A Design Process Centric Application of State Space Modeling as a Function of Communication and Cognitive Skills Assessments

by

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We have this hope as an anchor for the soul, firm and secure. - HEB 6:19

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Dedication

This document is dedicated to my beloved wife Kimberly, and our darling daughters Sophia and Abigail. Thank you for all of your love and support. I pray that God grants all the desires of your heart.

Acknowledgements

I would like to acknowledge all of the great people I have had to opportunity to work with at the University of Michigan. Specifically my advisor Dr. David Singer and doctoral committee chair. In addition to Dave, to the rest of my doctoral committee Dr. Armin Troesch, Dr. Matt Collette, and Dr. Larry Seiford, thank you for your personal investment in my development and more importantly your time. Your guidance and mentorship have made this effort both challenging and highly rewarding.

To my friends and colleagues at the US Navy, both past and present, thank you for your willingness to keep the lines of communication open as I pursued a path less traveled. I look forward to working with many of you again in new capacities.

Final my lab mates that have helped and encouraged me along the way, Justin, Nathan, Brian, Tom, Morgan, Doug, and Fang, thank you. And to Austin, Colin, Mike, Dorian, and Harleigh, you are closer than you think. I am grateful for the time I have spent with you all.

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Abstract

Humans have a reliable basic probabilistic intuition. We utilize our probabilistic intuition in many day-to-day activities such as driving. In fact any interaction that occurs in the presence of other independent actors requires some probabilistic assessment. While we are good at sorting between rare and common events, determining if these events are statistical significant is always subject to scrutiny. Quite often the bounds of statistical significance are at ends with the 'common sense' expectation.

While our probabilistic intuition is good for first moment effects such as driving a car, throwing a football and understanding simplistic mathematical models, our probabilistic intuition fails when we need to evaluate secondary effects such as high speed turns, playing golf or understanding complex mathematical models. When our probabilistic intuition is challenged misinterpretation of results and skewed perspectives of possible outcomes will occur.

The work presented in this dissertation provides a mathematical formulation that will provide a guide to when our probabilistic intuition will be challenged. This dissertation will discuss the development of the Process Failure Estimation Technique (ProFET). The mathematical formulation draws inspiration from physical system modeling, control theory, and multistage manufacturing processes.

A multitude of potential team parameters could have been selected, interpersonal communication effectiveness and cognitive skill assessments seemed the most obvious first steps. This is due to the prolific discussion on communication and the general acceptance of the cognitive testing as an indicator of performance potential. ProFET brings the importance of interpersonal communication and team member's cognitive skill to the forefront of the discussion about design team effectiveness.

The naval design community has been mapping the design process for 20 years in order to assess how to reduce error and automate much of the design calculation process. In fact most modern engineering communities have resorted to the "black box" approach. This approach provides excellent repeatability. In fact multiple codes are linked together with little user interface. The teams skill set must be variable with respect to time in order to accomplish the required objectives of each phase of the design process. ProFET develops a metric for the design process that is sensitive to the team composition and structure. This metric is applied to a domain that is traditionally devoid of objective scoring. With the use of ProFET more informed decisions on team structure and composition can be made at critical junctions of the design process. Specifically, ProFET looks at how variability propagates through the design activities as opposed to attempting to quantify the actual values of design activities, which is the focus of the majority of other design research.

CHAPTER 1

What is the Process Failure Estimation Technique (ProFET)

Humans are fairly good at first basic probabilistic intuition. We utilize our probabilistic intuition in many day-to-day activities such as driving. If we look at the driving example, those who have ever taught someone to drive commonly state that the most difficult thing for new drivers to understand is what to do in a high-speed turn. Common sense would say that one should slow down and brake through a turn, but in reality one needs to accelerate through a banked turn. While our probabilistic intuition is good for first moment effects, such as driving a car, throwing a football, and understanding simplistic mathematical models, our probabilistic intuition fails when we need to evaluate second moment effects such as high speed turns, playing golf or understanding complex mathematical models. When our probabilistic intuition is challenged, misinterpretation of results and a skewed perspective of possible outcomes will occur.

The work presented in this dissertation provides a mathematical formulation that will provide a guide to when our probabilistic intuition will be challenged. This dissertation will discuss the development of the Process Failure Estimation Technique (ProFET), a state space model that enables the analysis of the impact of communication and cognitive skills on the outcome of design activities. Specifically, ProFET looks at how variability propagates through the design activities as opposed to attempting to quantify the actual values of design activities, which is the focus of the majority of other design research.

This dissertation introduces a unique application of state space modeling techniques. ProFET models a design team as a physical system. This approach is in concert with the proliferation of nature-inspired modeling techniques. In these case studies the design team is modeled as a mechanical system with discrete inputs, outputs, and processes. Similar to most discretized measurement schema, a single assessment provides little information, but a series of assessments begins to illustrate the rate of change of the system. This rate of change can provide an indicator of likelihood of success.

An objective measurement of design team competency has been an elusive metric, despite modest attempts to quantify a design team's ability for successful completion of the current tasking. By focusing on the team rather than the traditional project success metrics, a new field of analysis has been opened. This analysis represents a novel technique for the objective assessment of a team's performance and a move away from the world of subjective character traits. This movement to an objective scoring technique is not competitive with the myriad of systems engineering, project management, and team organizational and behavioral techniques. The techniques described within this dissertation can be applied to various engineering fields, including: Naval Architecture, Systems Engineering, Organizational Engineering, and Organizational Analysis. I also feel that the functional disciplines of Risk Management and Design Team Management have the most to gain from the immediate implementation of ProFET.

This dissertation has been laid out in the following order. Chapter 2 outlines the Stages of a Design Activity. This chapter highlights the major functional components and activities associated with a design action. Further this chapter highlights ProFET's applicability to various design activities and varying design perspectives. Chapter 3 provides an overview of team formation techniques, and organizational structures. Additionally, this chapter begins to explain the underpinning parameters of ProFET. Understanding the influence of these parameters, an individual's communication effectiveness and cognitive skill help to define the overall team effectiveness. Chapter 4 is a linear case study with 11 successive calculations. This chapter also presents a series of deterministic calculations that are based on a stochastic input variable. Utilizing Monte Carlo (Random Walk) methods, distributions have been generated on the output of this proof of concept case study. Chapter 5 outlines the extension of the linear, successive case study presented in Chapter 4 to a more realistic representation of a modern engineering team, while still being utilized as a proof of concept for ProFET. The team utilized consists of four discipline focused agents that communicate in a variety of distinct communication pathways. While the linear study in Chapter 4 was designed to show error propagation within the team, the networked arrangement presented in Chapter 5 was developed to illustrate that the structure of the team matters to the end product. Chapter 6 outlines the unique contributions of this dissertation and briefly expands on their potential influence on the engineering community. Finally, Chapter 7 outlines a series of future efforts that should be undertaken to further the development of ProFET.

CHAPTER 2

The Stages of a Design Activity[1]

The quality revolution has married the concepts of engineering and management. Regardless of the discipline chosen almost all process improvement cultures have applied analytical tools to the process and the product portions of the triad to measure, predict, and control the result. This dissertation will document a technique to analyze a new aspect of a design team performance. The trick becomes the interfaces between physical zones and managing the inevitable conflicts between major disciplines. While these topics have received more academic interest recently (Deming, 2000; Drucker, 2011; Juran, 1989; Sobek II, Ward, & Liker, 1999; Taguchi, 1995), the effects of team dynamics, specifically designer proficiency and communication ability, have never been applied to the assessment of design robustness in a mathematical framework. This construct will begin to explicitly quantify that intangible quality of a "good" team, and to assist in the differentiation of why some teams succeed in obtaining the initial goal and others do not.

In regards to process control, Taguchi's famous three steps: system design, parameter design, and tolerance design (Taguchi, 1995) ignited a new paradigm that the control of the production and manufacturing process would ultimately lead to high customer satisfaction. This is summarized by his first paradigm: "quality problems of a product under customer usage

[1] Portions previously published in (Strickland & Singer, 2015)

conditions are only the symptoms of the functional variation" (Taguchi, 1995). Within quick succession a host of other techniques gained prevalence: Total Quality Management (TQM), Lean, and Six Sigma. These techniques have a broad appeal to other sections of business as well. "TQM, which was not only dealing with production but also all other processes in the company" (Dahlgaard & Dahlgaard-Park, 2006) was quickly adopted, and then discarded in favor of Lean. "[Lean] has its origin in the philosophy of achieving improvements in most economical ways with special focus on reducing muda (waste)." (Dahlgaard & Dahlgaard-Park, 2006). Finally, Six Sigma started as a mechanistic technique but has grown to be, "the envelope for all that Six Sigma and an associated quality initiative stands for, including a methodology for implementation" (Tennant, 2001). This evolution culminated in the modern International Organization for Standardization (ISO) certification process, where companies willingly submit to third party scrutiny for continuous process improvement. "ISO Certification can be a useful tool to add credibility, by demonstrating that your product or service meets the expectations of your customers. For some industries, certification is a legal or contractual requirement" (International Organization for Standardization, 2015).

Tremendous focus has been placed upon the product definition. Requirements Decomposition (Defense Acquisition University, 2001; Guenov & Barker, 2005; Haskins, Forsberg, Krueger, Walden, & Hamelin, 2010; Hong & Park, 2009; National Aeronautics and Space Administration, 2007), Functional Analysis and Allocation (Defense Acquisition University, 2013; Electronic Industries Alliance, 2002; IEEE Computer Society, 2007), Design Structure Matrices (Eppinger & Browning, 2012), Axiomatic Design (Suh, Cross, & Cross, 1995), and Design Modularization (Caprace, 2010) have all been employed to categorize or logically partition the larger problem into a smaller more tractable subset. It is perfectly logical to attempt to categorize, organize, and sort the produced artifacts or engineering systems; however, this will only generate information that is predicated on the realized solution or that derived from previous solutions.

Although there is another component of the system design process that is arguably more important than the system/subsystem design, yet is not the recipient of rigorous mathematical analysis, the design team itself. It is this team that amalgamates all of the disparate requirements, system/subsystem designs, and interfaces into a functional product. The communication ability and technical skills of the aggregate team ultimately determines the success or failure of the endeavor. Additionally, it is these same communication and technical skills that allow the team to adjust throughout the process to design changes and modifications created by the introduction of additional information.

Regardless of the end product, thanks to the instantiation of Systems Engineering as a discipline, the design process is now punctuated with numerous interim reviews that accomplish a specific focus. These interim reviews, whether they are technical or programmatic in nature, provide in situ awareness or a static snap shot of the project at that moment. It is these snap shots that provide stakeholders with indications of potential success or failure of the design endeavor. However, the design team is not similarly evaluated at these critical junctions. It would seem prudent to evaluate the team's skill portfolio as well, in order to determine if the correct "mix" of talent has been acquired for the next phase of the project.

For this dissertation, the portfolio has been limited to interpersonal communication skills and cognitive skill. It also seems logical that the skill set required to develop and execute a concept exploration or analysis of alternatives would be drastically different than that required to complete an effective preliminary design. This skill set would continue to evolve throughout the acquisition process, morphing and changing at each distinct phase of the project. This begins to address the need for incremental assessment of the design team's skill set as a variable, impacting the overall design success.

Design Stages

Whether a serial or concurrent design process is desired, the basic functional steps are the same. One must develop a concept, explore the feasibility of that concept, elucidate the requirements, develop a compliant design, and then produce that design. Figure 2-1 contrasts various product development lifecycles.

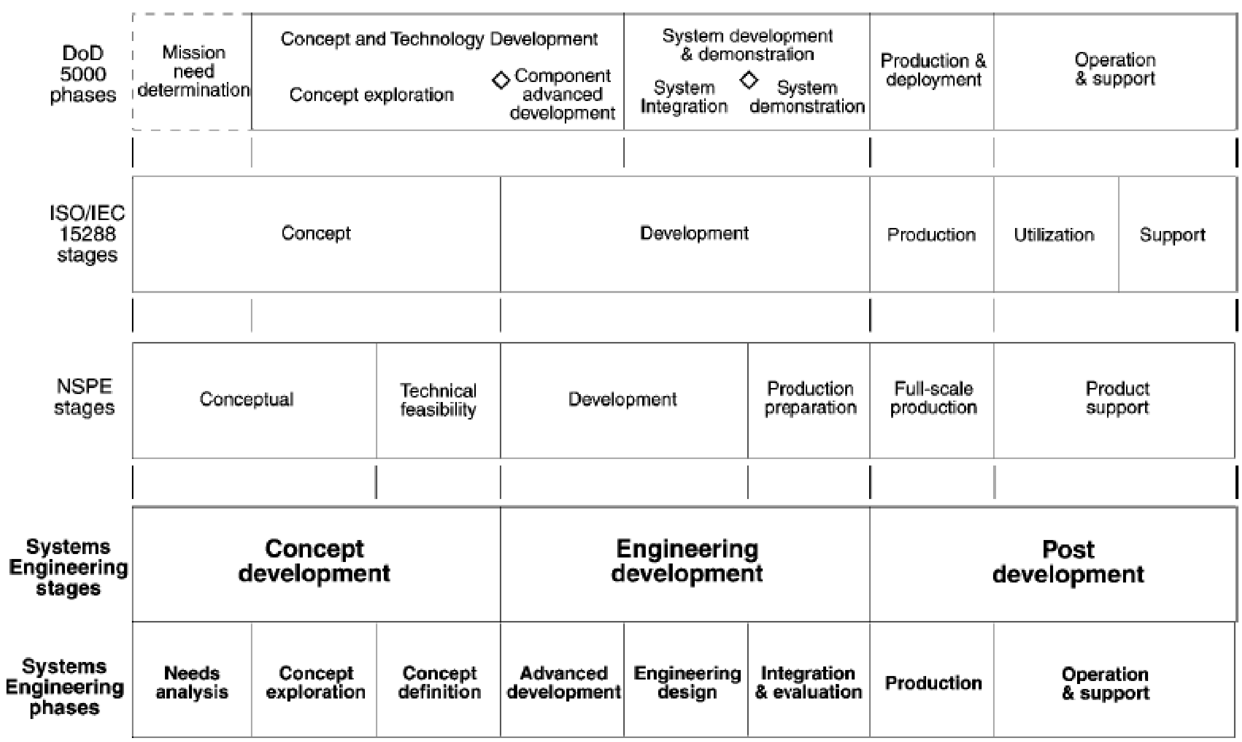

Figure 2-1 - Engineering Design Phase Comparison (Kossiakoff & Sweet, 2003)

The names change between each of these codified documents, but the basic intent is the same. While this is a broad brush categorization of all the steps that are required to articulate, define, and produce a design, it illustrates the early, middle, and late phases of design activity.

In *The Republic*, (Plato, 1994) the author remarked, “The beginning is the most important part of the work.” This tends to be true in the world of engineering design as well. A civil engineering example would be the construction of a house or a building. If the foundation, is flawed then the structure itself will ultimately be unstable. This analogy can be easily extended to analytical work. If the underpinning assumptions are flawed, then all subsequent calculations will propagate the error. To this end the engineering community has spent tremendous effort to codify approaches that answer the question, “What should we build?” Concept development, concept feasibility, and requirement elucidation have all been the focus of various qualitative techniques (Kossiakoff & Sweet, 2003; Saaty, 1988; Smith & Eppinger, 1997). The process of defining the entering argument for the engineering endeavor requires cognizance of the desired end state, effective interdisciplinary communications, and a high level of designer skill.

If the concept ideation, investigation of feasibility, and requirement derivation is considered the early phase of design activity then the development of a compliant design can be considered the middle phase of a design’s life cycle. Winston Churchill is often credited with the quip, “If you're going through hell, keep going.” This quote is most applicable the middle design lifecycle largely due to exogenous programmatic drivers. These drivers are typically cost, schedule, and performance and are often referred to as the project management iron triangle. If these top level metrics define the measures used to determine the success or failure of a project, then which of the three critical metrics are available to the design team during this phase of the effort?

Addressing each in turn, cost is typically predefined prior to the initiation of an engineering effort. This is wholly true for fixed price acquisitions. Even in cost plus acquisitions there is typically a not-to-exceed cost. This creates a cost limit and begins to bind some engineering solutions. How about schedule? The time horizon of the effort is critical, in fact this is also typically defined by a need date. Whether this date is a market introduction date in order to maintain a competitive posture or maximum allowable system downtime, the time horizon is typically fixed. This leaves only the level of performance as a variable for the design team at large during the middle phase of the development. Development of a compliant design is often the toughest phase of a design effort due to the imposed constraints, and the one that is typically labeled as design. This phase is the bridge between concept ideation and construction. During this middle phase the design becomes more and more self-constrained as definition is developed. Couple this constraint with the need for cost and schedule compliance, and the need for team performance becomes more apparent.

Is this same need apparent in the later phases of the design lifecycle? The poem *Elegiac Verse*, (Longfellow, 1893) added, “Great is the art of beginning, but greater the art is of ending.” In the context of the preceding section, this assertion is as true for an engineering design as it is for a poem. If the final phase of the engineering design lifecycle is the production and utilization of a product, then clearly effective production and operation is critical. The translation of a technical product from a design to a physical object introduces a wide variety of potential issues. It is possible to have a good design that fails due to production and operational issues. Whether the production failure is due to a communication error, cognitive skill error, or other manufacturing error, the results are similar.

Conclusion

The dissertations of Dr. Tom McKenney (McKenney, 2013) and Dr. Morgan Parker (Parker, 2013) provide a framework on the multiple perspectives of ship design. These perspectives include: design approaches, design processes, design methods, and design tools, defined by McKenney as follows:

- Design Approach: The overarching guiding principles of a design effort
- Design Process: A series of structured steps to implement the design approach
- Design Method: The way in which design alternatives are understood, analyzed, and selected for a particular approach and process
- Design Tool: In support of design methods, tools provide information that enables designer decision making.

ProFET itself is a design tool that enables insight into various possible design methods, such as systems engineering and set based design, and design processes, such as serial design activities of multidisciplinary design teams. As a tool, ProFET provides the necessary information regarding how variability propagation inherent in the people, product, and process of the design activity may impact a given design. This insight helps the decision maker in his understanding of how he may approach a design activity, select personnel for a project, or even identify better processes that reduce risk through proper error propagation management.

From personal experience as a ship design manager for the US Navy overseeing both the JSHV and T-AKE programs, I experienced this knowledge gap first-hand. I was part of multiple design teams with various levels of success. Some teams appeared to have the best personnel, yet their projects were not successful. Other teams suffered communication problems, yet their designs came out to be successful. Throughout these years, the author attempted to apply many of the standard team formation paradigms, such as IPPD (Defense Acquisition University, 2013; Dept of Defense, 1998), and personality typing (Shen, Prior, White, & Karamanoglu, 2007), to better understand this problem. This is when the author realized the need for an objective mathematical framework to help understand the effects of the variability in the teams and cognitive skills of the individual designers, as opposed to trying the measure the specific attributes of each individual and team structure. This is the primary objective of ProFET, to understand these variability effects, in attempt to inform the decision maker on better ways to understand and structure specific design processes and methods of a given design task.

Lu and Suh (2009) succinctly summarize many of the problems discussed in this thesis, and which ProFET aims to address.

> Complexity occurs in systems that have many elements with intricate dependencies among them. Due to their numerous sizes and relationships, the behaviors of complex systems are difficult to predict, even when the properties of their parts are given. As a result, complexity studies often lead to the question of probability of a system encounter a given condition once its characteristics are specified. (Lu & Suh, 2009)

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Chapter 3

Engineering Teams

This chapter will focus on the traditional elements and methodologies employed in the formation of engineering teams. A brief discussion of organizational structures on the continuums of hierarchical to flat and functional to matrix will be developed to support the construct of team formation. Following the organizational structure discussion, three team formation techniques will be presented. These techniques are selection, assignment, and personality typing. The team formation techniques will be evaluated relative to one another to highlight the advantages and disadvantages of each. Finally this document will address the importance and impact of communication and cognitive skill on the design teams overall performance.

It is the goal of this chapter to identify the importance of communication and cognitive skill to a design team's level of performance. These values can be quantified and incorporated into a team assignment decision process to yield higher performance teams.

Team Influence and Evolution

Engineering as an endeavor has existed since antiquity (Paz, Ceccarelli, Otero, & Snaz, 2010; Petroski, 1991). The original definition of an engineer was exclusively referencing a designer or operator of a military siege weapon. The term civil engineer quickly became a distinguishing characterization of engineers that worked on civilian projects (i.e. bridges, buildings, damns, retaining walls, etc.). This was the humble beginning of engineering specialization. Today ABET recognizes 28 unique engineering programs with distinct certification requirements associated with each discipline (ABET, 2014). This does not account for sub-disciplinary specialization within each domain.

As specialization became more pervasive design teams responded with an increase in the team size. Engineering teams now require generalists that are capable of envisioning the total picture, and specialists that have very narrow scopes but provide a depth of knowledge. It is important to realize that even with specialization, engineering is still very much a sequential activity sandwiched between research and production. This is often referred to as over-the-wall design, meaning that a new technology or technique is developed and vetted, then applied by the design team (Prasad, 1995). This new technology is an input to the design process. The output, or final design, is then handed to the production staff once it is completed. This concept benefits from stable team sizes. The process of sequential design is often iterative and can be illustrated by the classic ship design spiral, Figure 3-1. This approach illustrates both the effects of engineering specialization as well as sequential design practices, and served the community well for a number of years.

However, the motivation of business in an increasingly competitive global environment was to minimize their product development cycle times and thus reduce the incurred cost of development. Additional motivations that lead to the widespread use of concurrent engineering techniques were the quality revolution creating a desire to reduce waste and rework (Prasad, 1995). This gave birth to the concept of pairing manufacturing engineers with product designers. While this was an excellent step in reducing the rework traditionally experienced with in an engineering project, it ultimately added to the team size. This approach continued to grow and before long it was applied to nontechnical disciplines as well. The modern Integrated Product Team (IPT) will have representatives from every stage of the products lifecycle present from the inception (Dept of Defense, 1998).

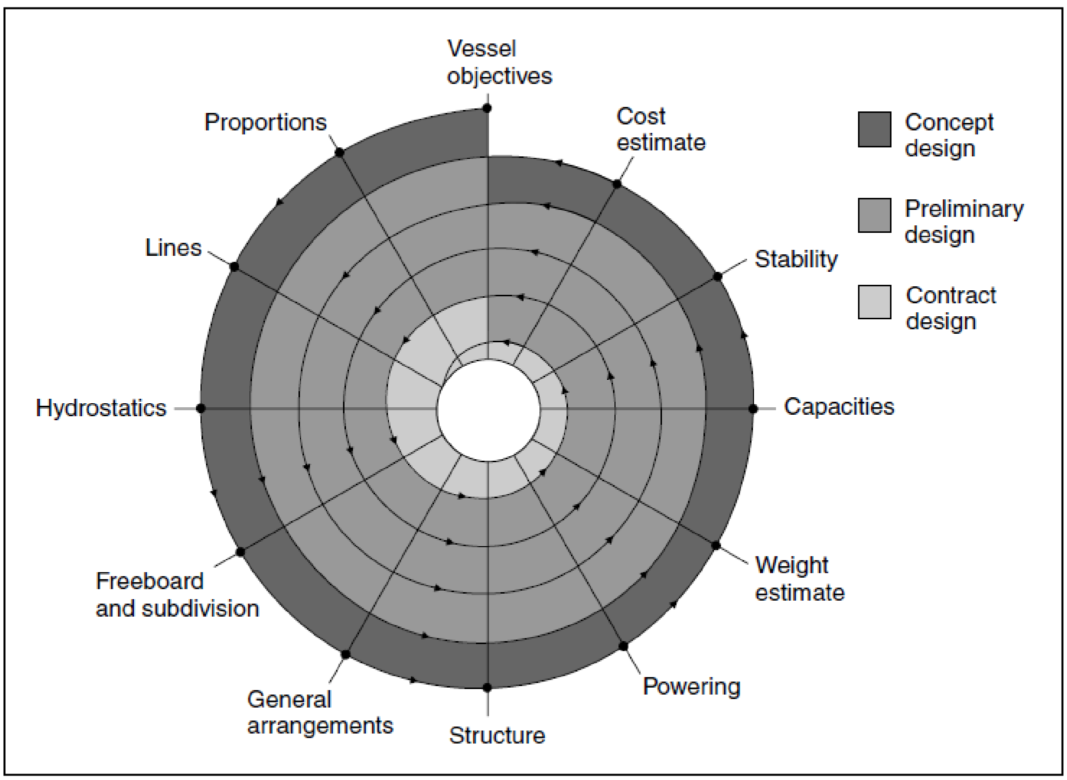

Figure 3-1 - Design Spiral (Fig 1.1 (Eyres, 2007)**)**

So far the discipline specialization and project execution strategy have affected the required team size, but what about the product complexity? Two examples will be outlined that demonstrate increasing complexity of a product with respect to time. The first example is the ubiquitous Microsoft Windows operating system, which is celebrating its 30-year anniversary. Table 3-1 outlines some of features of comparison between the first version of Microsoft Windows and the latest release. Starting with the left hand column, the initial version of Windows required 256 kilobytes (KB) of hard disk space versus the latest version which requires 16-20 gigabytes (GB) of hard disk space, an increase of 5 orders of magnitude. The fledgling Windows platform required 512 KB of memory; the current platform requires a minimum 1 GB, a 4^{th} order increase compared to the original. The goal of this example is to illustrate the exponential increase in capability has become part of our culture and is expected. The next version of a product needs to be developed better, faster, and cheaper from the manufacture's perspective and the consumer expects more capability with increased features. In this case we have a commercial producer, Microsoft, producing a product for civilian consumption. In the second example the developmental history of a US Naval asset will be evaluated in order to determine if the analogy holds for military products.

Table 3-1 - Microsoft Windows Requirements

	1985	**2015**
Windows Version	1.0 (Microsoft, 2013)	8.1 (Microsoft, 2015)
Internal Memory	256 KB	16 GB / 20 GB
RAM	512 KB	1 GB / 2 GB
Information Structure	16-bit	32-bit / 64-bit

The second example is the US Navy's development of the current multi-mission, all weather combatants. Table 3-2 illustrates how each successive class has increased, not only in capability but also in gross displacement. In Table 3-2, the first six classes have their respective standard tonnage listed. The full load tonnage of each would be in excess of these numbers. The last two classes identified in Table 3-2 only have the full load listed. Regardless of this dichotomy in the data, the trend is obvious. This same trend also can be seen in the intended mission of the vessels. For this comparison subclasses have been omitted, such that mainline destroyers can be compared to period counterparts.

Table 3-2 - US Naval Destroyer Comparison

Class	Tonnage [LT]	Year	Mission
BAINBRIDGE	433	1899	ASuW[a]
SMITH	700	1908	ASuW
CASSIN	1,010	1911	ASuW/ASW
CALDWELL	1,080	1916	ASuW/ASW/AAW
FARRAGUT	1,500	1932	ASuW/ASW[b]/AAW[b]
SIMS	1,570	1937	ASuW/ASW[b]/AAW[b]
FLETCHER	2,050/2,232[c]	1941	ASuW/ASW/AAW
ALLEN M. SUMNER	2,200/3,138[c]	1943	ASuW/ASW/AAW
GEARING	2,450/3,089[c]	1944	ASuW/ASW/AAW
FORREST SHERMAN	2,734/4,916[c]	1953	ASuW/ASW/AAW
SPRUANCE	9,250[c]	1972	ASuW/ASW/AAW
ARLEIGH BURKE	9,496[c]	1988	ASuW/ASW/AAW

a) Anti-Surface Warfare (ASuW)
b) Anti-Submarine Warfare (ASW) and Anti-Aircraft Warfare (AAW) capability add as a retrofit
c) Full load displacement
d) Information in above table gathered from (McComb, 2014)

The remainder of the analysis will focus on the modern surface combatants, i.e., Post WWII era vessels. Their end unit cost is plotted as a function of time in Figure 3-2. It should be noted that the cost axis is logarithmic. Figure 3-3 illustrates the increasing complexity of the installed weapons system of these same modern vessels. Considering the design effort as a series of incremental evolutionary steps and an occasional revolutionary step, one can begin to see the need for techniques to ensure design robustness and foster effective team dynamics. Both of these topics tend to be combinatorial in nature, thus the number of possible solutions increases geometrically when considering the addition of new technologies and additional design staff. Therefore, it can be inferred that increasing complexity leads to corresponding increases in specialization of team members and effectively larger teams.

