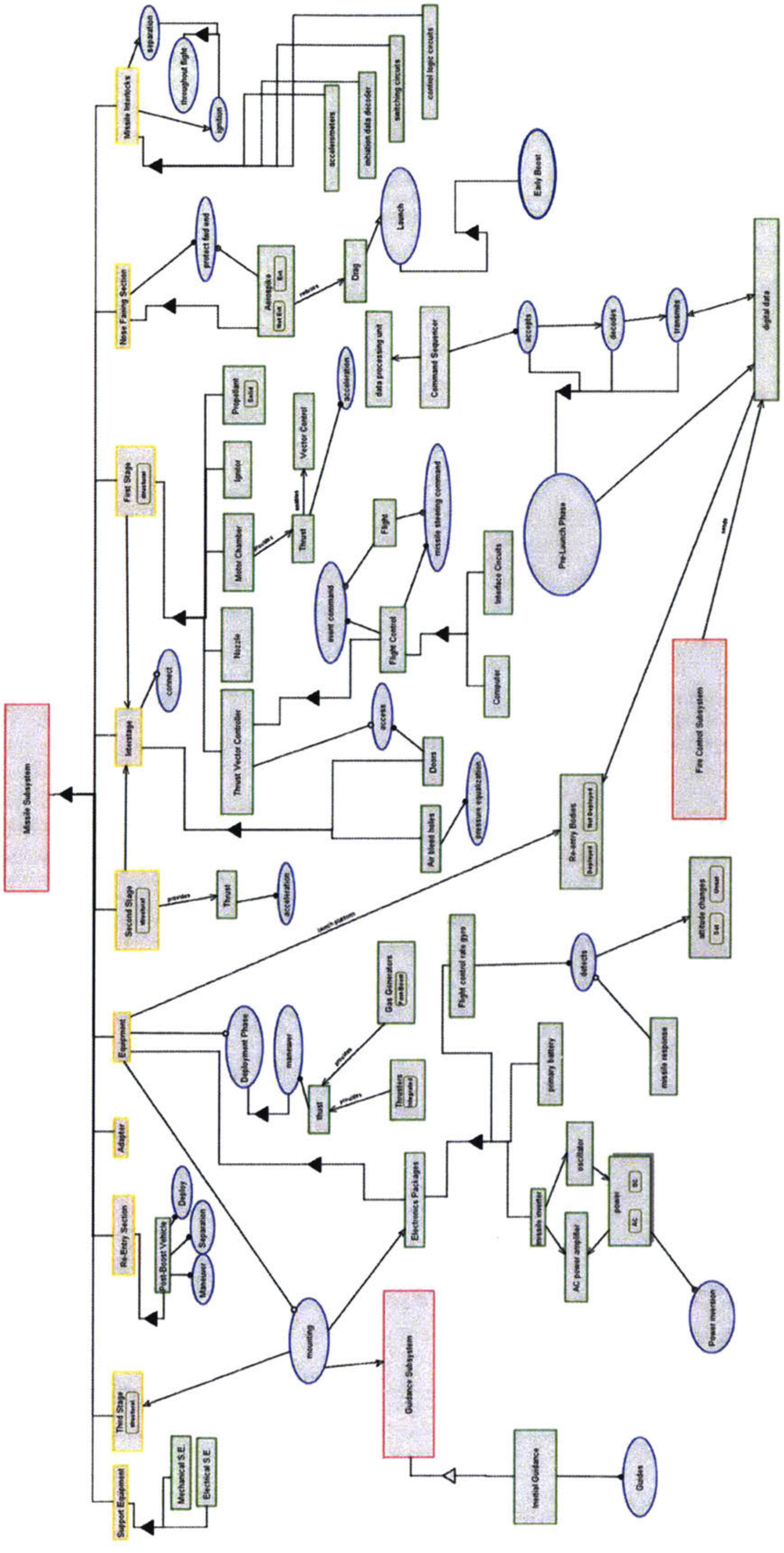


Figure 52: FSSM Missile Subsystem Object-Process Diagram

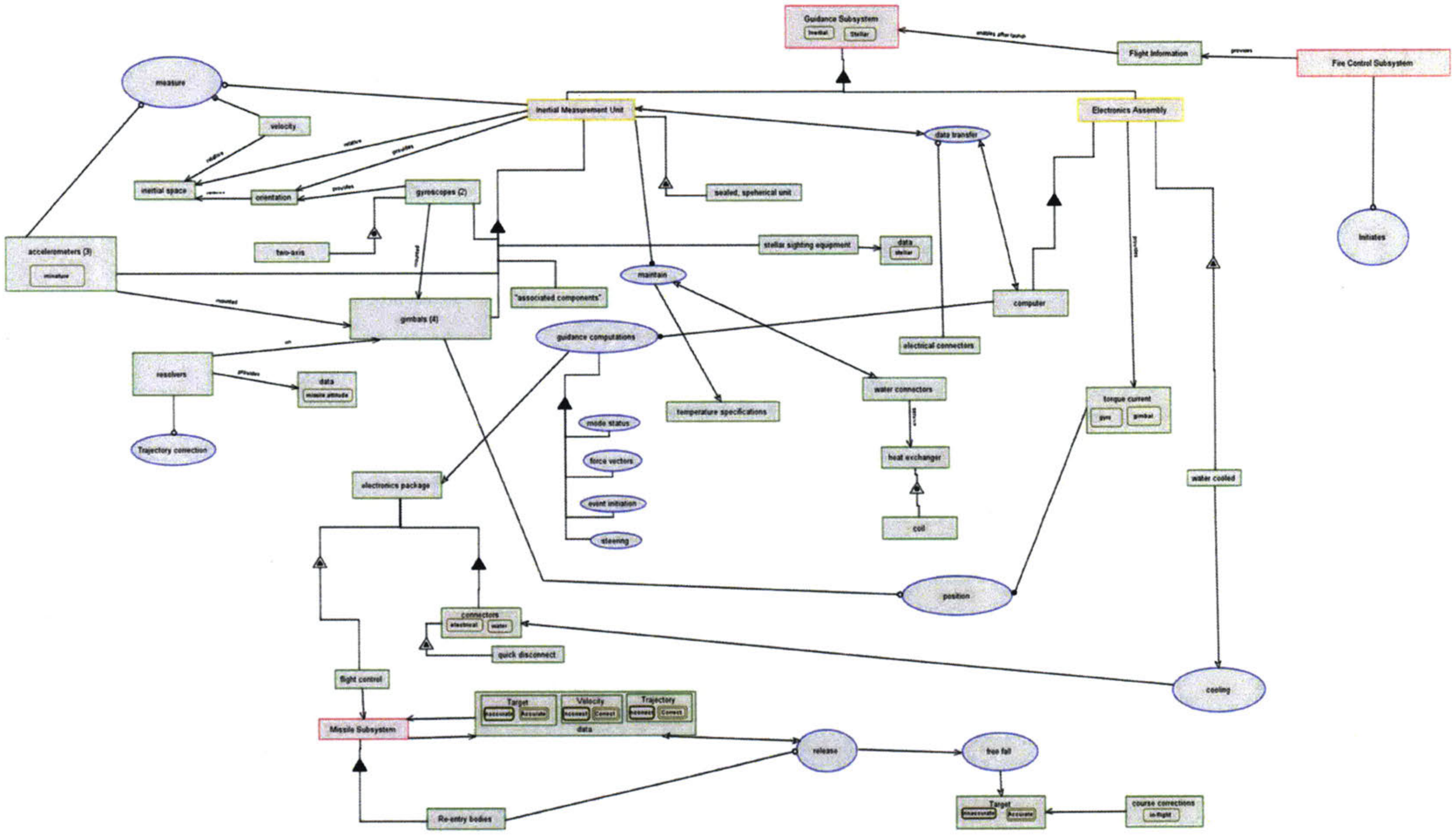


Figure 53: FSSM Guidance Subsystem Object Process Diagram

In Figure 54, focusing on a more detailed representation of the operations functional control structure identifies areas of concern for sub-system function. Functional control models enable visualization of key activities that each of the two subsystems are designed to accomplish by showing both the elements of the system and their function in mission accomplishment [93].

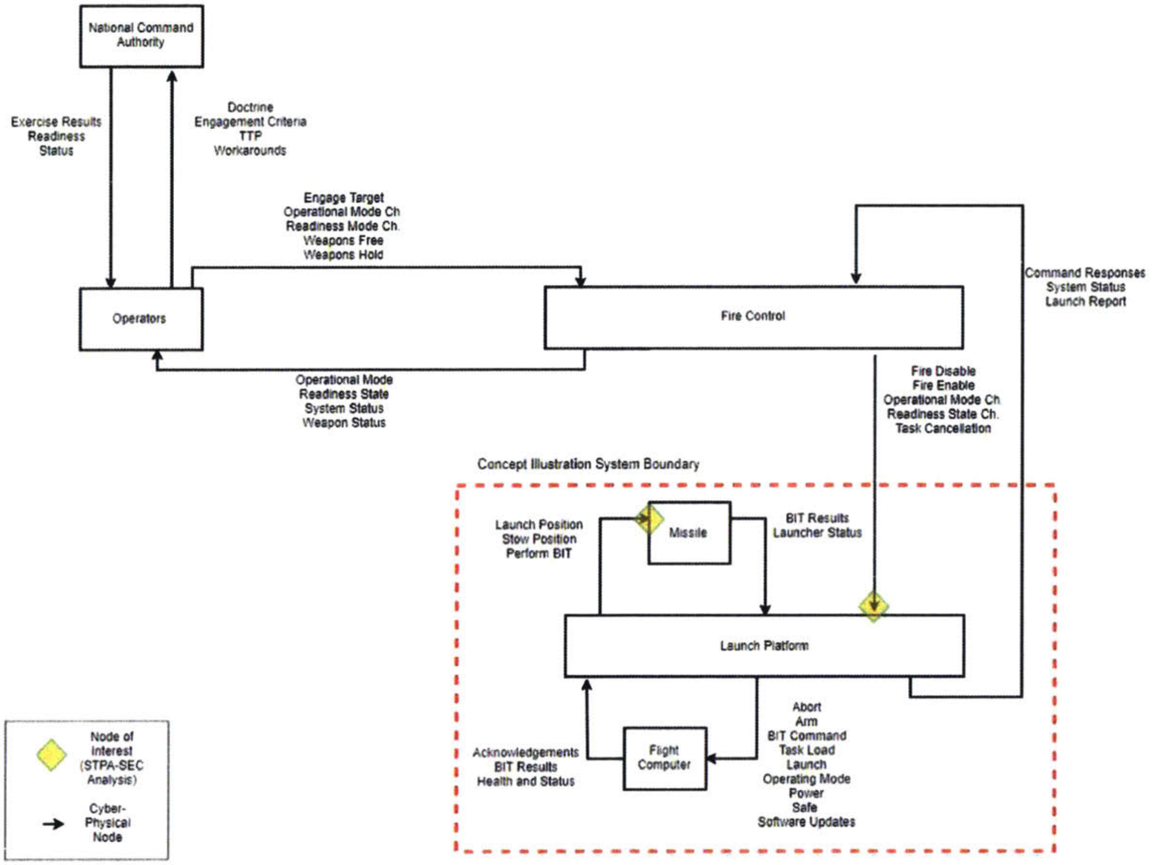


Figure 54: Operational control structure, adapted by author from [103]

The control structure can map, model, and demonstrate key activities of a system or sub-system which would then be explored in further detail using a tabular format. For the ballistic missile and its guidance package, the key activities are *flight* for the Missile sub-system and *location tracking* for the Guidance sub-system. Key activities are selected through reference back to the mission functional control structure. In Table 21 and Table 22, the activities are decomposed into elements and responsibilities with explanatory statements centered on how each element interacts and performs a function contributing to overall activity or mission accomplishment. These tables can be extended for each element of the sub-system to track their function in performance of these key activities.

Table 21: Missile sub-system element responsibility map to key activities [94]

Key Activity: Flight – Missile Sub-System	
Element	**Responsibility**
First Stage	Thrust for missile acceleration and thrust vector control
Interstage	Connects the first and second stage sections and has air-bleed holes to permit pressure equalization
Second Stage	Thrust for missile acceleration and thrust vector control
Equipment Section	Mounting platform for electronics packages, the Guidance sub-system, and is launch platform for reentry bodies
Flight Control Rate Gyro	Detects Missile response to attitude changes

Table 22: Guidance sub-system element responsibility map to key activities [94]

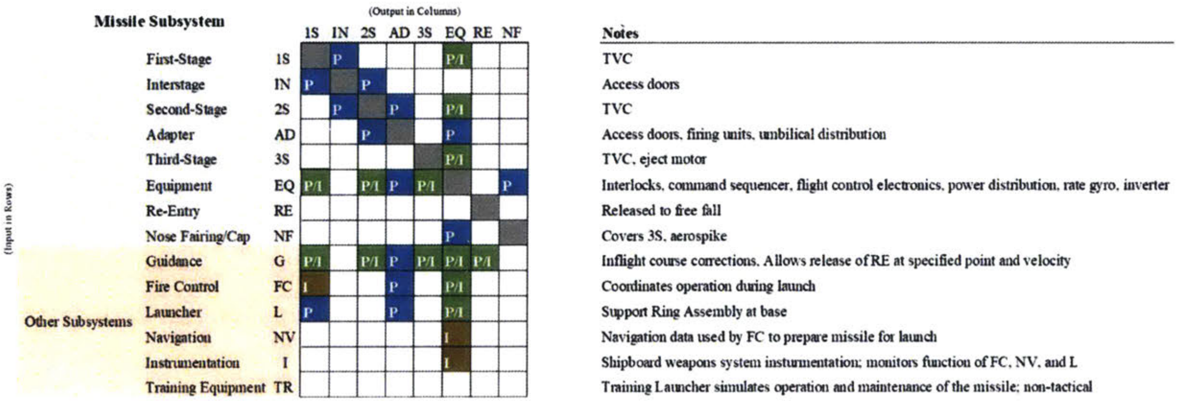
Key Activity: Location Tracking – Guidance Sub-System	
Element	**Responsibility**
Inertial Measurement Unit (IMU)	Provides the Missile with reference orientation relative to inertial space and measures missile velocity
Gimbal-mounted gyroscopes	Maintain stable orientation relative to inertial space during flight
Accelerometers	Measure Missile accelerations during flight
Electronics Assembly	Processes information from IMU to make guidance computations and provide steering and force vectors, model status and event initiation for the Missile

Step 5: Identify the interactions that give rise to the hazardous system states using modified Step 1 Table

During this phase of the analysis, incorrect, improperly sequenced, or missing control actions that place system operation at risk of a mission failure mode from Step 2 will be identified using models of the system [93]. Interactions can be characterized as either physical, informational, or a hybrid, "P", "I", or "P/I" respectively in the key in Figure 55. To find the interactions that give rise to hazardous system states, the sub-system Design Structure Matrices in Figure 56 and Figure 57 contextualize interactions between the components of the FSSM Weapon System. These diagrams can be used to capture the details of a project as it evolves. Eventually the DSMs may serve as a "single source of truth" model as this language is not necessarily confined to a specific representation or language. The OPM adds additional information to the interactions captured within the DSM by displaying a higher fidelity graphical model that can identify more information about the system and the interactions between its components in a single view.

P	Components share only a physical interface
I	Components share information during system operation but are not physically connected
P/I	Components both share information and are physically connected

Figure 55: Sub-system DSM interface map key

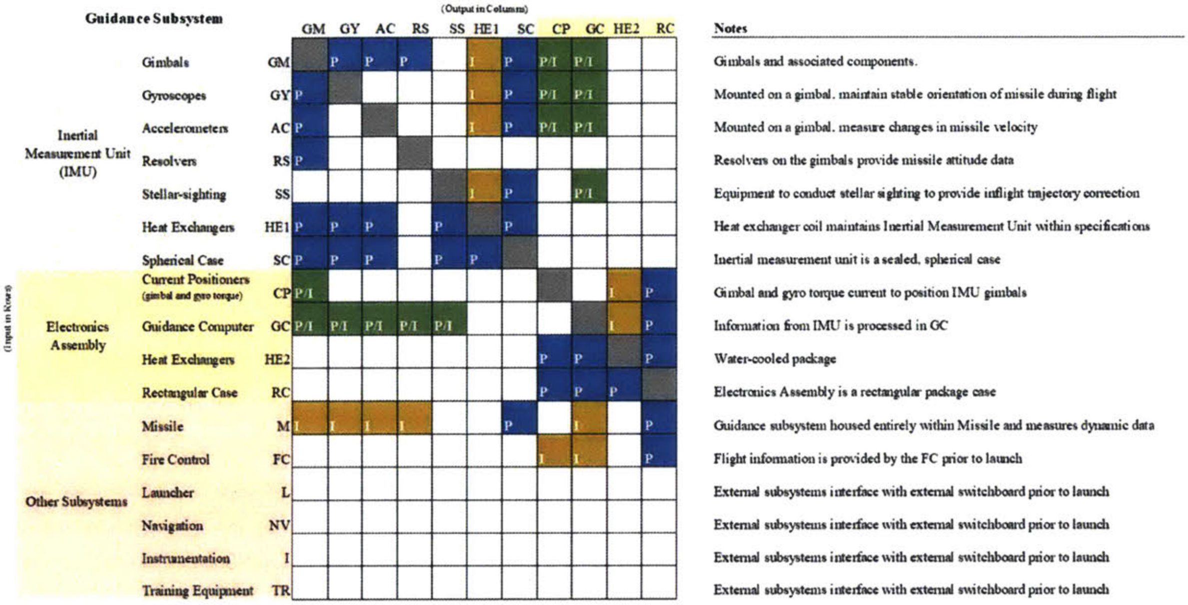


(Output in Columns)

(Input in Rows)

Missile Subsystem			1S	IN	2S	AD	3S	EQ	RE	NF	Notes
	First-Stage	1S		P				P/I			TVC
	Interstage	IN	P		P						Access doors
	Second-Stage	2S		P		P		P/I			TVC
	Adapter	AD			P			P			Access doors, firing units, umbilical distribution
	Third-Stage	3S						P/I			TVC, eject motor
	Equipment	EQ	P/I		P/I	P	P/I			P	Interlocks, command sequencer, flight control electronics, power distribution, rate gyro, inverter
	Re-Entry	RE									Released to free fall
	Nose Fairing/Cap	NF						P			Covers 3S, aerospike
Other Subsystems	Guidance	G	P/I		P/I	P	P/I	P/I	P/I		Inflight course corrections. Allows release of RE at specified point and velocity
	Fire Control	FC	I			P		P/I			Coordinates operation during launch
	Launcher	L	P			P		P/I			Support Ring Assembly at base
	Navigation	NV						I			Navigation data used by FC to prepare missile for launch
	Instrumentation	I						I			Shipboard weapons system insturmentation; monitors function of FC, NV, and L
	Training Equipment	TR									Training Launcher simulates operation and maintenance of the missile; non-tactical

Figure 56: FSSM Missile subsystem design structure matrix



Guidance Subsystem

(Output in Columns)

(Input in Rows)

			GM	GY	AC	RS	SS	HE1	SC	CP	GC	HE2	RC	Notes
Inertial Measurement Unit (IMU)	Gimbals	GM		P	P	P		I	P	P/I	P/I			Gimbals and associated components.
	Gyroscopes	GY	P					I	P	P/I	P/I			Mounted on a gimbal, maintain stable orientation of missile during flight
	Accelerometers	AC	P					I	P	P/I	P/I			Mounted on a gimbal, measure changes in missile velocity
	Resolvers	RS	P											Resolvers on the gimbals provide missile attitude data
	Stellar-sighting	SS						I	P		P/I			Equipment to conduct stellar sighting to provide inflight trajectory correction
	Heat Exchangers	HE1	P	P	P		P		P					Heat exchanger coil maintains Inertial Measurement Unit within specifications
	Spherical Case	SC	P	P	P		P	P						Inertial measurement unit is a sealed, spherical case
Electronics Assembly	Current Positioners (gimbal and gyro torque)	CP	P/I									I	P	Gimbal and gyro torque current to position IMU gimbals
	Guidance Computer	GC	P/I	P/I	P/I	P/I	P/I					I	P	Information from IMU is processed in GC
	Heat Exchangers	HE2								P	P		P	Water-cooled package
	Rectangular Case	RC								P	P	P		Electronics Assembly is a rectangular package case
Other Subsystems	Missile	M	I	I	I	I			P		I		P	Guidance subsystem housed entirely within Missile and measures dynamic data
	Fire Control	FC								I	I		P	Flight information is provided by the FC prior to launch
	Launcher	L												External subsystems interface with external switchboard prior to launch
	Navigation	NV												External subsystems interface with external switchboard prior to launch
	Instrumentation	I												External subsystems interface with external switchboard prior to launch
	Training Equipment	TR												External subsystems interface with external switchboard prior to launch

Figure 57: FSSM Guidance subsystem design structure matrix

Each system element, represented in the rows and columns of the above DSMs, fills a unique role in accomplishing individual activities that comprise the overall mission. Capturing the responsibilities of each element as performed in the previous step allows for vulnerability analysis using an informed interaction diagram as can be captured in Design Structure Matrices. In this step, a holistic picture of how each element contributes to the key activities is provided which can then be extended to identify specific vulnerabilities among elements – although the vulnerability identification has been omitted in the analysis.