The increase of the design complexity equates to a need for additional margin in order to maintain design robustness and account for unknown results. Larger team sizes demand a higher level of communication capability and accuracy. Experientially, the personnel resources and margin that would be required to adequately manage and deliver the BAINBRIDGE class would be much different than the ARLEIGH BURKE. It is actually a fairly straightforward process to divide the platform into “zones” to be managed by subject matter experts. The trick becomes the interfaces between zones and managing the inevitable conflicts between major disciplines. While these topics have received more academic interest recently (Deming, 2000; Drucker, 2011; Juran, 1989; Sobek II, Ward, & Liker, 1999; Taguchi, 1995), the effects team dynamics, specifically designer cognitive skill proficiency and communication ability, have never been applied to the assessment of design robustness in a mathematical framework.

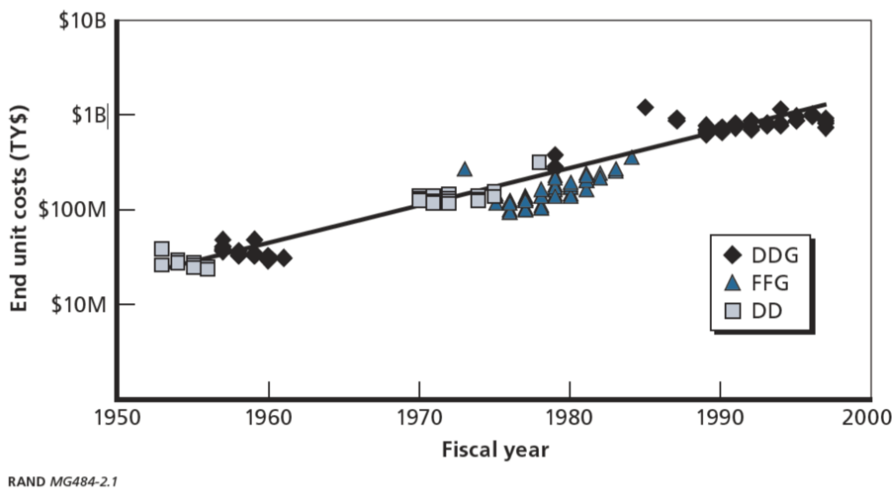

Figure 3-2 - Cost Escalation for Selected Surface Combatants (Arena, Blickstein, Younossi, & Grammich, 2006)

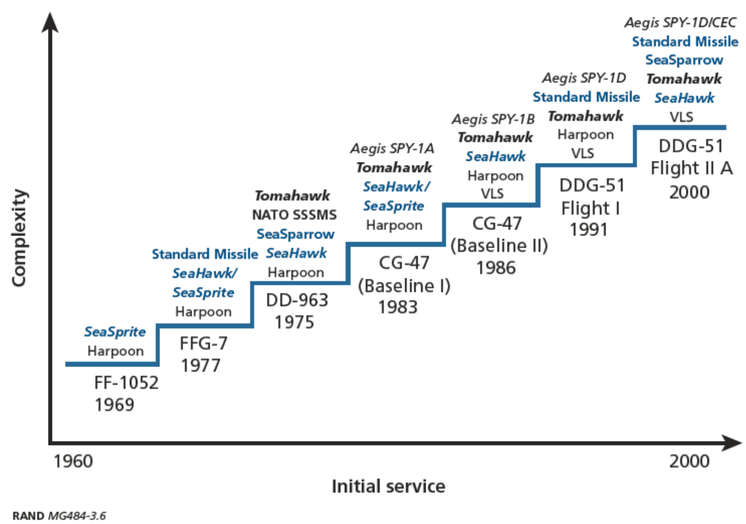

Figure 3-3 - Increasing Complexity of Weapon Systems for Surface Combatants (Arena et al., 2006)

Recapping the principle point, product development team sizes have ballooned in recent years due to discipline specialization, the use of concurrent engineering approaches, and the increase in product complexity. The motivation behind the following assessment technique is to offer a construct that will begin to explicitly quantify that intangible quality of a "good" team, and to assist in the differentiation of why some teams succeed in obtaining the initial goal and other do not.

Team Formation

It is almost impossible to discuss team formation without a brief discussion of organizational structures. By removing location from the discussion, it negates the concepts of centralized and decentralized organizations. This leaves two continuums for discussion that will be able to describe most organizations. These spectra are functional to matrix and hierarchical to flat. An organization can assume any position along these independent spectra. It is important to realize that the process of project team formation is different for each of these four combinations. However, before we discuss the process of team formation further, a basic understanding of these organizational types is required.

A hierarchical organization is characterized by defined team member roles, limited spans of control, and vertical layering of management. This is the "traditional" business model and likely the one that most are familiar with due to the pyramidal-shaped organizational chart. The hierarchical organization is in contrast to a flat organizational structure. If a hierarchical organization is defined by a multitude of layered personnel with defined responsibilities, then a flat organizational model is represented by a minimalistic vertical layering and a simple responsibility structure. Generally, a flat organizational structure is highly flexible and capable of innovative product developments, but is obviously capacity limited. This type of organizational structure is typical for smaller companies and entrepreneurial enterprises.

The spectrum of organizational description is bracketed by the extremes of functional and matrix organizations. A functional organization is again a more 'traditional' business model. In this organization there exist groups of functional expertise. This functional expertise could be represented by a technical discipline, a business process, or a fabrication capability. The functional organization typically provides a depth of capability and requires a functional manager to communicate with the rest of the organization. The reporting mechanism is largely the single biggest identifying factor for a functional organization. Results are reported vertically for integration into the rest of the project. This functional organization structure is contrasted with a matrix organization. In a typical matrix organization personnel are typically reporting laterally to a project lead via a functional manager.

Table 3-3 provides an illustrative example of the type of organization that falls in each of these archetypes. At a top level, the U.S. government is a hierarchical-functional organization. There are three distinct branches of the federal government, each with dramatically different foci. Even below this top tier the hierarchy and functional categorization continues to dictate the structure.

A flat-functional organization is most likely represented as an entrepreneurial or start-up endeavor. These types of organizations typically are teams in their own right, simply due to the lack of personnel and funding to allow for duplicative efforts. This implies that every project is an all hands effort to accomplish.

For a hierarchical-matrix organization, small scale military operations provide a rich field of examples. A Marine Air-Ground Task Force (MAGTF) illustrates the concept of scalable portions of units assembled in a variety of configurations to support special operations missions to small-scale contingency operations. These portions of units are operating within the purview of a mission commander but still maintain unit level reporting requirements.

Finally, a flat-matrix organization may be represented by an independent operating unit or a spinoff company (Lawrie, Cobbold, & Marshall, 2004). These units or companies can be utilized as risk-reduction techniques for larger companies. A smaller independent unit could be established doing business under a different moniker, in order to protect the parent company. Smaller personnel counts tend to drive the organization to the flat side of the continuum; this coupled with a new reporting structure to the project lead creates the matrix environment. The level of personnel autonomy with regards to the parent company will determine if it is a flat-functional or a flat-matrix organization (Lawrie et al., 2004).

Table 3-3 - Organizational Spectra

	Hierarchical	Flat
Functional	Federal Government	Technical Start-up
Matrix	Smaller Military Operations	Semi-Independent Operating Units

With this backdrop, team formation in terms of the four archetypes of hierarchy and reporting styles can be discussed. Within any of these archetypes teams may be formed through selection, assignment, or personality typing (Shen, Prior, White, & Karamanoglu, 2007). Selection tends to occur in larger organizations with multiple ongoing projects. This lends to its prevalent usage in hierarchical-functional and flat-matrix organization types, and can appear as a core team within an organization to maintain cohesiveness across multiple projects. This is sometimes referred to as the "A-team", which is usually highly functional and known for getting things done. The real secret is the team cohesiveness. This cohesiveness allows time for each of the members to fully understand the range of capabilities that other members have to offer. More surprisingly, the most important ingredients for a smart team remained constant regardless of its mode of interaction: team members who communicated a lot, participated equally and possessed good emotion-reading skills (Woolley, Malone, & Chabris, 2015).

As a point of clarification, the team formation method of selection implies the team self-selects members, i.e., selection is not made by a third party. If selection of the team members is made by a third party this is the team formation method of assignment. The assignment formation technique is the predominant mechanism employed by hierarchical-matrix organizations. These teams can span the spectrum of effectiveness, and typically follow the Tuckman Progression of Form-Storm-Norm-Perform (Tuckman, 1965). This type of team formation can be used in almost any organization type that has sufficient personnel. Using Tuckman's model the biggest difference in selection and assignment are the omission of the first two steps. The final team formation method, personality typing, is typically more utilized in academic environments.

Regardless of the typing instrument employed the theory is simple: diversification reduces risk. This is type of risk-based management is important but does not guarantee a positive outcome. Why do I say this is risk-based management? It is essentially the same methodology that is applied to financial portfolios. The diversification of personality attributes prevents "blind spots" and ensures that some portion of the team is functional in every possible scenario.

Selection is the methodology that creates the most productive teams. The problem is with limited resource pools, not every project can have the benefit of self-selecting teams. So then, how do we encourage assigned teams to achieve the level of performance of self-selecting teams? The answer may be quite simple: make better assignments. The immediate response would be to incorporate personality profiling in the selection process to inform the assignment decision. Most popular profiling management tools will provide you with a communication, conflict resolution, or preferred style on some continuum between opposing behavior patterns. While the information provides insight into how a perspective team member interfaces with the world around them, it is an incomplete picture. However it neglects attributes that are critical to the successful execution of a project. These attributes are interpersonal communication effectiveness and the individual's cognitive skill. These aspects are much more critical to the successful execution of a project. The communication ability and technical skills of the aggregate team ultimately determine the success or failure of the endeavor. Additionally it is these same communication and technical skills that allow the team to adjust throughout the process to design changes and modifications created by the introduction of additional information regardless of the programmatic phase.

Communication and Cognitive Skill

Team building is indeed a science, but it's young and evolving. Now that I have established patterns of communication as the single most important thing to measure when gauging the effectiveness of a group, I can begin to refine the data and processes to create more-sophisticated measurements, dig deeper into the analysis, and develop new tools that sharpen the view of team member types and team types (Pentland, 2012).

Few skills are more universal than effective communication. This skill is likely one of the most pervasive skills available to society. Indeed, no other skill is used or abused more on a daily basis. "In 2014, the majority of email traffic comes from the business world, which accounts for over 108.7 billion emails sent and received per day. Email remains the most common form of communication in the business space." (Radicati, 2014). One would struggle to find any discourse on business, management, or leadership without a discussion of the need for effective communication. Effective communication has been a safe area for authors and consultants, because who couldn't benefit from improvements in interpersonal communication.

Point 13 of Deming's famous 14 points, "Institute a vigorous program of education and self-improvement", speaks of self-improvement, and this can easily be considered as improvement of interpersonal communication (Deming, 2000). Peter Drucker authored 39 books on management and leadership (Drucker Institute, n.d.), of which communication is a principle thematic element of most of these offerings. John Maxwell, Jim Collins, Stephen Covey, Spencer Johnson, Dale Carnegie, and a host of other prolific authors have established the need for effective communication. Further, many of these authors have gone on to state that a major differentiator between successful endeavors and unsuccessful ones is leadership and, by proxy, effective communication. This should firmly establish the importance of communication within any endeavor.

The criticality of effective communications in time and schedule constrained activities is elevated due to the external pressure exerted by the forcing functions (Lingard et al., 2004; Sosa, Eppinger, & Rowles, 2007). So what is the impact of high external pressure and communication error? "PMI's 2013 Pulse of the Profession ™ report revealed that US$135 million is at risk for every US$1 billion spent on a project. Further research on the importance of effective communications uncovers that a startling 56 percent (US$75 million of that US$135 million) is at risk due to ineffective communications" (Project Management Institute (PMI), 2013b). By this account, 7.5 percent of a projects total value is at risk or lost due to poor communication. The Project Management Institute goes on to state that, "…ineffective communications is the primary contributor to project failure one third of the time, and had a negative impact on project success more than half the time" (Project Management Institute (PMI), 2013a). I have postulated that both communication and cognitive skills are principle parameters of a design team's performance, so how does cognitive skill become relevant?

Cognitive skill can be thought of as an individual's ability assimilate, process, and make a decision upon a given set of information. Human error can be categorized into two major types; skill-based and mistakes (Reason, 1990). Figure 3-4 provides a hierarchy of Reason's Human Error Model. This model is frequently presented as a triad of slips, lapses, and mistakes. A slip is an inadvertent action such as performing a task out of sequence. The task is performed correctly just not in the appropriate order. Contrasting this with a lapse, in which one forgets to execute a step. The tasking was simply not done when a lapse occurs.

It is important to understand that with both a slip and lapse, the action is unintended. "Slips and lapses occur in very familiar tasks which we can carry out without much conscious attention." (Health and Safety Executive, 2012) Mistakes, however, are judgement failures. While this category also is unintentional, there is a logic flaw or an inappropriate decision made. For example, a mistake may occur when using a modeling technique that has not been validated for a specific purpose or extrapolating data beyond its confidence bounds. In a manufacturing context, a mistake is installing a component with an incorrect orientation. While the component is located incorrectly, the correct sequence was followed, and there was no oversight of a step or tasking. As all three of these error types are free of malice, how do they correlate to design team decision making?

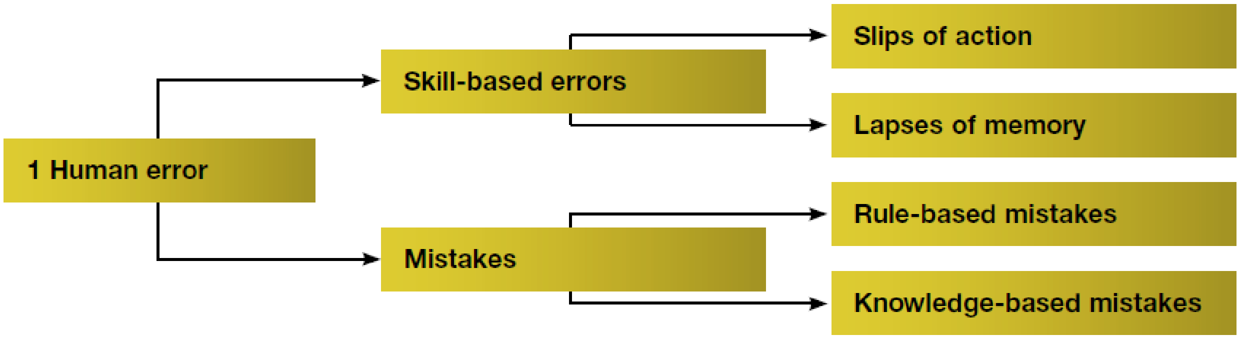

Figure 3-4 - Reason's Human Error Model (Health and Safety Executive, 2012)

The question becomes can one quantitatively measure communication effectiveness and cognitive skill in order to assess their impact on a design team? First, in regards to communication, "high reliability domains" have developed a specialized jargon such that connotation and inference have been removed from the discussion. Examples of these domains are surgical teams, disaster response teams, military units, and aviation pilots. The specialized jargon removes the vagary of language from the transmission of information. "All too frequently, effective communication is situation or personality dependent. Other high reliability domains, such as commercial aviation, have shown that the adoption of standardised tools and behaviours is a very effective strategy in enhancing teamwork and reducing risk" (Leonard, Graham, & Bonacum, 2004). These domains have necessitated a language unique to their discipline because human life is typically at risk. Typically, no one is threated in a normal design team environment; therefore, the impetus to define a discipline-specific vernacular has not been required. It also seems that the softer the failure, the less likely a team is to have a standardized vocabulary.

An interesting example of the lack of standardized vocabulary from Naval Architecture is the discussion of a vessel's length. The length overall (LOA), length between perpendiculars (LBP), length of waterline (LWL), length of deck (LOD), and length of hull (LOH) are all commonly utilized measures for marine vessels. Which is correct? That entirely depends on the discipline focus. With a multitude of metrics that describe the same characteristic of a singular vessel, one can begin to see how communication error may occur between design activities. While there are techniques that can ensure a common understanding (i.e. active listening), they all require an investment of time to ensure the transmitted message is identical to the message received. The quantitative measure is derived from this feedback mechanism. Without feedback or repetition we emulate the "Telephone Game." While this game is designed to be humorous, it does begin to simulate our modern, time-pressured, rapid-fire communication style. Therefore, it is possible to measure deviation from a standardized vernacular or, with a feedback mechanism, the discrepancy between intended message and received message.

Standardized testing has become a common feature of the academic experience, both domestically and worldwide. In fact, the process of obtaining a professional license for engineers, architects, doctors, and lawyers, also involves standardized testing. The primary question becomes "why?" Is it just for the sake of uniformity, or is it the concept of a fair and repeatable evaluation. Whether we condone the use of standardized testing or not, the need to have an objective assessment of capability is paramount to establishing an accurate evaluation of competency. So why has this practice not been leveraged for team formation? Before addressing this issue I must evaluate a few secondary questions that arise: is standardized testing an accurate indication of potential performance and what topics should be the subject of the evaluation to glean meaningful results? Addressing the first question, "The evidence is clear: The difference in ability test scores is mirrored by a corresponding difference in academic achievement and in performance on the job" (Hunter & Hunter, 1984). It is important to realize that the ability test scores referenced here are cognitive ability scores.

So what is cognitive ability and why is it pertinent to the discussion. Merriam Webster defines "cognitive" as the following: "of, relating to, or involving conscious mental activities (such as thinking, understanding, learning, and remembering)." An individual's cognitive ability therefore is their capacity for thinking about, understanding, learning, synthesizing, and applying information. Some definitions imply that it is the creation of new knowledge from the presented information, "at the individual level, knowledge is created through cognitive processes…" (Easterby-Smith, 2011).

If cognitive ability is a surrogate for the mental adaptability of an individual how does this predict job performance? "Cognitive ability predicts job performance in large part because it predicts learning and job mastery. Ability is highly correlated with job knowledge and job knowledge is highly correlated with job performance" (Hunter, 1986). Obviously these are only predictions and do not guarantee an individual's performance. However they are strong indicators of potential performance. "The major mental tests do indeed measure the cognitive abilities of native-born, English-speaking Americans validly and without cultural bias, regardless of race, ethnicity, gender, or social class." (Gottfredson, 2003).

Since one can establish a common metric of performance based upon cognitive ability testing, what would a subject syllabus for this type of testing entail? "At a minimum, verbal ability, mathematical reasoning, spatial-mechanical ability, and clerical speed/perception (they come by various names) define aptitude profiles that are relevant to sizeable groups of occupations" (Gottfredson, 2003). These aptitude profiles sound remarkably similar to the format of the testing currently used for academic admissions. The Graduate Record Examination (GRE) contains sections to test Verbal Reasoning, Quantitative Reasoning, and Analytical Writing. (ETS, 2015) The Graduate Management Admission Test (GMAT) includes Analytical Writing Assessment, Integrated Reasoning, Quantitative, and Verbal sections (Graduate Management Admission Council (GMAC), 2015). These lists of topical areas are virtually synonymous with the list provided by Gottfredson. There is validity in the results of the testing as an indicator of performance capability, and a distinct set of skills can be tested in order to develop this metric of capability. This brings me back to the question of why have these types of techniques not been employed in team development strategies.

Characteristic Parameters

There is no shortage of literature stating the importance of clear, concise, and accurate communication (Lingard et al., 2004; Maier, Kreimeyer, Lindemann, & Clarkson, 2009; Morelli, Eppinger, & Gulati, 1995; Terry, 2013). The sections above both demonstrate a trend towards increasing complexity in subsequent releases and increasing design team sizes with respect to time. The product complexity should correlate directly to the complexity of the design information being disseminated within the design team. Further, the size of the team is directly related to the number of possible communication paths (Strickland & Singer, 2015). Of additional consideration is the source of the information. Communiques can be initiated internally, within the design team as a function of performing the designated tasking, or externally, as directed by other parties outside of the proximate team. Figure 3-5 is a diagrammatic representation of the communication process. For internal communications the Source and Destination nodes are team members or functional disciplines within the larger design team. For external communications the Source node may represent a stakeholder or customer whom is outside of the proper team. The communication model outlined in Figure 3-5 has three possible error sources. These potential error sources are coincident with the encoding for transmission, noise introduced during the transmission, or decoding for receipt.

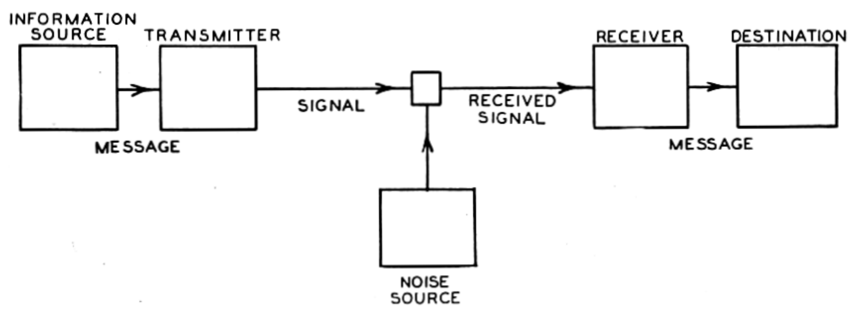

Figure 3-5 - Shannon-Weaver Communication Model (Shannon, 1948)

For this initial explanation the error sources have been condensed to a single error. This simplification facilitates a cleaner mathematical description. EQ 3-1, the matrix $[A]$ is square with the induced error on the main diagonal. The i^{th} entry represents the source of the information, and the $(i+1)^{\text{th}}$ entry corresponds to the destination. The vector x_i is a listing of key system attributes and physical characteristics of the product under development.

$$x_{i+1} = [A]x_i \qquad \text{EQ 3-1}$$

Potential sources for this error are technical jargon, discipline specific nomenclature, accents, dialects, idioms, or transcription. If the $[A]$ matrix is not limited to a diagonal square configuration, the off diagonal terms can be used to represent discipline bias or inconsistent attention to detail across functional subsets of the state vector.

The second primary parameter of the proposed model is derived largely from the field of industrial and organizational psychology. "The field of human cognitive abilities is one of the oldest and most technically sophisticated in all of psychology." (Gottfredson, 2003) As a society we have placed some belief in the assessments of cognitive skills and abilities as an indicator of future performance (Alexander, 2007; Hunter & Hunter, 1984; Hunter, 1986; Murphy, 1989; Schmidt, 2002). The idea of using standardized testing to measure aptitude is not a new endeavor. The following activities all use standardized testing: college entrance, graduate schools, medical schools, law schools, and professional licensure agencies. Given that a standardized testing is an acceptable methodology to assess capability, then lack of capability could be viewed as the potential for error.

People, process, and product comprise one popular variant of the 3P model. This model and variants thereof have made the 3P focus a cliché of modern business (Coletta, 2012; Hawker, 2002; Tseng, 2013). Error from these sources is typically attributed to personnel experience, task familiarity, and tool familiarity. This term of the equation accounts for the cognitive skill of the activity but also allows for the introduction of new data. The $[B]$ matrix could be developed from a cognitive skills battery. The vector, u, represents new information provided to the process at the current discretized step.

$$x_{i+1} = [A]_i x_i + [B]_{i+1} u_{i+1} \qquad \text{EQ 3-2}$$

In the formulation present in EQ 3-2, the $[B]u$ term represents the introduction of new information as well as the cognitive skill impact of the information upon the state vector. This formulation is the canonical presentation of the state equation for a fully developed state space model.

State space models have broad applications and have proven to be very versatile primarily due to their linear formulation and acceptance of various perturbation parameters. For explanatory purposes a kinematic system will be described within a state space modeling context. In this case the state vector, x_i, could represent a particle's position in three dimensional space with the three associated Euler angles to describe a discrete position and orientation. Thus x_i is a six element column vector. This means that $[A]$ is a 6x6 square matrix that describes the discretized transition from state i to state $i+1$. If the $[A]$ matrix assumed the identity value, I_{6x6}, this would imply that no additional translation or rotation occurred between these states.

This brings me to the second term of EQ 3-2. The $[B]u$ term in this analogy represents external forcing or a discrete perturbation applied at that time step. For this explanatory model to hold the product, $[B]u$, must produce a six element column vector. Therefore, $[B]$ is of size 6xp and u is of size px1. In this case, p, can assume any value deemed necessary by the problem formulation, but it will result in three translations and three rotations. Again within the context of this example the second term would produce a translation and rotation to the particle position created by some external forcing. This formulation is the basis of the Process Failure Estimation Technique (ProFET).

Synopsis

The design process is insensitive to the methodology employed, since it is only benchmarked by static snap shots at critical junctions. However the design team is not similarly evaluated at these critical junctions. It seems prudent to evaluate the team's skill portfolio as well, in order to determine if the correct “mix” of talent has been acquired for the next phase of the project.

This dissertation has been limited to interpersonal communication skills and technical proficiency. It also seems logical that the skill set required to develop and execute a concept exploration or analysis of alternatives would be drastically different than that required to complete an effective preliminary design. This skill set would continue to evolve throughout the acquisition process, morphing and changing at each distinct phase of the project. This dissertation begins to address the need for incremental assessment of the design team’s skill set as a variable, impacting the overall design success.

This dissertation develops the principle parameters of an objective mathematical framework that is capable of accounting for a design team’s skill portfolio. The proposed technique would be another tool to be applied in the suite of existing design tools. The fundamental difference is that the focus of this technique is on the design team and not the design.

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CHAPTER 4

Process Failure Estimation Technique (ProFET) – Sequential Model Development

This chapter will evaluate the error propagation patterns of a serial process as a function of peer-to-peer communication error. The Process Failure Estimation Technique (ProFET) is a novel technique intended to evaluate an activities likelihood of success. Further, this technique allows for the performance analysis of an engineering team, as a function of peer to peer communication and cognitive skill. This chapter develops this technique and provides a mathematically objective assessment of a team's effort.

While a model of successive actions is more appropriate for a traditional design process or sequential engineering development, it is acknowledged that sequential or "over the wall" engineering is counter to the developments of the last 30 years within the engineering design community. However, within a concurrent engineering model, sections of the design process still exhibit largely sequential behavior (Bernstein, 1998; Liker, Sobek, Ward, & Cristiano, 1996), thus this case study has continued utility. A non-sequential or parallel case study will be evaluated in Chapter 5.

Background

Thanks to the prevalence of concurrent engineering approaches, integrated product teams (IPTs) have become common place and indispensable for the technical execution of the design process (Bernstein, 1998; Guenov & Barker, 2005; Keane & Tibbitts, 1996; Naval Sea Systems Command, 2012). The modern technical team environment presents great opportunity for collaboration as well as a multitude of error sources; see Chapter 3 for additional discussion on the contribution of teams to the design process. The sources of error under investigation within this dissertation stem from miscommunication and cognitive failure.

Regarding communication error, “This issue [communication] is particularly crucial as design work becomes distributed across multiple players.” (Liker et al., 1996) In short, as the number of personnel and team members involved increases, communication becomes a more critical component of the efficient and successful task execution (Henderson & Lee, 1992; Maier, Kreimeyer, Lindemann, & Clarkson, 2009; Naval Sea Systems Command, 2012; PMI, 2008).

As noted in the previous chapter, “most major cognitive skills are used in everyday work.” (Hunter, 1986) It stands to reason that if the personnel are in fact the source of cognitive errors within a team environment (Reason, 1990), the larger the team, the higher the propensity for error. Either of these error sources can derail a project without assistance.

If this type of extreme failure seems unlikely within the modern teaming environment, the following three examples illustrate the effect of communication error within the design process. The USCG ISLAND Class extensions resulted in the loss of eight assets due to hull structural issues (Lipton, 2006; O’Rourke, 2012). Whether these assets were the subject of poor engineering practices or succumbed to structural wastage is immaterial to the current discussion. In this instance, communication error or omission contributed to the early retirement of eight vessels. The loss of the BP DEEPWATER HORIZON resulted in the largest oil spill in U.S. history (The Ocean Portal Team, n.d.). The proximate cause was the improper interpretation of the negative pressure test prior to initiating a planned well abandonment (National Academy, 2010). Yet again, another example of how communication or lack thereof can lead to catastrophic failure. Finally, the LPD 17 class construction and detailed design issues may be more attributable to cognitive skill error, but assuredly communication deficiencies contributed to the publicized failures (Rourke, 2011). These examples have been presented to illustrate that “extreme” events do occur within the modern engineering team.

Case Study Overview

In order to emulate a series of sequential engineering actions, a surrogate model process needed to be identified. This initial study models the communication error components of ProFET. The cognitive skill component contribution will be ignored at this time. The goal of this case study is to understand how communication error influences the overall successfulness of a team.