Evaluating a vulnerability sequence potentially reveals feedback impacting other elements of the system as well, making this process highly path dependent. Learning about how system components interact spawns feedback loops that trace back to earlier steps and components of the process, potentially yielding sources of undiscovered rework. By recursively identifying interactions that lead to vulnerabilities in a model, this stage of concept development is strengthened through more positively identifying requirements that address specific vulnerabilities. This recursive process can be described in theoretical terms through the principle of "double loop learning" shown in Figure 58 [98].

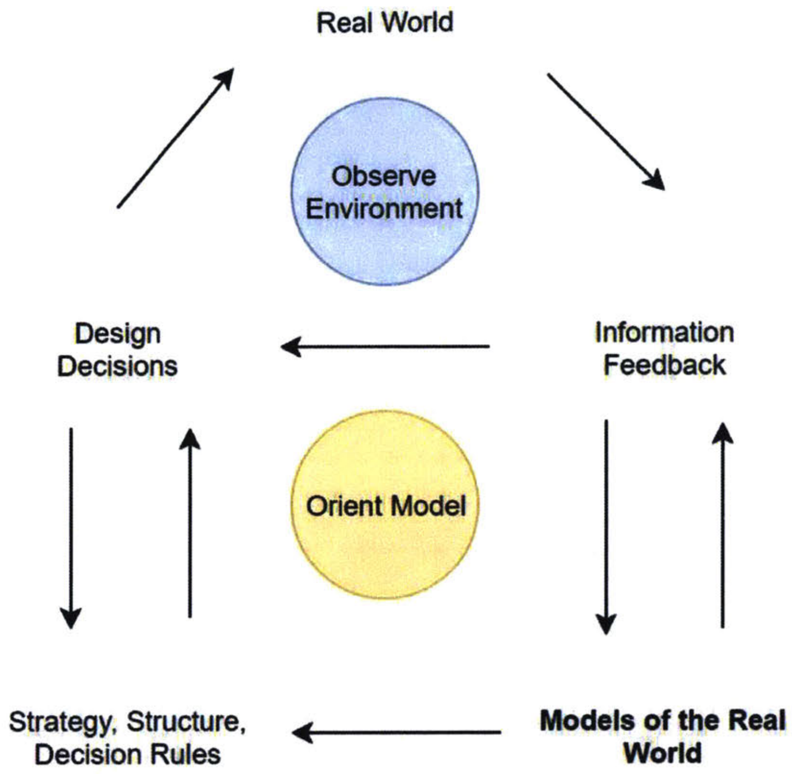


Figure 58: Double Loop Model Learning, adapted by author from [98]

Sterman's System Dynamics text, *Business Dynamics: Systems Thinking and Modeling for a Complex World*, describes the principle of double loop learning as applied to new understanding and reframing in models of the physical world [98]. Feedback from the real world can stimulate changes in models. Such learning, abstracted in Figure 58, involves a new understanding or reframing of a situation and leads to new goals and new *decision rules*, not just new *decisions*. We can extend this principle to this step of STPA-Sec through vulnerability identification and making the required adjustments to the model through a high-velocity rapid experimentation, trial-and-error process [38].

Figure 59 for the Missile and Figure 60 for the Guidance subsystems present a series of OPD model views that illustrate information transfer points vulnerable to exploitation. Since these models are based on elemental and functional descriptions, these "vulnerabilities" are only theoretic examples of what form their identification would take; however, they illustrate the concept of the approach a systems engineer would take with a fully detailed OPD for the control structure.

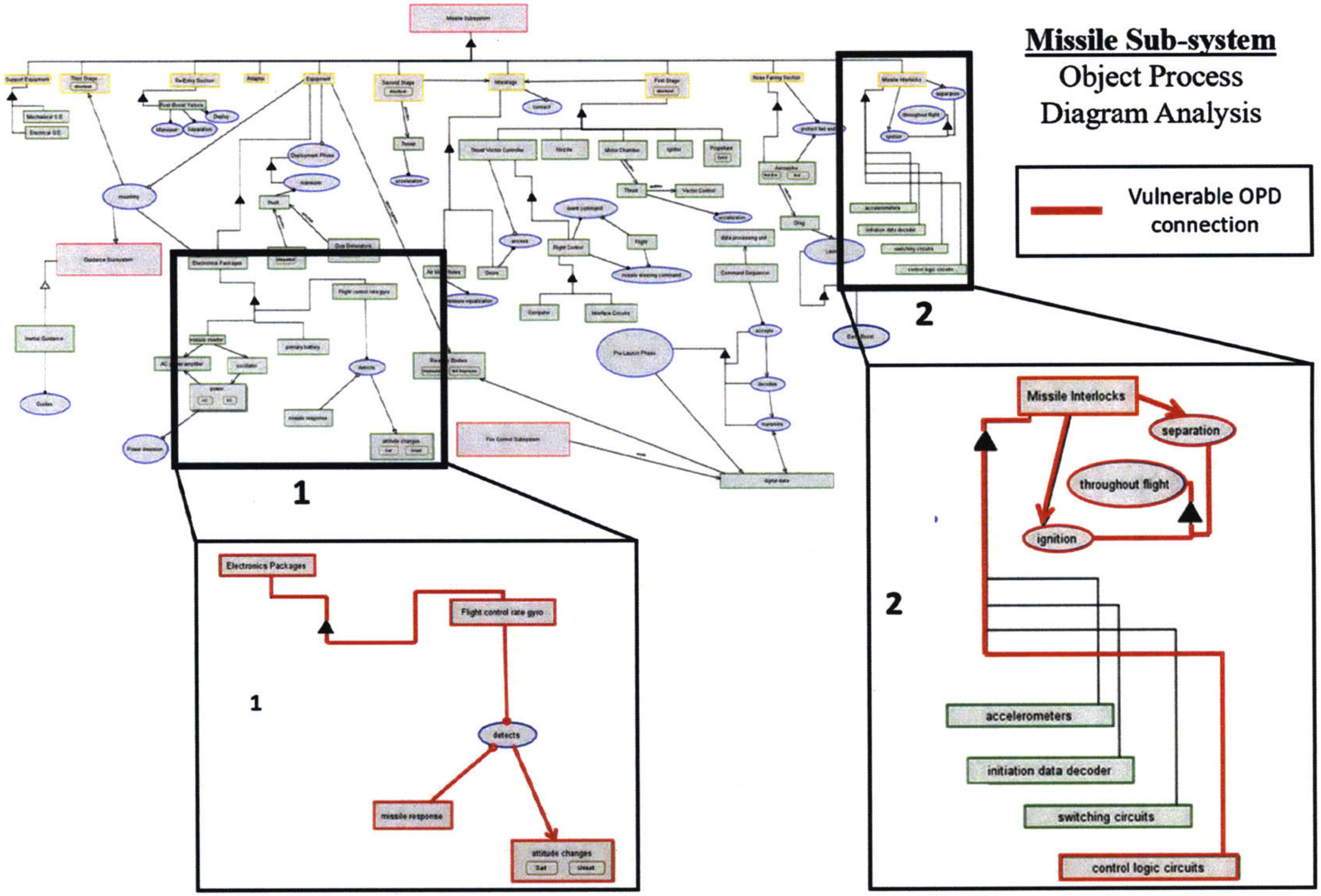


Figure 59: Missile Sub-system object process diagram with selected vulnerability analysis

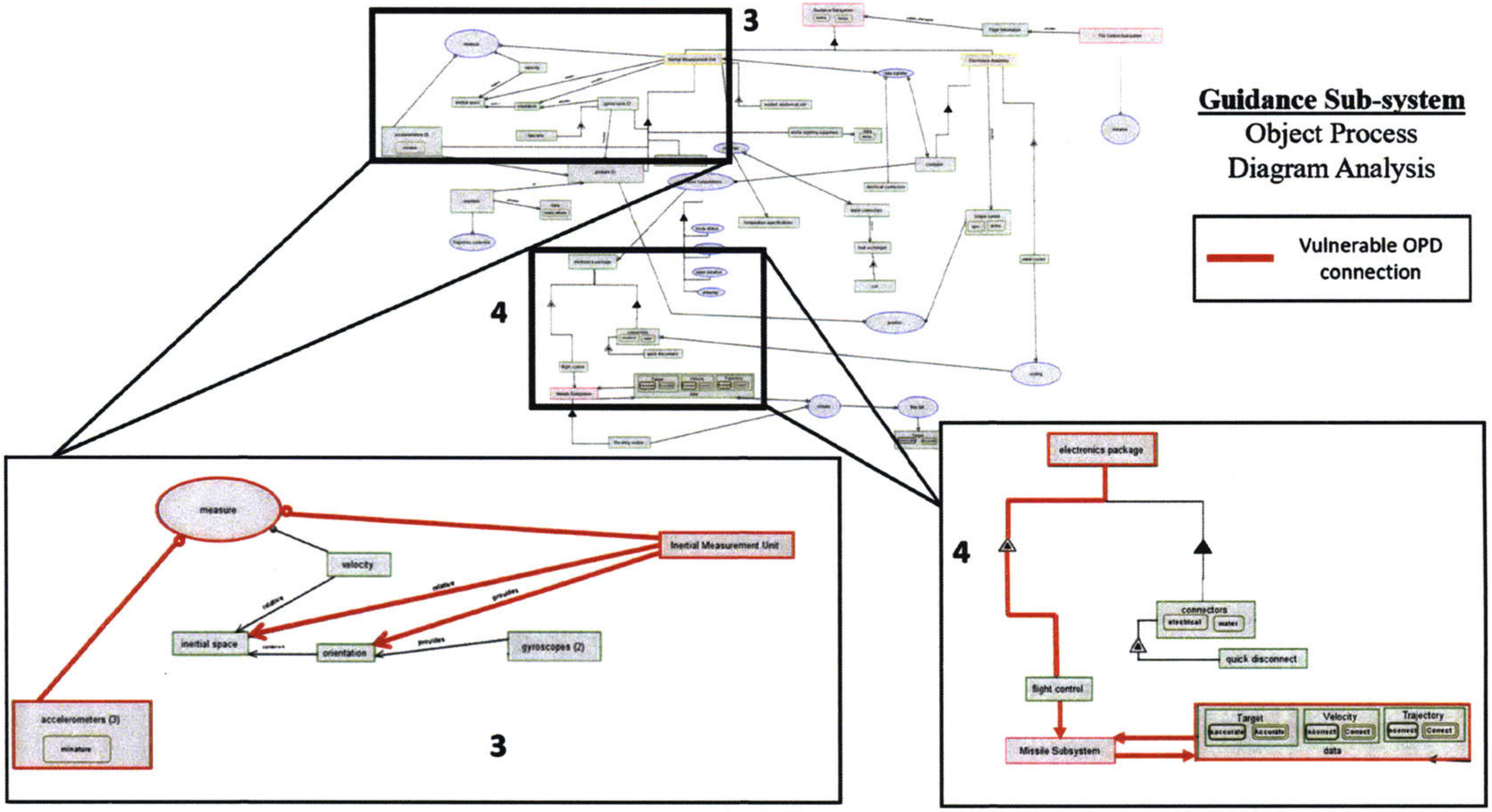
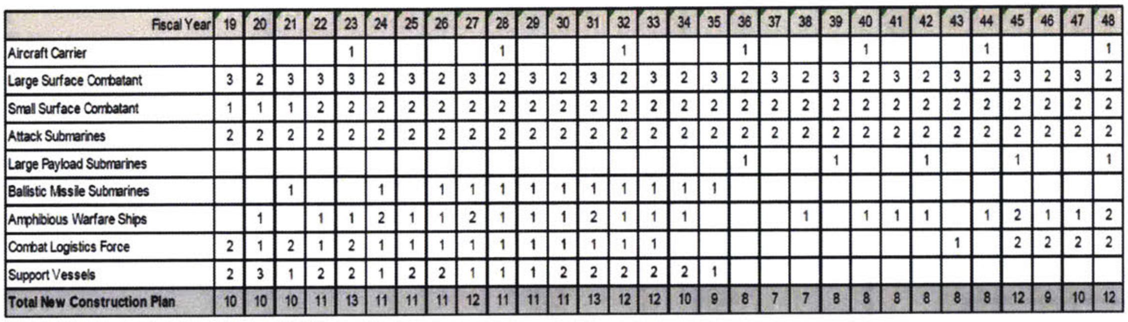


Figure 60: Guidance Sub-system object process diagram with selected vulnerability analysis

Step 6: Develop constraints to control these interactions

Based on the understanding developed regarding system operations gained in Step 5, high-level functional constraints can be developed regarding the component interactions. Constraints indicate types of control limits, fashioned as additional mission requirements, that assure system functionalities are executed securely [93].

Once constraints are designed to address a range of vulnerabilities, performance of the system architecture can be evaluated. Developing a constraint to control hazardous actions by a system could be evaluated based on measures of performance that map into mission driven measures of effectiveness. These will occur over a time period to indicate performance over time. The time scale considered will be the life of the platform under development.



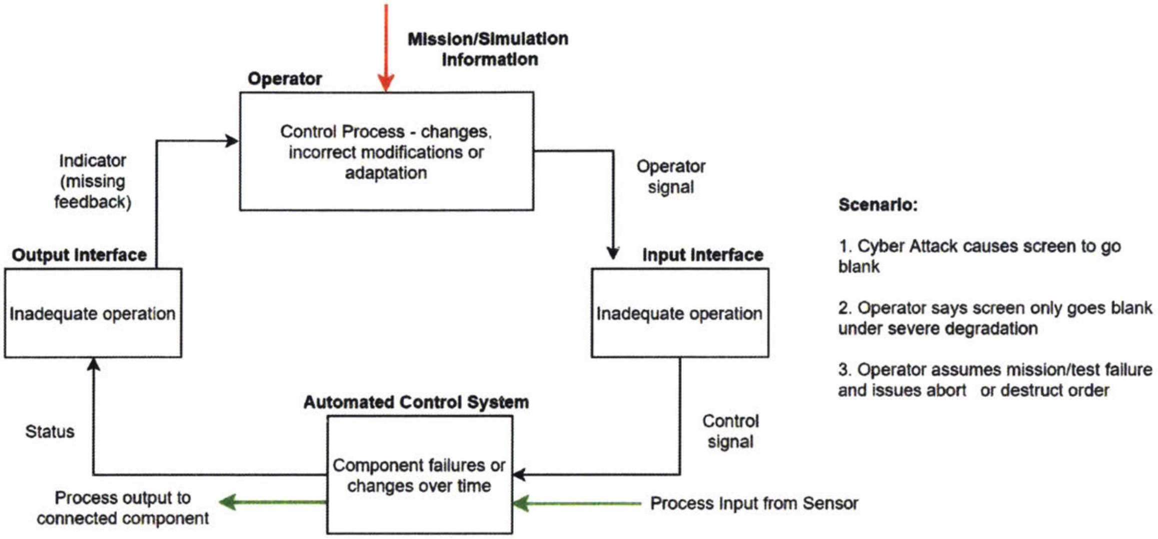
Fiscal Year	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
Aircraft Carrier					1					1				1				1				1				1				1
Large Surface Combatant	3	2	3	3	3	2	3	2	3	2	3	2	3	2	3	2	3	2	3	2	3	2	3	2	3	2	3	2	3	2
Small Surface Combatant	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Attack Submarines	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Large Payload Submarines																		1			1			1			1			1
Ballistic Missile Submarines			1			1		1	1	1	1	1	1	1	1	1	1													
Amphibious Warfare Ships		1		1	1	2	1	1	2	1	1	1	2	1	1	1				1		1	1	1		1	2	1	1	2
Combat Logistics Force	2	1	2	1	2	1	1	1	1	1	1	1	1	1	1										1		2	2	2	2
Support Vessels	2	3	1	2	2	1	2	2	1	1	1	2	2	2	2	2	1													
Total New Construction Plan	10	10	10	11	13	11	11	11	12	11	11	11	13	12	12	10	9	8	7	7	8	8	8	8	8	8	12	9	10	12

Figure 61: OPNAV FY19 Long Range Shipbuilding Plan [99]

As seen in Figure 61 (reproduced from [99]), in the U.S. Navy, Ballistic Missile Submarines will be constructed at a rate of approximately one per year from 2021 through 2035. Since the cyber-attack surface for strategic systems, supporting programs, and infrastructure shown in Figure 47 extends over the entire lifecycle, it will be necessary to protect the integrity of the system through the entire lifecycle – from concept development through deployment and operations of the next-generation ballistic missile submarine systems.

Step 7: Identify scenarios to understand how constraints might be violated (given existing architecture) using Step 2 Table

Table 19 in Step 2 identified the mission-critical functional losses possible for the Missile and Guidance sub-systems. Each of the controlling actions identified in Step 6 would be violated in some way during an identified loss event from Table 19. Figure 62 shows a notional control loop for a system used to perform simulation testing of either of the two sub-systems under different constraints. This simulation shows how components interact subject to different constraints. Under each constraint simulation, performance can be evaluated to identify which scenarios continue to have exploitation opportunities present – and, therefore, a system loss event.



Scenario:

1. Cyber Attack causes screen to go blank
2. Operator says screen only goes blank under severe degradation
3. Operator assumes mission/test failure and issues abort or destruct order

Figure 62: Test or Mission simulation control structure, adapted by author from [23], [93]

Step 8: Use Insights to Improve Existing Architecture

Improvements to the system architecture can be accomplished through Real Options executed in software, hardware, or both depending on the cyber-physical system and functional role. The Options are designed to be capable of addressing a range of adversary behaviors instead of a single robust solution [91]. Examples of these responses are inserting capability for mission keying, authentication, system flush and restore from a trusted store, randomized responses, or component redundancy for total continuity of operations [89]. Their critical attribute is the ability to execute within a short time frame and address a potential range of system vulnerabilities.

7.4 Final Concepts

This description of Model Based Engineering for Cyber Security demonstrates that Model Based Engineering is an emerging field across the defense systems development community. We have shown that MBE is domain agnostic through illustrating in as much detail as the classification level allows, the methods that can be used to incorporate system models into development of cybersecurity requirements and eventually components (software and hardware).

7.4.1 Next Steps

Selecting one or two individual components of the FSSM to analyze with STPA begins an initial step in a potential continuous analysis necessary for implementing systematic analysis as a useful tool in the design lifecycle phase, as Figure 63 illustrates. When implemented continuously and across varied sub-system boundaries, the emergent interactions in the system can begin to be captured and allow better understanding of the vulnerabilities that must be addressed before deployment or risk rework that proves costly for schedule and budget. In a hierarchical system, such as the one illustrated in this chapter, system interdependencies can often evoke new emergent properties in a system-of-systems [8]. This analysis is a proposed way to start the identification of cyber-security requirements in examining interactions between fully-expanded levels of system abstraction.

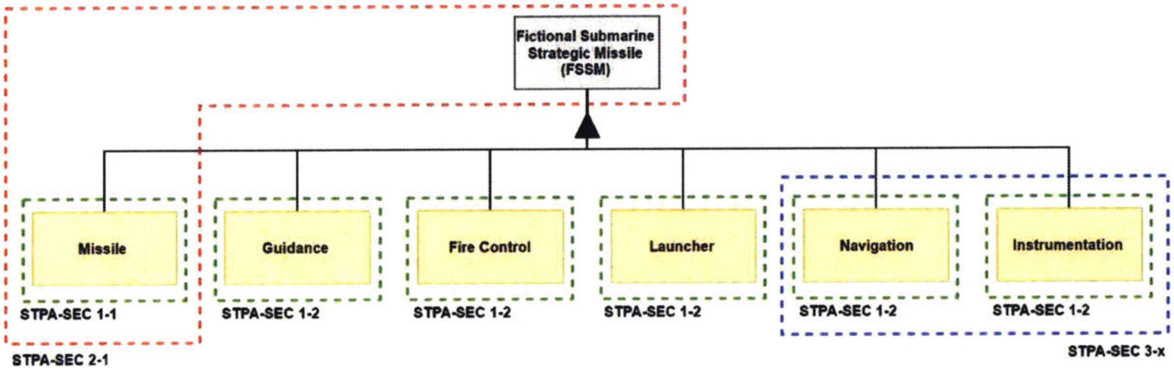


Figure 63: Hierarchical decomposition model of the weapon system and associated levels of potential STPA-Sec applications

Future work is possible to operationalize these conclusions in the field of applied formal computational methods at higher levels for the overall system. FSSM is a large and complex system-of-systems with a collective scale beyond the scope of a manual analysis such as the one performed in the preceding section. With the adoption of a model-based framework for engineering analysis and design, the possibility of automation through formal methods and structure can be realized [100]. As a result, an approach for formal methods could develop a pathway for automating model analysis performed during the STPA-Sec steps.