The calculation of a vessel’s floodable length curve was the chosen surrogate process. This process was chosen since it contains several successive and repetitive calculations. The process generates the allowable floodable length curve as outlined by the Society of Naval Architects and Marine Engineers (Lewis, 1988). The calculation of allowable floodable length is a good example of a design experience because it is iterative in nature and successive calculations are dependent of the previous calculations.

Communication error was interjected between each successive calculation, creating a stochastically perturbed process. After the generation of the floodable length curve the main subdivision bulkheads were deterministically located. The process of calculating a floodable length curve and placement of the main subdivision bulkheads will be briefly explained. In order to understand the influence of communication error on the success rate of the process, a range of error is evaluated.

This chapter presents and discusses a series of floodable length curves that have been subjected to stochastic perturbation of a single state element. A series of one dimensional probability density functions for the subdivision bulkhead locations are evaluated, and with the imposition of a limit of bulkhead deviation, the percentage of compliant iterations is determined. The subset of the compliant iterations is evaluated as a function of the induced communication error and the limit of bulkhead deviation. The following section outlines the methodology employed for this case study.

Methodology

A discretized state space model will be employed to emulate a design team conducting successive, serial calculations. This model has been adapted from the concept of Stream of Variation (SOV) (Abellan-Nebot, Liu, & Romero Subiron, 2011; Shi, 2006). The SOV construct was developed to predict the error accumulation during the multistage manufacturing process of automobile assembly. In the original formulation, the principle sources of error were introduced as material moved between operations or as a function of the operation. In this team centric formulation, the induced translational and rotational error has been replaced with a communication error, with the product no longer being a tangible work piece or subassembly, but a technical product or calculation result. The on-station error created during a multi stage manufacturing process has been replaced with a cognitive skill error. With these assumptions one facet of a design team can be analyzed. This model develops an analogous relationship from translational error to communication error, and tooling error to cognitive skill error. The relative importance of these two characteristic parameters is expanded upon in Chapter 3.

This case study will contain 11 successive calculations (i.e., n=11), which will be in some part reliant upon the preceding action. Eleven has been chosen as a reasonable number of iterations that will allow for the development of a smooth floodable length curve as well as for the deviation due to communication error to become apparent. The exact formulation of ProFET, the state space model employed, is described mathematically by EQ 4-1 and EQ 4-2, and pictorially by Figure 4-1. Additional information on ProFET derivation has been documented in Appendix A.

$$\overrightarrow{x_n}^{i} = [A]_{n-1}\,\overrightarrow{x_{n-1}}^{o} + [B]_n\overrightarrow{u_n} + \overrightarrow{w_n} \qquad \text{EQ 4-1}$$
$$\overrightarrow{y_n} = [C]_n\,\overrightarrow{x_n}^{o} + \overrightarrow{v_n} \qquad \text{EQ 4-2}$$

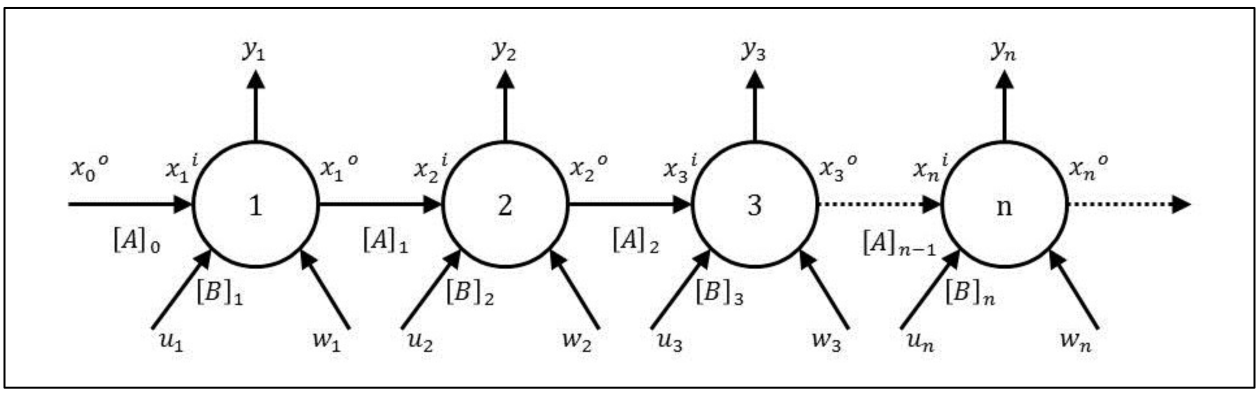

Figure 4-1 - Process Failure Estimation Technique

Expanding on Figure 4-1, each process is represented by the numbered node. Similar to other applications of state space modeling, (Liu & Shi, 2007; Luis, Zabala, All, Connor, & Sussman, 1996; Rohan, 2004; Rowell, 2002; Stengel & Mae, 2011; Zivot, Wang, & Koopman, 2003), this model is represented by a pair of equations, the state equation, EQ 4-1, and the observation equation, EQ 4-2. For engineering practitioners, the state vector ($\overrightarrow{x_n}$) can be thought of as a listing of system attributes (Shi, 2006; Strickland & Singer, 2015). Each element in the vector is a time-discrete, key system attribute (KSA) of a system. The values of KSAs evolve with time and developmental activities conducted at each step in the design process. The state vector is operated upon by a transformation matrix, $[A]_n$. For this case study, the transformation matrix represents communication error between operations. Each operation is treated as an independent calculation with defined inputs and outputs, providing the ability to use different transformation matrix between each operation. The product of the state vector and the transformation matrix at a given step is the state vector for the next step. The second equation in the model has a similar structure, but essentially takes any output state vector ($\overrightarrow{x_n^o}$) from any of the discretized steps, and projects the final results given the information provided. From a practitioner's perspective, the observation vector, ($\overrightarrow{y_n}$), can be thought of as a listing of a system's Key Performance Parameters (Shi, 2006; Strickland & Singer, 2015). Again, the elements of this vector would each represent entirely or a portion of a system's Key Performance Parameter (KPP). For a subset of deterministic and calculable values, the mapping matrix, $[C]_n$, provides a direct reflection of the result given the current information. In most cases, this should be viewed as a projection of the likely outcome at the current step – an estimate of the final system level parameters.

It is important to note that EQ 4-1 and EQ 4-2 represent the fully derived ProFET model. For the remainder of this chapter a reduced order model, EQ 4-3 and EQ 4-4, will be employed. The terms that have been omitted are either additional stochastic perturbations ($\overrightarrow{w_n}$, $\overrightarrow{v_n}$) or deal with the cognitive skill effects ($[B]_n\overrightarrow{u_n}$).

$$\overrightarrow{x_n{}^i} = [A]_{n-1}\,\overrightarrow{x_{n-1}{}^o} \qquad \text{EQ 4-3}$$

$$\overrightarrow{y_n} = [C]_n \overrightarrow{x_n{}^o} \qquad \text{EQ 4-4}$$

Floodable Length Calculation

Determination of the allowable floodable length is the essential step for determining the placement of transverse water tight bulkheads (International Maritime Organization, 1914). This process is nestled between hull form definition (i.e., shape, type) and the development of the initial arrangements (Eyres, 2007). It is a defining step in the arrangement process because it sets the transverse watertight integrity, creating boundaries for internal spaces. This process subdivides the hull form longitudinally into compartments that form the basis of damage stability for the vessel. This section will describe the process of calculating a floodable length curve and the subsequent location of the transverse watertight bulkheads.

To begin this process one needs a defined hull shape and an initial design waterline. For simplicity, an orthogonal box barge with the principle dimensions displayed in Table 4-1 has been utilized. The values for length (L), beam (B), depth (D), and draft (T) are of dimensionless length. This is allowable for this example because I am exclusively calculating volumes and centroids. Permeability is a variable that can theoretically hold values from 0 to 1, and may vary by compartment. For this initial case this value has been assigned to be unity for all compartments, or 100 percent volumetric flooding.

Table 4-1 - Box Barge Dimensions

Dimension	Value
Length (L)	100
Beam (B)	20
Depth (D)	10
Draft (T)	4
Permeability (μ_p)	1

The hull is then trimmed both by the bow and the stern at various percentages of the total hull depth until the margin line is in contact with the design waterline. The margin line is defined by regulation and is three inches below the bulkhead deck (US Coast Guard, 2010). The number of trims required depends on the shape of the hull form and the fairness desired for the floodable length curve. For this case study, the number of trims is equal to the number of required sequential calculations.

The ordinates of the floodable length curve are generated by a moment balance from a corresponding volume of water at some distance from amidships that would produce the static trim currently being evaluated, this produces one coordinate pair. The process is repeated until enough points have been generated to plot a smooth curve. The following equations provide the basis of information required to calculate a single coordinate pair. EQ 4-5 is the calculation of the differential volume; V_0 is the baseline undamaged displaced volume of the hull form, therefore, V is the new volume in the static trim condition. As alluded to earlier, EQ 4-6 is the moment balance, where C_x and $\delta\mathrm{C}_\mathrm{x}$ are the centroid locations of the original volume and the differential volume, respectively. Finally, EQ 4-7, calculates the allowable floodable length ordinate, which is the differential volume divided by the cross sectional area at the differential volume centroid.

$$\delta\mathrm{V} = \mathrm{V} - \mathrm{V}_0 \qquad \text{EQ 4-5}$$
$$\delta\mathrm{C}_\mathrm{x} = (\mathrm{V}\ \mathrm{C}_\mathrm{x})/\delta\mathrm{V} \qquad \text{EQ 4-6}$$
$$l = \delta\mathrm{V}/A_{y|\delta C_x} \qquad \text{EQ 4-7}$$

Again, this analysis is for a single trimmed condition, and must be repeated until the plot of $\delta\mathrm{C}_\mathrm{x}$ versus l produces a smooth curve.

Figure 4-2 represents the ideal floodable length curve for the barge of discussion. Since the barge is completely symmetric and the permeability along the length is uniform, the curve both forward and after amidships is an even function; therefore, only half the curve has been presented below. Further, Figure 4-2 also displays a half-length elevation of the nominal barge. Finally, a waterline has been represented as a horizontal line intersecting the origin of the coordinate system. For comparative purposes, Figure 4-3 displays a typical floodable length curve for a vessel with shape and variable permeability.

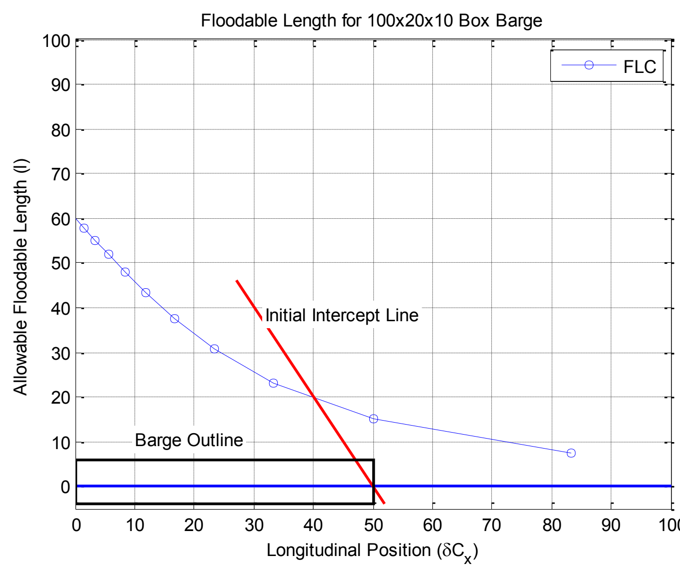

Figure 4-2 - Ideal Floodable Length Curve for the Subject Barge

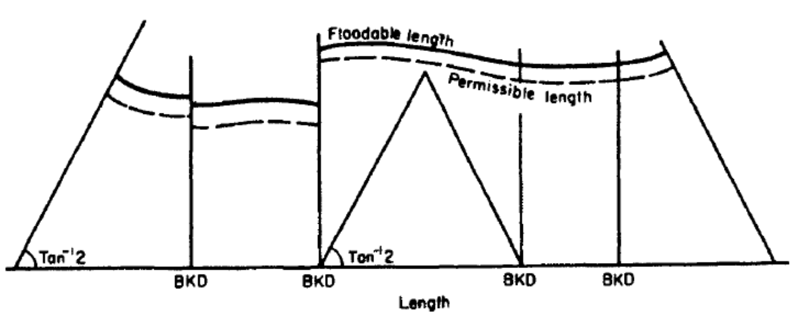

Figure 4-3 - Full Ship Floodable Length Curve (Rawson & Tupper, 2001)

Defining the locations of the transverse watertight bulkheads becomes an exercise in geometric analysis, but first the type of subdivision desired and other regulatory concerns need to be addressed. Regulations require that the collision bulkhead be placed at a position of no more than five percent of the overall length from the bow and stern shell plate (ABS, 2009). This defines the location of the first transverse bulkhead. Additionally, whether the vessel will comply with one, two, or higher compartment subdivision needs to be determined prior to initiation of the bulkhead placement analysis. This case study assumes compliance with two compartment subdivision. This means that any two adjacent compartments can be flooded without submergence of the margin line. Determining acceptability has been historically employed with the aid of isosceles triangles, Figure 4-3 displays a completed triangle for one compartment subdivision. In order for the two compartments to be compliant with the subdivision requirements, the apex of the isosceles triangle must be at or below the vessel's floodable length curve.

The X_1X_2 line depicted on Figure 4-4 is defined by the following key features. First it originates from the baseline at ½ T forward of the end of the barge, intersects the forward perpendicular at the design waterline, and has a slope of -2. This line is at $\arctan(2)$ above horizontal. Moving aft, each bulkhead will become the source of two additional lines with a slope of 2 and -2, creating a series of isosceles triangles. Satisfying two-compartment damaged stability requires the triangles be evaluated with a base equal to length of any two adjacent compartments. In practice, if the apex of the triangle is below the floodable length curve, then the bulkhead spacing is acceptable. In order to automate the bulkhead placement, it has been assumed that the bulkheads will be located by the exact point of intersection of all three lines.

Figure 4-4 illustrate the placement of the subdivision bulkheads utilizing the geometric determination of the location.

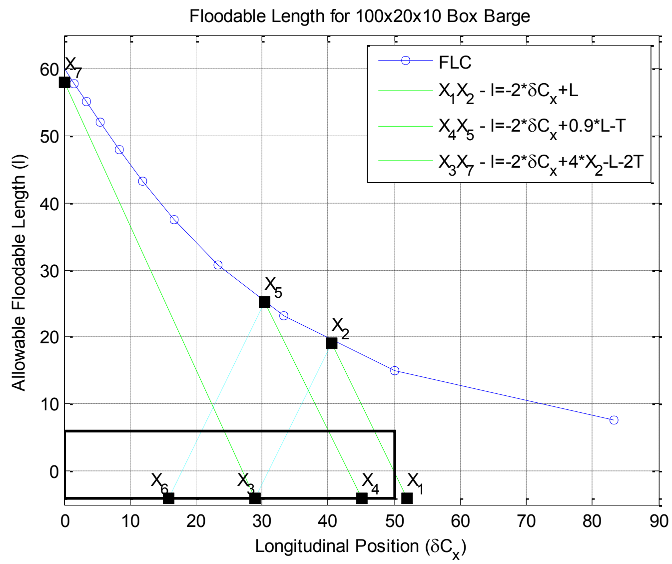

Figure 4-4 - Ideal Floodable Length Curve with BHD#1&3

Since the barge is completely symmetric across amidships the generated floodable length curve is an even function and the aft section of the barge is a mirror image of the forward section, a half-length can be analyzed for this case study. Table 4-2 delineates the positions highlighted in Figure 4-4. It is worth noting that a fifth bulkhead on this half-length is not required for subdivision; however, it may be dictated by other arrangement considerations. Additionally, if the illustration above is mirrored, center compartment X_3X_7 line would in fact be compliant with three-compartment subdivision requirements.

Table 4-2 - Ideal Transverse Bulkhead Locations

Designator	Bulkhead No.	Longitudinal Location
--	1	50
X_4	2	45
X_3	3	29
X_6	4	16
--	5	N/A

Introduction of Stochastic Error

In Figure 4-2, and Figure 4-4 an ideal floodable length curve has been plotted, 11 data points can be identified. Recalling how the coordinate pairs are calculated, EQ 4-5-EQ 4-7, the volumes and the centroids are a function of the base barge parameters in Table 4-1. A normally distributed stochastic perturbation has been introduced into the base parameters via the $[A]$ matrix. The vessel's length has the largest overall impact on the placement of the subdivision bulkheads; therefore, error has only been introduced on the first element of the state vector.

EQ 4-8 is the mathematical representation of the typical process output state vector. The principle barge dimensions occupy the first four elements of this vector. Each successive abscissa value of the floodable length curve has been appended to the end of the state vector. This implies the length of the state vector increases by one element for every successive step. For this evaluation the communication matrix, $[A]$, has been limited to a diagonal, identity matrix with the first row and column being replaced with a normally distributed random variable.

$$x_n^o = [L\ B\ D\ T\ l_n]^{\mathrm{T}}; n = 1:11 \qquad \text{EQ 4-8}$$

$$l_n = [l_1\ l_2\ l_3 \ldots l_n] \qquad \text{EQ 4-9}$$

$$[A]_n = I_{n+4};\ [A](1,1) \sim N(1.0, 0.004) \qquad \text{EQ 4-10}$$

With a random communication perturbation occurring between each subsequent coordinate calculation, it is possible to generate a multitude of unique curves. From each of these curves, one can deterministically place the subdivision bulkheads according to the calculation above. Figure 4-5 displays 10,000 floodable length curves developed using the methodology presented in the preceding sections. This analysis has a fixed communication standard deviation of 0.02 between successive calculations. Given the stochastic nature of the random variable each run has an error signature as a function of discretized time.

As a reference, an ideal barge elevation, floodable length curve, and initial line of intersection have been superimposed on the Figure 4-5. Given this set of geometric characteristics and successive communication error, calculations 9, 10, and 11 have little impact on the forth coming bulkhead analysis as these values fall beyond the initial line of intersection; however, these values are accounted for in the curve fitting process.

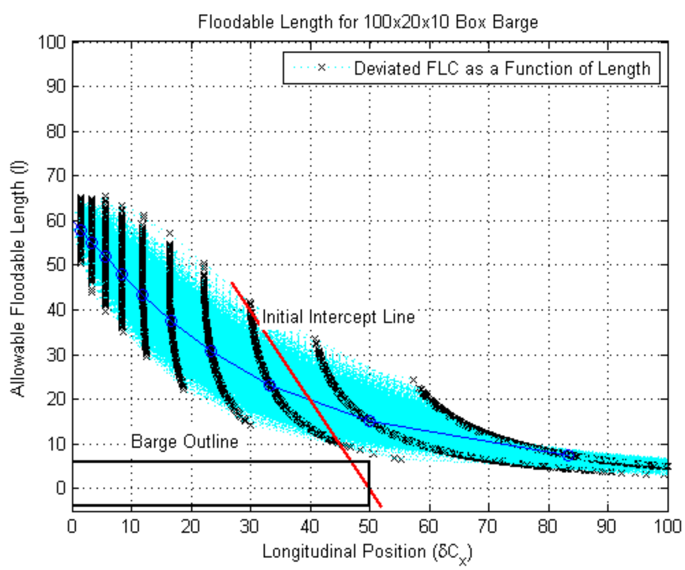

Figure 4-5 - Perturbed Floodable Length Curves

Results and Discussion

In order to understand how the stochastic floodable length curve affects the design space, a deeper analysis of the coordinates of the floodable length curve is warranted. Figure 4-6 depicts a box plot of the obtained ordinate values generated from the stochastically developed floodable length curves.

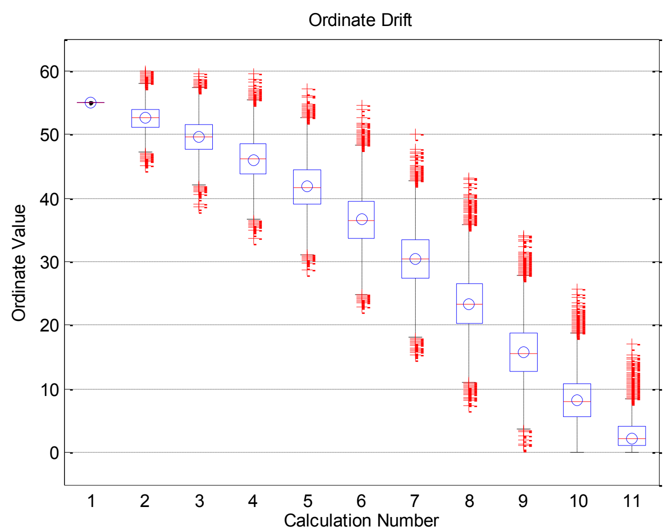

Figure 4-6 - Ordinate Drift with σ=0.02

This figure has several features that require discussion. First the circular data points represent the ideal ordinate value obtained from the floodable length curve development with no induced communication error. These values can be directly compared to the sample means represented by the horizontal line bisecting the box for each calculation. One can see that there is good agreement between the unperturbed value and the mean of the stochastic sample. The box represents the first and third quartiles; the lower line represents the 25th percentile value and the upper line represents the 75th percentile value. The first calculation has no box because there is only one value available. Now that the central portion of the distribution has been characterized, this leaves a discussion about the tails of the measured distributions.

The whisker's length corresponds to +/- 2.7 sample standard deviations, defining the normal range; values exceeding this value are considered extreme events. Calculations 1 through 8 demonstrate a high level of symmetry in whisker length, as well as observed extreme values. This implies that the tails of the distribution are a heavier than a normal distribution, however the symmetry may still allow for fitting with a normal distribution. Calculations 9 through 11 begin to demonstrate a substantial skewing of the data. Calculation 9 illustrates a reduced set of outliers on the lower bound, while calculations 10 and 11 demonstrate no lower outliers. While this is an artifact of the calculation process, it illustrates an important phenomenon – variability propagation depends on the relationship of product, process and time. The product controls variability through physical constraints and relations that in turn affects the process of information transfer and generation. The process itself is completed over time and the order of sub-processes contributes the overall variability in the results.

Analyzing the vertical distributions of the floodable length curve coordinates. Table 4-3 provides the mean (μ_y), standard deviation (σ_y), coefficient of skewness (β_1), and coefficient of kurtosis (β_2) for the measured sample at each independent calculation. The skewness and kurtosis of a sample are generally utilized to determine the appropriate distribution to characterize the measured data. Equations 4-11 and 4-12 provide a means to calculate the samples coefficient of skewness and kurtosis, respectively. These values in conjunction with Figure 4-7 can be utilized to determine the best distribution type to represent the measured data.

Table 4-3 - Ordinate Distribution Analysis; σ=0.02

Calculation Number	μ_y	σ_y	β_1	β_2
1	55.00	0.00	NaN	NaN
2	52.55	1.98	0.01	2.98
3	49.62	2.81	0.04	2.91
4	46.09	3.46	0.05	2.92
5	41.80	3.95	0.11	2.94
6	36.64	4.35	0.16	3.01
7	30.55	4.60	0.16	3.03
8	23.50	4.70	0.19	3.09
9	15.80	4.52	0.26	3.08
10	8.40	3.87	0.49	3.15
11	2.88	2.33	1.27	4.96

$$\beta_1^{1/2} = \frac{\mu_3}{\mu_2^{3/2}} \quad \text{EQ 4-11}$$

$$\beta_2 = \frac{\mu_4}{\mu_2^2} \quad \text{EQ 4-12}$$

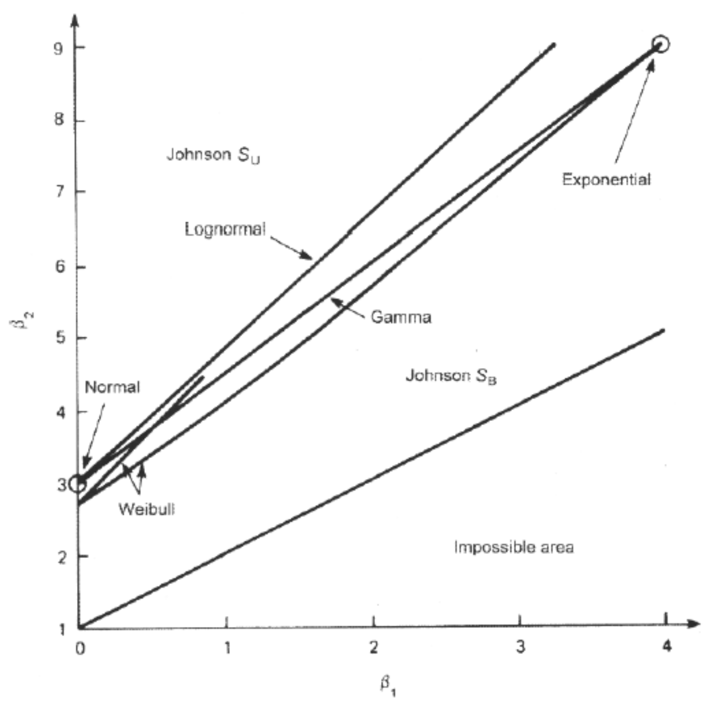

Figure 4-7 - Regions of Kurtosis versus Skewness ((Lee & McCormick, 2011) Fig. 2.5**)**

Once again, calculations 1 through 8 exhibit the behavior of a normal distribution. Or in the language of statistics, there is not sufficient evidence to disprove the null hypothesis that the responses of these calculations are normally distributed. With minimal skewing, less than 0.2, and kurtosis values of approximately 3.0, a normal distribution is appropriate. Calculations 9 through 11 begin to exhibit more Weibull, Gamma, and Lognormal characteristics. The cause of this is the reflection of the lower extreme values due to the enforcement of strictly positive ordinate values. For these cases, one can reject the null hypothesis, since the results indicate that the observed calculations do not conform to a normal distribution.

Now that the ordinate values of Figure 4-5 have been analyzed, I can now move to the analysis of the abscissa values. Similar to Figure 4-6, Figure 4-8 presents a box plot of the measured distributions of the floodable length curve abscissa drift. As in the previous box plot, the circular data points represent the ideal values obtained from the floodable length curve development with no induced communication error. These values can be directly compared to the sample means represented by the horizontal line bisecting the box for each calculation. One can see that there is good agreement between the unperturbed value and the mean of the stochastic sample. Again, the box represents the first and third quartiles. The first six calculations have no box because their standard deviation is relatively small. This can be visually discerned from Figure 4-8, since the sixth group is the first to exhibit noticeable horizontal drift. Calculations 7 through 11 begin to exhibit skewing in the positive x-direction. The relative magnitude of this data skewing increases with each successive step. For these distributions, a null hypothesis of normally distributed results is uniformly rejected. A quick scan of Table 4-4 reveals that none of the calculations conform to a normal or approximately normal distribution. Calculation number 1 has no distribution. Gamma, Lognormal, and Johnson S_u comprise calculations 2 through 8. The results from calculations 9 through 11 are heavily skewed. Some of this skewing is from the enforcement of positive ordinate values. While illustrating the compounding effect of sequential decision, it has little bearing on the bulkhead placement and following error analysis. Given another problem formation these calculations may not be negligible.

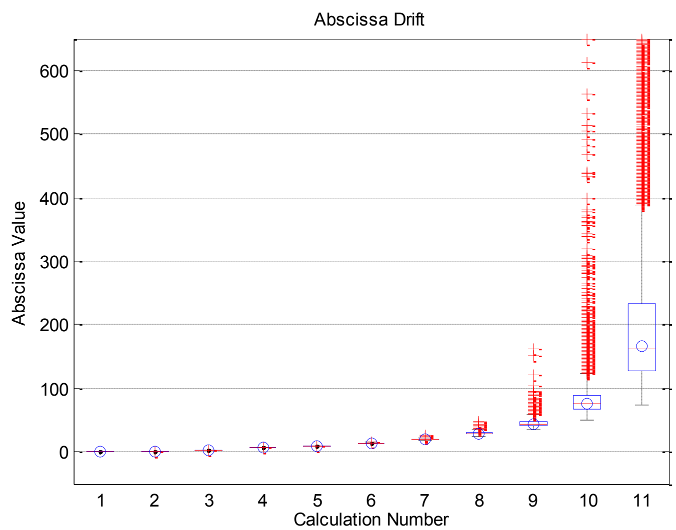

Figure 4-8 - Abscissa Drift with σ=0.02

To this point, the entire analysis has been conducted using a single fixed communication error, applied between each successive calculation. How do these results change with the induced communication error? Maintaining the same consistent communication error assumptions, Figure 4-9 illustrates how the standard deviation for ordinate, σ_y, and the abscissa, σ_x, vary with respect to calculation number and communication error. The communication error vector analyzed is a 10-step linear distribution spanning standard deviations on communication from 0.001 to 0.02. Figure 4-9 presents 20 lines, consisting of 10 pairs. Each pair corresponds to a specific communication standard deviation. The notation, $\sigma(i)$, represents the i^{th} value of the communication standard deviation vector.