7.4.2 Cyber Resiliency Conclusions

Figure 64 connects the goals of this concept illustration, presented as test hypotheses, with the conclusions of this chapter. Model-based engineering initially may seem more suited for physical analysis of the system; however, this concept illustration has displayed the domain-agnostic property of the MBE principles by extending them to cyber vulnerability analysis. By offering several views of system visualization, greater confidence may be gained that a system's cyber-attack surface (refer to Figure 47) has been reduced or eliminated, along with the accompanying uncertainty. However, recall that the cyber-attack surface represents only an estimation of the vulnerability points derived wholly from what is known about our own system (architectures, technologies, and organization) and demonstrated or estimated adversarial capabilities.

Modeling Cyber-Physical Systems	Model Based Engineering principles shown to be *domain agnostic* through ability to address operational aspects of cyber-physical systems
Design Resiliency	Model Based Engineering methods can *reduce uncertainty effects* by applying multi-domain approach to articulation of cybersecurity problem and system architecture vulnerabilities (notional)
Cyber Verification and Validation	Secure systems engineering pursued through a *unique and tailored verification and validation sequence* that starts with evaluating the impact of functional vulnerabilities before identifying a specific threat

Figure 64: Concept Illustration hypotheses and conclusions summary

MBE provides the framework for delivering a current holistic picture of the system and its interdependencies during development. This contributes to a valid conception of impact that change in requirements have on production, but also increases confidence in the physical performance of requirements, which may positively impact the date of IOC (high-velocity delivery of capability) as shown in Figure 65. These conclusions further extend to achieving operational excellence downstream of the acquisition process as well [89].

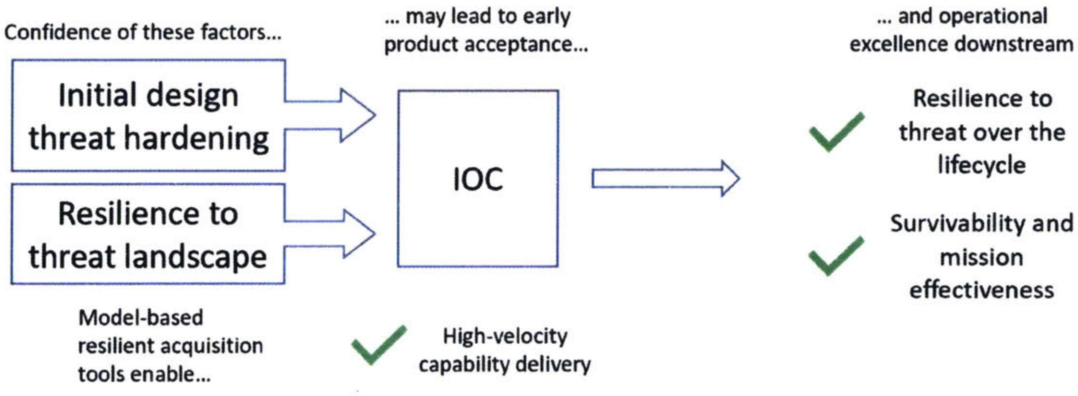


Figure 65: Why use MBE for resiliency in cyber-physical systems?

During creation of the models, interactions are identified by the engineer that might not have been as clear from a specification document. The modeling process is just as important as the model. These digital solutions also enable the testing of Real Option system architectures to identify which candidates should proceed for inclusion in the next software/hardware releases or updates, thereby unlocking the adaptability paradigm illustrated in Figure 46. During system verification and validation, MBE unlocks much of the utility that the methods of STPA-Sec bring to system design and analysis.

Table 23: Weapon System Cyber Resiliency, table adapted by author from [95], [96]

Characteristic	**Description**
Anticipate	Preparation for known, predicted, or unknown adverse events to include changes in the operational environment, modes of operation, business/mission functions, emerging threats, integration of novel technologies, and other necessary changes.
Withstand	To absorb negative impacts of adverse events such as system faults, user errors, software bugs, hardware failures, cyber-attacks, or major changes in operational environment/requirements.
Recover	To restore business/mission operations (and desired functionality) to an acceptable level within specified time and performance requirements. Recovery should include the ability of the system to "adapt" in order to reduce the impact(s) of future adverse events.

Table 23 summarizes the conclusions that this concept illustration demonstrated regarding resiliency. Although we can never limit how requirements may change in the future – we cannot affect what our adversary is developing to counter our technology – model-based engineering principles allow planners to rapidly account for the effects of adversarial cyber-attack technology. A unique feature of MBE is the ability to adapt to changing methods of analysis and demonstrate resiliency in the face of changing requirements or the substantiation of unknown (unknowable) future requirements.

Showing *where information might flow* in a model-based environment enables finding *where the vulnerabilities may exist*. Protecting this path accordingly ensures the product is delivered with the lethality assumed at Initial Operating Capability (IOC) determination. A product delivered with cyber-compromised systems may be irrelevant from Day 0 and require redesign (assuming that the cyber vulnerability has in fact been identified).

When a cybersecurity breach is identified, the whole design-build cycle is restarted in order to address what we know our adversary now knows regarding our systems, thus adding another spiral and cycle time to the overall process – which, as we have shown, could mean delaying delivery to the Fleet by years as shown in Figure 4 for lead ship delivery delays and Figure 10 for shipbuilding process timeline.

This debilitating rework cycle presents a direct threat to delivering strategic mission assurance and therefore motivates adopting a continuous development and adaptation process of cyber-resilient technologies and architectures enabled through a high-velocity adaptation of model-based engineering. This will ensure that strategic capabilities remain responsive and on pace with a rapidly responding organization that assuredly monitors emerging technologies, methods, and adversary threat capabilities.

Cyber MBE Concept Illustration Summary
Since MBE is domain agnostic, we have extended its application to formulating cybersecurity for a complex naval weapon system
Methods of concurrent design, verification, and validation demonstrate that model-based engineering methods reduce uncertainty effects through valid requirement scenarios
System requirements dictate a unique and tailored verification and validation sequence such as the use of the STPA-Security process
Various types of models illustrate that through their usage, the design of a notional strategic weapon system can be developed more resiliently to cybersecurity threats

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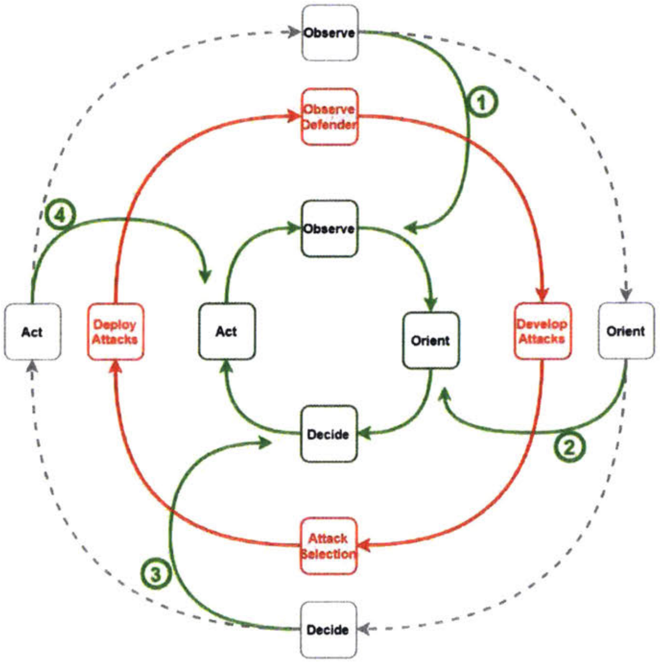
Chapter 8

8.0 Conclusion

The secret of air-to-air combat was to get inside the other guy's OODA loop. Get your opponent in a position where he was already reacting to one or more moves behind what you were able to do. [101]

This thesis offers a simple operating hypothesis that the underperformance in the production of complex systems can be attributed to a poorly executed and understood connection of requirements to technical specifications. The effects of uncertainty, complexity, and risk compound to the detriment of our force structure and operations and slow the cycle time of conceptualization, design, production, and delivery. This decision making cycle for acquisitions can be envisioned as an "Observe-Orient-Decide-Act" Loop (OODA Loop) – first suggested as a model for rapid cycle decision making of jet fighter pilots [101]. Using principles of a high-velocity application of model-based engineering enumerated (1) – (4) in Figure 66 , the Navy can "short-circuit" our own OODA Loop and get "inside" that of the adversary.



① **Disseminate and record observations via shared or "live" models, collaborative engineering and set-based analysis**

② **Automation of computational rules and constraints apply a consistent rule structure across interface and domain boundaries**

③ **Connection of required operational capabilities to technical specifications informs and smooths decision making process**

④ **Clear representation of meaning across multiple domains reduces unintended complexity, enabling design-for-production**

Figure 66: MBE speeds the OODA loop of production advancement

Observe. We have demonstrated how models increase the volume, quality, and speed of information collection. Observations regarding system design, production, and operation can be disseminated to teams via shared models, collaborative engineering, and set-based analysis.

Orient. Models can capture a collective design process and allow a team to manage uncertainty in a distributed fashion. Opening pathways toward eventual automation of computational rules and constraints, models contain consistent rule structures that maintain consistency across interface and domain boundaries. To be used effectively at scale, models must be able to be verified and validated. Validation works in parallel with system safety in operation which is verified using a systematic process enabled by modeling technology.

Decide. Built-in tests during the model creation or simulation can help to guide the formation of solutions when problems are uncovered. Connection of required operational capabilities to technical specifications smooths the decision-making process by building in the test of technical validation against the requirements of the system. Targets for problem-solving and improvement are identified in models through clear representation of meaning across multiple domains. These views can reduce unintended complexity by automatically illuminating a connection of technical solutions to system requirements.

Act. System validation and production is enabled through model digitization. Self-regulation of fulfilling requirements can ensure that problems are known as soon as possible for the fastest action and solution. Highlighting cause of problems before the issue perpetuates allows the designer to act and deliver the system on-time and as required [10].

Ultimately, successful acquisition of complex systems maximizes the capability and utility of the delivered total, while concurrently minimizing the overall time from need to delivery. Ensuring force strength into the future will require that the organization to adapt quickly to an indefinite landscape. Developing *resilience* in learning how to reconfigure and accommodate unknown system perturbations is shown to be an effective way to respond to complexity in what drives requirements. Migrating the conceptualization, design, and production processes to a Model-Based Environment strengthens our pursuit of networked agility to deliver systems sooner and in accordance with operator needs the first time.

8.1 Implications for the Defense Acquisitions Community

This thesis demonstrates a conceptual modernization of the principles that guide selection of tools for design, acquisition, and construction in defense acquisitions. Like cavalry units of the early twentieth century reconceptualized through the introduction of new technology in armor and machine-driven tanks, MBE presents a modern refresh to ways of doing business in keeping with the standard progression of development in information capture and display.

The applications presented in the preceding chapters focused on specifically what practices are enabled by it to make ships go through production faster, eliminate re-work, and join the operation Fleet on time and without some of the post-delivery delays that are often associated with new battle force assets. Executing this refreshed approach can be accomplished through identification of processes that utilize unadaptable document-based formats and converting them to a model-based approach resilient in its ability to accommodate change.

This thesis has aimed to remain tool-agnostic because this adoption is not contingent on a specific set of software. When requirements are poorly translated, the systemic structure of information passage across and within organizational boundaries is not universally attributable to a specific tool. *Specific* programs and technologies dictate which tools are appropriate for the constraints and nature of requirements. The principles of a high-velocity application of model-based engineering are *global* and help to guide the detailed framework of selecting the most appropriate tool for the acquisition program and phase.

8.2 Future Work

In the pursuit of our force structure goals, an equal emphasis must be made to ensure that we have the right mix of ships instead of designing the highest grade of technology and associated complexity into every corner of the vessel. Our force must be lethal – and that can come from extending a model-centric exploration approach back to Fleet-level requirements that determine the mix of what is acquired. Only then, will building the right thing, as was the focus of this thesis, will follow.

Integration of model-based design methods into modern requirement evaluation team (RET) framework is left to those with programmatic responsibility (see Chapter 2). Since the new RET methodology has been adopted in recent years in pursuit of high-velocity acquisitions inserting model-based engineering tools into the process can continue to make the requirement evaluation system more efficient. One potential method could be sharing models with industry and developing paradigms of co-ownership with industry partners so that the specifications are a living document that never miss a change and work toward a shared model as the single source of truth.

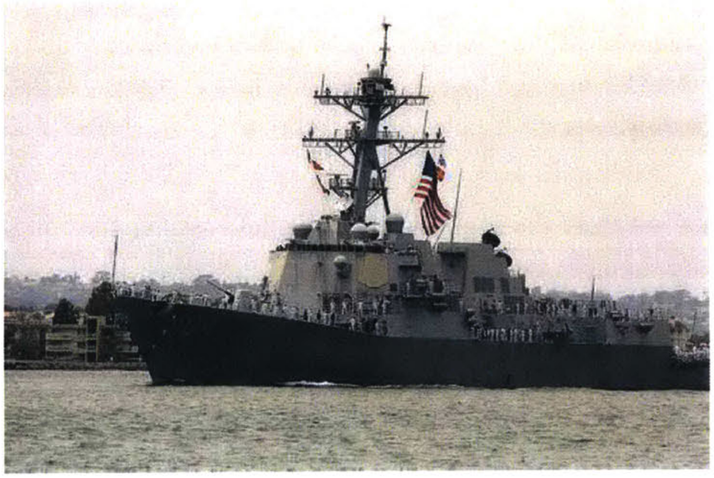
We can also extend the applicability of model-based engineering to gaining a high-velocity advantage in the maintenance and repair community. The U.S. Navy should invest in refurbished shipyards to perform the correct depot level maintenance while recognizing that maintenance and repair is just as critical in meeting force structure goals over time. Arguably, maintenance may be more critical when it comes to keeping what we have in the fight relevant and lethal to our adversaries. It will take adjustment for the global community that serves our purposes of repair to adjust to model-based systems engineering; however, future research would be able to show how the timeline would be accelerated and keep assets in operational status.

Finally, the application of MBE to alternative domains should continue to be pushed through realization of the general benefits of conceptual modeling. Chapter 7 suggested a method for extending MBE to the cybersecurity domain; the limits of other domains in which this would work in a parallel fashion can continue to be explored such as human-user interfaces, and artificial intelligence/machine learning through methods such as predictive design.

8.3 Personal Takeaways

This thesis allowed me to connect with the acquisition process of the Navy and apply a skeptical look at the observed processes, both within the government and outside of it in search of the root cause of "inefficiency" or "Low Velocity Learning." The experience-oriented nature of this thesis opened meaningful collaboration across MIT, Draper, private and public shipyards, contacts within the U.S. Navy engineering establishment, experts in navy medicine, and civil construction that lent their experience with complex system design and management that helped to inform my thinking and play a significant role in the information that went into this thesis.

Adding survey and case study evidence strengthened the case for clarifying and simplifying the specification of complex engineering systems design using digital models that can be shared, edited and tracked much easier than legacy document-based methods. Although much of the focus is placed on new ship construction and weapons systems design, these findings remain clearly relevant in any field that receives functional requirements to inform the design of a complex engineering system. Extrapolating these assertions regarding requirement fidelity, design performance and system resiliency outside of the Department of Defense enterprise can be accomplished in progressing towards a common goal to deliver capability faster.



Guided missile destroyer USS Sterett (DDG 104) returns to Naval Base San Diego on July 5, 2012 (Official U.S. Navy Photo)

Appendix A: Uncertainty in U.S. Navy Force Structure Assessment

Navy force structure assessments were collected for analysis using data reported to the U.S. Congress via various long-range projections shown in Figures A-1 and A-2 [1], [2], [99].

	2001 QDR	2002-2004	2005 V1	2005 V2	2006 V1	2006 V2	2011	2012	2013	2015	2016 NNN	2019 Actual
SSBN	14	14	14	14	14	12	12	14	12	12	12	14
SSGN	2	4	4	4	4	0	4	4	0	0	0	4
SSN	55	55	41	37	48	48	48	48	48	48	66	53
CVN	12	12	11	10	11	11	11	11	11	11	12	11
CRUDES	116	104	92	67	88	94	94	90	88	88	104	90
FFG	0	0	0	0	0	0	0	0	0	0	0	0
LCS	0	56	82	63	55	55	55	55	52	52	52	14
AMPHIB	36	37	24	17	31	33	33	32	33	34	38	32
MPF(F)	0	0	20	14	12	0	0	0	0	0	0	0
AUX	34	42	26	24	30	30	30	29	29	29	32	29
MIW	16	26	0	0	0	0	0	0	0	0	0	11
JHSV	0	0	0	0	3	21	10	10	10	10	10	1
Other	25	25	11	10	17	24	16	23	23	24	29	28
Total	310	375	325	260	313	328	313	316	306	308	355	287

Note: *Year denotes publication of U.S. Navy Force Structure Assesment unless otherwise noted.*
QDR = Quadrennial Defense Review
NNN = "Navy the Nation Needs"

Figure A-1: Long-range shipbuilding projections 2001-2019

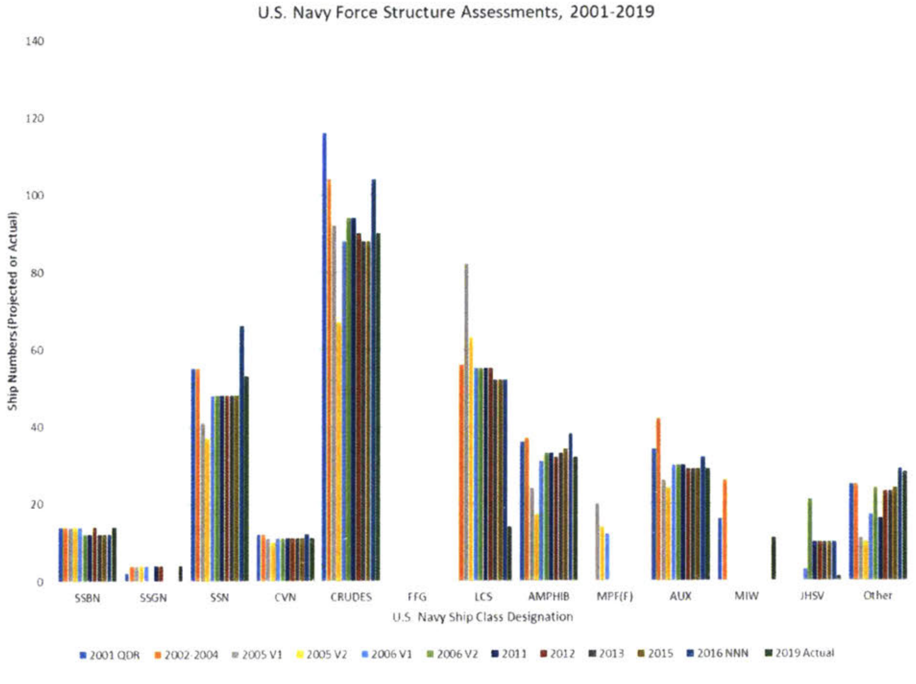


Figure A-2: Force structure assessments 2001-2019

Force structures with end strengths shown in Figure A-3 can vary by as much as 40% from the smallest total force size as predicted during the height of the land wars in the middle east (2005) from only three years prior (2002) when the global security landscape was vastly different.

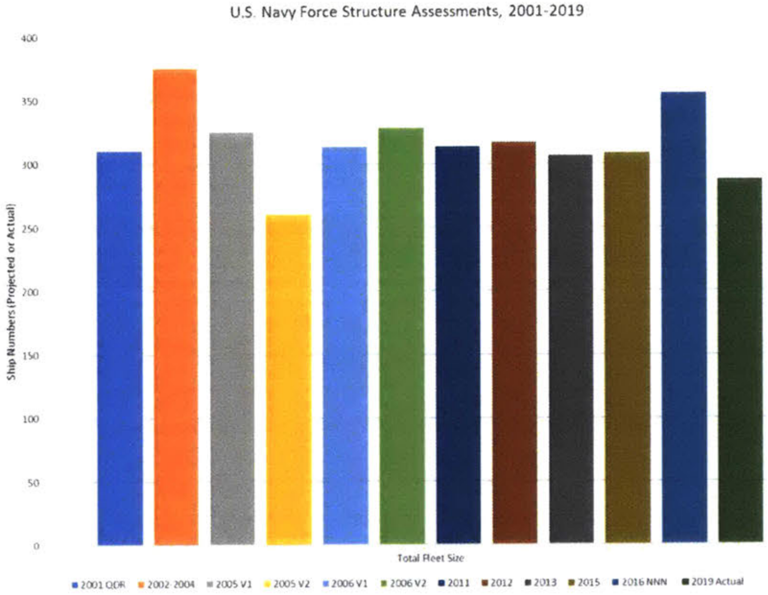


Figure A-3: Overall end-strength predicted in various U.S. Navy force structure assessments

Statistical analysis results shown in Figure A-4 yields the following results of total force structure, by class.

	Standard Deviation	Projection Max	Projection Min	Percent Difference
SSBN	0.99	14	12	16.7%
SSGN	1.85	4	0	-
SSN	6.93	66	37	78.4%
CVN	0.55	12	10	20.0%
CRUDES	11.40	116	67	73.1%
FFG	0.00	0	0	-
LCS	21.11	82	0	-
AMPHIB	5.57	38	17	123.5%
MPF(F)	6.85	20	0	-
AUX	4.27	42	24	75.0%
MIW	8.26	26	0	-
JHSV	6.34	21	0	-
Other	6.00	29	10	190.0%
Total	28.69	375	260	44.2%

Figure A-4: Statistical summary by ship class of U.S. Navy force structure assessments

From 2001 through the present day, the United States has been engaged in a Global War on Terrorism. Over this time, the Navy has seen national security priorities shift from global post-Cold War stability maintenance to supporting a largely land-focused conflict in the Middle Eastern Area of Operations. Changes in Force Structure Projections could be characterized by an analogous shifting of priority away from "blue water" operation, to supporting forces ashore, and now back to the open ocean with the global re-emergence of the naval forces of near-peer nations. Ship classes which have experienced the most significant variation in their emphasis as part of the U.S. Navy Fleet correlate strongly with this generalization of national security priority shift and re-alignment. The principal missions of SSN and CRUDES combatant vessels is control and force projection on the high seas, while the primary missions of auxiliary and amphibious ships are movement of material and forces ashore. Additionally, the Littoral Combat ship has emerged as a relevant component of the Battle Force during the range of years considered here, correlating with the early-2000's increased emphasis in fighting shallow water military engagements.

As Donald Rumsfeld, the Secretary of Defense during the early chapters of the Global War on Terrorism, stated regarding the relevance of U.S. Army capability in the face of a changing enemy, "You go to war with the army you have, not the army you might want or wish to have at a later time" [102]. Of course, this statement also extrapolates to naval capabilities, which are planned far in advance of when they will be needed to be employed. Even if one assumes the budget environment remains somewhat stable, alterations in the global security landscape will continue to produce corresponding shifts in the acquisition strategy of the U.S. Navy.

Appendix B: Shipyard Visits

The information from shipyards visited and consulted, summarized in Table B-1, were made possible by the MIT Naval Construction and Engineering Professional Summer course series, the Officers in Charge, and Production Managers of the respective Supervisors of Shipbuilding cited below [32], [33], [35], [37], [76].

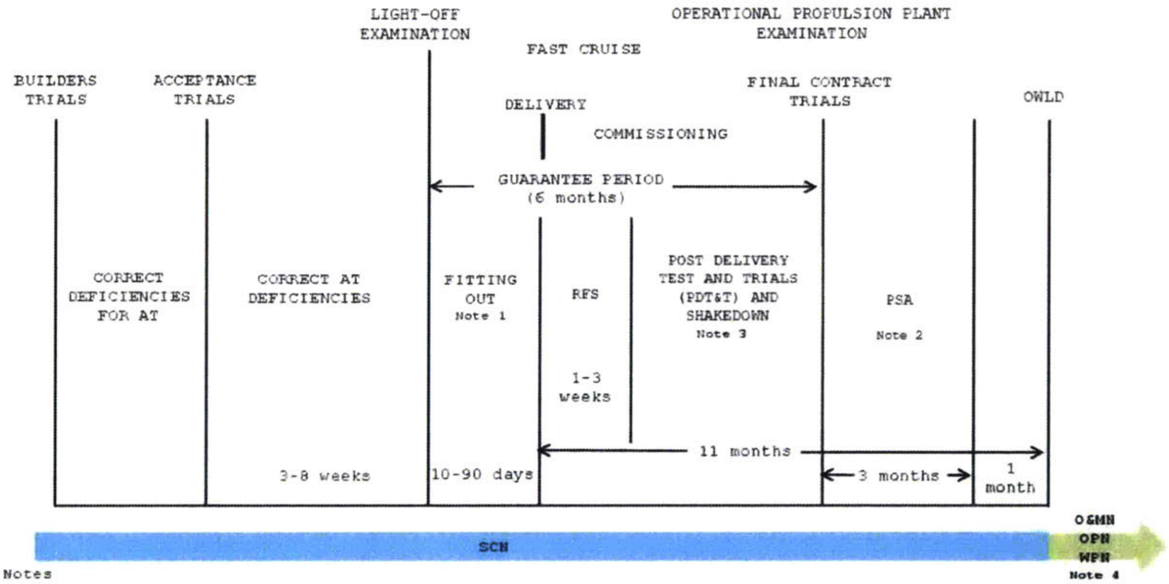
Table B-1: Shipyards visited and consulted

Ship Construction Site Visits and Consultations		
General Dynamics	Bath Iron Works	Bath, ME
General Dynamics	Electric Boat	Groton, CT Quonset Point, RI
General Dynamics	National Steel and Shipbuilding Company (NASSCO)	San Diego, CA
Fincantieri Marine Group	Fincantieri Marinette Marine	Marinette, WI
Huntington Ingalls Industries (HII)	Ingalls Shipbuilding	Pascagoula, MS

Appendix C: Delivery, Test, and Certification Timeline Illustration

Figure E-1 is taken from Instruction 4700.8K from the Office of the Chief of Naval Operations which defines the "trials, acceptance, commissioning, fitting out, shakedown, and post-shakedown availability of U.S. Naval Ships undergoing construction or conversion" [36]. This chart "illustrates the chronological relationship between the major milestones in the construction and conversion process."

NOTIONAL MAJOR MILESTONES DURING CONSTRUCTION/CONVERSION



Notes

1. For submarines outfitting is complete prior to delivery. Hence, the SCN obligation work limiting date is at the end of the 11th month after the month in which delivery occurs.
2. PSA is normally scheduled to complete 1 month prior to the obligation work limiting date.
3. Total period of PDT&T and shakedown shall be a minimum of 6 months. A waiver may be granted for a period greater than 8 months; a request to extend SCN obligation work limiting date may be required.
4. Operations and maintenance, Navy (O&MN), other procurement, Navy (OPN), weapons procurement, Navy (WPN).

Figure C-1: Notional major milestones during construction and conversion of U.S. Navy ships and submarines, public domain figure from [36]

Appendix D: Requirement and Component Interaction Model Detail

ROC	Requirement
CCC-1	Provide Communications for Own Unit
CCC-2	Provide Own Unit's Command and Control Functions
CCC-3	Provide C2 Facilities for a Task Organization Comander and Staff
CCC-4	Maintain and Operate Deployable C4I Systems
FHP-1	Provide First Aid Assistance
FHP-2	Provide Triage of Casualties/Patients
FHP-3	Provide Medical, Surgical, Post-Operative, and Nursing Care for Casualties and Patients
FHP-4	Provide Medical Regulation, Transport/Evacuation and Receipt of Casualties/Patients
FHP-5	Provide Routine and Emergency Dental Care
FHP-6	Provide Definitive Dental Care for Casualties and Patients
FHP-7	Provide Oral Surgery and Maxillofacial Care for Casualties and Patients
FHP-8	Augment Assigned and Embarked Medical Personnel
FHP-9	Provide Medical and Dental Support Services to Other Units or Military Services
FHP-10	Provide Medical Care to Assigned and Embarked Personnel
LOG-1	Conduct Underway Replenishment
LOG-2	Transfer and Receive Cargo and Personnel
LOG-3	Coodinate and provide in-theater operational support
LOG-4	Provide Political-Military Support to Other Nations, Groups, and Government Agencies
MOB-1	Operate Ship's Propulsion Plant to Designed Capability
MOB-2	Prevent and Control Damage
MOB-3	Perform Seamanship, Airmanship, and Navigation Tasks
MOB-4	Maintain Mount-Out Capabilites

Figure D-1: Partial listing of requirements for next-generation hospital ship (T-AH 21)

SWBS	Description
100	Hull Structure, General
110	Shell and Support Structure
120	Hull Structural Bulkheads
130	Hull Decks
140	Hull Platforms and Flats
150	Deck House Stucture
160	Special Structures (e.g. ramp)
170	Masts, Kingposts, and Service Platforms
180	Foundations
190	Special Purpose Systems
200	Propulsion Plant, General
220	Energy Generating System (Non-nuclear)
230	Propulsion Units
240	Transmission and Propulsor Systems
250	Propulsion Support System
260	Propulsion Support Systems - Fuel and Lube Oil
290	Special Purpose Systems (e.g. bow thruster)
300	Electric Plant, General
310	Electric Power Generation
320	Power Distribution Systems
330	Lighting System
340	Power Generation Support Systems
390	Special Purpose Systems (e.g. Energy Storage)
400	Command and Surveillance, General
410	Command and Control Systems
420	Navigation Systems
430	Interior Communications
440	Exterior Communications
450	Surveillance Systems (Surface)
490	Special Purpose Systems
500	Auxiliary Systems, General
510	Climate Control
520	Sea Water Systems
530	Fresh Water Systems
540	Fuels and Lubricants, Handling and Storage
550	Air, Gas, and Misc. Fluid Systems
560	Ship Control Systems
570	Underway Replenishment Systems
580	Mechanical Handling Systems
590	Special Purpose Systems (e.g. auxiliary medical service)
600	Outfit and Furnishings, General
610	Ship Fittings
620	Hull Compartmentation
630	Preservatives and Coatings
640	Living Spaces
650	Service Spaces
660	Working Spaces
670	Stowage Spaces
690	Special Purpose Systems - Medical

Figure D-2: T-AH 21 Sub-systems, listed by SWBS Group

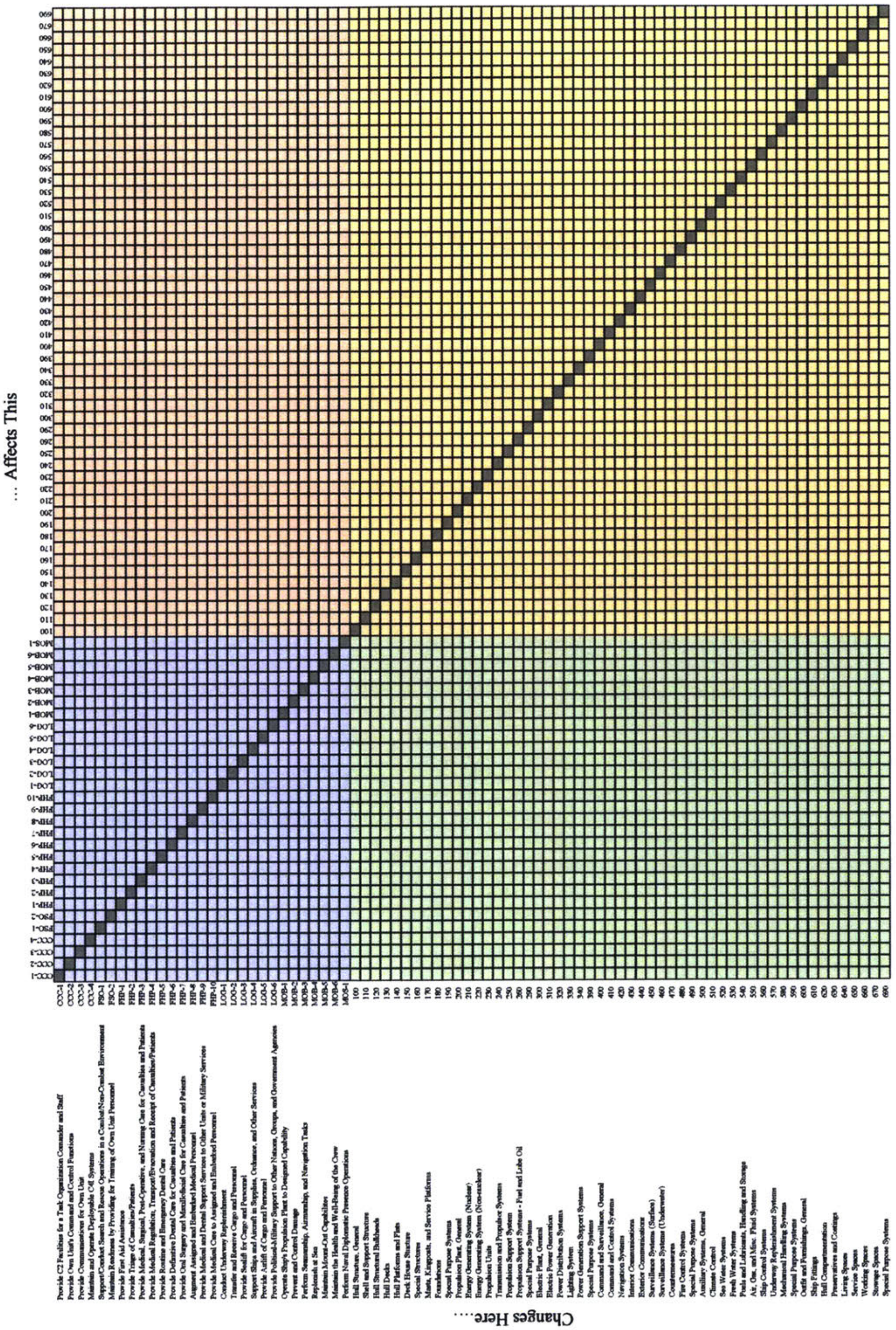


Figure D-3: Structure of the Design Structure Matrix (DSM) with row and column labels

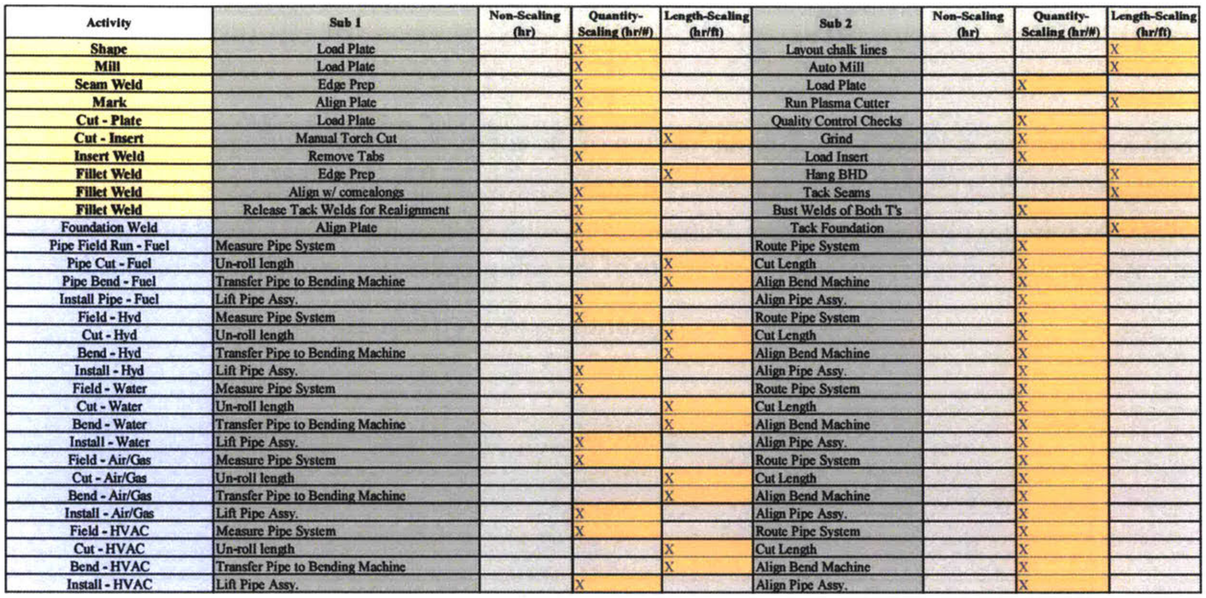
Appendix E: Shipbuilding Processes and Rate Coefficients

Rate coefficients are determined through a sum of the sub-process inputs grouped by units of measurement. In a model of a real-world shipyard process, each sub-process would have an observed rate. To protect proprietary shipyard data, only figures for a generalized rate coefficient are used in this model, however, the structure of the sub-process decomposition is retained.

$$T_i = \kappa_{1,i} + \kappa_{2,i}[\text{Quantity}_i] + \kappa_{3,i}[\text{Length}_i]$$

Activity	Process Inputs		Coefficients		
	Units	Units	k1	k2 (hr/#)	k3 (hr/FT)
Shape	Plates	Ft of torch passes	0.2	0.5	0.05
Mill	Plates	Ft of edges to mill	0.1	0.55	0.04
Seam Weld	Resulting panels	Ft of seams	0.2	0.6	0.035
Mark	Panels	Ft of marking	0.1	0.4	0.02
Cut - Plate	Cut Plates	Ft of cut perimeter	0.2	0.3	0.05
Cut - Insert	cutouts	Ft of cutout perimeter	0.2	0.3	0.05
Insert Weld	inserts	Ft of insert perimeter	0.2	0.3	0.07
Fillet Weld	units	Ft of BHD-deck joints	0.2	0.3	0.06
Fillet Weld	units	Ft of BHD BHD joints	0.2	0.3	0.06
Fillet Weld	T connections	[redacted]	0.2	0.3	0.06
Foundation Weld	Poimts	Ft of foundation	0.2	0.3	0.06
Pipe Field Run - Fuel	Pipe lines	Ft of pipung	0.1	2	0.01
Pipe Cut - Fuel	Pipe lines	Ft of pipung	0.1	0.1	0.01
Pipe Bend - Fuel	Pipe lines	Ft of pipung	0.1	0.4	0.01
Install Pipe - Fuel	Pipe lines	Ft of pipung	0.1	1	0.01
Field - Hyd	Pipe lines	Ft of pipung	0.1	2	0.01
Cut - Hyd	Pipe lines	Ft of pipung	0.1	0.1	0.01
Bend - Hyd	Pipe lines	Ft of pipung	0.1	0.4	0.01
Install - Hyd	Pipe lines	Ft of pipung	0.1	1	0.01
Field - Water	Pipe lines	Ft of pipung	0.1	2	0.01
Cut - Water	Pipe lines	Ft of pipung	0.1	0.1	0.01
Bend - Water	Pipe lines	Ft of pipung	0.1	0.4	0.01
Install - Water	Pipe lines	Ft of pipung	0.1	1	0.01
Field - Air/Gas	Pipe lines	Ft of pipung	0.1	2	0.01
Cut - Air/Gas	Pipe lines	Ft of pipung	0.1	0.1	0.01
Bend - Air/Gas	Pipe lines	Ft of pipung	0.1	0.4	0.01
Install - Air/Gas	Pipe lines	Ft of pipung	0.1	1	0.01
Field - HVAC	Pipe lines	Ft of pipung	0.1	2	0.01
Cut - HVAC	Pipe lines	Ft of pipung	0.1	0.1	0.01
Bend - HVAC	Pipe lines	Ft of pipung	0.1	0.4	0.01
Install - HVAC	Pipe lines	Ft of pipung	0.1	1	0.01
Electrical Distribution Line	Wire lines	Ft of wiring	0.1	0.4	0.01
Communication Line	Communication lines	Ft of wiring	0.1	0.4	0.01
Grind Paint	Units	L+W+H Total Dimension	0.2	0.5	0.2
Paint	Units	L+W+H Total Dimension	0.2	0.5	0.2
Remove Insulation (Lagging)	Units	L+W+H Total Dimension	0.2	0.5	0.2
Insulate (Lagging)	Units	L+W+H Total Dimension	0.2	0.5	0.2
Surrounding Space	Spaces affected	[redacted]	0	5	0
Fire Watch	Jobs	[redacted]	0	5	0
Weld Deconfliction	Jobs	[redacted]	0	5	0
Shipfitting Deconfliction	Jobs	[redacted]	0	5	0
Crane	Equipment Pieces	[redacted]	0	5	0
Drydock	Equipment Pieces	[redacted]	0	5	0
Weld Equipment	Equipment Pieces	[redacted]	0	5	0
Shipfitting Equipment	Equipment Pieces	[redacted]	0	5	0