Table 4-4 - Abscissa Distribution Analysis; σ=0.02

Calculation Number	μ_x	σ_x	β_1	β_2
1	0.00	0.00	-1.00	1.00
2	1.67	0.00	0.92	4.08
3	3.71	0.00	2.89	16.75
4	6.26	0.03	1.77	7.35
5	9.55	0.12	1.18	4.83
6	13.95	0.34	1.04	4.53
7	20.15	0.86	1.11	5.08
8	29.58	2.20	1.39	6.97
9	45.86	6.48	2.79	27.11
10	83.98	81.68	68.43	5845.61
11	367.50	2975.63	42.92	2331.62

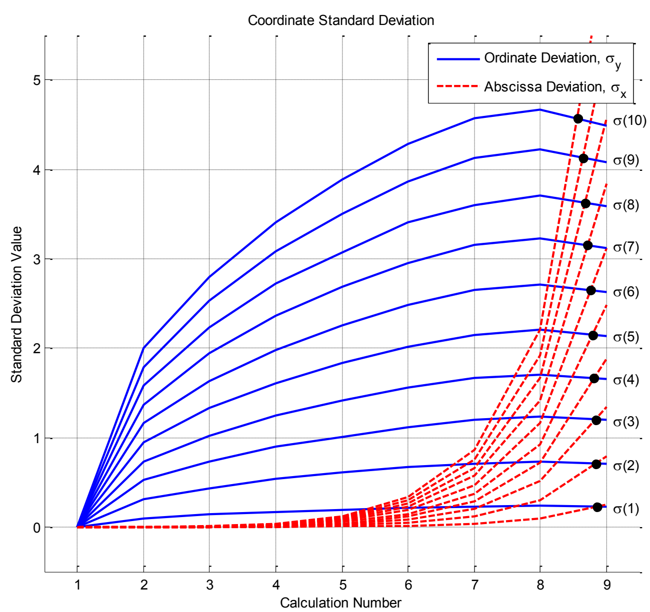

Figure 4-9 - Coordinate Standard Deviation with Varying Communication Error;

σ=[0.001 0.003 0.005 0.007 0.009 0.012 0.014 0.016 0.018 0.02]

A point and label has been placed at the second intersection point of these line pairs. For graphical purposes, calculations 10 and 11 have been omitted from this graphic due to the dominating effect of the exponential behavior of the abscissa deviation. Regarding the abscissa values, all cases demonstrate the same exponential behavior. Prior to executing this analysis, it was believed that an increase in the communication error would directly correlate to an increase in the standard deviation of subsequent abscissa values. This hypothesis has proven correct. Further the increasing value modifies the growth rate, causing more error to be present earlier in the process. Similarly, the standard deviation of the ordinate values was expected to increase commensurately with the increasing communication error. What was unexpected was the downturn following calculation 8. This is another anomaly of the example, due to the reflected values. Additionally, this is the departure point for a normally distributed ordinate value.

Recalling Table 4-2 - Ideal Transverse Bulkhead Locations, these values are bulkhead locations generated with an unperturbed floodable length curve and the concept of the isosceles triangles. As the height of the floodable length curve varies one can begin to see the "length" of variation for the subsequent bulkheads is dependent upon the exact intersection point.

Figure 4-10 through Figure 4-13 display the bulkhead placement error for the subject barge. I will utilize Figure 4-10 for the discussion of the key features on these graphics. To begin with, the longitudinal deviation for each of the 10,000 bulkhead placements has been plotted as a histogram, with the ideal location represented by the zero position. This histogram was fitted with a normal distribution; this probability density function has been superimposed upon the histogram. The histogram has been normalized by the relative bin area in order to scale the incident values to match the probability distribution function. A normal distribution was expected because the communicated perturbation to length is normally distributed with a mean of one and a standard deviation of 0.02, $N(1.0,0.004)$.

Finally, all of the subsequent figures also contain statistical metrics on the presented distributions. The first two values presented are the mean (μ) and standard deviation (σ). The third metric present is the Kullback-Leibler Divergence (KL) is a "measure of the distance or divergence between statistical populations." (Kullback & Leibler, 1951) This divergence has been derived from the resultant distribution and a second continuous distribution with a zero mean and identical standard deviation. The final two metrics presented in this discussion are the distributions' kurtosis (β_2) and skewness (β_1). "Kurtosis is a measure of whether the data are peaked or flat relative to a normal distribution." (NIST, 2012) A normal distribution has a kurtosis value of three. "Skewness is a measure of symmetry, or more precisely, the lack of symmetry." (NIST, 2012) In general, as a distribution's skewness approaches zero it becomes more symmetric about the mean value.

In general, the locations of bulkhead numbers 1 and 2 conform to a normal distribution. This was expected since the side shell and the collision bulkhead are purely functions of vessel's length. What was unexpected was the rejection of the null hypothesis for normally distributed values of bulkhead numbers 3 and 4. Bulkhead 3 illustrates behaviors similar to a lognormal distribution. While bulkhead 4 offers a gamma or Weibull distribution. These bulkheads' location distributions are the result of a deterministic calculation with a normally distributed starting condition and a normally distributed boundary condition.

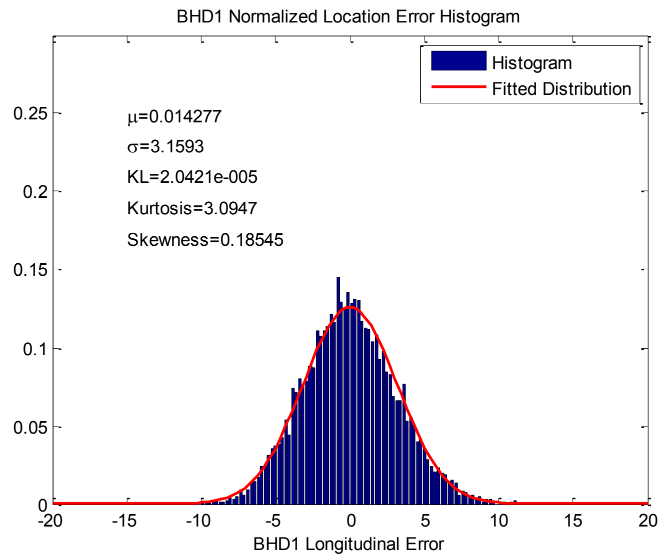

Figure 4-10 - BHD1 Error Analysis

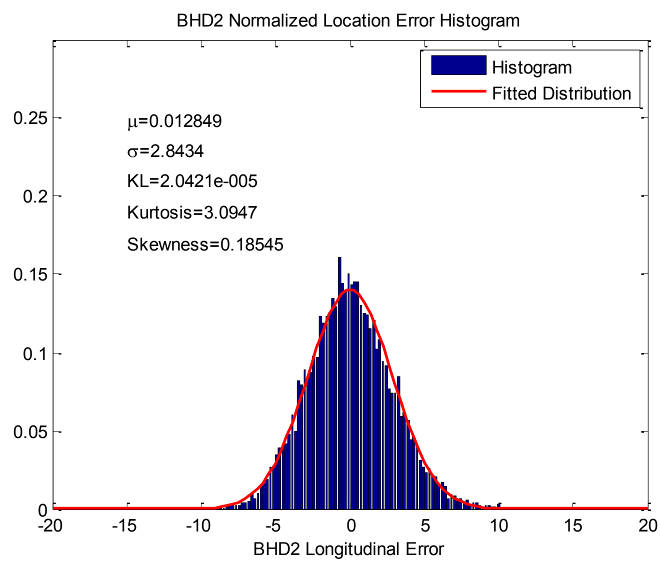

Figure 4-11 - BHD2 Error Analysis

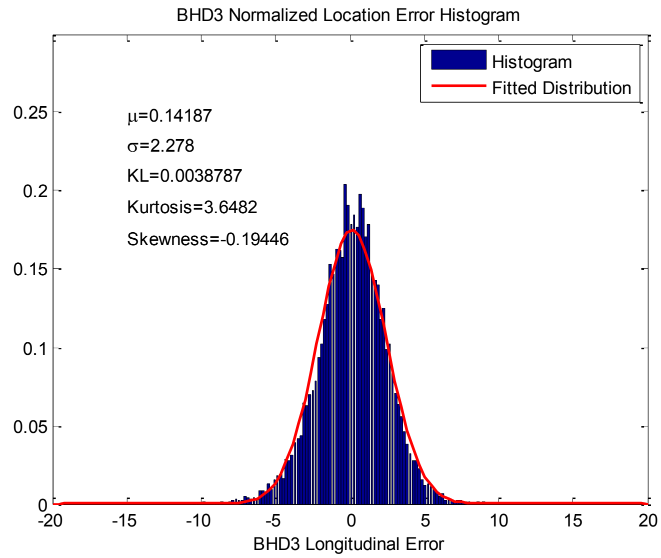

Figure 4-12 - BHD3 Error Analysis

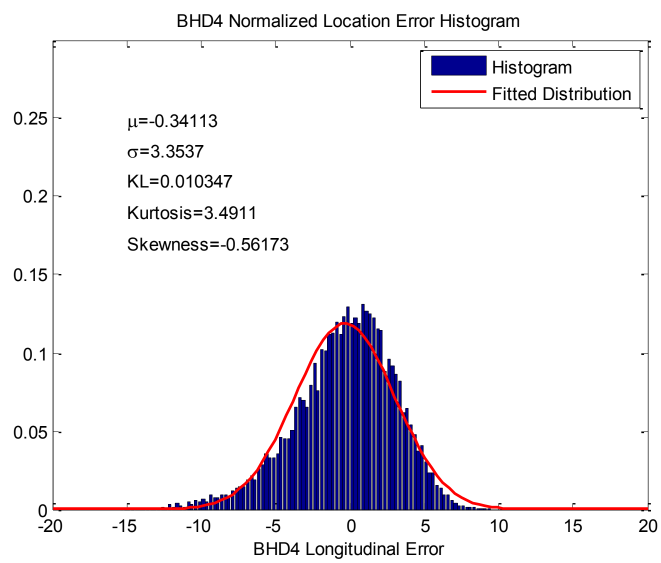

Figure 4-13 - BHD4 Error Analysis

The bulkhead location variation is a function of the induced communication error between calculations. If a limit is established on the bulkhead location variation, a set of compliant runs can be identified. This is possible since each of the stochastic perturbations have a distinct error signature. This signature may not be unique, but the successful perturbation paths can be identified. Figure 4-14 depicts the evolution of length with respect to calculation number or state number for compliant arrangements. Imposing deviation limit (ϵ) equal to 0.1 units of length, results in 251 successful iterations of 10,000 at bulkhead 1. Two lines have been superimposed on Figure 4-14. The upper line is the cumulative average of the lengths above the nominal value, and the lower line is the cumulative average of the length below the nominal value. For this case, the averages exhibit ±1.5 percent departure from nominal.

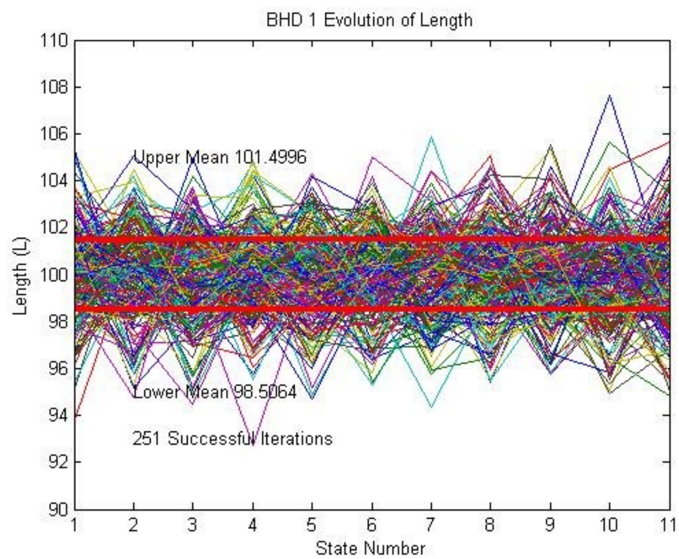

Figure 4-14 - Bulkhead 1 Iterations within Limits, σ=0.02 ϵ=0.1

Since the excursion limit could be varied for each bulkhead, it is important to understand all of the possible set intersections. Figure 4-15 illustrates one representation of a four set Venn diagram. This representation has 15 unique intersections. These set intersections have been appropriately labeled on Figure 4-15. For the following set analysis, a constant limit of deviation will be applied to all of the sets. It should be noted that a fully compliant system would be represented by the intersection, $A \cap B \cap C \cap D$, and is located at the center of the Venn diagram. Set A is defined as the number of iterations that occur between a defined limit of deviation for bulkhead 1. This analogy continues such that the compliant iterations of bulkhead 4 correspond to Set D.

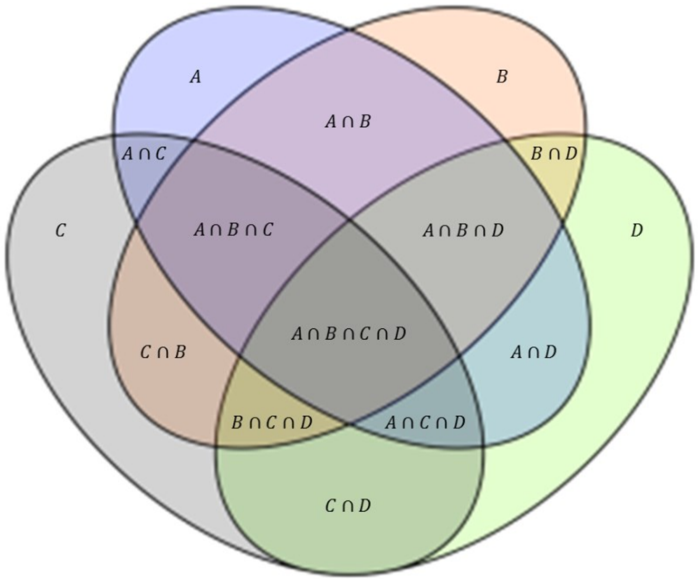

Figure 4-15 - Four Set Venn Diagram

For a prescribed set of parameters, $\sigma = 0.02$ and $\epsilon = 0.1$, Figure 4-16 depicts the values of the unique set intersections. As mentioned, the intersection of all the sets, $A \cap B \cap C \cap D$, is the region of interest. For this instance, 5 iterations produce a compliant bulkhead arrangement with the induced communication error and the limit of bulkhead deviation.

How does this value respond to variation in the communication error and the limit of deviation? It is expected that as communication error (σ) is reduced, the number of successful iterations will increase. Another way to increase the number of successful iteration would be to increase the deviation limit (ϵ). However, this has other potentially negative implications by accepting designs with higher and higher deviations.

Figure 4-16 - Set Intersection Analysis, σ=0.02 ϵ=0.1

In order to test the assertion above, the communication error standard deviation was varied between 0.001 and 0.02, and the bulkhead deviation limit was varied from 0.1 to 0.5. The resultant compliant population for the $A \cap B \cap C \cap D$ intersection was translated to the vertical value of Figure 4-17 and Figure 4-18. The data presented on these two surfaces is the same. The only difference between them is the vertical axis is linear in Figure 4-17 versus logarithmic in Figure 4-18. A fairly flat surface was expected. While it does exhibit the expected behavior of increased compliance with a reduction in communication error and an increase in the bulkhead limit of deviation, there is an exponential behavior. It also appears that the influence on successful iterations of communication error and the limit of deviation are inversely correlated. Increasing the deviation limit at lower values of communication error enables growth of the total set population. Additionally, it appears that there is a critical value for communication error at which the number of viable iterations is dramatically reduced.

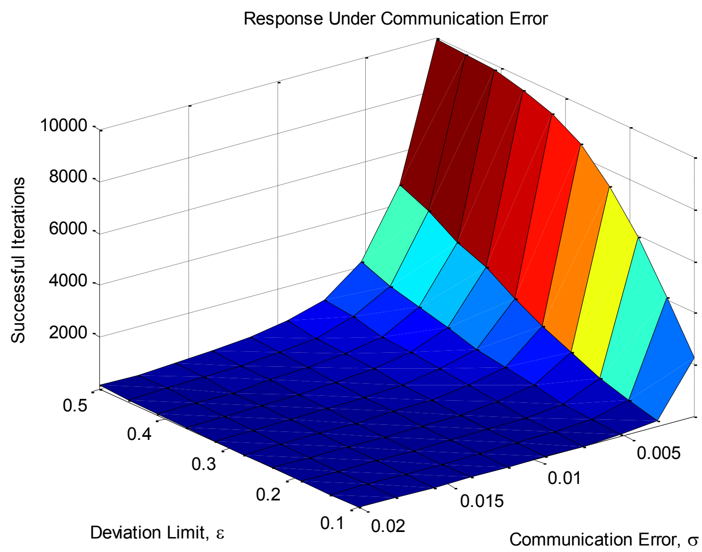

Figure 4-17 - Set Population, A∩B∩C∩D

Figure 4-18 is included to illustrate that while the lower area of the surface appears flat and uniform, it is not. The terrain in the surface is created by the use of a stochastic perturbation. While this is interesting and may lead to some local optimization approaches, the real take away of this analysis is the identification of the critical communication error value for a given deviation limit. This would then correspond to a maximum allowable communication error, implying that continued successive calculations would show an increase in the error or a reduction in the set population of interest. Applying this concept to the traditionally iterative design process employed within the marine field, one can see how an incorrect answer can be arrived upon, even with proper calculation techniques utilized.

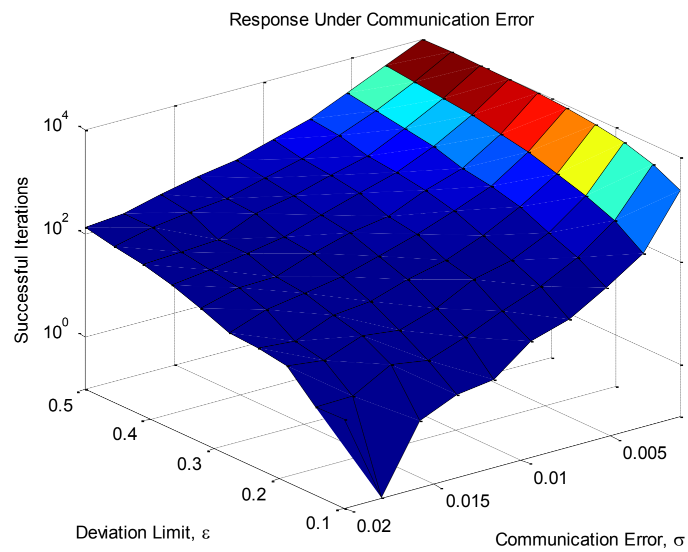

Figure 4-18 - Set Population, A∩B∩C∩D

This study showed the quantification of a small, successive communication error producing potentially disastrous results for the design and construction effort. To further extend this analogy, if a bulkhead was improperly located by half a unit of length potential ramifications could be lack of regulatory compliance, increased cost, or project infeasibility. The obvious response to this inaccuracy would be to reduce the communication error for successive steps. The general increases in these statistical values would tend to suggest that if additional calculations followed these, the distribution would be less and less normal. Finally, this was the result of a chain of 11 successive calculations having only one of the base barge parameters subjected to a stochastic perturbation. Obviously, it is not hard to conceive an example within the modern design environment where you have more than 11 successive calculations or where more than one of the base parameter is perturbed. This leads to a potentially unquantified combinatorial effect.

Conclusions

This chapter demonstrated how the relationship between people, process and product can be mathematically captured and modeled. The technique is beneficial to an organization because it allows them to understand the implication of design team decisions on process results. Emulating the communication of a design team is accomplished through a stream of variation model, detailed in Appendix A. Analyzing the results of the emulation shows the relationship between how a process is structured, the skill of the personnel involved, and the product itself. This relation is often alluded to in management and business literature (Drucker 2011; Deming 2000; Covey 1990; Collins 2001; Maxwell 2007), capturing it is a new, powerful analysis tool.

ProFET captures the effect of cognitive skill, interpersonal communication, and team formation in a mathematical framework. This requires significant model assumptions that are based on driving mechanics of communication and team processes. Loss of fidelity associated with these assumptions makes understanding the holistic system behavior as impotant, if not more important, than the exact model results. Set populations of satisfied criteria provide a qualitative metric for the process output, the probability of success. Parameter sweeps of the ProFET model reveals how the set populations change as a result of communications, providing new insight into process behavior. As discussed in Sole, identifying phase transitions, regions of rapid change, reveals important features of the underlying system (Sole 2011). The ability to identify critical amounts of communication error, which separate regions of high populations satisfying all criteria and regions with low populations, gives unique insight into the mechanisms driving successful processes.

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CHAPTER 5
Process Failure Estimation Technique (ProFET) – Multidisciplinary Model Development

Teams are without a doubt a critical component of the modern engineering enterprise. Modern naval design programs require large teams of highly-skilled engineers. While high performance teams are extremely desirable, there are limited objective mathematical methods to determine a team's performance level. Experientially, I have found that communication and cognitive skill are the most critical elements in a technical team's performance. This chapter of the thesis will present a multidisciplinary case study that will expand the ProFET model to assess the team performance characteristics beyond communication and include cognitive skill as well.

Multidiscipline Case Study

This chapter presents a second application of ProFET developed in the previous chapter. The principle difference is that this application is applied to a small network of design activities intended to emulate an interdisciplinary design team. This network along with the ProFET notation is displayed in Figure 5-1. The mechanics of ProFET remain consistent from the preceding chapter; however, the content of the applicable vectors and matrices are defined below. Further, each of the activities also will be discussed herein.

Figure 5-1 is a directed network connecting four distinct design activities; four communication paths have been analyzed. These communication pathways are displayed graphically in Figure 5-2. These four distinct communication configurations can be represented in a matrix representation as the adjacency matrix. For this case study, since all of the communication paths are unidirectional, the adjacency matrix is an asymmetric, upper triangular matrix. This type of representation has been shown to provide insight into the networks characteristic behavior (Newman, 2010; Parker, 2014; Rigterink, 2014). This compact notation will become increasingly important as the network size grows or as bidirectional communication is considered.

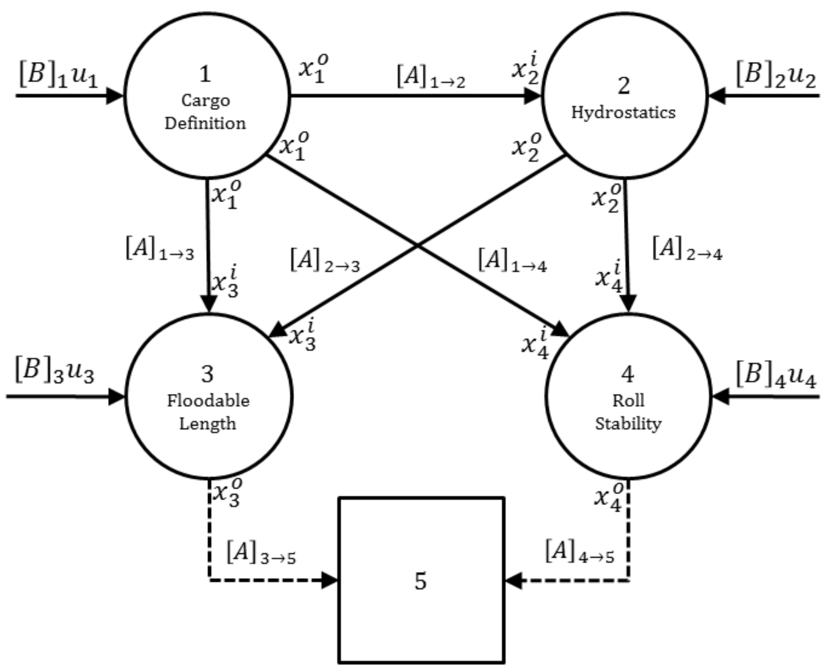
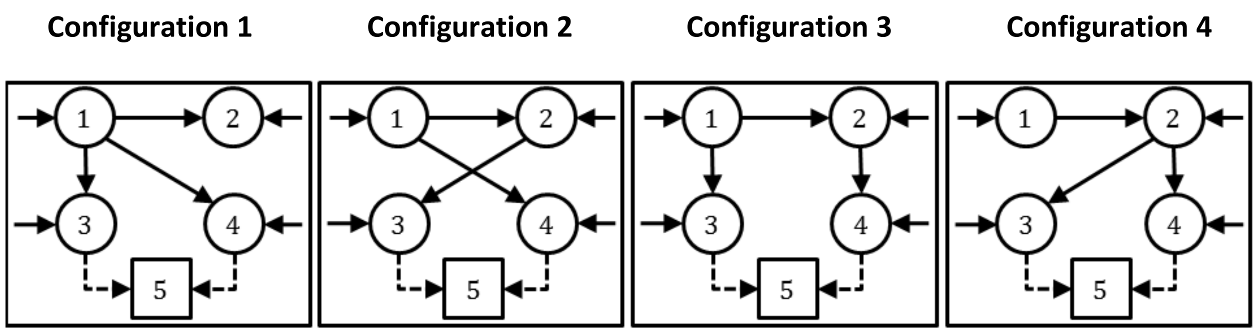


Figure 5-1 - Proposed Model Structure



$$\begin{bmatrix}1 & 1 & 1 & 1\\0 & 1 & 0 & 0\\0 & 0 & 1 & 0\\0 & 0 & 0 & 1\end{bmatrix} \quad \begin{bmatrix}1 & 1 & 0 & 1\\0 & 1 & 1 & 0\\0 & 0 & 1 & 0\\0 & 0 & 0 & 1\end{bmatrix} \quad \begin{bmatrix}1 & 1 & 1 & 0\\0 & 1 & 0 & 1\\0 & 0 & 1 & 0\\0 & 0 & 0 & 1\end{bmatrix} \quad \begin{bmatrix}1 & 1 & 0 & 0\\0 & 1 & 1 & 1\\0 & 0 & 1 & 0\\0 & 0 & 0 & 1\end{bmatrix}$$

Figure 5-2 - Information Exchange Configurations

The reader will be presented information as if the position of node 5 was assumed. This section will describe each action status and then present the results for four distinct information dissemination configurations from both node 3 and node 4. The four distinct information dissemination configurations are depicted in Figure 5-2 and highlighted in Figure 5-2

With the information dissemination pathways explained, one can now focus on the information being distributed. The state vector is expanded in Table 5-1. It is comprised of three principle subsections. Element positions 1-4, 5-11, and 12-18 represent the basic barge dimensional characteristics, cargo parameters, and the attitude of the loaded system, respectfully.