Figure E-1: Process inputs and rate coefficients



Activity	Sub 1	Non-Scaling (hr)	Quantity-Scaling (hr/#)	Length-Scaling (hr/ft)	Sub 2	Non-Scaling (hr)	Quantity-Scaling (hr/#)	Length-Scaling (hr/ft)
Shape	Load Plate		X		Layout chalk lines			X
Mill	Load Plate		X		Auto Mill			X
Seam Weld	Edge Prep		X		Load Plate		X	
Mark	Align Plate		X		Run Plasma Cutter			X
Cut - Plate	Load Plate		X		Quality Control Checks		X	
Cut - Insert	Manual Torch Cut			X	Grind		X	
Insert Weld	Remove Tabs		X		Load Insert		X	
Fillet Weld	Edge Prep			X	Hang BHD			X
Fillet Weld	Align w/ comealongs		X		Tack Seams			X
Fillet Weld	Release Tack Welds for Realignment		X		Bust Welds of Both T's		X	
Foundation Weld	Align Plate		X		Tack Foundation			X
Pipe Field Run - Fuel	Measure Pipe System		X		Route Pipe System		X	
Pipe Cut - Fuel	Un-roll length			X	Cut Length		X	
Pipe Bend - Fuel	Transfer Pipe to Bending Machine			X	Align Bend Machine		X	
Install Pipe - Fuel	Lift Pipe Assy.		X		Align Pipe Assy.		X	
Field - Hyd	Measure Pipe System		X		Route Pipe System		X	
Cut - Hyd	Un-roll length			X	Cut Length		X	
Bend - Hyd	Transfer Pipe to Bending Machine			X	Align Bend Machine		X	
Install - Hyd	Lift Pipe Assy.		X		Align Pipe Assy.		X	
Field - Water	Measure Pipe System		X		Route Pipe System		X	
Cut - Water	Un-roll length			X	Cut Length		X	
Bend - Water	Transfer Pipe to Bending Machine			X	Align Bend Machine		X	
Install - Water	Lift Pipe Assy.		X		Align Pipe Assy.		X	
Field - Air/Gas	Measure Pipe System		X		Route Pipe System		X	
Cut - Air/Gas	Un-roll length			X	Cut Length		X	
Bend - Air/Gas	Transfer Pipe to Bending Machine			X	Align Bend Machine		X	
Install - Air/Gas	Lift Pipe Assy.		X		Align Pipe Assy.		X	
Field - HVAC	Measure Pipe System		X		Route Pipe System		X	
Cut - HVAC	Un-roll length			X	Cut Length		X	
Bend - HVAC	Transfer Pipe to Bending Machine			X	Align Bend Machine		X	
Install - HVAC	Lift Pipe Assy.		X		Align Pipe Assy.		X	

Figure E-2: Selected sub-process list and coefficient units, sub-process 1-3

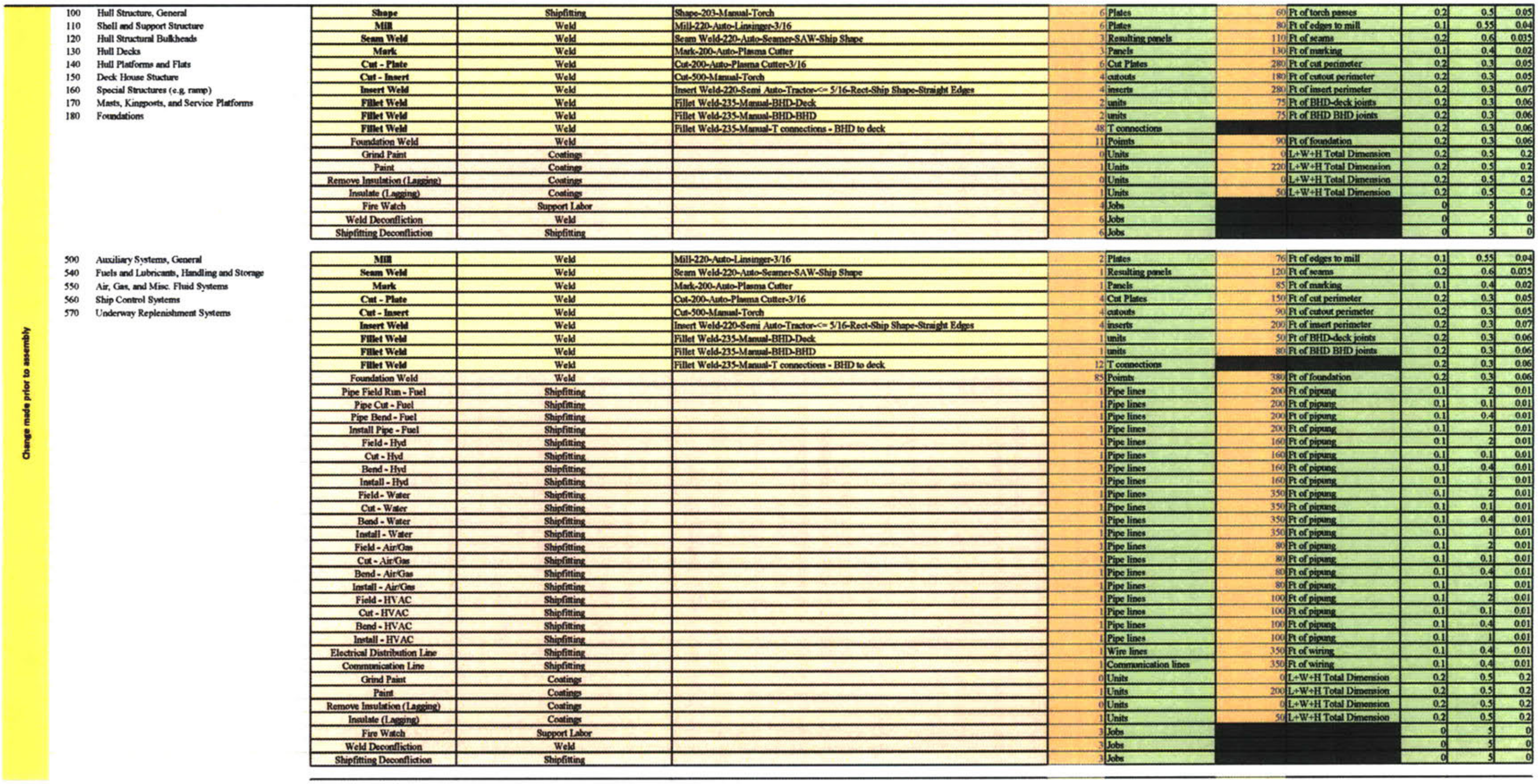
Activity	Sub 3	Non-Scaling (hr)	Quantity-Scaling (hr/#)	Length-Scaling (hr/ft)	Sub 4	Non-Scaling (hr)	Quantity-Scaling (hr/#)	Length-Scaling (hr/ft)	Sub 5	Non-Scaling (hr)	Quantity-Scaling (hr/#)	Length-Scaling (hr/ft)
Shape	Line Heat			X	Quench			X				
Mill												
Seam Weld	Clamp Plates		X		Tack			X	Auto Seamer Weld			X
Mark												
Cut - Plate	Load Nest Tape		X		Set axes (3 pt)		X		Mark Plate			X
Cut - Insert												
Insert Weld	Hammer		X		Grind Insert			X	Cut Base			X
Fillet Weld	Tack Angle Bars		X		Tack Seam			X	Grind and Repair			X
Fillet Weld	Manual Weld Seam			X	Grind and Repair			X				
Fillet Weld	Align Ts together		X		Saddle and Wedge		X		Tack unwelded T seams to plate		X	
Foundation Weld												
Pipe Field Run - Fuel												
Pipe Cut - Fuel												
Pipe Bend - Fuel	Bend Pipe			X	Transfer Pipe	X						
Install Pipe - Fuel	Clamp Pipe Assy.		X									
Field - Hyd												
Cut - Hyd												
Bend - Hyd	Bend Pipe			X	Transfer Pipe	X						
Install - Hyd	Clamp Pipe Assy.		X									
Field - Water												
Cut - Water												
Bend - Water	Bend Pipe			X	Transfer Pipe	X						
Install - Water	Clamp Pipe Assy.		X									
Field - Air/Gas												
Cut - Air/Gas												
Bend - Air/Gas	Bend Pipe			X	Transfer Pipe	X						
Install - Air/Gas	Clamp Pipe Assy.		X									
Field - HVAC												
Cut - HVAC												
Bend - HVAC	Bend Pipe			X	Transfer Pipe	X						
Install - HVAC	Clamp Pipe Assy.		X									

Figure E-3: Selected sub-process list and coefficient units, sub-process 4-6

Appendix F: Simulation of Shipbuilding Processes for SWBS Group 580 Requirement Change

		580 - Mechanical Handling Systems
	SWBS	**Tender Boat Crane Capacity Increase**
Initial SOC	100	Hull Structure, General
	110	Shell and Support Structure
	120	Hull Structural Bulkheads
	130	Hull Decks
	140	Hull Platforms and Flats
	150	Deck House Stucture
	160	Special Structures (e.g. ramp)
	170	Masts, Kingposts, and Service Platforms
	180	Foundations
	500	Auxiliary Systems, General
	540	Fuels and Lubricants, Handling and Storage
	550	Air, Gas, and Misc. Fluid Systems
	560	Ship Control Systems
	570	Underway Replenishment Systems
Unit Assembly SOC	100	Hull Structure, General
	110	Shell and Support Structure
	120	Hull Structural Bulkheads
	130	Hull Decks
	140	Hull Platforms and Flats
	150	Deck House Stucture
	160	Special Structures (e.g. ramp)
	170	Masts, Kingposts, and Service Platforms
	180	Foundations
	300	Electric Plant, General
	310	Electric Power Generation
	320	Power Distribution Systems
	330	Lighting System
	500	Auxiliary Systems, General
	540	Fuels and Lubricants, Handling and Storage
	550	Air, Gas, and Misc. Fluid Systems
	560	Ship Control Systems
	570	Underway Replenishment Systems
Outfitting SOC	100	Hull Structure, General
	110	Shell and Support Structure
	120	Hull Structural Bulkheads
	130	Hull Decks
	140	Hull Platforms and Flats
	150	Deck House Stucture
	160	Special Structures (e.g. ramp)
	170	Masts, Kingposts, and Service Platforms
	180	Foundations
	300	Electric Plant, General
	310	Electric Power Generation
	320	Power Distribution Systems
	330	Lighting System
	400	Command and Surveillance, General
	430	Interior Communications
	500	Auxiliary Systems, General
	540	Fuels and Lubricants, Handling and Storage
	550	Air, Gas, and Misc. Fluid Systems
	560	Ship Control Systems
	570	Underway Replenishment Systems
	600	Outfit and Furnishings, General
	610	Ship Fittings
	650	Service Spaces
	660	Working Spaces
	670	Stowage Spaces

Figure F-1: Affected sub-systems listed by stage of construction in which requirement change issued



Change made prior to assembly

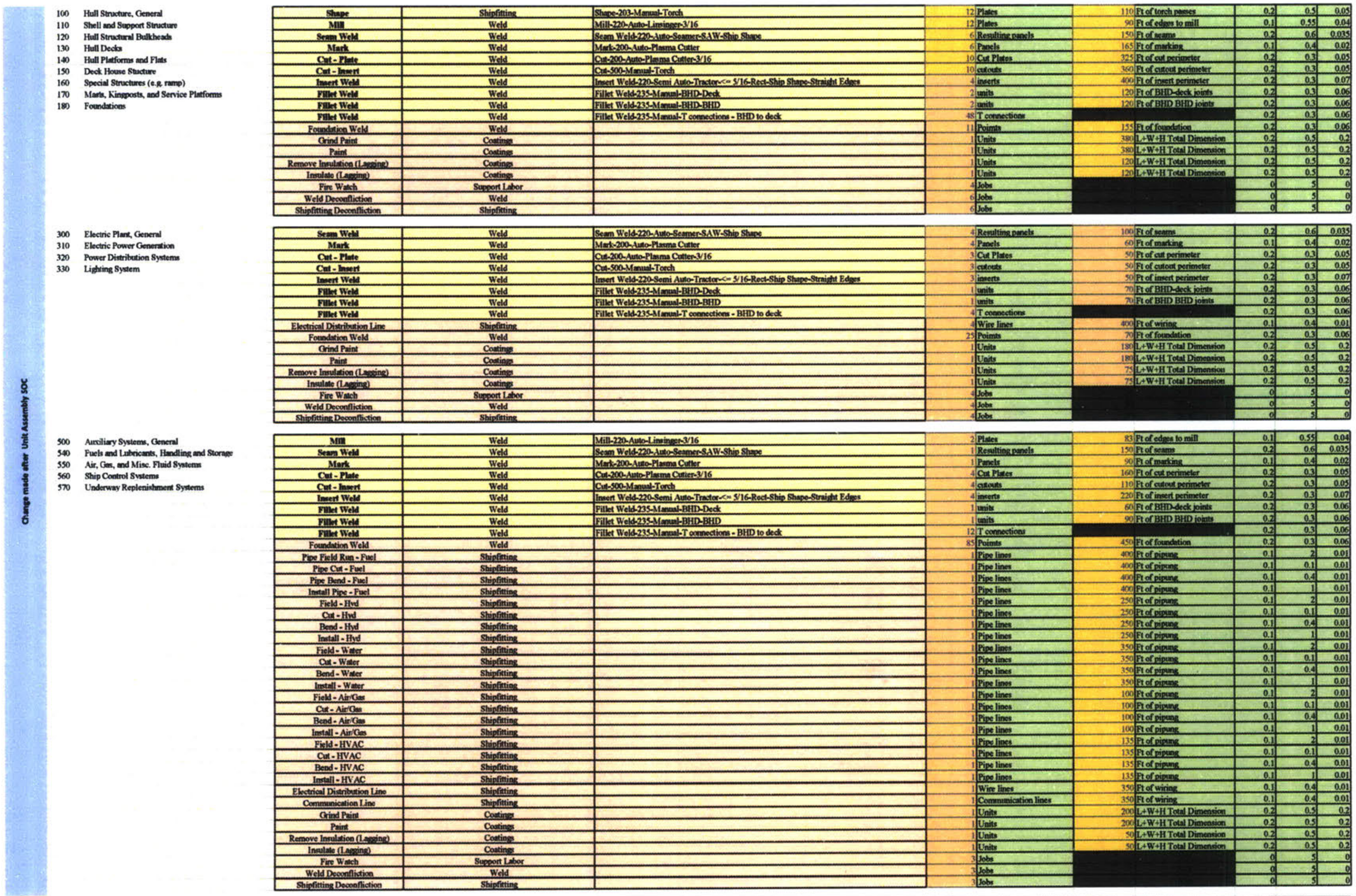
100	Hull Structure, General
110	Shell and Support Structure
120	Hull Structural Bulkheads
130	Hull Decks
140	Hull Platforms and Flats
150	Deck House Stucture
160	Special Structures (e.g. ramp)
170	Masts, Kingposts, and Service Platforms
180	Foundations

Shape	Shipfitting	Shape-203-Manual-Torch	6	Plates	60	Ft of torch passes	0.2	0.5	0.05
Mill	Weld	Mill-220-Auto-Linsinger-3/16	6	Plates	80	Ft of edges to mill	0.1	0.55	0.04
Seam Weld	Weld	Seam Weld-220-Auto-Seamer-SAW-Ship Shape	3	Resulting panels	110	Ft of seams	0.2	0.6	0.035
Mark	Weld	Mark-200-Auto-Plasma Cutter	3	Panels	130	Ft of marking	0.1	0.4	0.02
Cut - Plate	Weld	Cut-200-Auto-Plasma Cutter-3/16	6	Cut Plates	280	Ft of cut perimeter	0.2	0.3	0.05
Cut - Insert	Weld	Cut-500-Manual-Torch	4	cutouts	180	Ft of cutout perimeter	0.2	0.3	0.05
Insert Weld	Weld	Insert Weld-220-Semi Auto-Tractor-<= 5/16-Rect-Ship Shape-Straight Edges	4	inserts	280	Ft of insert perimeter	0.2	0.3	0.07
Fillet Weld	Weld	Fillet Weld-235-Manual-BHD-Deck	2	units	75	Ft of BHD-deck joints	0.2	0.3	0.06
Fillet Weld	Weld	Fillet Weld-235-Manual-BHD-BHD	2	units	75	Ft of BHD BHD joints	0.2	0.3	0.06
Fillet Weld	Weld	Fillet Weld-235-Manual-T connections - BHD to deck	48	T connections			0.2	0.3	0.06
Foundation Weld	Weld		11	Points	90	Ft of foundation	0.2	0.3	0.06
Grind Paint	Coatings		0	Units	0	L+W+H Total Dimension	0.2	0.5	0.2
Paint	Coatings		1	Units	220	L+W+H Total Dimension	0.2	0.5	0.2
Remove Insulation (Lagging)	Coatings		0	Units	0	L+W+H Total Dimension	0.2	0.5	0.2
Insulate (Lagging)	Coatings		1	Units	50	L+W+H Total Dimension	0.2	0.5	0.2
Fire Watch	Support Labor		4	Jobs			0	5	0
Weld Deconfliction	Weld		6	Jobs			0	5	0
Shipfitting Deconfliction	Shipfitting		6	Jobs			0	5	0

500	Auxiliary Systems, General
540	Fuels and Lubricants, Handling and Storage
550	Air, Gas, and Misc. Fluid Systems
560	Ship Control Systems
570	Underway Replenishment Systems

Mill	Weld	Mill-220-Auto-Linsinger-3/16	2	Plates	76	Ft of edges to mill	0.1	0.55	0.04
Seam Weld	Weld	Seam Weld-220-Auto-Seamer-SAW-Ship Shape	1	Resulting panels	120	Ft of seams	0.2	0.6	0.035
Mark	Weld	Mark-200-Auto-Plasma Cutter	1	Panels	85	Ft of marking	0.1	0.4	0.02
Cut - Plate	Weld	Cut-200-Auto-Plasma Cutter-3/16	4	Cut Plates	150	Ft of cut perimeter	0.2	0.3	0.05
Cut - Insert	Weld	Cut-500-Manual-Torch	4	cutouts	90	Ft of cutout perimeter	0.2	0.3	0.05
Insert Weld	Weld	Insert Weld-220-Semi Auto-Tractor-<= 5/16-Rect-Ship Shape-Straight Edges	4	inserts	200	Ft of insert perimeter	0.2	0.3	0.07
Fillet Weld	Weld	Fillet Weld-235-Manual-BHD-Deck	1	units	50	Ft of BHD-deck joints	0.2	0.3	0.06
Fillet Weld	Weld	Fillet Weld-235-Manual-BHD-BHD	1	units	80	Ft of BHD BHD joints	0.2	0.3	0.06
Fillet Weld	Weld	Fillet Weld-235-Manual-T connections - BHD to deck	12	T connections			0.2	0.3	0.06
Foundation Weld	Weld		85	Points	380	Ft of foundation	0.2	0.3	0.06
Pipe Field Run - Fuel	Shipfitting		1	Pipe lines	200	Ft of pipung	0.1	2	0.01
Pipe Cut - Fuel	Shipfitting		1	Pipe lines	200	Ft of pipung	0.1	0.1	0.01
Pipe Bend - Fuel	Shipfitting		1	Pipe lines	200	Ft of pipung	0.1	0.4	0.01
Install Pipe - Fuel	Shipfitting		1	Pipe lines	200	Ft of pipung	0.1	1	0.01
Field - Hyd	Shipfitting		1	Pipe lines	160	Ft of pipung	0.1	2	0.01
Cut - Hyd	Shipfitting		1	Pipe lines	160	Ft of pipung	0.1	0.1	0.01
Bend - Hyd	Shipfitting		1	Pipe lines	160	Ft of pipung	0.1	0.4	0.01
Install - Hyd	Shipfitting		1	Pipe lines	160	Ft of pipung	0.1	1	0.01
Field - Water	Shipfitting		1	Pipe lines	350	Ft of pipung	0.1	2	0.01
Cut - Water	Shipfitting		1	Pipe lines	350	Ft of pipung	0.1	0.1	0.01
Bend - Water	Shipfitting		1	Pipe lines	350	Ft of pipung	0.1	0.4	0.01
Install - Water	Shipfitting		1	Pipe lines	350	Ft of pipung	0.1	1	0.01
Field - Air/Gas	Shipfitting		1	Pipe lines	80	Ft of pipung	0.1	2	0.01
Cut - Air/Gas	Shipfitting		1	Pipe lines	80	Ft of pipung	0.1	0.1	0.01
Bend - Air/Gas	Shipfitting		1	Pipe lines	80	Ft of pipung	0.1	0.4	0.01
Install - Air/Gas	Shipfitting		1	Pipe lines	80	Ft of pipung	0.1	1	0.01
Field - HVAC	Shipfitting		1	Pipe lines	100	Ft of pipung	0.1	2	0.01
Cut - HVAC	Shipfitting		1	Pipe lines	100	Ft of pipung	0.1	0.1	0.01
Bend - HVAC	Shipfitting		1	Pipe lines	100	Ft of pipung	0.1	0.4	0.01
Install - HVAC	Shipfitting		1	Pipe lines	100	Ft of pipung	0.1	1	0.01
Electrical Distribution Line	Shipfitting		1	Wire lines	350	Ft of wiring	0.1	0.4	0.01
Communication Line	Shipfitting		1	Communication lines	350	Ft of wiring	0.1	0.4	0.01
Grind Paint	Coatings		0	Units	0	L+W+H Total Dimension	0.2	0.5	0.2
Paint	Coatings		1	Units	200	L+W+H Total Dimension	0.2	0.5	0.2
Remove Insulation (Lagging)	Coatings		0	Units	0	L+W+H Total Dimension	0.2	0.5	0.2
Insulate (Lagging)	Coatings		1	Units	50	L+W+H Total Dimension	0.2	0.5	0.2
Fire Watch	Support Labor		3	Jobs			0	5	0
Weld Deconfliction	Weld		3	Jobs			0	5	0
Shipfitting Deconfliction	Shipfitting		3	Jobs			0	5	0

Figure F-2: Initial SOC tasks for SWBS 580 requirement change



100 Hull Structure, General
110 Shell and Support Structure
120 Hull Structural Bulkheads
130 Hull Decks
140 Hull Platforms and Flats
150 Deck House Stucture
160 Special Structures (e.g. ramp)
170 Marts, Kingposts, and Service Platforms
180 Foundations

Shape	Shipfitting	Shape-203-Manual-Torch	12	Plates	110	Ft of torch passes	0.2	0.5	0.05
Mill	Weld	Mill-220-Auto-Linsinger-3/16	12	Plates	90	Ft of edges to mill	0.1	0.55	0.04
Seam Weld	Weld	Seam Weld-220-Auto-Seamer-SAW-Ship Shape	6	Resulting panels	150	Ft of seams	0.2	0.6	0.035
Mark	Weld	Mark-200-Auto-Plasma Cutter	6	Panels	165	Ft of marking	0.1	0.4	0.02
Cut - Plate	Weld	Cut-200-Auto-Plasma Cutter-3/16	10	Cut Plates	325	Ft of cut perimeter	0.2	0.3	0.05
Cut - Insert	Weld	Cut-500-Manual-Torch	10	cutouts	360	Ft of cutout perimeter	0.2	0.3	0.05
Insert Weld	Weld	Insert Weld-220-Semi Auto-Tractor-<= 5/16-Rect-Ship Shape-Straight Edges	4	inserts	400	Ft of insert perimeter	0.2	0.3	0.07
Fillet Weld	Weld	Fillet Weld-235-Manual-BHD-Deck	2	units	120	Ft of BHD-deck joints	0.2	0.3	0.06
Fillet Weld	Weld	Fillet Weld-235-Manual-BHD-BHD	2	units	120	Ft of BHD BHD joints	0.2	0.3	0.06
Fillet Weld	Weld	Fillet Weld-235-Manual-T connections - BHD to deck	48	T connections			0.2	0.3	0.06
Foundation Weld	Weld		11	Points	155	Ft of foundation	0.2	0.3	0.06
Grind Paint	Coatings		1	Units	380	L+W+H Total Dimension	0.2	0.5	0.2
Paint	Coatings		1	Units	380	L+W+H Total Dimension	0.2	0.5	0.2
Remove Insulation (Lagging)	Coatings		1	Units	120	L+W+H Total Dimension	0.2	0.5	0.2
Insulate (Lagging)	Coatings		1	Units	120	L+W+H Total Dimension	0.2	0.5	0.2
Fire Watch	Support Labor		4	Jobs			0	5	0
Weld Deconfliction	Weld		6	Jobs			0	5	0
Shipfitting Deconfliction	Shipfitting		6	Jobs			0	5	0

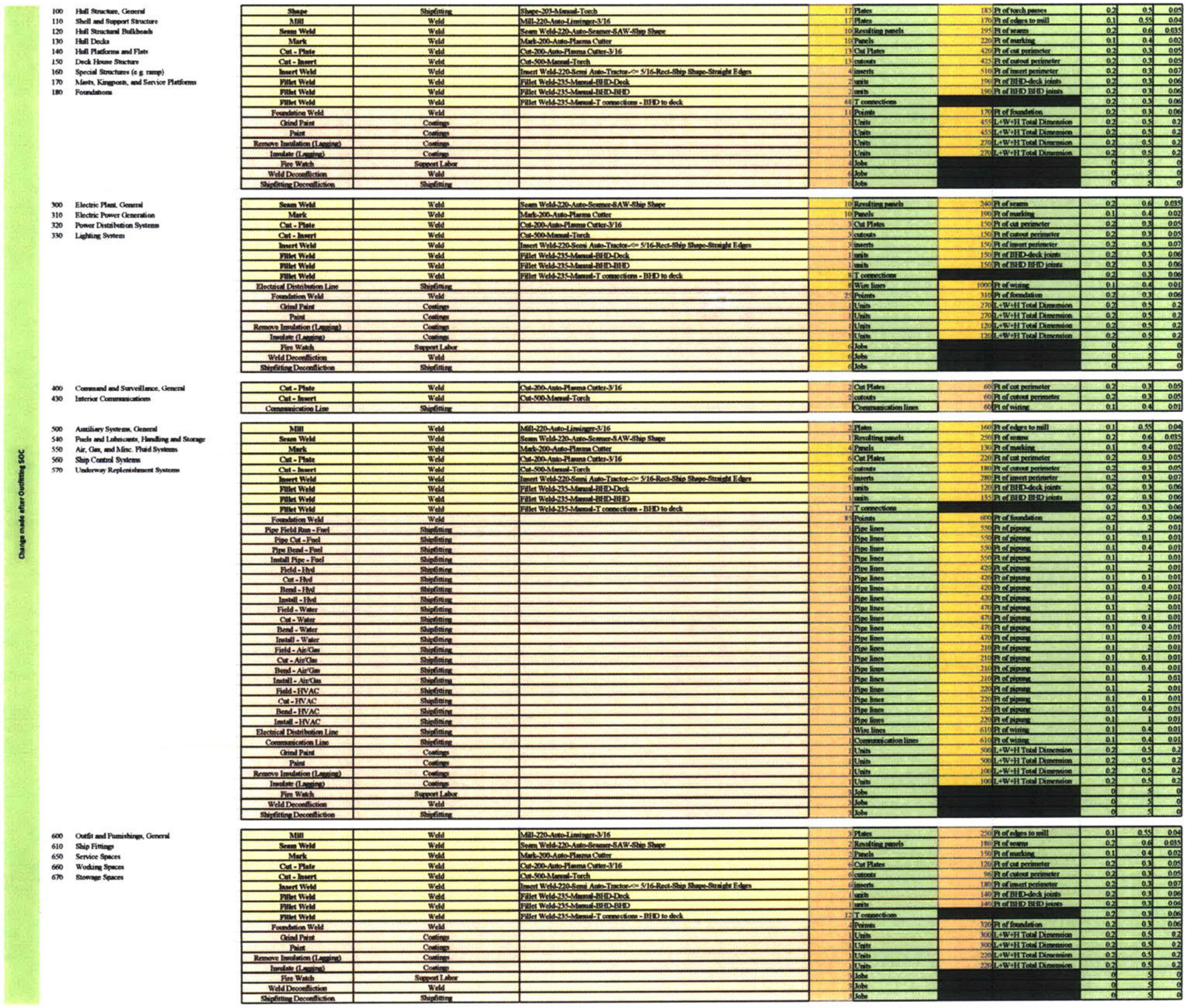
300 Electric Plant, General
310 Electric Power Generation
320 Power Distribution Systems
330 Lighting System

Seam Weld	Weld	Seam Weld-220-Auto-Seamer-SAW-Ship Shape	4	Resulting panels	100	Ft of seams	0.2	0.6	0.035
Mark	Weld	Mark-200-Auto-Plasma Cutter	4	Panels	60	Ft of marking	0.1	0.4	0.02
Cut - Plate	Weld	Cut-200-Auto-Plasma Cutter-3/16	3	Cut Plates	50	Ft of cut perimeter	0.2	0.3	0.05
Cut - Insert	Weld	Cut-500-Manual-Torch	3	cutouts	50	Ft of cutout perimeter	0.2	0.3	0.05
Insert Weld	Weld	Insert Weld-220-Semi Auto-Tractor-<= 5/16-Rect-Ship Shape-Straight Edges	3	inserts	50	Ft of insert perimeter	0.2	0.3	0.07
Fillet Weld	Weld	Fillet Weld-235-Manual-BHD-Deck	1	units	70	Ft of BHD-deck joints	0.2	0.3	0.06
Fillet Weld	Weld	Fillet Weld-235-Manual-BHD-BHD	1	units	70	Ft of BHD BHD joints	0.2	0.3	0.06
Fillet Weld	Weld	Fillet Weld-235-Manual-T connections - BHD to deck	4	T connections			0.2	0.3	0.06
Electrical Distribution Line	Shipfitting		4	Wire lines	400	Ft of wiring	0.1	0.4	0.01
Foundation Weld	Weld		25	Points	70	Ft of foundation	0.2	0.3	0.06
Grind Paint	Coatings		1	Units	180	L+W+H Total Dimension	0.2	0.5	0.2
Paint	Coatings		1	Units	180	L+W+H Total Dimension	0.2	0.5	0.2
Remove Insulation (Lagging)	Coatings		1	Units	75	L+W+H Total Dimension	0.2	0.5	0.2
Insulate (Lagging)	Coatings		1	Units	75	L+W+H Total Dimension	0.2	0.5	0.2
Fire Watch	Support Labor		4	Jobs			0	5	0
Weld Deconfliction	Weld		4	Jobs			0	5	0
Shipfitting Deconfliction	Shipfitting		4	Jobs			0	5	0

500 Auxiliary Systems, General
540 Fuels and Lubricants, Handling and Storage
550 Air, Gas, and Misc. Fluid Systems
560 Ship Control Systems
570 Underway Replenishment Systems

Mill	Weld	Mill-220-Auto-Linsinger-3/16	2	Plates	83	Ft of edges to mill	0.1	0.55	0.04
Seam Weld	Weld	Seam Weld-220-Auto-Seamer-SAW-Ship Shape	1	Resulting panels	150	Ft of seams	0.2	0.6	0.035
Mark	Weld	Mark-200-Auto-Plasma Cutter	1	Panels	90	Ft of marking	0.1	0.4	0.02
Cut - Plate	Weld	Cut-200-Auto-Plasma Cutter-3/16	4	Cut Plates	160	Ft of cut perimeter	0.2	0.3	0.05
Cut - Insert	Weld	Cut-500-Manual-Torch	4	cutouts	110	Ft of cutout perimeter	0.2	0.3	0.05
Insert Weld	Weld	Insert Weld-220-Semi Auto-Tractor-<= 5/16-Rect-Ship Shape-Straight Edges	4	inserts	220	Ft of insert perimeter	0.2	0.3	0.07
Fillet Weld	Weld	Fillet Weld-235-Manual-BHD-Deck	1	units	60	Ft of BHD-deck joints	0.2	0.3	0.06
Fillet Weld	Weld	Fillet Weld-235-Manual-BHD-BHD	1	units	90	Ft of BHD BHD joints	0.2	0.3	0.06
Fillet Weld	Weld	Fillet Weld-235-Manual-T connections - BHD to deck	12	T connections			0.2	0.3	0.06
Foundation Weld	Weld		85	Points	450	Ft of foundation	0.2	0.3	0.06
Pipe Field Run - Fuel	Shipfitting		1	Pipe lines	400	Ft of pipung	0.1	2	0.01
Pipe Cut - Fuel	Shipfitting		1	Pipe lines	400	Ft of pipung	0.1	0.1	0.01
Pipe Bend - Fuel	Shipfitting		1	Pipe lines	400	Ft of pipung	0.1	0.4	0.01
Install Pipe - Fuel	Shipfitting		1	Pipe lines	400	Ft of pipung	0.1	1	0.01
Field - Hyd	Shipfitting		1	Pipe lines	250	Ft of pipung	0.1	2	0.01
Cut - Hyd	Shipfitting		1	Pipe lines	250	Ft of pipung	0.1	0.1	0.01
Bend - Hyd	Shipfitting		1	Pipe lines	250	Ft of pipung	0.1	0.4	0.01
Install - Hyd	Shipfitting		1	Pipe lines	250	Ft of pipung	0.1	1	0.01
Field - Water	Shipfitting		1	Pipe lines	350	Ft of pipung	0.1	2	0.01
Cut - Water	Shipfitting		1	Pipe lines	350	Ft of pipung	0.1	0.1	0.01
Bend - Water	Shipfitting		1	Pipe lines	350	Ft of pipung	0.1	0.4	0.01
Install - Water	Shipfitting		1	Pipe lines	350	Ft of pipung	0.1	1	0.01
Field - Air/Gas	Shipfitting		1	Pipe lines	100	Ft of pipung	0.1	2	0.01
Cut - Air/Gas	Shipfitting		1	Pipe lines	100	Ft of pipung	0.1	0.1	0.01
Bend - Air/Gas	Shipfitting		1	Pipe lines	100	Ft of pipung	0.1	0.4	0.01
Install - Air/Gas	Shipfitting		1	Pipe lines	100	Ft of pipung	0.1	1	0.01
Field - HVAC	Shipfitting		1	Pipe lines	135	Ft of pipung	0.1	2	0.01
Cut - HVAC	Shipfitting		1	Pipe lines	135	Ft of pipung	0.1	0.1	0.01
Bend - HVAC	Shipfitting		1	Pipe lines	135	Ft of pipung	0.1	0.4	0.01
Install - HVAC	Shipfitting		1	Pipe lines	135	Ft of pipung	0.1	1	0.01
Electrical Distribution Line	Shipfitting		1	Wire lines	350	Ft of wiring	0.1	0.4	0.01
Communication Line	Shipfitting		1	Communication lines	350	Ft of wiring	0.1	0.4	0.01
Grind Paint	Coatings		1	Units	200	L+W+H Total Dimension	0.2	0.5	0.2
Paint	Coatings		1	Units	200	L+W+H Total Dimension	0.2	0.5	0.2
Remove Insulation (Lagging)	Coatings		1	Units	50	L+W+H Total Dimension	0.2	0.5	0.2
Insulate (Lagging)	Coatings		1	Units	50	L+W+H Total Dimension	0.2	0.5	0.2
Fire Watch	Support Labor		3	Jobs			0	5	0
Weld Deconfliction	Weld		3	Jobs			0	5	0
Shipfitting Deconfliction	Shipfitting		3	Jobs			0	5	0

Figure F-3: Unit Assembly SOC tasks for SWBS 580 requirement change



100 Hull Structure, General
110 Shell and Support Structure
120 Hull Structural Bulkheads
130 Hull Decks
140 Hull Platforms and Flats
150 Deck House Stucture
160 Special Structures (e.g. ramp)
170 Masts, Kingposts, and Service Platforms
180 Foundations

Shape	Shipfitting	Shape-203-Manual-Torch	17	Plates	185	Ft of torch passes	0.2	0.5	0.05
Mill	Weld	Mill-220-Auto-Linsinger-3/16	17	Plates	170	Ft of edges to mill	0.1	0.55	0.04
Seam Weld	Weld	Seam Weld-220-Auto-Seamer-SAW-Ship Shape	10	Resulting panels	195	Ft of seams	0.2	0.6	0.035
Mark	Weld	Mark-200-Auto-Plasma Cutter	10	Panels	220	Ft of marking	0.1	0.4	0.02
Cut - Plate	Weld	Cut-200-Auto-Plasma Cutter-3/16	13	Cut Plates	420	Ft of cut perimeter	0.2	0.3	0.05
Cut - Insert	Weld	Cut-500-Manual-Torch	13	cutouts	425	Ft of cutout perimeter	0.2	0.3	0.05
Insert Weld	Weld	Insert Weld-220-Semi Auto-Tractor-<= 5/16-Rect-Ship Shape-Straight Edges	4	inserts	510	Ft of insert perimeter	0.2	0.3	0.07
Fillet Weld	Weld	Fillet Weld-235-Manual-BHD-Deck	2	units	190	Ft of BHD-deck joints	0.2	0.3	0.06
Fillet Weld	Weld	Fillet Weld-235-Manual-BHD-BHD	2	units	190	Ft of BHD BHD joints	0.2	0.3	0.06
Fillet Weld	Weld	Fillet Weld-235-Manual-T connections - BHD to deck	48	T connections			0.2	0.3	0.06
Foundation Weld	Weld		11	Points	170	Ft of foundation	0.2	0.3	0.06
Grind Paint	Coatings		1	Units	455	L+W+H Total Dimension	0.2	0.5	0.2
Paint	Coatings		1	Units	455	L+W+H Total Dimension	0.2	0.5	0.2
Remove Insulation (Lagging)	Coatings		1	Units	270	L+W+H Total Dimension	0.2	0.5	0.2
Insulate (Lagging)	Coatings		1	Units	270	L+W+H Total Dimension	0.2	0.5	0.2
Fire Watch	Support Labor		4	Jobs			0	5	0
Weld Deconfliction	Weld		6	Jobs			0	5	0
Shipfitting Deconfliction	Shipfitting		6	Jobs			0	5	0

300 Electric Plant, General
310 Electric Power Generation
320 Power Distribution Systems
330 Lighting System

Seam Weld	Weld	Seam Weld-220-Auto-Seamer-SAW-Ship Shape	10	Resulting panels	240	Ft of seams	0.2	0.6	0.035
Mark	Weld	Mark-200-Auto-Plasma Cutter	10	Panels	190	Ft of marking	0.1	0.4	0.02
Cut - Plate	Weld	Cut-200-Auto-Plasma Cutter-3/16	3	Cut Plates	150	Ft of cut perimeter	0.2	0.3	0.05
Cut - Insert	Weld	Cut-500-Manual-Torch	3	cutouts	150	Ft of cutout perimeter	0.2	0.3	0.05
Insert Weld	Weld	Insert Weld-220-Semi Auto-Tractor-<= 5/16-Rect-Ship Shape-Straight Edges	3	inserts	150	Ft of insert perimeter	0.2	0.3	0.07
Fillet Weld	Weld	Fillet Weld-235-Manual-BHD-Deck	1	units	150	Ft of BHD-deck joints	0.2	0.3	0.06
Fillet Weld	Weld	Fillet Weld-235-Manual-BHD-BHD	1	units	150	Ft of BHD BHD joints	0.2	0.3	0.06
Fillet Weld	Weld	Fillet Weld-235-Manual-T connections - BHD to deck	8	T connections			0.2	0.3	0.06
Electrical Distribution Line	Shipfitting		8	Wire lines	1000	Ft of wiring	0.1	0.4	0.01
Foundation Weld	Weld		25	Points	310	Ft of foundation	0.2	0.3	0.06
Grind Paint	Coatings		1	Units	270	L+W+H Total Dimension	0.2	0.5	0.2
Paint	Coatings		1	Units	270	L+W+H Total Dimension	0.2	0.5	0.2
Remove Insulation (Lagging)	Coatings		1	Units	120	L+W+H Total Dimension	0.2	0.5	0.2
Insulate (Lagging)	Coatings		1	Units	120	L+W+H Total Dimension	0.2	0.5	0.2
Fire Watch	Support Labor		6	Jobs			0	5	0
Weld Deconfliction	Weld		6	Jobs			0	5	0
Shipfitting Deconfliction	Shipfitting		6	Jobs			0	5	0

400 Command and Surveillance, General
430 Interior Communications

Cut - Plate	Weld	Cut-200-Auto-Plasma Cutter-3/16	2	Cut Plates	60	Ft of cut perimeter	0.2	0.3	0.05
Cut - Insert	Weld	Cut-500-Manual-Torch	2	cutouts	60	Ft of cutout perimeter	0.2	0.3	0.05
Communication Line	Shipfitting			Communication lines	60	Ft of wiring	0.1	0.4	0.01

500 Auxiliary Systems, General
540 Fuels and Lubricants, Handling and Storage
550 Air, Gas, and Misc. Fluid Systems
560 Ship Control Systems
570 Underway Replenishment Systems