Table 5-1 - State Vector Composition

Element	Units	Position
Length (L)	Ft	1
Beam (B)	Ft	2
Depth (D)	Ft	3
Draft Unloaded (T)	Ft	4
Depth Cargo (D_C)	Ft	5
Mean Specific Gravity Cargo (γ_c)	Lbf/cf	6
Standard Deviation Specific Gravity Cargo (σ_c)	Lbf/cf	7
Longitudinal Center of Gravity Cargo (LCG_C)	Ft	8
Transverse Center of Gravity Cargo (TCG_C)	Ft	9
Vertical Center of Gravity Cargo (VCG_C)	Ft	10
Weight Cargo (W_C)	LT	11
Specific Gravity Water (γ_w)	Lbf/cf	12
Draft Loaded (T_1)	Ft	13
Heel (ϕ)	Deg	14
Trim (θ)	Deg	15
Longitudinal Center of Gravity System (LCG)	Ft	16
Transverse Center of Gravity System (TCG)	Ft	17
Vertical Center of Gravity System (VCG)	Ft	18

The state vector composition remains constant in this case study. Therefore, the process input and the output vectors will have the same configuration. This is contrasted against the "growing" state vector from the linear example. Given this formulation, the state vector can be succinctly represented by the following column vector.

$$x_n^- = [L \ \ B \ \ D \ \ T \ \ D_C \ \ \gamma_c \ \ \sigma_c \ \ LCG_C \ \ TCG_C \ \ VCG_C \ \ W_C \ \ \gamma_w \ \ T_1 \ \ \phi \ \ \theta \ \ LCG \ \ TCG \ \ VCG]^T \qquad \text{EQ 5-1}$$

As a reminder for the reader, the governing equation for ProFET, EQ 5-1, requires $[A]$ to be a square matrix, with dimensions equal to the state vector. For this formulation, $[A]$ and $[B]$ are 18x18, while x and u are 18x1 vectors.

$$\overrightarrow{x_m}^i = [A]_{n\to \mathrm{m}}\, \overrightarrow{x_n}^o + [B]_m \overrightarrow{u_m} \qquad \text{EQ 5-2}$$

The $[A]$ matrix is defined by the following approach. The rows (i) and columns (j) are allowed to assume integer values from 1 to 18. With the aid of the Kronecker Delta, EQ 5-2, an identity matrix is constructed. Assuming the variable, a_i, is a single sample from a normally distributed communication error, the communication effectiveness matrix can be expressed as the product of a_i and the Kronecker Delta, EQ4.

$$i = j = 1{:}\,18$$

$$\delta_{ij} = \begin{cases} 0, \text{if } i \neq j \\ 1, \text{if } i = j \end{cases} \quad \text{EQ 5-3}$$

$$a_i \sim N(\mu_{comms}, \sigma_{comms}{}^2) \quad \text{EQ 5-4}$$

$$[A]_{n \to m}\,(i, j) = a_i * \delta_{ij} \quad \text{EQ 5-5}$$

The first term in EQ 5-1, determines the effectiveness of communication. The second term determines the local effect on the calculation. It determines the amount of error that is introduced in to the specific process. Additionally, it allows for the introduction of new information into the network for follow-on calculations, and introduces a normally distributed variable, b_i, for cognitive skill effectiveness. A familiar approach can be applied to the $[B]$ matrix.

$$i = j = 1{:}\,18$$

$$\delta_{ij} = \begin{cases} 0, \text{if } i \neq j \\ 1, \text{if } i = j \end{cases} \quad \text{EQ 5-6}$$

$$b_i \sim N\left(\mu_{cog}, \sigma_{cog}{}^2\right) \quad \text{EQ 5-7}$$

$$[B]_n(i, j) = b_i * \delta_{ij} \quad \text{EQ 5-8}$$

This leaves for discussion the u vector. This is a means to interject new information or bias in the local calculations. For this illustrative case study, the u vector serves both purposes. In the case of Processes 1 and 2, the $[B]u$ term is employed to add additional information to the principle calculation. EQ 5-8 and EQ 5-9 explicitly describe the composition of the u_1 and u_2 respectively. Thus in this case, if $[B]$ is equal to the identity matrix then the information is additive to the state vector without deviation for this specific process. Therefore, when the [B] matrix is not equal to the identity matrix, an internal cognitive error can be modeled.

$$u_1 = [0\ \ 0\ \ 0\ \ 0\ \ D_C\ \ \gamma_c\ \ \sigma_c\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0]^T \quad \text{EQ 5-9}$$

$$u_2 = [0\ \ 0\ \ 0\ \ T\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ \gamma_w\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0]^T \quad \text{EQ 5-10}$$

$$u_3(:,k) = U_{mod} * x_k^o; k = 1{:}2 \quad \text{EQ 5-11}$$

$$u_4(:,k) = U_{mod} * x_k^o; k = 1{:}2 \quad \text{EQ 5-12}$$

Further the u vector can be used to introduce bias into the calculation process. This is the case for Process 3 and Process 4. For these processes, the u vector becomes a fraction of the input vector. The variable U_{mod} becomes the fractional scalar of the output vector of the proceeding process sans communication error.

With the ground work laid for the components of the state vector and subsequent calculations, I can now discuss the calculation processes and the additional underlying assumptions required to execute ProFET.

Vessel Parameters

I will utilize the ProFET assessment upon a nominal ship design problem. In order to quickly facilitate this example, I will assign a notional geometry. A box end, hopper barge will be utilized for this example. This notional geometry will be subjected to the four calculations outlined in the following sections. This barge will conform to the nominal standard for inland waterway transport evidenced by the volume of barges in operation with similar dimensions to those presented in Table 5-2. (Bruceoakley.com, 2013; Canalbarge.com, 2014; MarineLink.com, 2014)

Table 5-2 - Notional Barge Dimensions

Dimension	Value
Length (L)	200’
Beam (B)	35’
Depth (D)	12’
Draft Unloaded (T)	1.25’

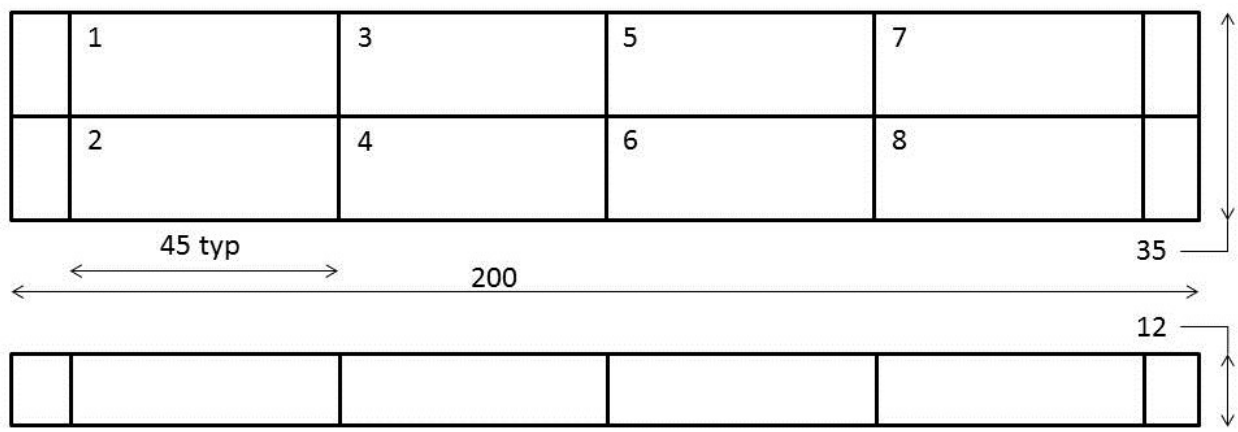


Figure 5-3 - Notional Barge Plan and Elevation

Figure 5-3 presents the notional plan and elevation drawings of the barge under evaluation. The barge will be assumed to be of uniform construction and the geometric centroid would coincide with the center of gravity. It is further assumed that the empty draft, T, of the barge would be 1.25’. (Bruceoakley.com, 2013; Canalbarge.com, 2014)

Process 1: Cargo Definition

Simulated cargo will be located as if placed on the deck in order to exaggerate the effect upon the systems total vertical center of gravity. The approach defines a fixed volume and allows density to vary stochastically. In this case the eight deck loads are all unique. Variance tuning is limited to a single distribution. Cargo placement can be simplified by enforcing volumetric uniformity. The volumetric constraint can be relaxed or redefined for specific considerations once the model has been developed.

Some basic characteristics for the cargo being sought include individual and total cargo weight, W_i and W_t respectively. Coupled with the geometric centroids this gives the effect on the nominal barge. The weight variance will be tuned to allow for significant deviations on the total system center of gravity, thus creating a trim and list. Calculation of the system centroid is eased by the assumption of volumetric uniformity; as such, the effect on the total vertical center of gravity will be limited by the initial cargo volumetric constraint. Under this approach, the expected outcome would be a bivariate normal distribution with respect to the vessels attitude and the corresponding stochastic trim and list. Additional considerations will be required to prevent submergence of the deck edge.

The principle output of the Cargo Definition process is the location of the system center of gravity and weight. The system weight will be comprised of the initial barge weight and the loading of the eight unique cargo elements. The system center of gravity will be derived from these weights and their geometric position. Table 5-3 illustrates the eight unique cargo loads with a uniform volumetric constraint. With the enforcement of volumetric cargo uniformity, the geometric centroid of the eight cargo items will assume a common vertical position, one of four discrete longitudinal positions, and one of two transverse positions.

The geometric centroid of these cargo loads are defined by permutations of the values delineated in Table 5-3. Further, to calculate the total system centroids (geometric and center of gravity), one needs to know the initial barge weight in addition to the cargo loading as well as the location of the barge center of gravity. Additional assumptions required will be the use of imperial units and fresh water. These assumptions imply that the gravimetric constant will be 32.2 $\frac{ft}{s^2}$ and density of water will be 1.94 $\frac{slugs}{ft^3}$. While the volume of the each individual cargo element will be identical, the cargo density will be allowed to vary in accordance with a normal distribution.

Table 5-3 - Cargo Geometric Centroids

Individual Cargo Longitudinal Center of Gravity, $\boldsymbol{LCG_i}$	$\frac{9}{10}L_0[-\frac{3}{8}, -\frac{1}{8}, \frac{1}{8}, \frac{3}{8}]$	[-67.5, -22.5, 22.5, 67.5]
Individual Cargo Vertical Center of Gravity, $\boldsymbol{VCG_i}$	$D_0 + D_i/2$	[12.38]
Individual Cargo Transverse Center of Gravity, $\boldsymbol{TCG_i}$	$B_0[-\frac{1}{4}, \frac{1}{4}]$	[-8.75, 8.75]

The following section will be presenting the results and providing discussion for each functional area. Figure 5-4 represents the two dimensional distribution of the composite cargo center of gravity in the horizontal plane. In this case, eight locations were allocated with a control volume height uniformly established at 0.75 ft (9 in). The resultant cargo location volume, 591 ft^3, was multiplied by a stochastic sample chosen from the cargo specific gravity normal distribution with a mean of 200 lbf/ft^3, and a standard deviation of 10 lbf/ft^3. This resultant load was then used to generate a composite cargo centroid. Figure 5-4 illustrates the longitudinal and transvers movement of the cargo centroid as a function of number of occurrences. The vertical axis represents the total number of occurrences out of 10,000. This bivariate distribution was then tested for a normal fit in both directions. The location of the stochastic mean centroid, [0.0082,-0.0002], can be contrasted with an ideal location, [0,0], in the absence of error. The minimal skewing and the lack of excess kurtosis for both the longitudinal and the transverse directions suggest that a normal distribution is a good approximation of the observed behavior (Bulmer, 1967). This leaves only the standard deviation to discuss. The $\pm 3\sigma$ range for the longitudinal center of gravity is [-1.32,1.32] and [-

0.46,0.46] for the transverse centroid location. Relative to the overall barge dimensions, these ranges equate to 1.32 percent for the barge length and 2.63 percent for the barge width. The asymmetry in the data would indicate that there is a correlation between beam and length. It should be discussed that the current model generates a unique bivariate distribution with each communication configuration. However, given the modest departure in the means from the ideal case, these differences can be neglected without loss of accuracy.

As a reminder the cargo definition effort and results are not subjected to perturbation of the base barge dimensions. Further they have not been subject to any other source of error other than cargo specific gravity variability. The second process node is the calculation of the barge hydrostatics. This node defines the disposition and attitude of the floating body.

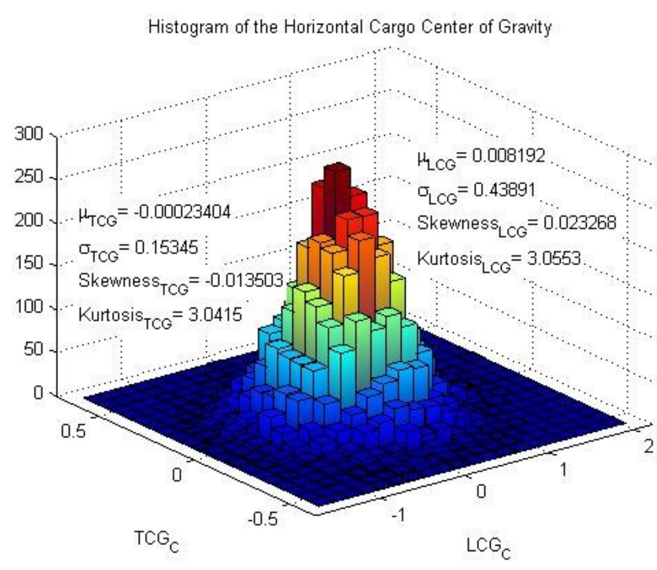


Figure 5-4 - Distribution of Cargo CG

Process 2: Hydrostatics

In order to calculate the system hydrostatics, Process 2 will require the characteristics defined in the Cargo Definition process. The characteristics specifically required are the total system weight and the dimensional values of the hull for the calculation of the even keel draft. The amount and direction of the resultant heel and trim are directly attributable to the location of the transverse and longitudinal center of gravity with respect to the geometric centroid and the inertia of the water plane. Figure 5-5 displays how a floating object adjusts its orientation to align the center of buoyancy with the center of gravity. This process would be repeated in order to determine both the trim and the heel.

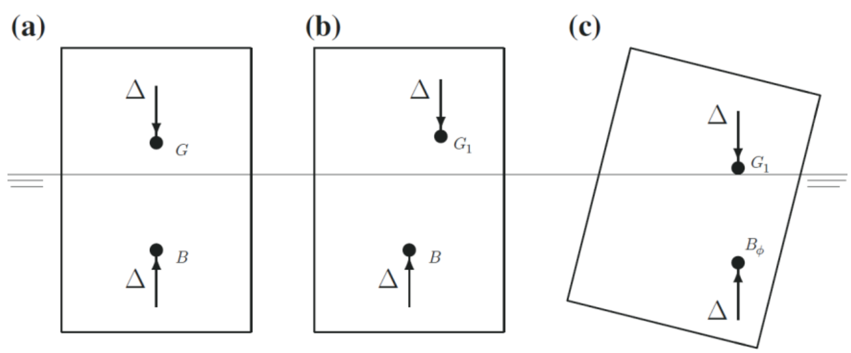


Figure 5-5 - The Effects of Off Center Centroids (Birbanescu-Biran & Pulido, 2014a)

Since the determination of the system centers of gravity occurs during the execution of Process 1, the communication of these values in addition to the base dimensional values of the barge and the system's component weights are subject to communication error. Further cognitive skills error can be introduced during the calculation of the longitudinal and transverse metacentric height of the system.

It is currently envisioned that Process 2 will calculate the even keel draft, heel, and trim. These three values are expected to be stochastic in nature due to the variability in the cargo loading. It is important to note that the determination of the even keel draft is purely a function of the barge geometry and the total system weight. The calculation of the system heel is predominantly a function of the system's transverse centroid, even keel draft, and the barge beam. The calculation of the system trim is predominantly a function of the system's longitudinal centroid, even keel draft, and the barge length. As highlighted in the previous section, there are ample opportunities to interject error either due to communication or cognitive skills. The current illustration of the model has condensed these actions into a single process. However, given the difference in focus for each calculation, subsequent revisions may subdivide Process 2 into three distinct processes.

Process 2 calculates the even keel draft, the still water heel, and trim of the loaded barge. Figure 5-6 illustrates a typical shift in the transverse centers of interest. This graphic demonstrates how a shift in the transverse center of gravity (TCG) affects the center of buoyancy (CB) and the metacentric height (M). An analogous process is applied to the longitudinal case with similar results. The static heel and trim are determined by calculating the orientation of the new waterline. This orientation is defined by the vector normal to the line of action originating from the geometric centroid of the water plane. This line of action connects the center of buoyancy to the metacenter; if the center of gravity is collinear, then no additional moment is acting upon the system. As a reminder to the reader, node 2 is the recipient of flawed input information due to communication error. Therefore, not only is the cargo centroid potentially flawed but the principle barge dimensions as well. In fact, any element of the x_1^o vector is subject to communication error. Errors in the cargo centroid and base barge dimensions propagate into the calculation of the system level centroid location and the magnitude of the weight. This error can further be disseminated to the system's resultant even keel draft, heel, and trim.

There is only one of the examined information dissemination scenarios that have the hydrostatic calculations as a dead-end activity. This means that the majority of the cases evaluated utilize this node to pass information to subsequent calculations. In these three cases, this node passes information to one or both of the final calculation nodes. One of the potential recipients of the output of the hydrostatic calculations is the floodable length module.

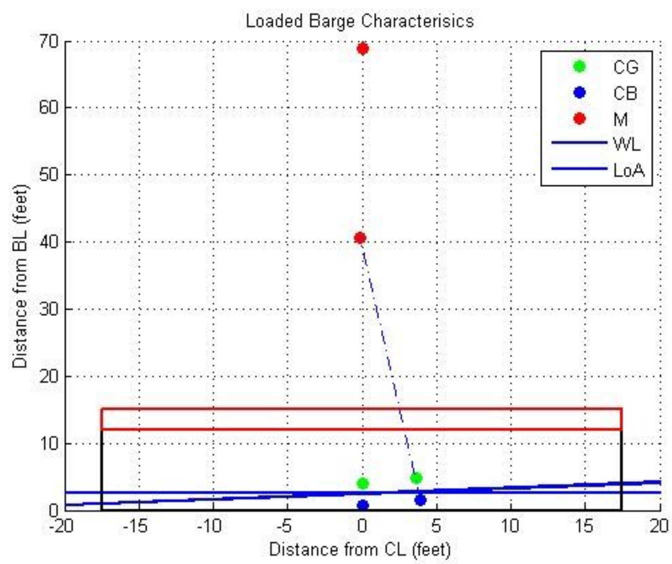


Figure 5-6 - Transverse Static Stability

Process 3: Floodable Length

Definition of the systems floodable length curve is an essential step for the designation of main longitudinal subdivision. (International Maritime Organization, 1914) Figure 5-7 below is a notional floodable length curve for a similar box barge. This curve is defined by coordinate pairs that correspond to the centroid of a theoretical "block" of water, δC_x, and the allowable length of flooding at that centroid, l. This process is typically employed in order to ensure that the longitudinal bulkhead spacing is sufficient for damage stability. In other words, the vessel may take on water over a given allowable length and will not submerge the margin line. Bulkhead compliance is evaluated with the aid of isosceles triangles. This method extends a line originating from the intersection of the baseline and the bulkhead position at an angle of $\arctan(2)$ above horizontal. These evaluation guides are depicted in Figure 5-7. The floodable length curve generated below is for an even keel draft of four feet. The barge complies with two-compartment subdivision; hence, each isosceles triangle is straddling an additional bulkhead location. The even keel draft, heel, and trim will all affect this calculation. This information would be ideally provided by the hydrostatic analysis, node 2. This is the first process that could have received potentially flawed information from two sources. Communication error in the base dimensions, coupled with the derived system hydrostatic properties, have a direct effect on the set compliant bulkhead arrangements.

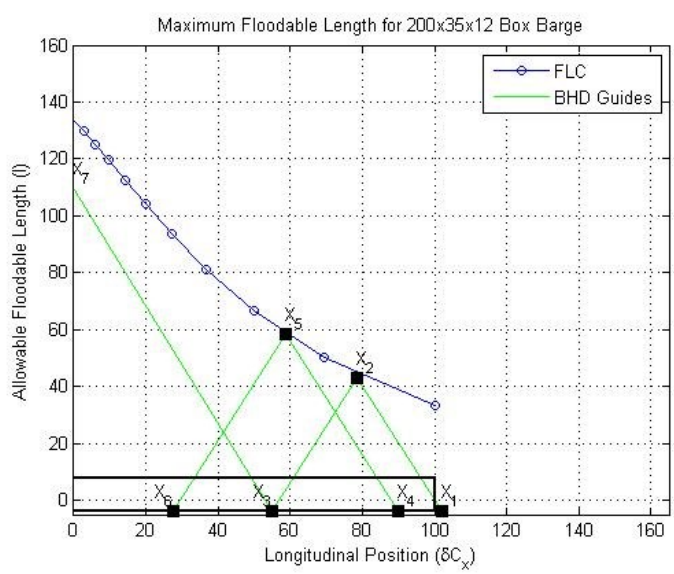


Figure 5-7 - Notional Floodable Length Curve

The principle outputs of the Floodable Length Analysis are the main subdivision bulkhead locations, and the coordinates of the floodable length curve. These are end process outputs for this model, and will be evaluated against an ideal baseline with no induces error.

A nominal output of the floodable length calculation is presented in Figure 5-8. The most prominent feature of this graphic are the five “peaks” or the apex of the five isosceles triangles. These apex points represent the length of flooding under evaluation. If the apex is above the allowable floodable length curve, then the length of flooding is too great to pass the subdivision requirements. Figure 5-8 clearly documents that, in this case no two adjacent compartments may be flooded without immersion of the deck edge. One can begin to see that based upon the barge dimensions and the loaded draft provided, it is possible to have specific solutions that span from noncompliant in any compartment pair to fully compliant. For this thesis the information presented to node 5 from the floodable length calculation is the difference between the apex value and the corresponding value on the floodable length curve, Figure 5-11 and Figure 5-13.

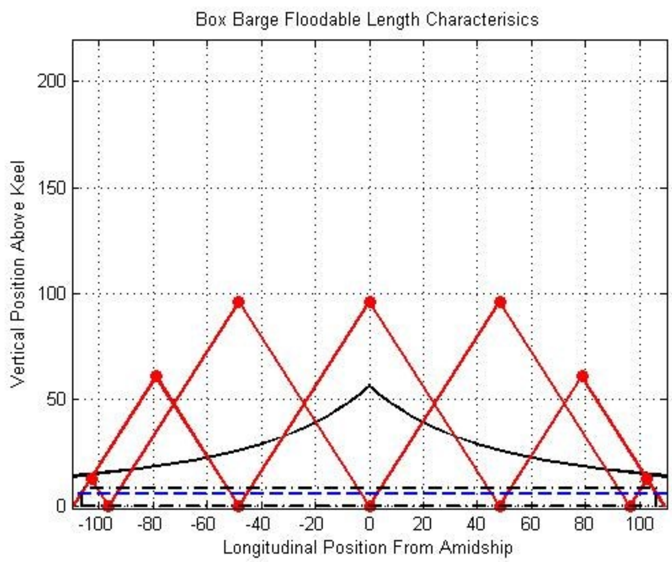


Figure 5-8 - Two Compartment Floodable Length

Process 4: Roll Stability

This process will examine the roll stability of the overall system. Figure 5-9 displays the righting arm curve for the subject barge at a draft of four feet. The righting arm plot is directly influenced by the applied heeling moment. "Heeling moments can be caused by wind, by the centrifugal force developed in turning, by transverse displacements of masses, by towing, or by the lateral pull developed in cables that connect two vessels during the transfer of loads at sea" (Birbanescu-Biran & Pulido, 2014b). The righting arm is the effective lever arm between the lines of action of the center of buoyancy and the center of gravity. If a floating vessel has a transverse center of gravity equal to zero, then this curve will originate from the origin, proceed to some maximum value and then return towards the baseline. The second root of this function is called the angle of vanishing stability. In this case that angle is 90 degrees. This is the point at which the vessel will capsize.

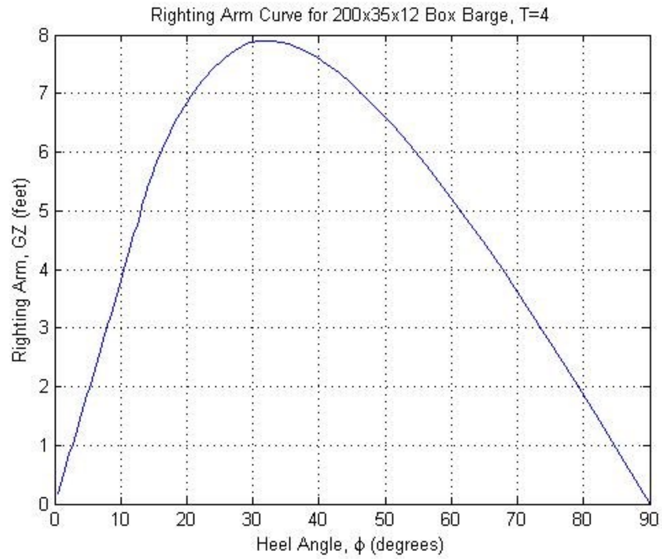


Figure 5-9 - Typical GZ Curve

In the current model this process receives information from two previous sources. Again, similar to the floodable length process, the results of this process will be utilized to evaluate the overall reaction of the system due to induced error. This process will require information on the vessels centerline cross section and information regarding the hydrostatic disposition.

The principle output of this process is the calculation of a standard lever arm versus angles of static heel. This curve is an approximation of the overall stability of the vessel. This process provides another opportunity to examine the quantitative effect of error on the system. The GZ curve will exhibit volatility as the input parameters, hull dimensions and the hydrostatic properties are stochastically perturbed. Once an ideal curve is established, this baseline can be evaluated against the rest of the population to determine the effects of induced error on the system.

The last independent process to be discussed is the roll stability process. Figure 5-10 displays a cross sectional elevation of the notional barge. There are two solid lines depicted on the diagram that represent the resultant waterline at the 0 and 90 degree roll positions. In addition to these waterlines, there are two dash-dot lines that represent the linear range of roll for both waterlines. It is important to understand that within this linear range the waterplane centroid does not move. The area between the two linear regions requires some special attention. Essentially, the process enforced a fixed angle of roll and then allowed the barge to settle to maintain hydrostatic equilibrium. The migration of the waterplane centroid and the center of buoyancy have also been mapped as the barge executes a 90 degree roll. One can begin to see how the righting arm is calculated as a function of roll angle. This is traditionally labeled as the GZ length, or the perpendicular distance from the center of gravity to line of action containing the transverse metacenter and center of buoyancy. The maximum righting arm, initial metacentric height, and the integral areas from 0 to 30 and 40 degrees all are used as indicators of stability sufficiency. (O'Rourke, 2012)

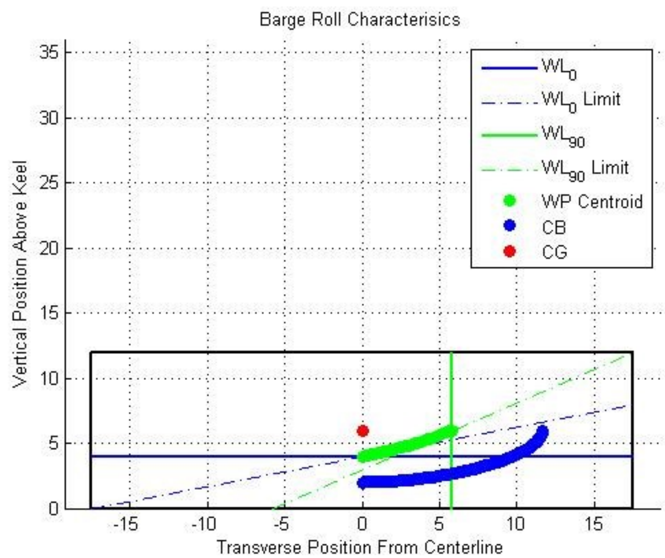


Figure 5-10 - Barge Roll Characteristics

Results & Discussion

The following results are presented for the floodable length process and the roll stability process. Each of the four unique configurations will be addressed in turn. The following analysis will focus on communication error solely for the floodable length process. Both communication and cognitive skill will be addressed in the roll stability results.

Floodable Length Results

Does the team structure affect the outcome? This is the first question undertaken in this discussion. Recalling the four distinct communication paths, one plot has been provided for the output of the floodable length process. For this analysis there is a fixed communication error applied consistently across all of the communication paths. In addition, there is not cognitive skill error interjected at this point. The charts will be discussed in pairs based upon where the input information was provided. Figure 5-11 and Figure 5-13 receive their information directly, while Figure 5-12 and Figure 5-14 receive their information indirectly. The most notable feature on this set of graphs is the similarity of shape within a corresponding couple. Examination of the first graphical couple composed of Figure 5-11 and Figure 5-13 reveals that in both information configurations the majority, nearly all, of the runs pass the floodable length analysis, with the proposed longitudinal subdivision. Two distinct response patterns are presented within this couple. The first pattern only documents a reduction in the excess floodable length at bulkhead number 4. The second documents a reduction in the excess floodable length at bulkheads 3 – 5. This seems to imply that given direct communication to this process one should expect one of two possible outcomes, with the upper response pattern seemingly as the mathematically-preferred solution.

The next graphical couple also yields some interesting comparative observations. First, two new response patterns are introduced and one has been removed. This yields a total set of three possible responses, two of which were not previously evaluated. Again, the similarity between Figure 5-12 and Figure 5-14 is undeniable. Also of interest is the fact that the preferred solution presented in the previous couple is no longer presented as a viable solution. Within this couple there is a clearly preferred response.