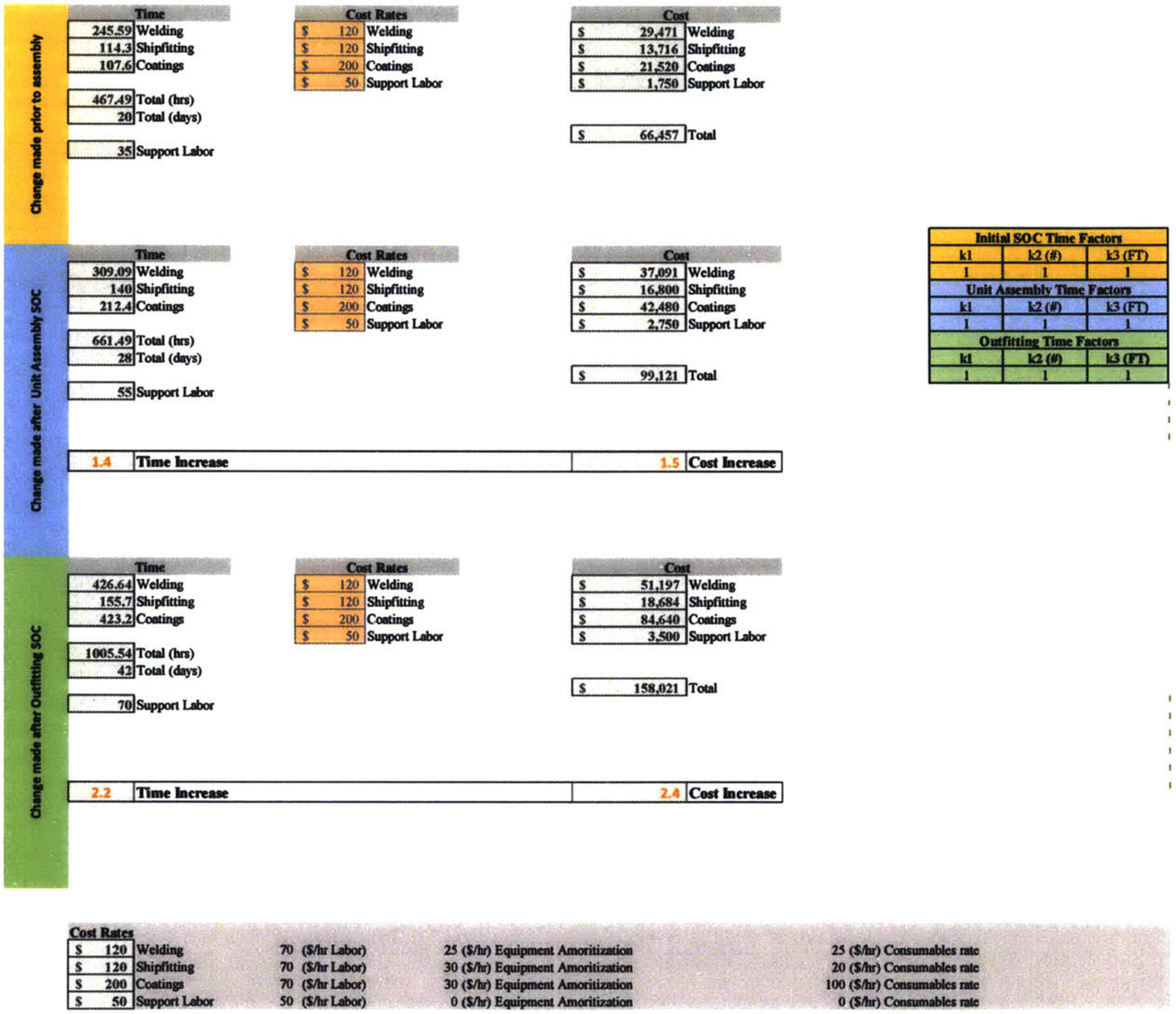
Mill	Weld	Mill-220-Auto-Linsinger-3/16	2	Plates	160	Ft of edges to mill	0.1	0.55	0.04
Seam Weld	Weld	Seam Weld-220-Auto-Seamer-SAW-Ship Shape	1	Resulting panels	250	Ft of seams	0.2	0.6	0.035
Mark	Weld	Mark-200-Auto-Plasma Cutter	4	Panels	130	Ft of marking	0.1	0.4	0.02
Cut - Plate	Weld	Cut-200-Auto-Plasma Cutter-3/16	6	Cut Plates	220	Ft of cut perimeter	0.2	0.3	0.05
Cut - Insert	Weld	Cut-500-Manual-Torch	6	cutouts	180	Ft of cutout perimeter	0.2	0.3	0.05
Insert Weld	Weld	Insert Weld-220-Semi Auto-Tractor-<= 5/16-Rect-Ship Shape-Straight Edges	6	inserts	280	Ft of insert perimeter	0.2	0.3	0.07
Fillet Weld	Weld	Fillet Weld-235-Manual-BHD-Deck	1	units	120	Ft of BHD-deck joints	0.2	0.3	0.06
Fillet Weld	Weld	Fillet Weld-235-Manual-BHD-BHD	1	units	135	Ft of BHD BHD joints	0.2	0.3	0.06
Fillet Weld	Weld	Fillet Weld-235-Manual-T connections - BHD to deck	12	T connections			0.2	0.3	0.06
Foundation Weld	Weld		85	Points	600	Ft of foundation	0.2	0.3	0.06
Pipe Field Run - Fuel	Shipfitting		1	Pipe lines	550	Ft of piping	0.1	2	0.01
Pipe Cut - Fuel	Shipfitting		1	Pipe lines	550	Ft of piping	0.1	0.1	0.01
Pipe Bend - Fuel	Shipfitting		1	Pipe lines	550	Ft of piping	0.1	0.4	0.01
Install Pipe - Fuel	Shipfitting		1	Pipe lines	550	Ft of piping	0.1	1	0.01
Field - Hyd	Shipfitting		1	Pipe lines	420	Ft of piping	0.1	2	0.01
Cut - Hyd	Shipfitting		1	Pipe lines	420	Ft of piping	0.1	0.1	0.01
Bend - Hyd	Shipfitting		1	Pipe lines	420	Ft of piping	0.1	0.4	0.01
Install - Hyd	Shipfitting		1	Pipe lines	420	Ft of piping	0.1	1	0.01
Field - Water	Shipfitting		1	Pipe lines	470	Ft of piping	0.1	2	0.01
Cut - Water	Shipfitting		1	Pipe lines	470	Ft of piping	0.1	0.1	0.01
Bend - Water	Shipfitting		1	Pipe lines	470	Ft of piping	0.1	0.4	0.01
Install - Water	Shipfitting		1	Pipe lines	470	Ft of piping	0.1	1	0.01
Field - Air/Gas	Shipfitting		1	Pipe lines	210	Ft of piping	0.1	2	0.01
Cut - Air/Gas	Shipfitting		1	Pipe lines	210	Ft of piping	0.1	0.1	0.01
Bend - Air/Gas	Shipfitting		1	Pipe lines	210	Ft of piping	0.1	0.4	0.01
Install - Air/Gas	Shipfitting		1	Pipe lines	210	Ft of piping	0.1	1	0.01
Field - HVAC	Shipfitting		1	Pipe lines	220	Ft of piping	0.1	2	0.01
Cut - HVAC	Shipfitting		1	Pipe lines	220	Ft of piping	0.1	0.1	0.01
Bend - HVAC	Shipfitting		1	Pipe lines	220	Ft of piping	0.1	0.4	0.01
Install - HVAC	Shipfitting		1	Pipe lines	220	Ft of piping	0.1	1	0.01
Electrical Distribution Line	Shipfitting		1	Wire lines	610	Ft of wiring	0.1	0.4	0.01
Communication Line	Shipfitting		1	Communication lines	610	Ft of wiring	0.1	0.4	0.01
Grind Paint	Coatings		1	Units	500	L+W+H Total Dimension	0.2	0.5	0.2
Paint	Coatings		1	Units	500	L+W+H Total Dimension	0.2	0.5	0.2
Remove Insulation (Lagging)	Coatings		1	Units	100	L+W+H Total Dimension	0.2	0.5	0.2
Insulate (Lagging)	Coatings		1	Units	100	L+W+H Total Dimension	0.2	0.5	0.2
Fire Watch	Support Labor		3	Jobs			0	5	0
Weld Deconfliction	Weld		3	Jobs			0	5	0
Shipfitting Deconfliction	Shipfitting		3	Jobs			0	5	0

600 Outfit and Furnishings, General
610 Ship Fittings
650 Service Spaces
660 Working Spaces
670 Stowage Spaces

Mill	Weld	Mill-220-Auto-Linsinger-3/16	3	Plates	250	Ft of edges to mill	0.1	0.55	0.04
Seam Weld	Weld	Seam Weld-220-Auto-Seamer-SAW-Ship Shape	2	Resulting panels	180	Ft of seams	0.2	0.6	0.035
Mark	Weld	Mark-200-Auto-Plasma Cutter	2	Panels	150	Ft of marking	0.1	0.4	0.02
Cut - Plate	Weld	Cut-200-Auto-Plasma Cutter-3/16	6	Cut Plates	120	Ft of cut perimeter	0.2	0.3	0.05
Cut - Insert	Weld	Cut-500-Manual-Torch	6	cutouts	96	Ft of cutout perimeter	0.2	0.3	0.05
Insert Weld	Weld	Insert Weld-220-Semi Auto-Tractor-<= 5/16-Rect-Ship Shape-Straight Edges	6	inserts	180	Ft of insert perimeter	0.2	0.3	0.07
Fillet Weld	Weld	Fillet Weld-235-Manual-BHD-Deck	1	units	140	Ft of BHD-deck joints	0.2	0.3	0.06
Fillet Weld	Weld	Fillet Weld-235-Manual-BHD-BHD	1	units	140	Ft of BHD BHD joints	0.2	0.3	0.06
Fillet Weld	Weld	Fillet Weld-235-Manual-T connections - BHD to deck	12	T connections			0.2	0.3	0.06
Foundation Weld	Weld		4	Points	320	Ft of foundation	0.2	0.3	0.06
Grind Paint	Coatings		1	Units	300	L+W+H Total Dimension	0.2	0.5	0.2
Paint	Coatings		1	Units	300	L+W+H Total Dimension	0.2	0.5	0.2
Remove Insulation (Lagging)	Coatings		1	Units	220	L+W+H Total Dimension	0.2	0.5	0.2
Insulate (Lagging)	Coatings		1	Units	220	L+W+H Total Dimension	0.2	0.5	0.2
Fire Watch	Support Labor		3	Jobs			0	5	0
Weld Deconfliction	Weld		3	Jobs			0	5	0
Shipfitting Deconfliction	Shipfitting		3	Jobs			0	5	0

Figure F-4: Outfitting SOC tasks for SWBS 580 requirement change

Appendix G: Cost and Schedule Simulator Views



Change made prior to assembly

Time		Cost Rates		Cost	
245.59	Welding	$ 120	Welding	$ 29,471	Welding
114.3	Shipfitting	$ 120	Shipfitting	$ 13,716	Shipfitting
107.6	Coatings	$ 200	Coatings	$ 21,520	Coatings
		$ 50	Support Labor	$ 1,750	Support Labor
467.49	Total (hrs)				
20	Total (days)				
				$ 66,457	Total
35	Support Labor				

Change made after Unit Assembly SOC

Time		Cost Rates		Cost	
309.09	Welding	$ 120	Welding	$ 37,091	Welding
140	Shipfitting	$ 120	Shipfitting	$ 16,800	Shipfitting
212.4	Coatings	$ 200	Coatings	$ 42,480	Coatings
		$ 50	Support Labor	$ 2,750	Support Labor
661.49	Total (hrs)				
28	Total (days)				
				$ 99,121	Total
55	Support Labor				
1.4	Time Increase			1.5	Cost Increase

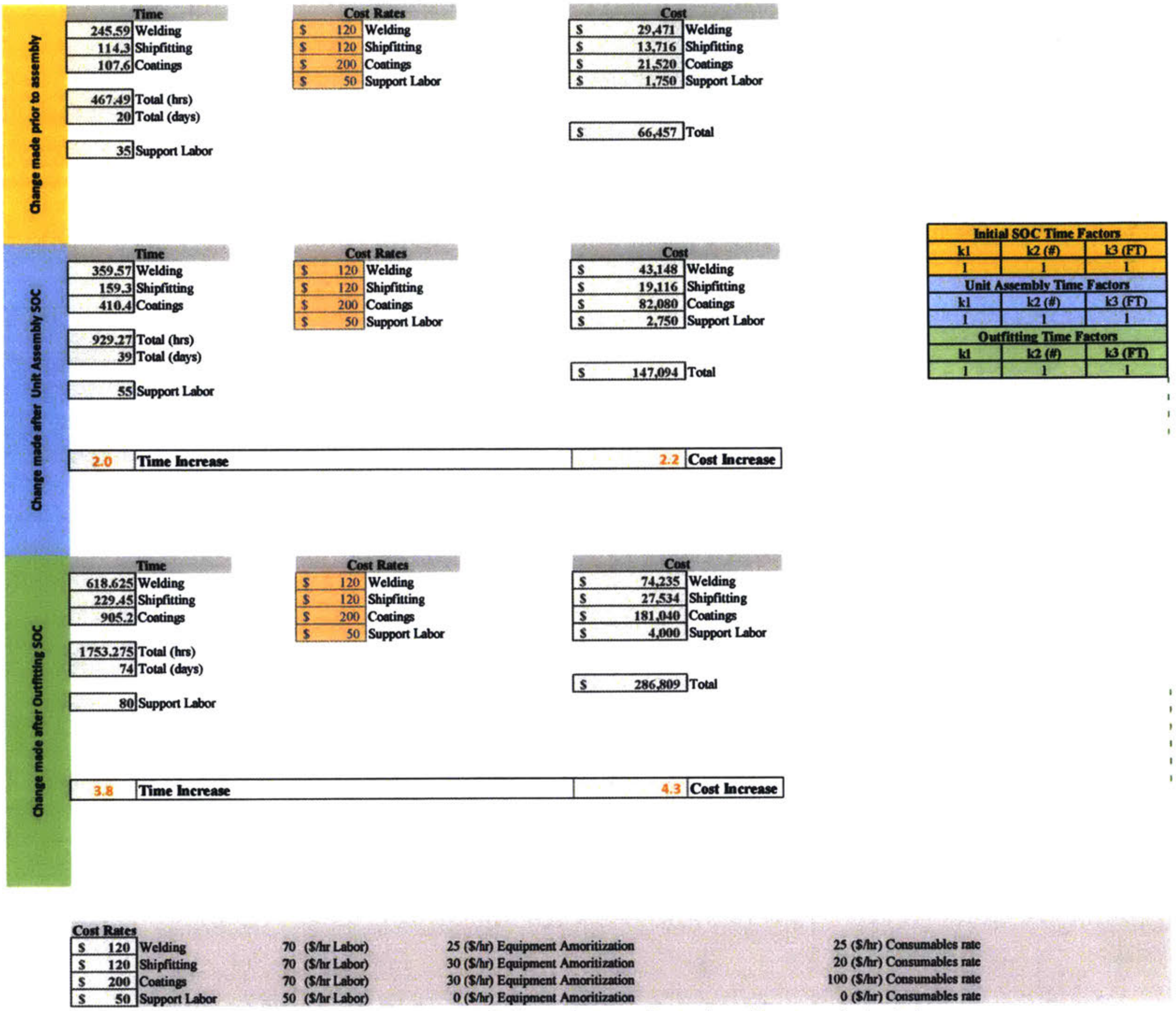
Change made after Outfitting SOC

Time		Cost Rates		Cost	
426.64	Welding	$ 120	Welding	$ 51,197	Welding
155.7	Shipfitting	$ 120	Shipfitting	$ 18,684	Shipfitting
423.2	Coatings	$ 200	Coatings	$ 84,640	Coatings
		$ 50	Support Labor	$ 3,500	Support Labor
1005.54	Total (hrs)				
42	Total (days)				
				$ 158,021	Total
70	Support Labor				
2.2	Time Increase			2.4	Cost Increase

Initial SOC Time Factors		
k1	k2 (#)	k3 (FT)
1	1	1
Unit Assembly Time Factors		
k1	k2 (#)	k3 (FT)
1	1	1
Outfitting Time Factors		
k1	k2 (#)	k3 (FT)
1	1	1

Cost Rates				
$ 120	Welding	70 (\$/hr Labor)	25 (\$/hr) Equipment Amoritization	25 (\$/hr) Consumables rate
$ 120	Shipfitting	70 (\$/hr Labor)	30 (\$/hr) Equipment Amoritization	20 (\$/hr) Consumables rate
$ 200	Coatings	70 (\$/hr Labor)	30 (\$/hr) Equipment Amoritization	100 (\$/hr) Consumables rate
$ 50	Support Labor	50 (\$/hr Labor)	0 (\$/hr) Equipment Amoritization	0 (\$/hr) Consumables rate

Figure G-1: Layer 1 Simulation Results (Deterministic)



Change made prior to assembly

Time		Cost Rates		Cost	
245.59	Welding	$ 120	Welding	$ 29,471	Welding
114.3	Shipfitting	$ 120	Shipfitting	$ 13,716	Shipfitting
107.6	Coatings	$ 200	Coatings	$ 21,520	Coatings
		$ 50	Support Labor	$ 1,750	Support Labor
467.49	Total (hrs)				
20	Total (days)			$ 66,457	Total
35	Support Labor				

Change made after Unit Assembly SOC

Time		Cost Rates		Cost	
359.57	Welding	$ 120	Welding	$ 43,148	Welding
159.3	Shipfitting	$ 120	Shipfitting	$ 19,116	Shipfitting
410.4	Coatings	$ 200	Coatings	$ 82,080	Coatings
		$ 50	Support Labor	$ 2,750	Support Labor
929.27	Total (hrs)				
39	Total (days)			$ 147,094	Total
55	Support Labor				
2.0	Time Increase			2.2	Cost Increase

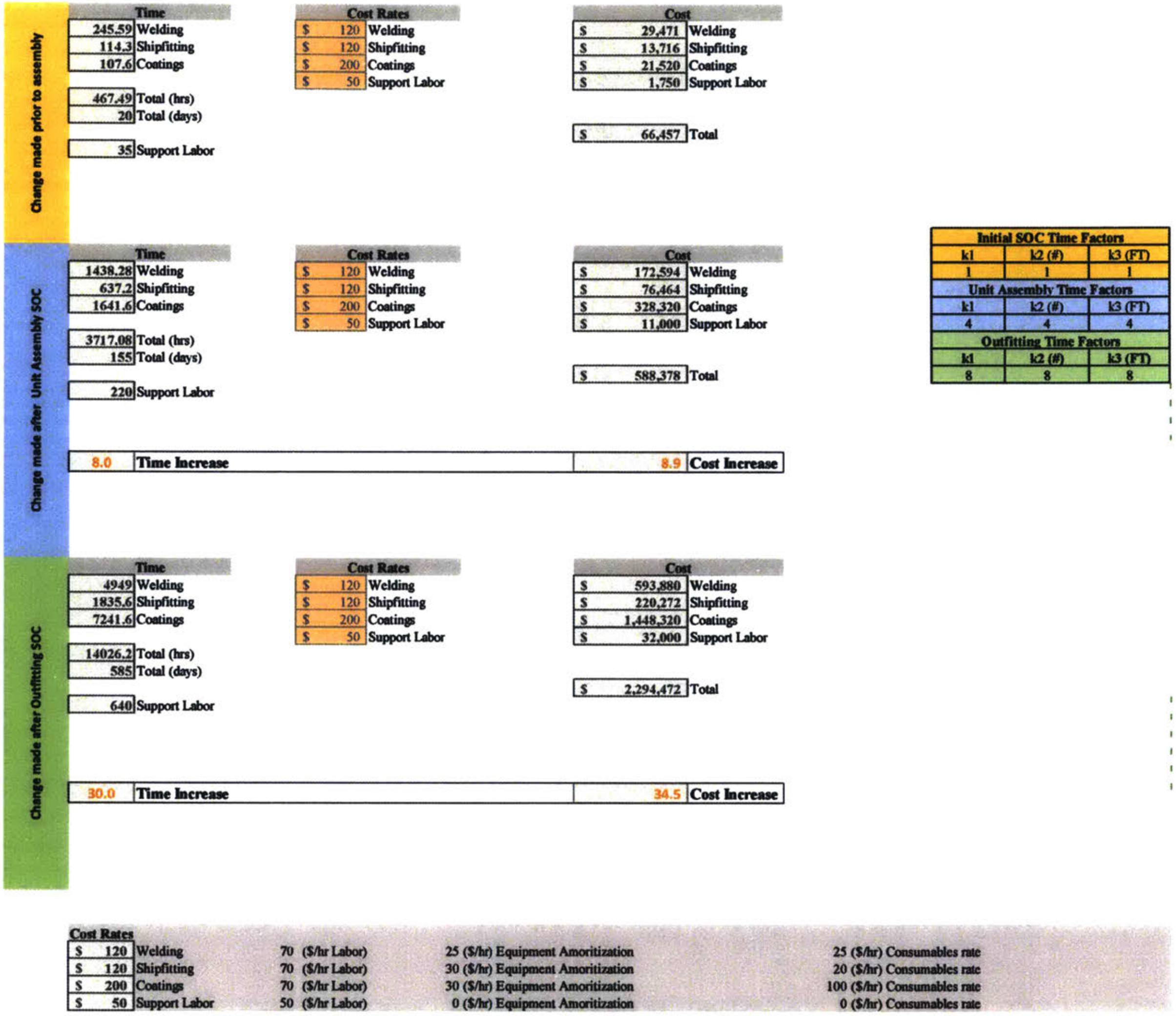
Change made after Outfitting SOC

Time		Cost Rates		Cost	
618.625	Welding	$ 120	Welding	$ 74,235	Welding
229.45	Shipfitting	$ 120	Shipfitting	$ 27,534	Shipfitting
905.2	Coatings	$ 200	Coatings	$ 181,040	Coatings
		$ 50	Support Labor	$ 4,000	Support Labor
1753.275	Total (hrs)				
74	Total (days)			$ 286,809	Total
80	Support Labor				
3.8	Time Increase			4.3	Cost Increase

Initial SOC Time Factors		
k1	k2 (#)	k3 (FT)
1	1	1
Unit Assembly Time Factors		
k1	k2 (#)	k3 (FT)
1	1	1
Outfitting Time Factors		
k1	k2 (#)	k3 (FT)
1	1	1

Cost Rates				
$ 120	Welding	70 (\$/hr Labor)	25 (\$/hr) Equipment Amoritization	25 (\$/hr) Consumables rate
$ 120	Shipfitting	70 (\$/hr Labor)	30 (\$/hr) Equipment Amoritization	20 (\$/hr) Consumables rate
$ 200	Coatings	70 (\$/hr Labor)	30 (\$/hr) Equipment Amoritization	100 (\$/hr) Consumables rate
$ 50	Support Labor	50 (\$/hr Labor)	0 (\$/hr) Equipment Amoritization	0 (\$/hr) Consumables rate

Figure G-2: Layer 2 Simulation Results (Deterministic)



Change made prior to assembly

Time		Cost Rates		Cost	
245.59	Welding	$ 120	Welding	$ 29,471	Welding
114.3	Shipfitting	$ 120	Shipfitting	$ 13,716	Shipfitting
107.6	Coatings	$ 200	Coatings	$ 21,520	Coatings
		$ 50	Support Labor	$ 1,750	Support Labor
467.49	Total (hrs)				
20	Total (days)				
				$ 66,457	Total
35	Support Labor				

Change made after Unit Assembly SOC

Time		Cost Rates		Cost	
1438.28	Welding	$ 120	Welding	$ 172,594	Welding
637.2	Shipfitting	$ 120	Shipfitting	$ 76,464	Shipfitting
1641.6	Coatings	$ 200	Coatings	$ 328,320	Coatings
		$ 50	Support Labor	$ 11,000	Support Labor
3717.08	Total (hrs)				
155	Total (days)				
				$ 588,378	Total
220	Support Labor				
8.0	Time Increase			8.9	Cost Increase

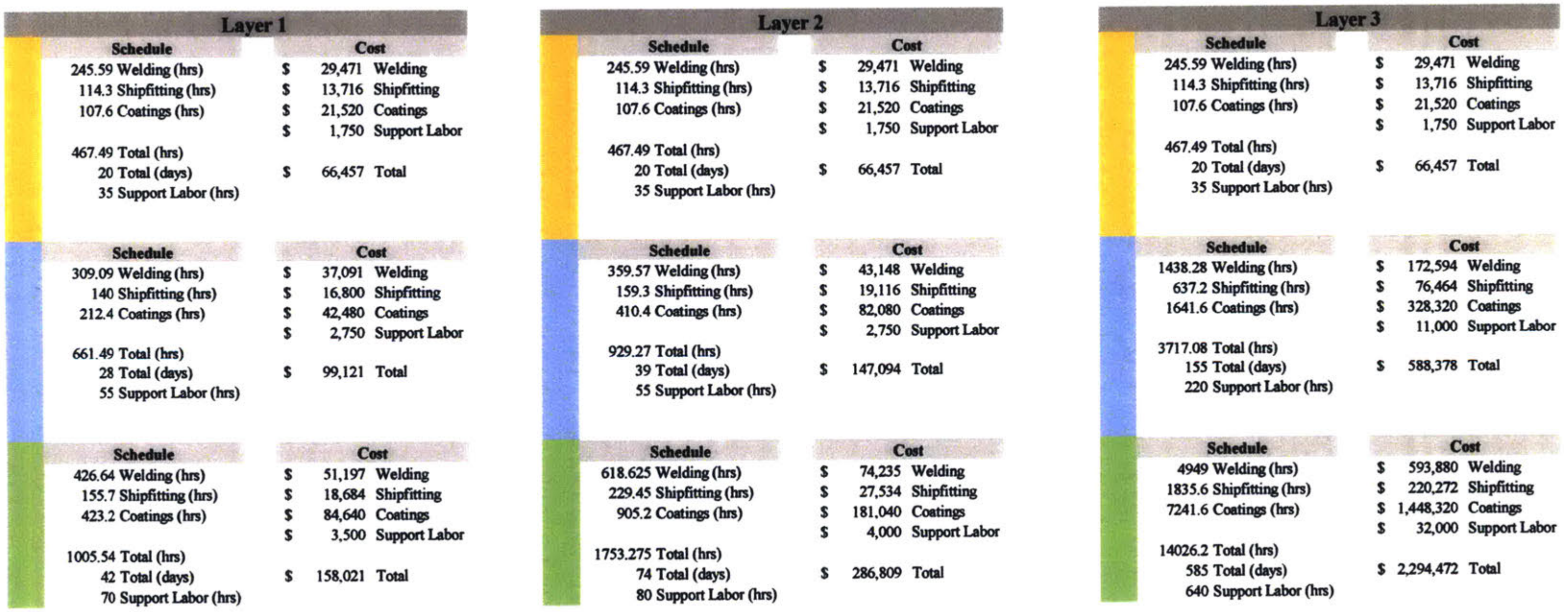
Change made after Outfitting SOC

Time		Cost Rates		Cost	
4949	Welding	$ 120	Welding	$ 593,880	Welding
1835.6	Shipfitting	$ 120	Shipfitting	$ 220,272	Shipfitting
7241.6	Coatings	$ 200	Coatings	$ 1,448,320	Coatings
		$ 50	Support Labor	$ 32,000	Support Labor
14026.2	Total (hrs)				
585	Total (days)				
				$ 2,294,472	Total
640	Support Labor				
30.0	Time Increase			34.5	Cost Increase

Initial SOC Time Factors		
k1	k2 (#)	k3 (FT)
1	1	1
Unit Assembly Time Factors		
k1	k2 (#)	k3 (FT)
4	4	4
Outfitting Time Factors		
k1	k2 (#)	k3 (FT)
8	8	8

Cost Rates				
$ 120	Welding	70 ($/hr Labor)	25 ($/hr) Equipment Amoritization	25 ($/hr) Consumables rate
$ 120	Shipfitting	70 ($/hr Labor)	30 ($/hr) Equipment Amoritization	20 ($/hr) Consumables rate
$ 200	Coatings	70 ($/hr Labor)	30 ($/hr) Equipment Amoritization	100 ($/hr) Consumables rate
$ 50	Support Labor	50 ($/hr Labor)	0 ($/hr) Equipment Amoritization	0 ($/hr) Consumables rate

Figure G-3: Layer 3 Simulation Results (Deterministic)



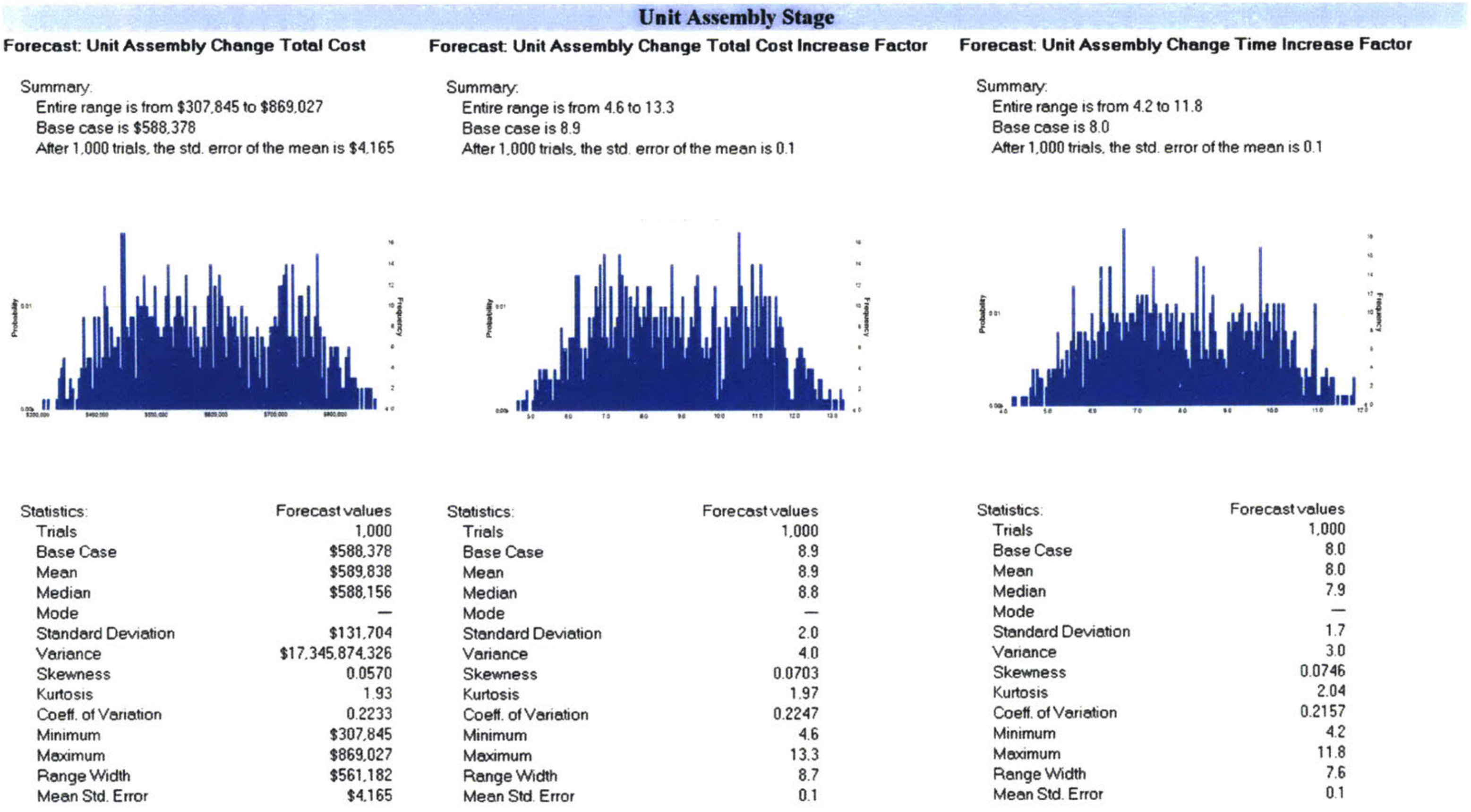
Layer 1	Schedule		Cost	
🟨	245.59 Welding (hrs)	$	29,471	Welding
	114.3 Shipfitting (hrs)	$	13,716	Shipfitting
	107.6 Coatings (hrs)	$	21,520	Coatings
		$	1,750	Support Labor
	467.49 Total (hrs)			
	20 Total (days)	$	66,457	Total
	35 Support Labor (hrs)			
	Schedule		**Cost**	
🟦	309.09 Welding (hrs)	$	37,091	Welding
	140 Shipfitting (hrs)	$	16,800	Shipfitting
	212.4 Coatings (hrs)	$	42,480	Coatings
		$	2,750	Support Labor
	661.49 Total (hrs)			
	28 Total (days)	$	99,121	Total
	55 Support Labor (hrs)			
	Schedule		**Cost**	
🟩	426.64 Welding (hrs)	$	51,197	Welding
	155.7 Shipfitting (hrs)	$	18,684	Shipfitting
	423.2 Coatings (hrs)	$	84,640	Coatings
		$	3,500	Support Labor
	1005.54 Total (hrs)			
	42 Total (days)	$	158,021	Total
	70 Support Labor (hrs)			

Layer 2	Schedule		Cost	
🟨	245.59 Welding (hrs)	$	29,471	Welding
	114.3 Shipfitting (hrs)	$	13,716	Shipfitting
	107.6 Coatings (hrs)	$	21,520	Coatings
		$	1,750	Support Labor
	467.49 Total (hrs)			
	20 Total (days)	$	66,457	Total
	35 Support Labor (hrs)			
	Schedule		**Cost**	
🟦	359.57 Welding (hrs)	$	43,148	Welding
	159.3 Shipfitting (hrs)	$	19,116	Shipfitting
	410.4 Coatings (hrs)	$	82,080	Coatings
		$	2,750	Support Labor
	929.27 Total (hrs)			
	39 Total (days)	$	147,094	Total
	55 Support Labor (hrs)			
	Schedule		**Cost**	
🟩	618.625 Welding (hrs)	$	74,235	Welding
	229.45 Shipfitting (hrs)	$	27,534	Shipfitting
	905.2 Coatings (hrs)	$	181,040	Coatings
		$	4,000	Support Labor
	1753.275 Total (hrs)			
	74 Total (days)	$	286,809	Total
	80 Support Labor (hrs)			

Layer 3	Schedule		Cost	
🟨	245.59 Welding (hrs)	$	29,471	Welding
	114.3 Shipfitting (hrs)	$	13,716	Shipfitting
	107.6 Coatings (hrs)	$	21,520	Coatings
		$	1,750	Support Labor
	467.49 Total (hrs)			
	20 Total (days)	$	66,457	Total
	35 Support Labor (hrs)			
	Schedule		**Cost**	
🟦	1438.28 Welding (hrs)	$	172,594	Welding
	637.2 Shipfitting (hrs)	$	76,464	Shipfitting
	1641.6 Coatings (hrs)	$	328,320	Coatings
		$	11,000	Support Labor
	3717.08 Total (hrs)			
	155 Total (days)	$	588,378	Total
	220 Support Labor (hrs)			
	Schedule		**Cost**	
🟩	4949 Welding (hrs)	$	593,880	Welding
	1835.6 Shipfitting (hrs)	$	220,272	Shipfitting
	7241.6 Coatings (hrs)	$	1,448,320	Coatings
		$	32,000	Support Labor
	14026.2 Total (hrs)			
	585 Total (days)	$	2,294,472	Total
	640 Support Labor (hrs)			

Figure G-4: Three layers shipbuilding production effects simulated across three stages of construction

Appendix H: Uncertainty Forecasts



Unit Assembly Stage

Forecast: Unit Assembly Change Total Cost

Summary:
Entire range is from $307,845 to $869,027
Base case is $588,378
After 1,000 trials, the std. error of the mean is $4,165

Statistics:	Forecast values
Trials	1,000
Base Case	$588,378
Mean	$589,838
Median	$588,156
Mode	—
Standard Deviation	$131,704
Variance	$17,345,874,326
Skewness	0.0570
Kurtosis	1.93
Coeff. of Variation	0.2233
Minimum	$307,845
Maximum	$869,027
Range Width	$561,182
Mean Std. Error	$4,165

Forecast: Unit Assembly Change Total Cost Increase Factor

Summary:
Entire range is from 4.6 to 13.3
Base case is 8.9
After 1,000 trials, the std. error of the mean is 0.1

Statistics:	Forecast values
Trials	1,000
Base Case	8.9
Mean	8.9
Median	8.8
Mode	—
Standard Deviation	2.0
Variance	4.0
Skewness	0.0703
Kurtosis	1.97
Coeff. of Variation	0.2247
Minimum	4.6
Maximum	13.3
Range Width	8.7
Mean Std. Error	0.1

Forecast: Unit Assembly Change Time Increase Factor

Summary:
Entire range is from 4.2 to 11.8
Base case is 8.0
After 1,000 trials, the std. error of the mean is 0.1

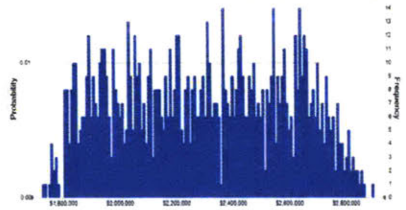
Statistics:	Forecast values
Trials	1,000
Base Case	8.0
Mean	8.0
Median	7.9
Mode	—
Standard Deviation	1.7
Variance	3.0
Skewness	0.0746
Kurtosis	2.04
Coeff. of Variation	0.2157
Minimum	4.2
Maximum	11.8
Range Width	7.6
Mean Std. Error	0.1

Figure H-1: Unit Assembly SOC uncertainty simulation statistical results

Final Outfitting Stage

Forecast: Final Assembly Change Total Cost

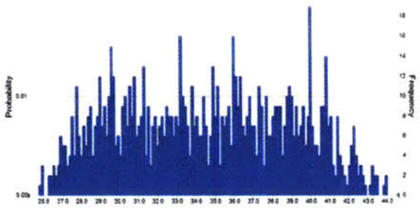
Summary:
Entire range is from $1,724,261 to $2,898,356
Base case is $2,294,472
After 1,000 trials, the std. error of the mean is $9,267



Statistics:	Forecast values
Trials	1,000
Base Case	$2,294,472
Mean	$2,295,382
Median	$2,298,269
Mode	—
Standard Deviation	$293,048
Variance	$85,877,337,767
Skewness	-1.2567E-05
Kurtosis	1.84
Coeff. of Variation	0.1277
Minimum	$1,724,261
Maximum	$2,898,356
Range Width	$1,174,095
Mean Std. Error	$9,267

Forecast: Final Assembly Change Total Cost Increase Factor

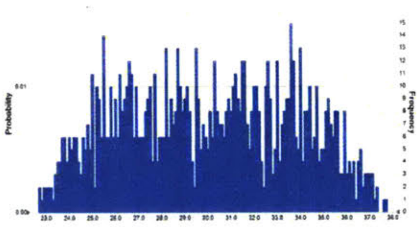
Summary:
Entire range is from 25.8 to 44.0
Base case is 34.5
After 1,000 trials, the std. error of the mean is 0.1



Statistics:	Forecast values
Trials	1,000
Base Case	34.5
Mean	34.5
Median	34.6
Mode	—
Standard Deviation	4.5
Variance	19.8
Skewness	0.0230
Kurtosis	1.91
Coeff. of Variation	0.1290
Minimum	25.8
Maximum	44.0
Range Width	18.2
Mean Std. Error	0.1

Forecast: Final Assembly Change Total Time Increase Factor

Summary:
Entire range is from 22.7 to 37.8
Base case is 30.0
After 1,000 trials, the std. error of the mean is 0.1



Statistics:	Forecast values
Trials	1,000
Base Case	30.0
Mean	30.0
Median	30.1
Mode	—
Standard Deviation	3.7
Variance	13.8
Skewness	0.0135
Kurtosis	1.92
Coeff. of Variation	0.1237
Minimum	22.7
Maximum	37.8
Range Width	15.1
Mean Std. Error	0.1

Figure H-2: Final Assembly SOC uncertainty simulation statistical results

Appendix I: Verification and Validation Artifacts

In accordance with AIAA Standard S-117A-2016, the following types of V&V artifacts are presented as examples in-practice standards of determining requirement satisfaction of a system or model [73].

Table I-1: Example V&V artifacts in accordance with AIAA S-117A-2016 [73]

Type	Description	Example
Analysis	Modeling and analytical techniques to predict compliance with the requirements in accordance with quantitative data	Computational Fluid Dynamics (CFD) simulation of hullform performance characteristics during Set Based Design downselection process
Demonstration	Operating the system to demonstrate that requirements are fulfilled to cover the qualitative requirement set	Demonstration and Shakedown Operations (DASO) used to operationally test submarine launched weapon systems
Inspection	Visually examining the system, model, or interfaces to ensure compliance or verify design features correspond to stated requirements	Evaluating physical characteristics such as dimensions, features, layout, or clearances between hardware. Checking pass/fail criteria remains valid in a requirement
Test	Proof of concept or preliminary performance characteristics of a model or system using alternate prototype or engineering modules prior to implementing	Conducting qualification level test such as Pre-INSURV Assessments, Acceptance Trials, or Builders Trials

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