Since the stochastic nature of the inputs has been preserved, the most likely explanation for the disparity between these graphical couples is the information pathway. Physically within the ship design case study, the output of Figure 5-11 and Figure 5-13 indicates that the original subdivision is sufficient. While the output of Figure 5-12 and Figure 5-14 tend to indicate insufficient subdivision.

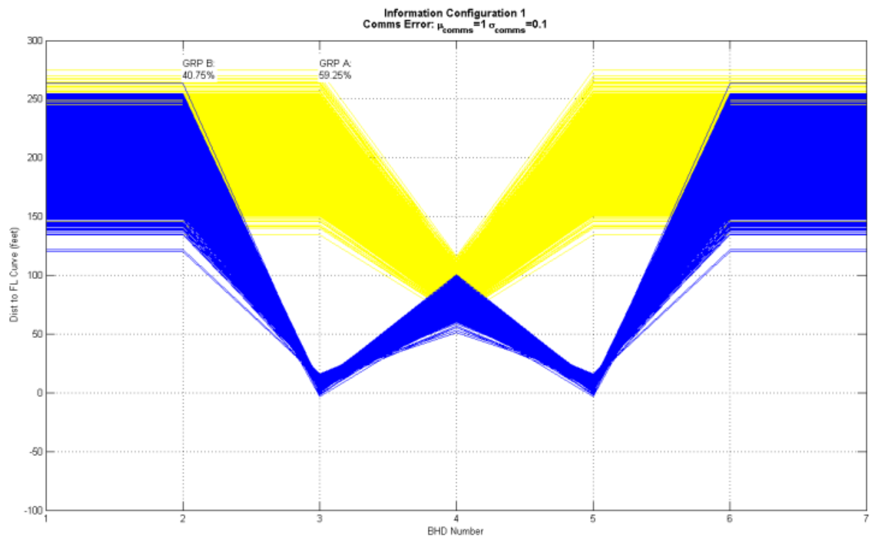


Figure 5-11 - Excess Floodable Length: Config 1

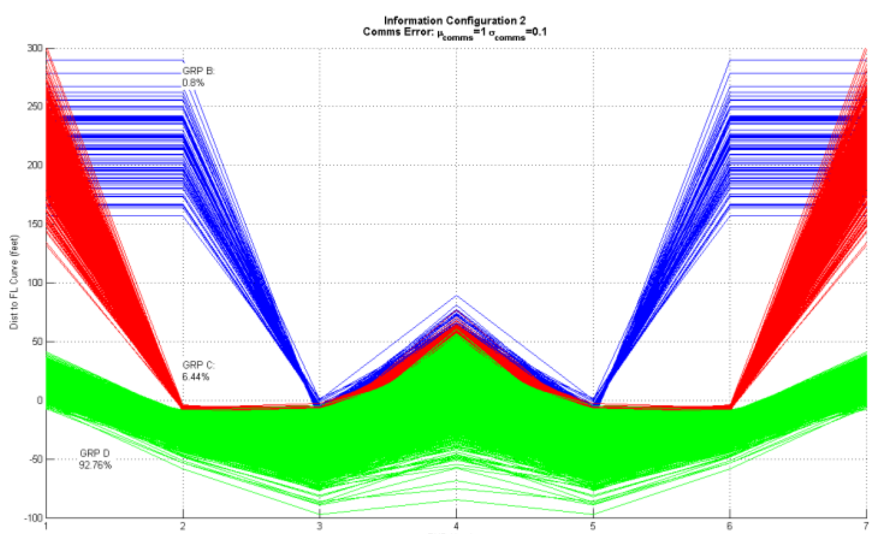


Figure 5-12 - Excess Floodable Length: Config 2

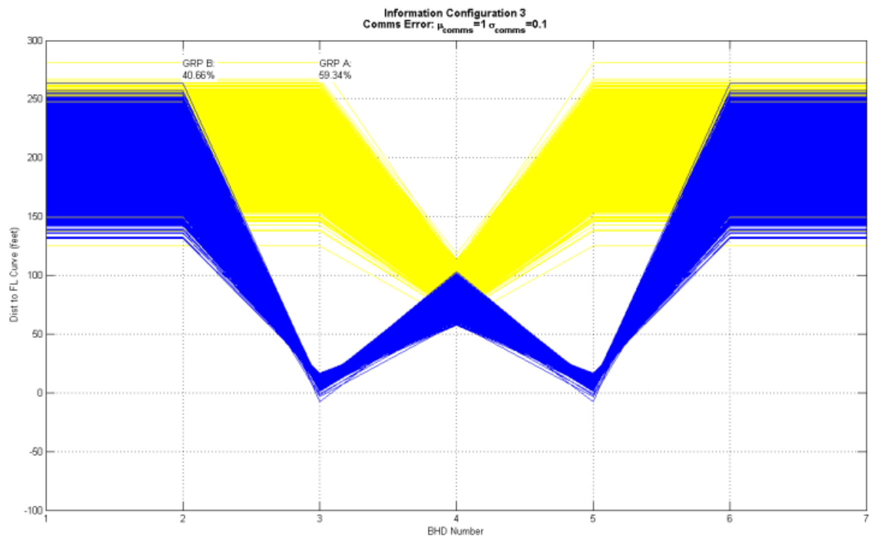


Figure 5-13 - Excess Floodable Length: Config 3

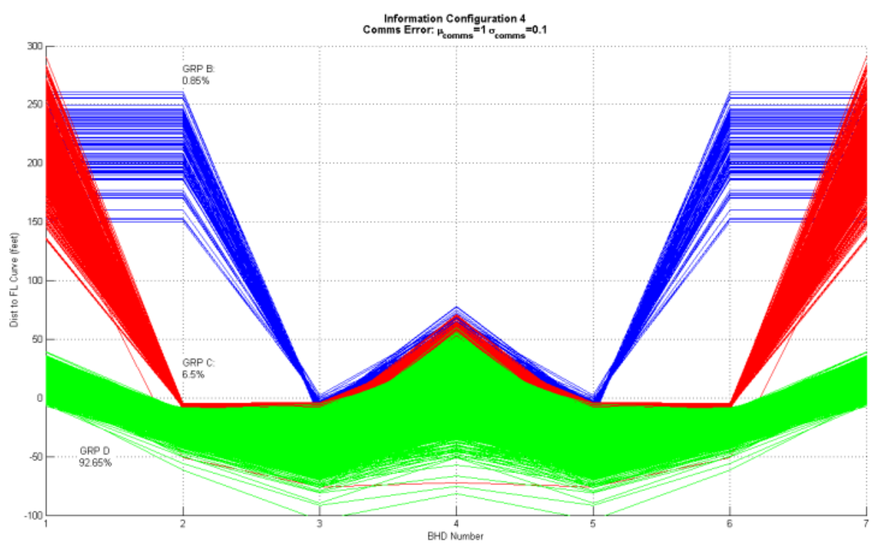


Figure 5-14 - Excess Floodable Length: Config 4

Roll Stability Results

The difficulty of naval ship design is a function of many factors but one undeniable truth is that the type of design activity impacts the difficulty of the project as well as the strategy used to manage the design. This section will be used to describe how ProFET has successfully emulated three design concepts: an oiler, DDG Flight IIa, and LCS. In addition to describing the design concepts, a discussion of how the method can be used to manage the implications of the combination of communication error and cognitive skill has on variability propagation will be presented.

A major theme of this thesis is, “are the assumption of normality valid?” This is the second question this analysis will undertake. Continuing with the analysis of the area beneath the GZ curve depicted in Figure 5-9. Figure 5-15-Figure 5-19 display a normalized histogram of the total area beneath the GZ curve. The mean, standard deviation, skewness, and kurtosis are presented for each distribution as a function of information configuration. The following distributions demonstrate no appreciable mean shift, present approximately symmetric data sets, and exhibit an appropriate level of kurtosis for normal distributions. (Bulmer, 1967) For this calculation, Figure 5-15 and Figure 5-16 both receive their input information directly from node 1, Cargo Definition. This implies that increase in the standard deviation growth illustrated in Figure 5-17 and Figure 5-18 is the result of receiving the required input information indirectly. The average standard deviation of the configurations with direct communication is 100.73 ft-deg. The average standard deviation of the configurations with indirect communication is 128.68 ft-deg. This 28 percent increase is attributable to the induced communication error experienced as part of the information dissemination pathway. It is an assertion of this analysis that the inclusion of additional incremental calculations will directly increase the resultant standard deviation.

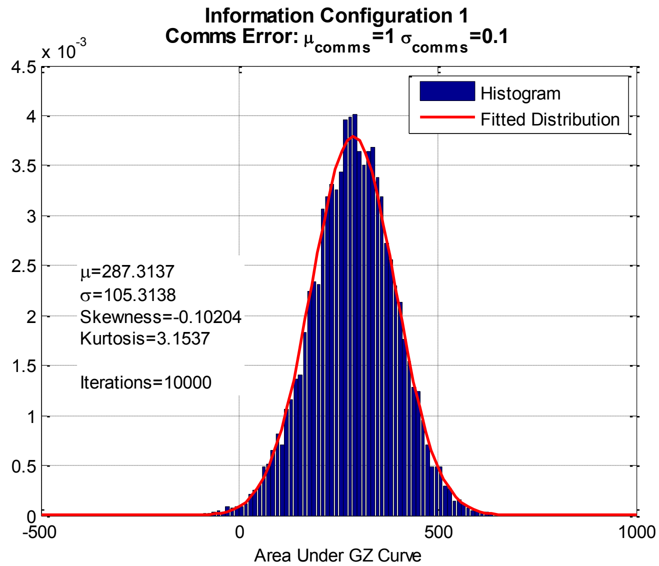


Figure 5-15 - GZ Area Distribution: Config 1

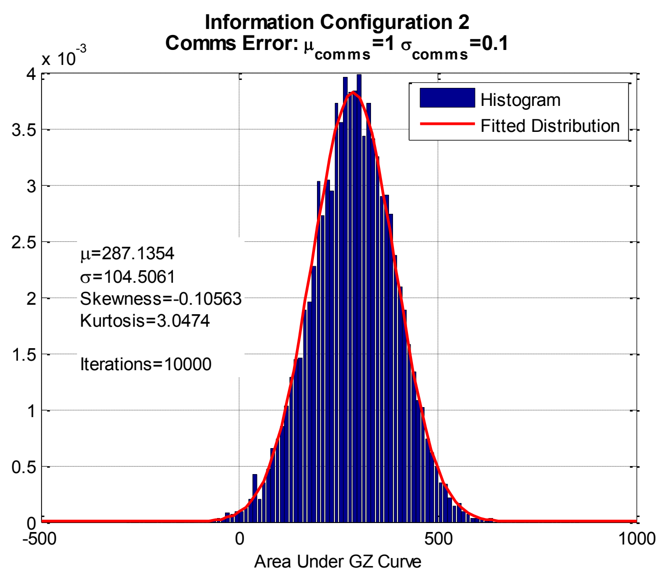


Figure 5-16- GZ Area Distribution: Config 2

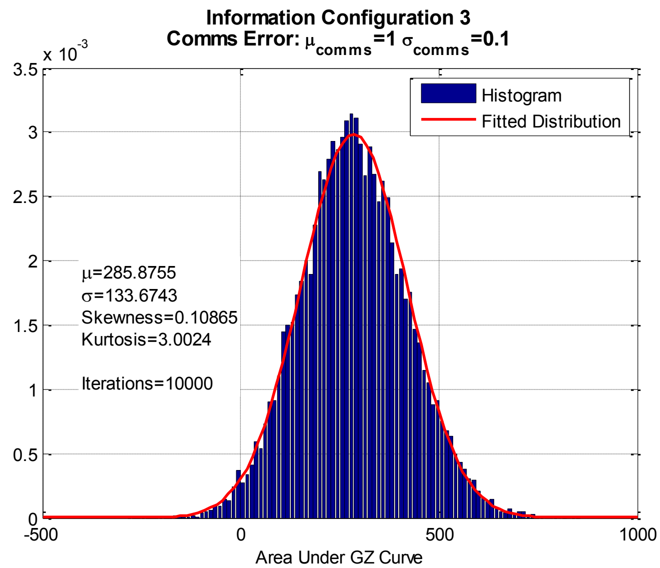


Figure 5-17- GZ Area Distribution: Config 3

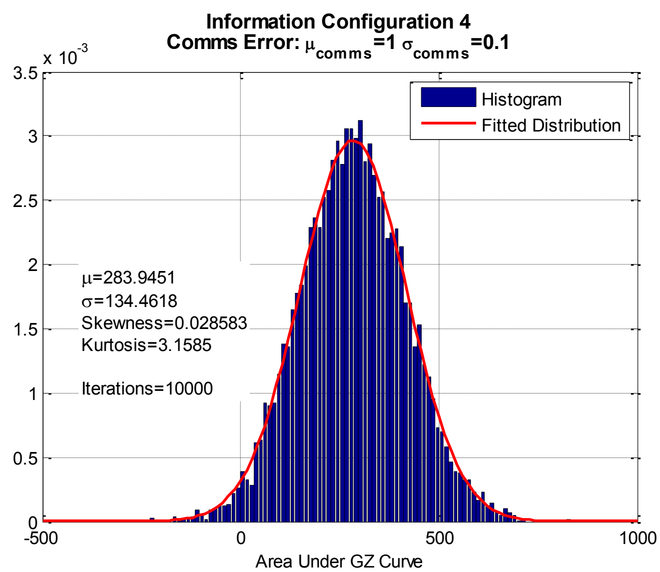


Figure 5-18- GZ Area Distribution: Config 4

Figure 5-19 is provided to show the effect of surface resolution, and begins the discussion of the combination of communication error and cognitive skill error. The work presented here is one of the major contributions of this thesis. This surface was created by sweeping the communication standard deviation and mean of zero to two. The functional value assigned is the calculated skewness and kurtosis of the GZ distribution. Remember that in order to have a normal distribution the skewness and kurtosis should approach zero and three, respectively. If one considers Figure 5-19, the first row is a 5x5 surface; while it creates a computationally crude surface the evaluation time is very short when compared to the 15x15 surface. The interesting finding is that even the crude approximation shows a similar trend of increasing standard deviations with commensurate increases in the mean. This creates a "safe zone", in the southeast, where the normality assumption holds.

The next question becomes apparent when one considers if these results are consistent across all of the communication configurations. Figure 5-20 and Figure 5-21 present the kurtosis and skew surfaces for communication pathways 1 and 3, at the previously described fidelities. The kurtosis surfaces show good agreement amongst all the results. The notable exception is kurtosis surface 3 with the 5x5 resolution. The cause of this loss of the area, where the normality hypotheses hold is likely due to the low surface resolution and potentially an extreme event with in the following ranges: $\sigma_{comms} = [0.5,1.0]$, $\mu_{comms} = [1.5,2.0]$.

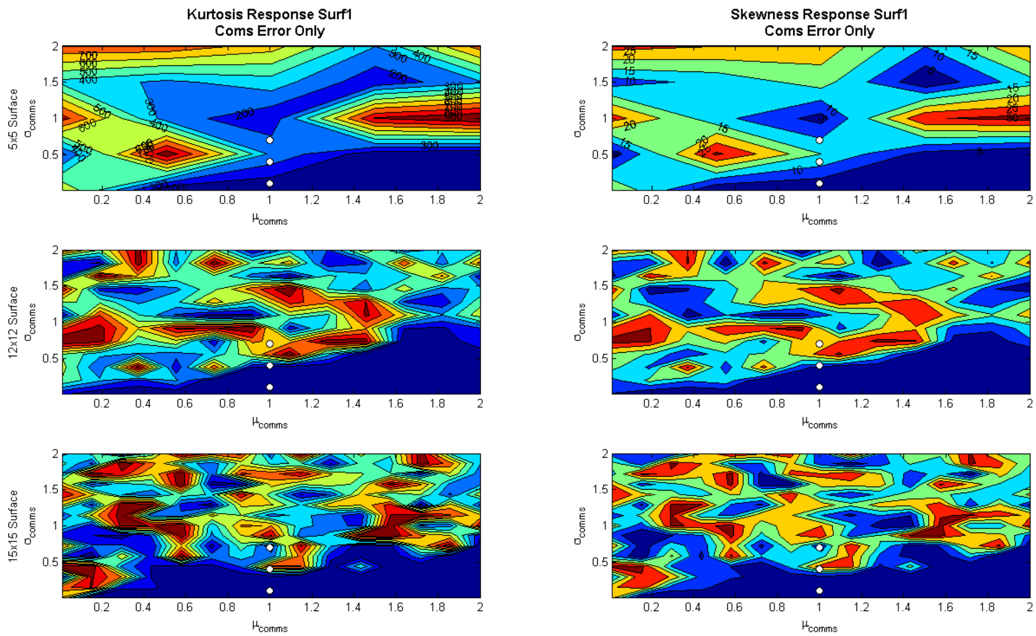


Figure 5-19 - Surface Resolution Comparison

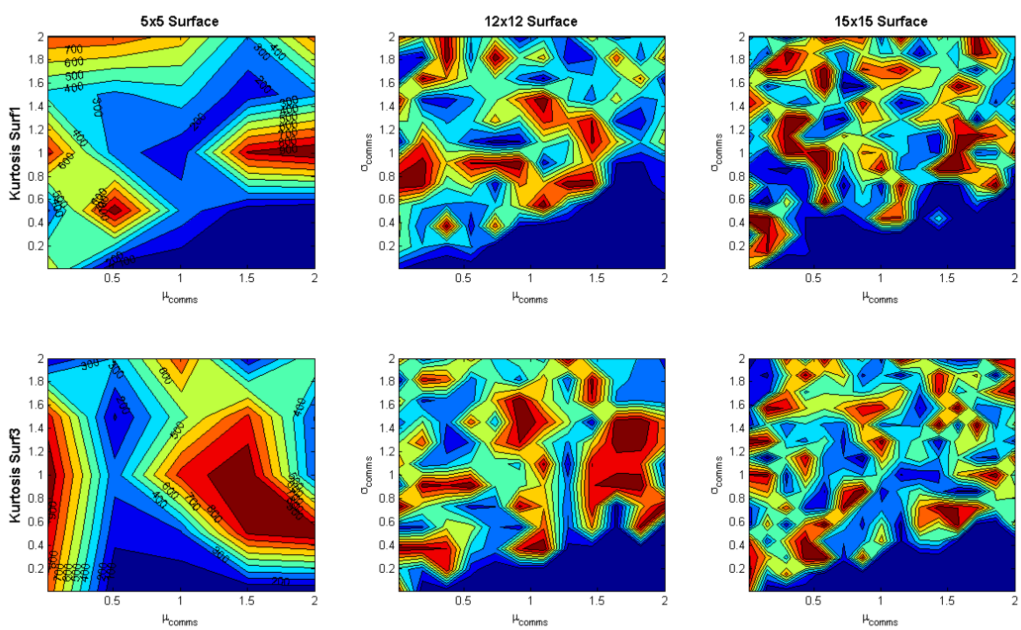


Figure 5-20 - Kurtosis Surfaces for each Path

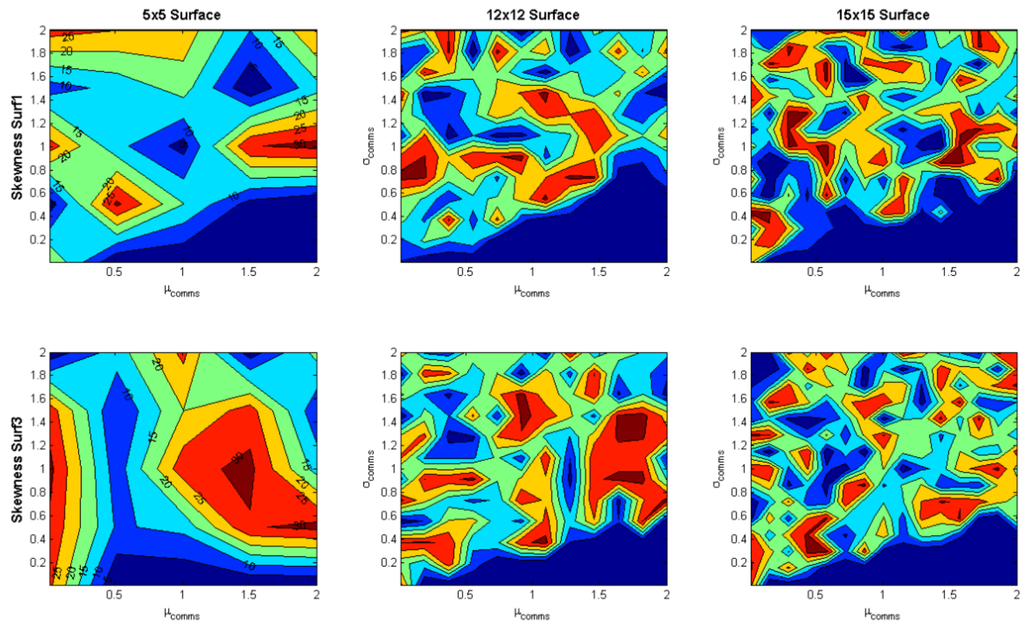


Figure 5-21 - Skewness Surfaces for each Path

The skewness surfaces also yield similar results as the kurtosis surfaces presented previously. Good general agreement across communication pathway and fidelity with a few exceptions. Once again, the third communication path at the 5x5 grid illustrates a loss in the safe area of the southeastern section of the graph, with a localized high value at [1.5, 0.5]. This time, the fourth communication pathway also exhibits a similar behavior, although the high value is present at [1.0, 0.5]. In both cases, I feel that the resolution for those particular runs contribute significantly to the loss in the safe area. Normality as the null hypothesis is valid for a range of values that generally fall within the southeastern quadrant of the surface plots. This is good agreement across communication pathway and surface fidelity.

How does the assumption of normality hold up once cognitive skill error is introduced? Figure 5-22 and Figure 5-23 once again presents the kurtosis and skewness surfaces of the righting arm area distributions. However, this time, a fixed mean and standard deviation for communications have been selected. With a fixed communication error, ProFET allows for the systematic sweeping of the mean and standard deviation for cognitive skill error. Communication error has been selected to be the fixed entity because it may be less controversial to quantitatively measure. Although, this process of sweeping the team's cognitive score is helpful, rudimentary assessment techniques for team building would begin to convey a rough estimate of the team's cognitive competence. Figure 5-22 presents three distinct coordinate pairs, across all four communication pathways. These coordinate pairs are marked on Figure 5-19 for reference, and listed as column headers within Figure 5-22 and Figure 5-23.

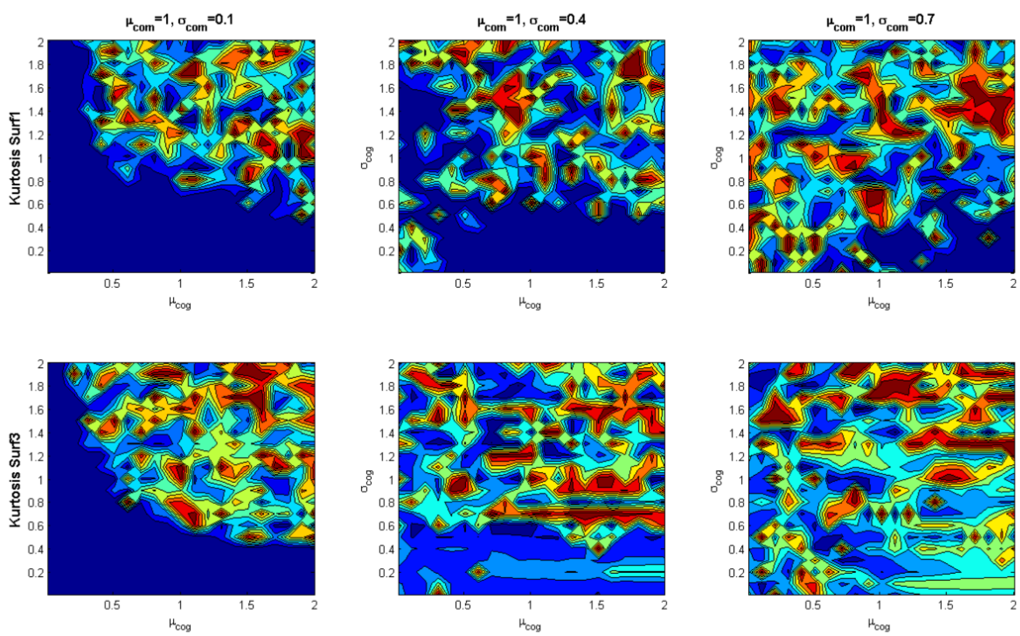


Figure 5-22 - Kurtosis Surfaces with Cognitive Error

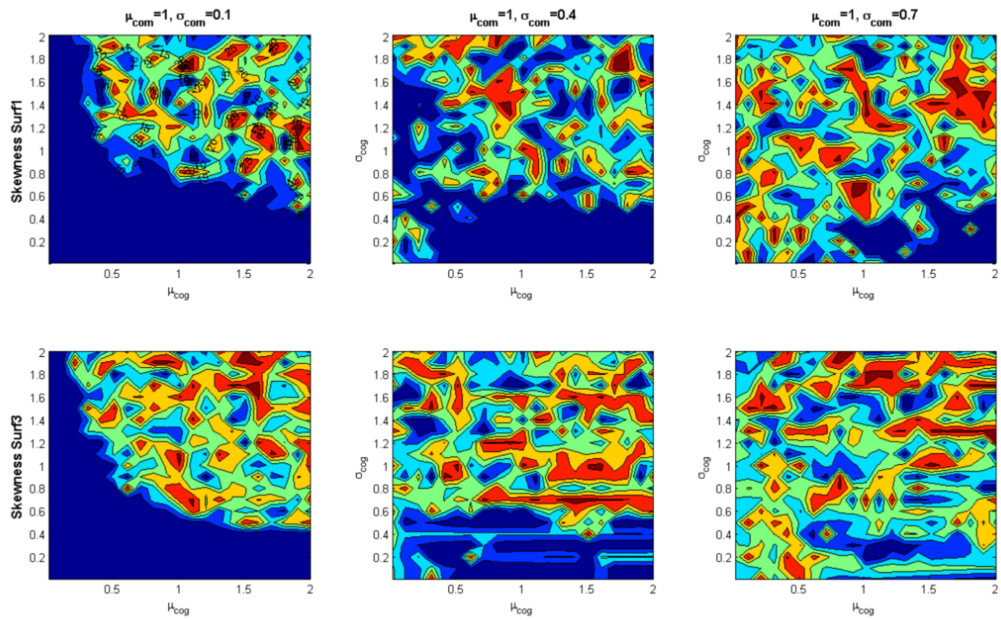


Figure 5-23 - Skewness Surfaces with Cognitive Error

The difficulty of naval ship design is a function of many factors but one undeniable truth is that the type of design activity impacts the difficulty of the project as well as the strategy used to manage the design. Figure 5-24 and Figure 5-25 will be used to describe how ProFET has successfully emulated three design concepts: an Oiler, DDG Flight IIa, and LCS. Additionally how the method can be used to manage the implications of the combination of communication error and cognitive skill have on variability propagation will be discussed.

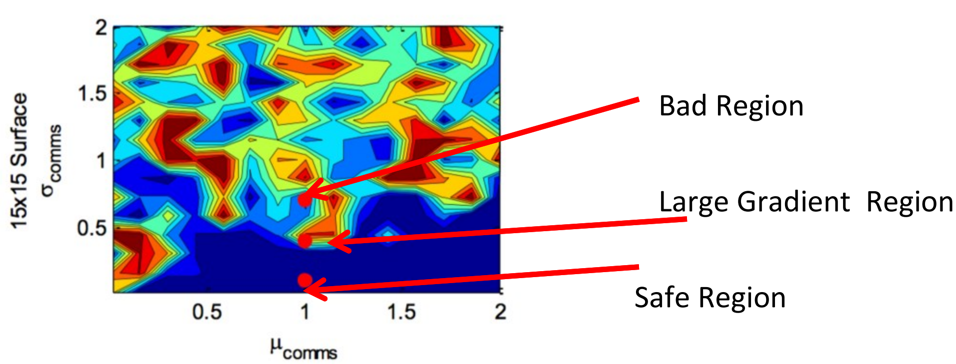


Figure 5-24 – Communication Error Evaluation Locations

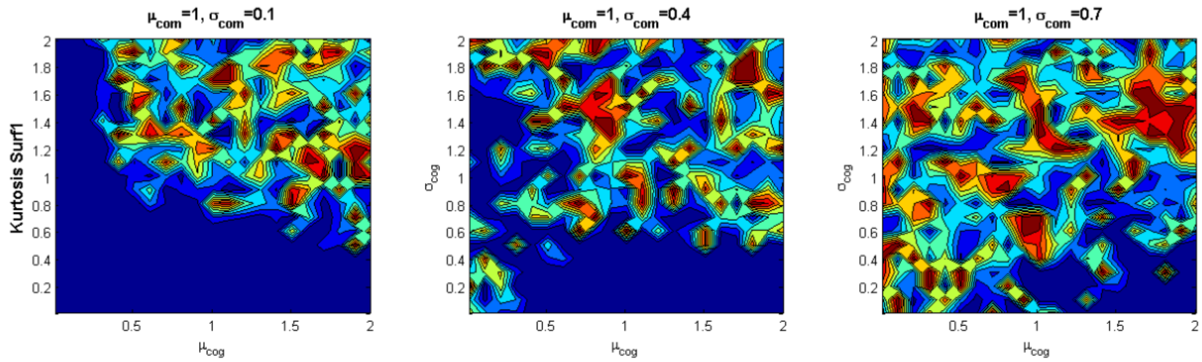


Figure 5-25 - Cognitive Skill Kurtosis Plots for Each Communication Error Evaluation Locations

There are three dots identified in Figure 5-24. Figure 5-25 shows the kurtosis of the sweeping through the mean and standard deviation of cognitive skill error for the stability node at each of the three communication error locations. As I evaluate Figure 5-24 and Figure 5-25 some unique conclusions and contributions are identified.

First, as the mean of communication error increases to an extreme unrealistic value, the results of the stability calculation are obviously incorrect, but the kurtosis plot shows that as the mean increases a large safe region is created. This safe region is created due to the fact that the large value of the mean dominates the statistics. The opposite extreme can be seen in the same plot, Figure 5-24. When the mean of communication error is zero, then the output statistics are dominated by the standard deviation. In this case, the kurtosis value is large meaning that the output statistics are not normal. As stated earlier, when the input statistics don't match the output statistics humans have a very difficult time predicting the outcome.

Second, the three dots located on Figure 5-24 represent three distinctly unique design locations. These cases are the safe region, large gradient region and bad region. The three dots shown in Figure 5-24 are the locations of the communication error at a mean of 1.0 and a standard deviation of 0.1, 0.4, and 0.7, respectively. At these communication error locations, a sweep of cognitive skill error is provided in Figure 5-25. The surface plots demonstrate the interdependency between communication error and cognitive skill error.

If one looks at the three points in the communication surface plot, one can see that the safe area is a point located where the kurtosis is very low. The corresponding cognitive skill surface plot, the left most plot in Figure 5-25, shows a distinctive shape similar to a Pareto front. There is a large safe region when compared to the other plots. This is akin to the design challenges associated with designing a relatively simple ship, such as an oiler or another basic auxiliary ship. It is relatively difficult to fail in the design of a basic ship. As one sees in this case, since the communication error is located in a safe region when normally distributed variability enters the stability node normally distributed variability exits that node. Within this safe zone, one can see that it takes a relatively large combination of cognitive skill error mean shift and standard deviation to produce large kurtosis values. If one extends the corollary idea of designing an oiler, then, as one would expect, as long as the communication is good, the stability engineer's skill would have to be poor to cause a situation where the kurtosis is high.

The second dot is associated with a region described as the large gradient region. This is a region located where communication error has a mean of 1.0 and a standard deviation of 0.4. It should be noted that this location is right on the border between the safe region and the bad region. If one evaluates the cognitive skill surface plot for this location, one sees something different; the safe zone no longer resembles a front and the surface begins to become chaotic. The plot, middle graph in Figure 5-25, shows that the safe region now only exists when the cognitive skill mean is higher than 0.5 and the standard deviation is lower than 0.5. Regardless of the mean value, above a standard deviation of 0.5, the surface has many peaks and valleys. An additional interesting finding is that, below a mean of 0.5, any standard deviation value can produce pockets of large kurtosis. At this design location, one can see that controlling the standard deviation of cognitive skill error is the key to staying in a region of good probabilistic intuition.

The traditional belief in naval design management is that if you control sigma, the mean will take care of itself. ProFET has shown that the standard deviation in this case is what is driving the high kurtosis values. It is not that the mean takes care of itself, but that if you want to increase the understanding of how the variability will propagate within this design, then you need to control variation. The design of the DDG IIa is a good example of how this idea is executed in practice. The DDG IIa was a redesign of an existing vessel in which capability was increased through the introduction of a few architectural changes such as plug and play technology and the inclusion of a vertical launch system. During my time as a ship design manager, I had the privilege of working with some of the DDG IIa design managers. The key to managing this program, according to them, was to make sure that they had confidence in the ability of the engineers working on the design. Given that the design was based on an existing ship there were many constraints. Additionally many of the details associated with the existing design were missing or misrepresented. Given that the information received by an engineer could possibly be incorrect the only way one could manage the program was to guarantee that the analysis completed by the engineers was correct. If one looks at the surface plot of the cognitive skill for the large gradient case, this is what one can see. If you want to maintain your intuition you need to stay in the safe region, which in this case is located where the engineer's skill is near perfect.

The final location for discussion is the bad region. In this region, the standard deviation of communication error is high. From the cognitive skill plot, one sees that the surface is chaotic with no clear reasonable safe region. Regardless of the skill of the engineer, the output from the stability node is not normal. The corollary to this example is the LCS program. From a congressional report, "The LCS program has been controversial due to past cost growth, design and construction issues with the lead ships built to each design, concerns over the ships' survivability (i.e., ability to withstand battle damage), concerns over whether the ships are sufficiently armed and would be able to perform their stated missions effectively, and concerns over the development and testing of the ships' modular mission packages." (O'Rourke, 2013) The LCS program's issues are not relevant to this thesis, but what is relevant are the characteristics of this program that ProFET can model.

Regarding the communication error, the LCS programs mission and budget requirements were a moving target. This is well documented. This is akin to the large communication error standard deviation that is seen in Figure 5-25. Additionally, many of the tools needed to analyze the LCS performance had never been developed. Again, the communication of the results had a large standard deviation. As the design was being developed so too were the analysis tools. As one can see from the cognitive skill surface, one quickly loses probabilistic intuition. How the design evolves is a function of how the variability propagates through the design activities. Even with the best engineers, there is little that can be done to track how the design system will respond over time. This is what the U.S. Navy saw within the LCS program. With the methods developed in this thesis one could articulate that, in a program like LCS, unpredictable failures may occur.

Conclusion

The goal of this chapter was not to develop an object oriented design synthesis tool. The goal was to demonstrate the value of ProFET through the combination of communication error, communication pathways and cognitive skill. An additional goal was to demonstrate how, through the introduction of cognitive skill, probabilistic intuition can quickly erode. Extending the ProFET model to include cognitive skill error enabled simulation of a design team activity to understand the impact of communication pathways.

Effects of communication and cognitive skill were evaluated through variability propagation, specifically, if inputs lead to normally distributed outputs. This was measured and analyzed through kurtosis and skewness surfaces which were created for each pathway. Using ProFET's ability to emulate the design process through the pathways allowed me to identify areas of interest within the product (i.e., bulkheads 3 and 5 in Figure 5-11) as well as the impact of error on the available solutions. This supports the conclusion from the previous chapter that the product, process and people are strongly linked in design and that the ProFET model can mathematically identify unpredicted areas of concern in each of these aspects.

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Chapter 6

Contributions

I have developed a mathematical construct that is applicable to every design endeavor. Any effort that requires the use of teams, interpersonal communication, or the application of cognitive skill can benefit from ProFET. It is a unique representation of design team behavior utilizing state space modeling techniques. The mathematical application draws inspiration from physical system modeling, control theory, and multistage manufacturing processes. A multitude of potential team parameters could have been selected, but interpersonal communication effectiveness and cognitive skill assessments seemed the most obvious first steps. This selection is due to the prolific discussion on the need for effective interpersonal communication and the general acceptance of cognitive testing as an indicator of performance potential. ProFET brings the importance of interpersonal communication and team member's cognitive skill to the forefront of the discussion about design team effectiveness.

ProFET contributes to the fields of Naval Architecture, Systems Engineering, Organizational Engineering and Organizational Analysis.

The Naval Design Community has been mapping the design process for 20 years in order to assess how to reduce error and automate much of the design calculation process. Most modern engineering communities have resorted to the "black box" approach. This approach provides excellent repeatability, and multiple codes are linked together with little user interface. The teams skill set must be variable with respect to time in order to accomplish the required objectives of each phase of the design process. ProFET develops a metric for the design process that is sensitive to the team composition and structure. This metric is applied to a domain that is traditionally devoid of objective scoring. With the use of ProFET more informed decisions on team structure and composition can be made at critical junctions of the design process.

The domain of systems engineering has evolved from the quality revolution. This is a process heavy discipline that focuses on the programmatic questions regarding design phase specific techniques and scheduling matters. Unfortunately, it has lost touch on the human element of the engineering process. The ability to assess a team in situ and with data logging, temporally, is a tremendously powerful metric. In short, ProFET will help to predict the error propensity of the team at a discrete time, and it would then be the responsibility of the systems engineer to ensure that alignments with difficult project sections are avoided. A ProFET assessment should be incorporated into formal Risk Management approaches.

Organizational Engineering and Organization Analysis have been utilized extensively since the quality revolution. Teams quickly became the focal point of effective working environments. Unfortunately, team analysis is left with generic attribute types, or personality preferences. ProFET analyzes the reaction of the total team rather than the individuals within the team. Further, ProFET provides an objective score in a domain that is dominated by pairs of opposing characteristics. This scoring allows for an easier comparison of the design team's effectiveness. The following recounts the novel contributions presented in this dissertation:

- Repurposed stream of variation model for analyzing variability propagation through communication pathways.
- Demonstrated how the model can be applied to emulate communication within a design process.
- Identified and proved that variability propagates through relationships between product, process, and people.
- Demonstrated that processes can exhibit large shifts in success due to small increases in error, causing phase transitions from a reliable to an unreliable process.
- Analyzed the impact of communication pathways through the lens of variability propagation and normality of output distributions.
- Demonstrated ProFET's ability to mathematically link process and product. Figures 5-11 – 5-14 highlighted the methods ability to identify not only areas of design interest (bulkhead 3 and 5 in Figure 5-11), but the impact of error propagation of on available solutions as well (Figure 5-12).
- Through the addition of cognitive skill, ProFET's ability to provide designers a guide to probabilistic intuition has been demonstrated. The analysis of Figure 5-24 and Figure 5-25 clearly shows that the relationship between communication skill variability and cognitive skill variability is complex and often non-intuitive. It is important to note that one of the major contributions of this work is the realization that for complex naval design a mathematical method that enables designers to understand when and where their intuition will fail is more

important than the actual results of an analysis. Through the use of kurtosis surface plots, ProFET successfully modeled when, where and why designer intuition would be challenged.

CHAPTER 7

Future Work

The methods and results in this dissertation have laid the foundation for further investigation into the relationship of team dynamics and process outcomes. The theory and methods behind ProFET are general enough to permit modeling of a wide range of human interaction, and captures how those interactions and the people involved contribute to a process. Identifying and modeling these underlying mechanics creates a new perspective of the design process, which in turn enables many new analysis opportunities. A few types of analysis were explored in this dissertation demonstrating how ProFET could be used. Building from this foundation, this section will outline other possible applications and analysis.

Intelligent Integration

The multidisciplinary case study demonstrated how communication pathways can have significant impact on process outcome. In the case study, node 5 represented an integration of the information created by the engineering processes. However, node 5 only observed the information, it did not operate on what it received. Adding a method for actual integration and feedback to the overall process in node 5 may assist in better capturing team dynamics. This could be done by not accepting egregious errors or resubmitting data to previous calculations.

Doing so would model oversight by a manager or a group review process which is currently not included in ProFET.

Network Theory

ProFET models the processing and transmission of information through a team of any size. In this dissertation, the largest team considered had 4 "members," each with their own set of methods. One can imagine how modeling an actual design team or even a full organization would require many more modeling steps and analysis. This may make full parameter sweeps and consideration of all possible communication pathways intractable. Incorporating network theory into ProFET analysis may help alleviate these issues. Network metrics based on communication structure could be incorporated with ProFET to recognize sections of communication pathways that are most critical to the process. These sections could then be separately modeled and analyzed to be used as proxy for the overall team, which may be impractical to model.

Topology Analysis

Kurtosis and skewness topologies were created to analyze the relationship between team structure and process predictability. The topologies were compared to find and understand which parameters led to predictable outcomes, but the topologies themselves were not actually analyzed. Topology characteristics, such as the percentage of distributions represented or the clustering of distributions, may provide new insight into process performance. For example, identifying the distance to "regions of safety" where the process is predictable may indicate how difficult it is for a team to correct once a process becomes unstable.

Temporal Effects

ProFET currently models a purely unidirectional communication model in which information flows through the team. However, in a real team environment, information is generated over time and arrival of information is critical to how decisions are made and a process progresses. Modeling the temporal aspects of information generation and transfer may give insight into how a process should be approached. Additionally, it presents an opportunity to incorporate iterative communication within a team that may contribute to process outcomes.

Regardless of which directions future researchers take, ProFET and its methods have unique potential to assist in learning about team dynamics and mechanics that drive successful processes.

Appendix

Impact of Error Propagation within a Design Team

Jason D Strickland[1] and David J Singer[1]

ABSTRACT

Modern engineering projects rely on three critical components: People – Process – Products. The goal of this paper is to document the development of an objective mathematical framework that is capable of accounting for the inherit communication and technical skill of a design team. This technique will begin to apply rigor and consistency to this traditional, 'soft science'.

KEY WORDS

State space model; communication error; cognitive skills error; design team

INTRODUCTION

The quality revolution has married the concepts of engineering and management. Regardless of the discipline chosen almost all process improvement cultures have applied analytical tools to the process and the product portions of the triad to measure, predict, and control the result. This paper will document a technique to analyze a new aspect of a design team of design team performance. The trick becomes the interfaces between zones and managing the inevitable conflicts between major disciplines. While these topics have received more academic interest (Deming, 2000; Drucker, 2011; Juran, 1989; Sobek II, Ward, & Liker, 1999; Taguchi, 1995) recently the effects of team dynamics, specifically designer proficiency and communication ability, have never been applied to the assessment of design robustness in a mathematical framework. This construct will begin to explicitly quantify that intangible quality of a 'good' team, and to assist in the differentiation of why some teams succeed in obtaining the initial goal and others do not.

In regards to process control, Taguchi's famous three steps: system design, parameter design, and tolerance design (Taguchi, 1995) ignited a new paradigm that the control of the production and manufacturing process would ultimately lead to high customer satisfaction. This is summarized by his *first paradigm: quality problems of a product under customer usage conditions are only the symptoms of the functional variation*. (Taguchi, 1995) Within quick succession a host of other techniques gained prevalence, Total Quality Management (TQM), Lean, and Six Sigma. These techniques have a broad appeal to other sections of business as well. *TQM, which was not only dealing with production but also all other processes in the company* (Dahlgaard & Dahlgaard-Park, 2006) was quickly adopted, and then discarded in favor of Lean. *[Lean] has its origin in the philosophy of achieving improvements in most economical ways with special focus on reducing muda (waste).* (Dahlgaard & Dahlgaard-Park, 2006) Finally, Six Sigma started as a mechanistic technique but has grown to be *the envelope for all that Six Sigma and an associated quality initiative stands for, including a methodology for implementation.* (Tennant, 2001) This evolution culminated in the modern International Organization for Standardization (ISO) certification process, were companies willingly submit to third party scrutiny for continuous process improvement. *ISO Certification can*

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be a useful tool to add credibility, by demonstrating that your product or service meets the expectations of your customers. For some industries, certification is a legal or contractual requirement. (International Organization for Standardization, 2015)

Tremendous focus has been placed upon the product definition. Requirements Decomposition (Defense Acquisition University, 2001; Guenov & Barker, 2005; Haskins, Forsberg, Krueger, Walden, & Hamelin, 2010; Hong & Park, 2009; National Aeronautics and Space Administration, 2007), Functional Analysis and Allocation (Defense Acquisition University, 2013; Electronic Industries Alliance, 2002; IEEE Computer Society, 2007), Design Structure Matrices (Eppinger & Browning, 2012), Axiomatic Design (Suh, Cross, & Cross, 1995), and Design Modularization (Caprace, 2010) have all been employed to categorize or logically partition the larger problem into a smaller more tractable subset. It is perfectly logical to attempt to categorize, organize, and sort the produced artifacts or engineering systems; however, this will only generate information that is predicated on the realized solution or that derived from previous solutions.

Although there is another component of the system design process that is arguably more important than the system/subsystem design and is not the recipient of rigorous mathematical analysis. This component is the design team itself. In effect it is this team that amalgamates all of the disparate requirements, system/subsystem designs, and interfaces into a functional product. The communication ability and technical skills of the aggregate team ultimately determines the success or failure of the endeavor. Additionally it is these same communication and technical skills that allow the team to adjust throughout the process to design changes and modifications created by the introduction of additional information.

Regardless of the end product, thanks to the instantiation of Systems Engineering as a discipline, the design process is now punctuated with numerous interim reviews that accomplish a specific focus. These interim reviews, whether they are technical or programmatic in nature, provide in situ awareness or a static snap shot of the project at that moment. It is these snap shots that provide stakeholders with indications of potential success or failure of the design endeavor. However the design team is not similarly evaluated at these critical junctions. It would seem prudent to evaluate the team's skill portfolio as well, in order to determine if the correct 'mix' of talent has been acquired for the next phase of the project.

For this paper the portfolio has been limited to interpersonal communication skills and technical proficiency. It also seems logically that the skill set required to develop and execute a concept exploration or analysis of alternatives would be drastically different than that required to complete an effective preliminary design. This skill set would continue to evolve throughout the acquisition process, morphing and changing at each distinct phase of the project. This begins to address the need for incremental assessment of the design team's skill set as a variable, impacting the overall design success.

BACKGROUND

This paper documents the development of an objective mathematical framework that is capable of accounting for a design team's skill portfolio while producing an incremental, discrete, leading indicator of projected design sufficiency. This technique would not replace the methodologies utilized to decompose and understand the materiel solution of the design process. The fundamental difference is that the focus of this technique is on the design team and not the design.

The Stream of Variation (SoV) process was designed to model and quantify the in-process variation of multistage, manufacturing/machining processes (MMP). *SoV attempts to describe the complex production stream and data stream involved in the modeling and analysis of variation and its propagation in a MMP.* (Shi, 2006) The concept of Stream of Variation (SoV) was developed at the University of Michigan's Engineering Research Center for Reconfigurable Manufacturing Systems.

The fundamental focus for the development of SoV was the automobile industry. This industry provided a rich source of multistage, multicomponent manufacturing and assembly processes. Additionally it created an environment that suffered from error accumulation as the process progressed. Figure 1 provides a top level perspective of an automobile body assembly process. It can be seen that not only are there sequential activities but also parallel ones. Further it illustrates the complexity of the system where major components are in fact assemblies themselves.

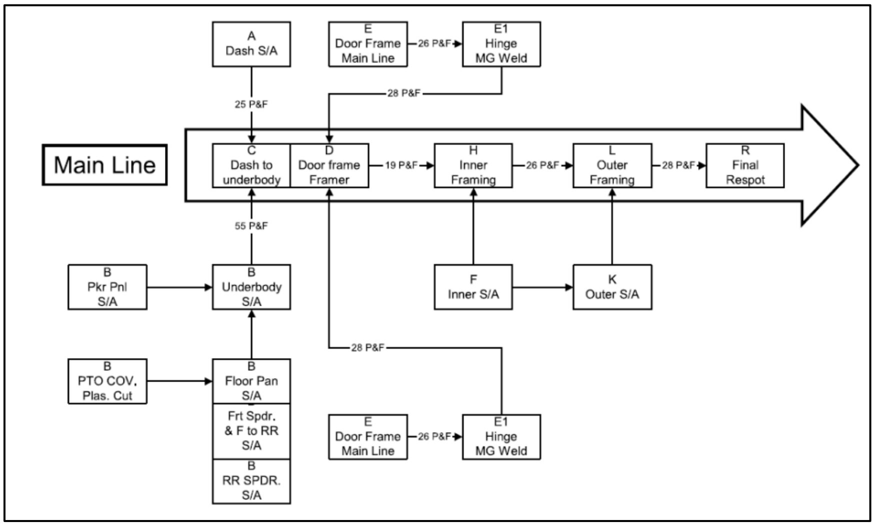

Figure 1 - Layout of a multistage automotive body assembly process (Fig 1.3 Shi, 2006)

Mapping the process is the first step required in attempting to describe and quantify the potential sources of error and variation within a system, but this mapping alone is insufficient. An additional more generalized model needed to be developed, in order to effectively calculate the error accumulation and potential results of that accumulation. Figure 2 outlines the process in the preceding figure as a state space representation

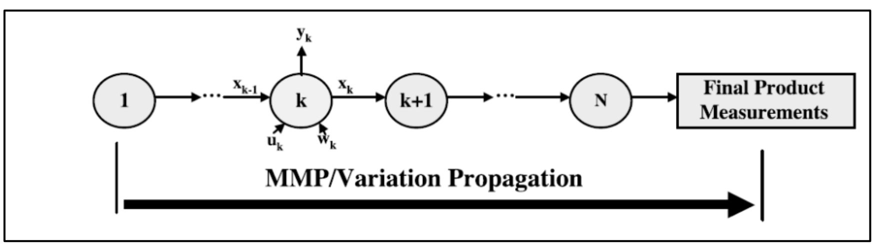

Figure 2 - Variation propagation and notation in SoV modeling (Fig 1.5 Shi, 2006)

The graphical state space representation of the process can be modeled by equations, [1] and [2].

$$\overrightarrow{x_k} = [A]_{k-1}\,\overrightarrow{x_{k-1}} + [B]_k\overrightarrow{u_k} + \overrightarrow{w_k} \quad [1]$$

$$\overrightarrow{y_k} = [C]_k\,\overrightarrow{x_k} + \overrightarrow{v_k} \quad [2]$$

SoV is based upon state space models and analysis techniques have been used extensively within the engineering community to model physical systems. *State-space models are models that use state variables to describe a system by a set of first-order differential or difference equations, rather than by one or more n^{th}-order differential or difference equations*" (Mathworks, 2013) To that end electrical circuits (Rohan, 2004), feedback control systems (Rowell, 2002), rigid body dynamics (Stengel & Mae, 2011), structural response (Luis, Zabala, All, Connor, &

Sussman, 1996), biomechanical analysis (Liu & Shi, 2007), and financial analysis (Zivot, Wang, & Koopman, 2003) have all been modeled utilizing a variety of state space models. State space models regardless on instantiation consist of two equations. The first is generally called a state equation [3] the second is called either the observation or the output equation [4]. By using a linear or linearized state space model arranged in a system of equations, matrix mathematics and linear algebra can be applied.

Quite possibly the easiest state space model (SSM) to visualize is one that is purely kinematic in nature. As denoted in [3], x_k is the state vector at position k. This vector is updated at each discretized time step by the matrix $[A]_k$ and the perturbation vector, ϵ_k. In a kinematic system the elements of the state vector may represent the three translational and three rotational positions of an item referenced to an initial datum, or the items rotational and translational velocities, or accelerations. The vector composition is uniquely defined by the problem context. The observation equation, [4], again contains the state vector at position k. In this equation the state vector is multiplied by the matrix $[B]_k$, this can be thought of as a transformation matrix. Again in the kinematic example, if the state vector represents the six modes of motion relative to the object, the transformation matrix will potentially relate the objects motion to an absolute location or an observed location, y_k. The delta vector, δ_k, can represent an error in the estimation or an additional perturbation.

$$\overrightarrow{x_{k+1}} = [A]_k \, \overrightarrow{x_k} + \overrightarrow{\epsilon_k} \qquad [3]$$

$$\overrightarrow{y_k} = [B]_k \, \overrightarrow{x_k} + \overrightarrow{\delta_k} \qquad [4]$$

It is acknowledged that state space analysis techniques are a subject with much technical depth and almost endless variations, for the purposes of this paper is an explicit discrete time invariant model will be utilized, the exact formulation of the model employed will be expanded upon in forthcoming sections.

As you can see the first two equations presented are similar to the general state equations above. SoV extends those basic equations but the impetus is the same. *This model has a state space representation that describes the deviation and its propagation in an N-station process* x_k *is the state vector representing the key quality characteristics of the product (or intermediate work piece) after stage k.* u_k *is the control vector representing the tooling errors (e.g., tolerance when no faults occur, or deviation when failures occur on the tooling) at stage k.* y_k *is the measurement vector representing product quality measurements at stage k.* w_k *and* v_k *are the modeling error and sensing error, respectively. The coefficient matrices* A_k*,* B_k*, and* C_k *are determined by product and process design information:* A_k *represents the impact of deviation transition from stage k-1 to stage k,* B_k *represents the impact of the local tooling deviation on product quality at stage k, and* C_k *is the measurement matrix, which can be obtained from the defined key product quality features at stage k.* (Shi, 2006)

This model was specifically tuned and tailored to the multistage process that was being evaluated, i.e. the automobile body assembly process. Further this state space representation was then compared to the standard statistical simulation software that was employed by the manufacturer. This effort yielded the following results, *the discrepancy between the std (standard deviation) values from the two models is less than 0.054%...* (Shi, 2006) This is a highly encouraging result that the newly developed state space representation of the process was at least as accurate as the existing error measurement system actively utilized. This supports the extension of this methodology to larger systems given that similar attention to detail can be applied to tailor the model to the specific process.

MODEL

Design, despite its ever increasing sophistication and the application of new techniques and tools is still largely iterative and imprecise at best. Newer design techniques and an increased awareness of the total design space implications have created a greater focus on the development of sets of acceptable designs versus a singular point design. This greatly improves the opportunity for success of the design activity, but there is an obvious gap in understanding or quantification of the design team's contribution to the development of a successful design. This contribution becomes more important as the design complexity increases, design team sizes balloon due to engineering specialization, the lack of design team centralization, and reduced construction numbers place a higher premium on getting it right the first time.

This creates multiple potential sources for error due to the iterative nature of design and number of people involved in the activity. This is how SoV becomes applicable. Stream of Variation was developed for highly complex sequential mass production as a means to predict end-item sufficiency. This technique demonstrated tremendous accuracy once tuned to the process. If one replaces the base error sources introduced during component translation and on-station machining with design team communication and designer cognitive skill, a clear analogy can be created. Communication error can occur at multiple locations along an information exchange and the nature of the response is compounded as information continues to be disseminated. This is identical to the translation of a component through a multistep process. Further, cognitive skill and ability testing is an accurate indicator of overall job performance. Therefore a lack of performance can be interpreted as an indicator of induced error. This can be a direct replacement for the error introduced on-station in the original construct of SoV. With these modifications to the basic approach the SoV techniques can be modified to be an indicator of success for a personnel centric model directly analogous to a MMP.

As it was discussed previously a major issue associated with complex product design is the ability to dynamically understand how the activities, calculations and tools will impact the final design. Stream of Variation Analysis was developed for the evaluation of a multistage manufacturing process will be modified to accommodate an iterative design process. As a property of state space modeling, the design process will be treated as a dynamic system of independent processes linked by inter-process information flow. Each process has a unique set of inputs and outputs. These processes can be any one of numerous design activities which are undertaken by design teams. The use of Stream of Variation modeling directly is not applicable since it will not allow for the integration of the team member communication, and cognitive elements directly, however it does allow for a temporally discrete, forecast prediction of the final key performance parameters, at multiple instances during the design development provided a suitable transformation matrix can be identified.

This estimation of key performance parameters is based upon the current instantiation of key system attributes at a discrete time step. The system level key performance parameters are developed prior to the initiation of the design process. The use of SoV within the design process will allow for the quantification of the likelihood of attainment of a desired goal. Stream of Variation was originally developed and applied to the error prediction of complex multi stage manufacturing, assembly, and machining processes. The technique utilizes a state space model to measure and predict the accumulated and propagated errors developed by flexible manufacturing techniques. The extension of this technique to a design process is novel. The basic structure of an assembly line or multistage manufacturing and machining process, is analogous to the structure of the design process. The design process is a series of steps that must be performed in order to accomplish or complete the design effort. Further each of these steps requires input from other side line efforts. It becomes easy to visualize that if the design spiral was arranged in a sequential model it would be extremely similar to the manufacturing model, Figure 1. Further given the flexibility of state space modeling the previous equations, [1] [2], could be applied to this new construct. It will require a revision to the process and the definitions presented in the preceding section.

One can see that its general format is similar to Figure 2, however there are subtle differences. In Figure 3, each of the n stations represents a design action vice a manufacturing or assembly activity. The largest departure in structure of these two state space representations is in the transmission of the state vector. While it is possible that this expansion could be collapsed to reflect the previous format this allows for greater clarity in the process.

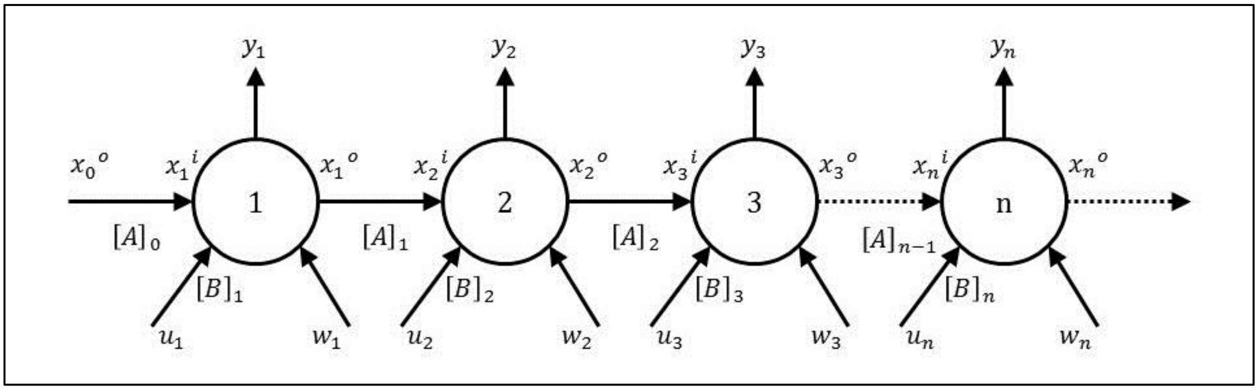

Figure 3 – Process Failure Estimation Technique

Similar to the basic SoV state space model x_n is a vector of key system attributes that is transmitted from activity to activity, unlike the base model the state vector has been appended with a superscript that in conjunction with the subscript denotes the station of action and whether the current state vector is an input or an output for that design station. The output or observation vector y_n has not changed in meaning or intent; it is a vector of key performance parameters. Other modifications to the base model include the location of operation of the A_n coefficient matrix. This seems logical since the original model utilized the A matrix to account for error introduced into the system by the transfer of work in progress (WIP) from station to station. In the design focused model where each activity can be a designer or design activity the error is again introduced when information is passed from station to station, therefore the error induced is due to communication errors. To continue the comparison of these models the B_n coefficient matrix which represents on station fixture variation in the base model can be modified to represent effect of designer induced variation. The effect of designer induced variation maybe due to education, experience, tool familiarity, interpersonal skills, or any other quantifiable characteristic. This would require that u_n become a designer score card of sorts based on the attributes chosen for the B_n coefficient matrix and relevant process information. This leaves the w_n and v_n vectors. These vectors represented modeling and sensing error in the original model, at this time these vectors can be assumed to be random error introduced in to the system during the design activity and the conversion of the key system attributes to key performance parameters, respectively. This nomenclature modification can be seen in [5] and [6].

$$\overrightarrow{x_n{}^i} = [A]_{n-1}\,\overrightarrow{x_{n-1}{}^o} + [B]_n\overrightarrow{u_n} + \overrightarrow{w_n} \qquad [5]$$

$$\overrightarrow{y_n} = [C]_n\,\overrightarrow{x_n{}^o} + \overrightarrow{v_n} \qquad [6]$$

COMMUNICATIONS

It usually takes me more than three weeks to prepare a good impromptu speech – Mark Twain. Needless to say the art of communication is imprecise at best. While several techniques have been developed to address the programmatic big questions: ‘How do we work together effectively?’, ‘What are we going to build?’, ‘When will we have it done?’, and ‘What are the project requirements?’. These techniques include Integrated Product and Process Development (Dept of Defense, 1998), Analytic Hierarchy Process (Saaty, 2012), Program Evaluation and Review Technique/Critical Path Method (PMI, 2008), Set Based Design (Sobek II et al., 1999), and several others. The ultimate goal of these techniques is to facilitate, decompose, or track information in order to, hopefully, clarify inter and intra team communications. Engineering products have become increasingly complex. This translates into a corresponding increase in the complexity of information that must be disseminated. Couple this with the increasing specialization of engineering disciplines, ballooning team sizes, and the prevalence on non-value added information it is clear to see how communications can breakdown. In order to discuss the potential of communication error further we need to establish a model of communication.

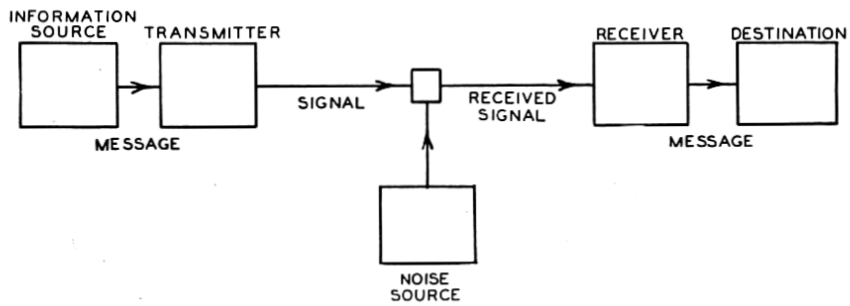

Figure 4 - Shannon-Weaver Communication Model (Fig 1 Shannon, 1948)

To that end Figure 4 - Shannon-Weaver Communication Model (Fig 1 Shannon, 1948) is the seminal model of information theory and basis of signal processing. I have introduced this model as a discussion point for how information is communicated and where potential error can occur. The Information Source on the left hand side of the graphic can represent a stakeholder, a sub-team, a designer, or a computer model. Assuming that there is no error at the source, the first opportunity for error is introduced upon encoding the information for transmission. In an ideal scenario no additional error would be possible until the information is decoded by the Receiver. However, noise can be introduced during the transmission furthering the entrained error in the message. With noise error and transmission error the receiver must be calibrated to remove, filter, or ignore the introduced error in order to obtain the original source information. If the receiver cannot remove or account for the introduced error then the message received at the destination is different than the original, and this is a miscommunication. Now consider that this model represents each communication interaction within a design team. So any design decision could be represented by a chain of these models where the output of the first becomes the input for the second, and so on. It quickly becomes apparent the compounding effect of error. Table 1 illustrates the effect of 1% constant error over X successive steps.

Table 1 - Cumulative Error Given 1% Constant Error

Step	Received Value
1	101
10	110.5
100	270.5
1,000	2,095,916
10,000	1.64E+45

The truth is that effective communication requires thought and time to formulate. Further, error is also seldom ever constant. So given that error has some distribution and not all error is additive it is possible for an error to improve the overall response. Therefore, even the clearest of transmissions can be misinterpreted.

COGNITIVE SKILLS ASSESSMENTS

The field of human cognitive abilities is one of the oldest and most technically sophisticated in all of psychology. (Gottfredson, 2003) We operate within an environment that heavily utilizes standardized testing to assess cognitive skills and abilities. To that end they seem to be divided between capability and generalized personality traits, see Table 2. However the true reason for this type of testing is to determine if an individual has the capacity to perform a specific task and potentially how they will perform in a team environment.

Table 2 - Techniques Employed to Quantify Individuals

Capability Assessments	Personality Assessments
Intelligence Quotient	Myers Briggs Type Indicator (MBTI)[1]
K-12 Scholastic	Dominance-influence-Steadiness-Conscientiousness (DiSC)[2]
College Entrance (SAT/ACT)	Circumplex[3]
Graduate School Entrance (GRE/MCAT/LSAT/GMAT)	Herrmann Brain Dominance Instrument (HBDI)[4]
Professional Certification (FE/PE/UBE/USMLE)	Five-Factor Model[5]

1. http://www.myersbriggs.org/my-mbti-personality-type/mbti-basics/
2. https://www.discprofile.com/what-is-disc/overview/
3. http://www.humansynergistics.com/OurApproach/TheCircumplex
4. http://www.herrmannsolutions.com/solutions/?framework=0
5. http://www.personalityresearch.org/papers/popkins.html

Given the amount of data that can be assembled on a specific individual it does not seem that it would be a stretch to assume that a testing mechanism could be developed that would assess the skill and proficiency of an individual for a specific task. In short, can a consistent, repeatable measure of job performance be developed? *The evidence is clear: The difference in ability test scores is mirrored by a corresponding difference in academic achievement and in performance on the job.* (Hunter & Hunter, 1984) It should be noted that this is still an active area of research and debate within in the field of Industrial/Organizational Psychology. But the debate seems to be less about the merit of the predictive capability of this type of testing and more about the potential litigious issues for using this type of data to make hiring and promotion decisions. In fact, *mental ability measures are often used because of their well-documented validity for predicting job performance in a variety of settings*. (Whipple, 1991) So what would a generalized assessment cover, in regards to content? What would it test as an indication of job performance? *At a minimum, verbal ability, mathematical reasoning, spatial-mechanical ability, and clerical speed/perception (they come by various names) define aptitude profiles that are relevant to sizeable groups of occupations.* (Gottfredson, 2003) It would seem that there is a general concurrence in the fact that cognitive assessments can be an indicator of overall job performance. (Gottfredson, 2003; Hunter & Hunter, 1984; Hunter, 1986; Whipple, 1991) It is also acknowledged that *there is lot of evidence that a number of factors significantly affect performance; for example, ability, experience, biodata, personality, motivation, environmental constraints, and many more*. (Whipple, 1991) the debate of whether these batteries measure or predict on-the-job performance or solely academic aptitude is still ongoing.

Asserting that there is a cognitive evaluation tool that can predict job performance within a reasonable margin of error; then it should possible to also predict the inverse. If job performance can be defined as doing a task without error, then a lack of performance would be insightful to the error created by the individual. This is the applicability to this paper. It is not the creation of a tool or skills battery that will actually assess the performance. This is currently beyond the scope of this work, however the construct that it can be developed will allow for the continuation of this effort. Additionally, it is my belief that much if not all of the information required to developed this targeted assessment already exists. Today's workforce is bombarded by a myriad of team dynamics assessments, personality profiles, and voodoo management concepts and techniques. All of these constructs have a similar stated goal: increase the effectiveness of the overall team. It is my supposition that the best way to increase the total effectiveness of the team is more in line with traditional manufacturing principles of error identification and reduction. This brings up the harsh reality of diminishing returns. Eventually the incremental cost of improvement is prohibitive or the gain is unappreciable.

STATISTICAL BEHAVIOR

It is desired to determine the statistical behavior of the base state equation, in order to better understand how the selected variables and parameters will influence the response of the outputs. The correct parameter ranges are unknown at this time. The first equation, [7], below is repeated from the preceding section for clarity. This equation can be idealized and represented as [8]. For this initial evaluation, y is a function of four continuous variables, arbitrarily bound on the interval, $[-10{:}\,10]$. Employing a two level-four variable, full factorial Design of Experiments (DOE) requires 16 unique tests to fully enumerate the space.

$$\overrightarrow{x_n{}^i} = [A]_{n-1}\,\overrightarrow{x_{n-1}{}^o} + [B]_n\overrightarrow{u_n} + \overrightarrow{w_n} \qquad [7]$$

$$y = x_1x_2 + x_3x_4 \qquad [8]$$

Statistical analysis is typically conducted in the absence of a known model and strictly relies on the measured or observed data. In this case we do not have a defined data set and the observations will be created via simulation. In order to create a set of observations we will begin with the idealized model, [8], and augment it with a zero mean, normally distributed random variable having a standard deviation of 1, [9]. In addition to the random variable a coefficient will be added to each variable pair. These coefficients, β_i, can be thought of as weighting factors or a mechanism to tune the model to achieve the desired effect. Multiple observation vectors can be created. These observations will all have the same mean structure and a stochastic element that makes them all unique in of themselves.

$$y_h = \beta_1x_1x_2 + \beta_2x_3x_4 + \mathcal{N}(0,1) \qquad [9]$$

Given a set of n observation vectors, each containing 16 unique test results, one can then calculate the per test mean and the grand average. The per test mean would be the average value obtain for a single testing configuration across all of the observations. This value allows for the determination of how much deviation occurs between observations for a given configuration. The next calculation that is pertinent is the global mean or the grand average. This is the mean value of all the recorded results. This value allows for the determination of how much variation is present for any result from the global mean.

In addition to an ANOVA table, it is useful to calculate an estimation of variable effects, interactions, and influence on average with equation [10]. The per test averages are signed in accordance with the DOE. One additional measure of error is the error variance or the standard error squared, [11] provides a means to calculate this error variance. Where N is the total number of tests executed. If a single set of observations was created N would equal 16 for this case. If two sets of observations were created N would equal 32, and so on.

$$\mathrm{E}_i = \frac{2}{h}(\pm\bar{y}_1 \pm \bar{y}_2 \pm \cdots \pm \bar{y}_h) \qquad [10]$$

$$s_{effect}^2 = \frac{4s_p^2}{N} = \frac{4}{N}\mathrm{MS}_{\text{within tests}} \qquad [11]$$

Once the mean effects for each combination have been calculated then one can determine the confidence interval, providing another test for the validity of the null hypothesis on higher order effects. The null hypothesis implies that E_{mean} is zero, therefore the estimated value plus the interval should contain zero as a potential value. The confidence interval, CI, is defined by a confidence percentage (i.e. 5% and the number of unique test configurations executed). This will define $t_{16,0.975}$ and $t_{16,0.025}$, these points are derived from a t-distribution, any calculated t value in excess of the limits should be reviewed further. This effectively defines the limits for the confidence interval and if the null hypothesis is valid for the effect under review. This concept is easily visualized with the use of a Box Plot, Figure 5. The horizontal line in the middle of each box is the calculated Effect Value, E_i. The whiskers represent the CI. In this case it is obvious that 13 of 15 effects contain zero as a potential value. Therefore the null hypothesis is valid for these effects on this given observation set.

$$t_i = \frac{E_i - E_{mean}}{s_{effect}} \quad [12]$$

$$CI = t_{h,1-\frac{\alpha}{2}} * s_{effect} \quad [13]$$

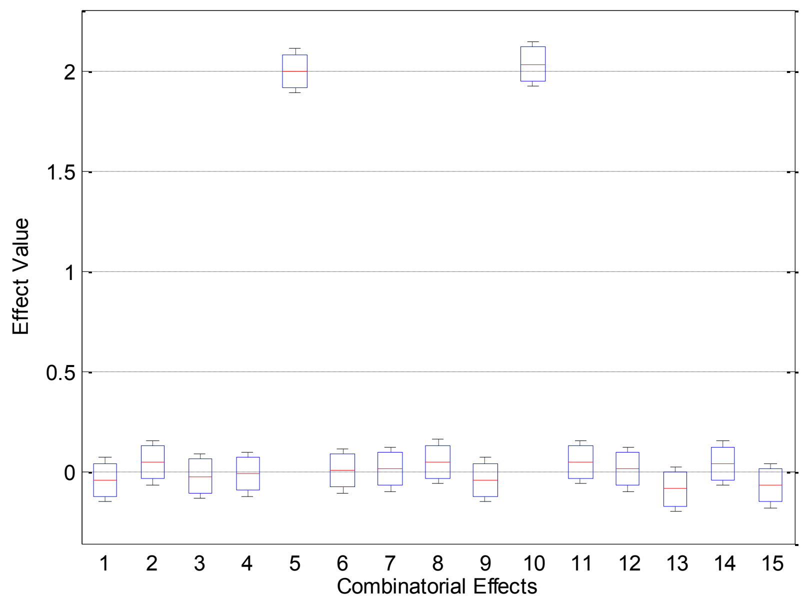

Figure 5 - Box Plot of Effects with 95% CI

If the null hypothesis is not valid, the effect are considered statistically significant and will be included in a reduced order model, [14]. This reduced order model is a linear combination of coefficients, which are half the estimated effect, [16], and the combinatorial variables.

$$\hat{y} = b_0 + \sum_{i=1}^{15} b_i \tilde{x}_i \quad [14]$$

$$b_0 = \bar{\bar{y}} = \frac{1}{nm}\left(\sum_{h=1}^{m}\sum_{i=1}^{n} y_{hi}\right) \quad [15]$$

$$b_i = \frac{E_i}{2} \quad [16]$$

$$\hat{y}_h = b_0 + b_5 x_5 + b_{10} x_{10} = b_0 + b_5 x_1 x_2 + b_{10} x_3 x_4 \quad [17]$$

[17] is the reduced order model that can deterministically estimate the stochastic observation set. Now that a deterministic model has been developed, how does it respond? Figure 6 is a surface plot of the estimated response, $\hat{y}$ as a function of x_5 and x_{10}. In this representation it is a planar surface with no curvature. Further the surface is monotonically increasing in both directions. This surface was defined by the observation set created from the following parameters: $[\beta_1, \beta_2, \sigma] = [1,1,1]$. Figure 7, the contour plot of the surface suggests that one can select a $\hat{y}$ value and then determine the combinations of x_5 and x_{10} that would produce the desired value.

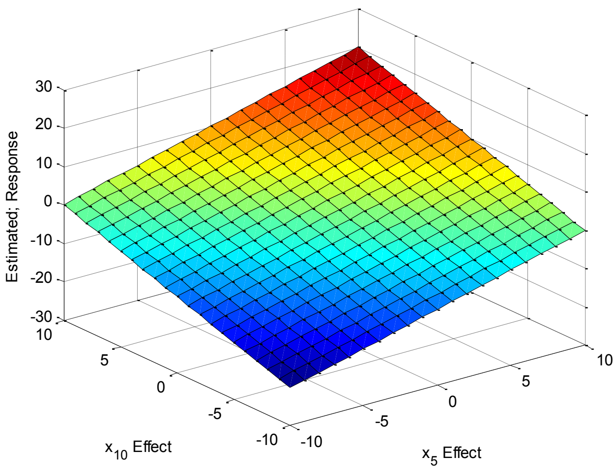

Figure 6 - Deterministic Response as a Function of x_{10} & x_5

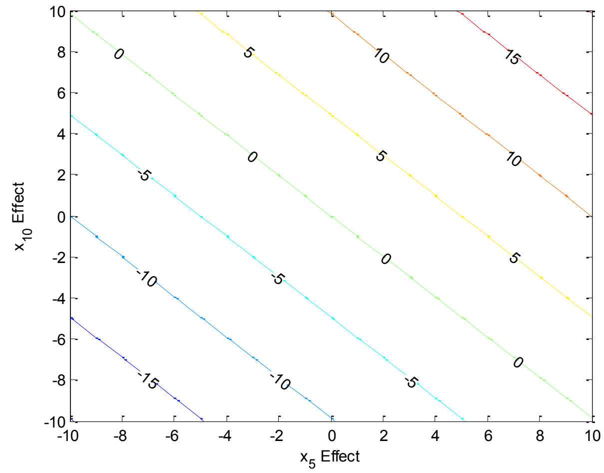

Figure 7 - Response Contours as a Function of x_{10} & x_5

Recalling that x_5 is actually x_1x_2, and x_{10} is actually x_3x_4. Reverting to the base variables makes the structure of the response more interesting. Let us select an iso-line of $\hat{y} = 0$, and investigate how the equation response changes. With a little algebra, we are able to change the variables and plot Figure 8 and Figure 9. The interesting point about these saddle plots is that previously changes to β_1 and β_2 only changed the inclination of the planar surface. Now they change the slopes of the saddle in two directions. This illustrates that the reduced order model is sensitive to the weighting coefficients utilized to generate the initial observations. Now, how does the standard deviation of the stochastic perturbation affect the modeling outcome?

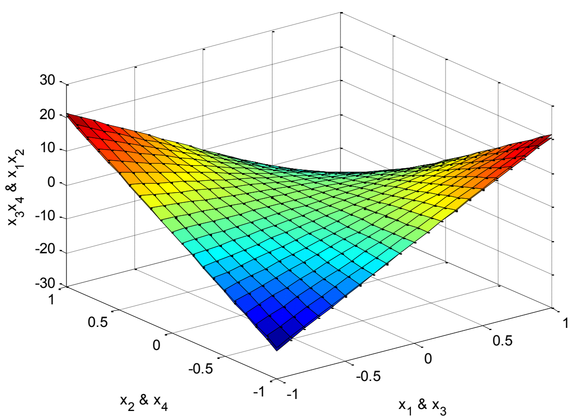

Figure 8 - Estimating Function Response [1,1,1] (1)

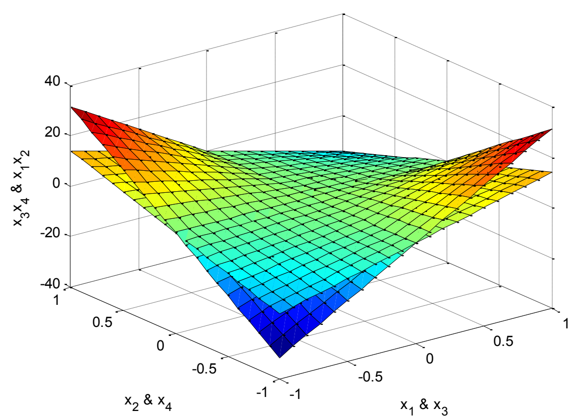

Figure 9 - Estimating Function Response [1,1.5,1] (2)

Up to this point the stochastic variable has had a mean, μ, of zero and a standard deviation, σ, of 1. One can see that the general tendency is an overall flattening of the probability distribution function, with an increasing likelihood of extreme values and a corresponding decrease in the likelihood of a value being close to the mean.

So how does this discussion of the effect of standard deviation on the normal distribution translate to the propose modeling technique and the selection of β_1 and β_2? Recall [9], and the defining parameters, $[\beta_1, \beta_2, \sigma]$. So how does one select these parameters in a logical manner? This is where the coefficient of correlation, R^2, is of value. This coefficient is essentially how well the deterministic model fits the stochastic observations. This coefficient must assume a value on the interval [0:1]. A score of 1 is perfect. Figure 10 plots the generated R^2 values for the five standard deviations previously discussed. As the standard deviation increases the maximum allowable value of β_1 and β_2 increases. The risk of arbitrarily assigning values to weighting coefficients is that of auto correlation, in other words the value of β_i is of such a degree that the remainder of the equation becomes trivial. The contour plots below all follow a similar structure. There is a 'zero' value that occurs at the origin, and the R^2 value increases linearly in concentric circles until it reaches a value of 1. A R^2 value of 0.50 – 0.75 is fairly common for data fits. This can explicitly define the range of β_1 and β_2, for a given σ and thus generate a plausible observation set. The $\sigma = 2$ plot has been repeated in a three dimensional format for illustrative purposes to show the general shape of all these plots.

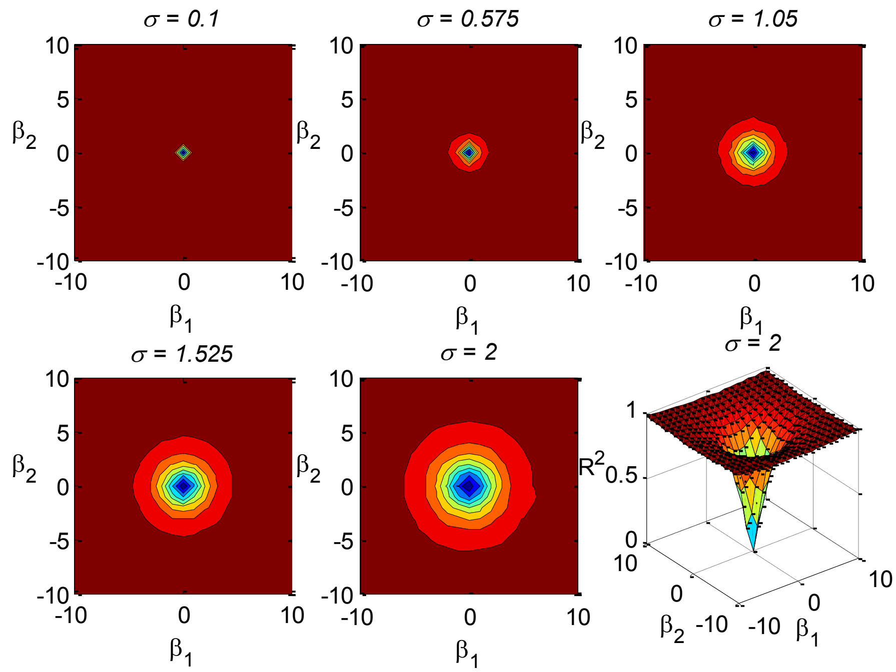

Figure 10 - Effects of Parameters: [β_1,β_2,σ] on R^2

FLOODABLE LENGTH MODEL WITH STREAM OF VARIATION

The goal of the case study is to demonstrate how the calculation of Floodable Length can be modeled as a modified SoV iterative design process to which will be used to actually create a rough general arrangement of a barge with the inclusion of an error associated with one of the design variables. The error will be introduced in the calculation of the floodable length curve ordinates. No additionally error will be introduced in the determination of the bulkhead locations at this time. This section will follow the same calculation path as the previous section, with the inclusion of an error into one element of the KSA vector at each sequential step. Length has been chosen as the element of focus due to its direct impact on floodable length. Recalling the statistical observation model developed previously, [18], including a standard normal distribution, α. The next series of equations simplifies the $[A]_{n-1}$ coefficients to an identity matrix in order to illustrate how the addition of the stochastic variable influences the total variance in progressive steps. Further the random variable has a consistent mean and variance for successive steps, this need not be true in all cases.

$$y_h = \beta_1 x_1\, x_2 + \beta_2 x_3 x_4 + \alpha \qquad [18]$$

$$\alpha \sim N(0,1), \qquad \beta_1 = 1, \qquad \beta_2 = 0$$

$$\overrightarrow{x_n}^{i} = \beta_1 [A]_{n-1}\, \overrightarrow{x_{n-1}}^{o} + \alpha_n \qquad [19]$$

$$\overrightarrow{y_n} = [C]_n\, \overrightarrow{x_n}^{o} \qquad [20]$$

For the process of determining a floodable length curve within the design focused SSM of Figure 3, each point calculation has been modeled as an independent process. This implies that since 11 trims have been evaluated, there will be 11 serial processes each with their own error source that ultimately define the curve. Further the ordinate value obtained as a result of the process is appended to the state vector. This is a moment when one can see the potential for extension to the broader design context. Each process could be complete disciplines, Hull Definition, Damage Stability, Powering, etc.

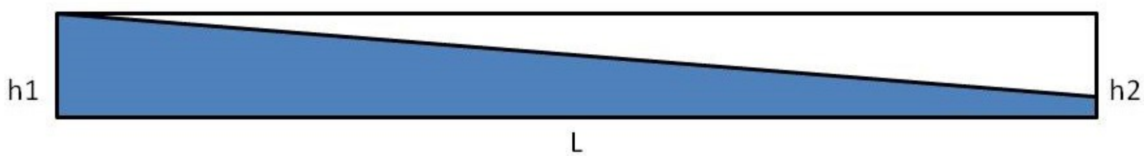

Figure 11 – Box Barge Long'l Area

Each process will have an assigned trim as the static damaged trim is evaluated in 10% increments from 0% to 100% of the total barge depth, [21]. [22] & [23] are the resultant water height vectors of the box barge depicted in Figure 11. Since an orthogonal box barge is being used we will only need to trim the vessel in one direction. If the vessel had any shape or a variable permeability, the Floodable Length Curve (FLC) would not be symmetric and the trimming process would need to be repeated in the opposite direction.

$$t = [0 \quad 0.1 \quad 0.2 \quad 0.3 \quad \cdots \quad 1]^T \qquad [21]$$

$$h1 = [D \quad \cdots \quad D]^T \qquad [22]$$

$$h2 = [D \quad 0.9D \quad 0.8D \quad 0.7D \quad \cdots \quad 0]^T \qquad [23]$$

This results in longitudinal areas ranging from DL to 0.5DL, [24] allows for the calculation of all of the intermediate trapezoidal areas. [25] & [26] are the calculation of the first longitudinal area. The next step in the process is the calculation of a differential volume. This is the submerged volume in the new static damage waterline less the submerged volume in the design condition. This is additional displacement that would be required to trim the barge in the current condition. [27] provides the general formulation for this difference. [28] & [29] are the calculation for the first differential volume.

$$A_i = {}^1/_2\,(h1_i + h2_i)L \qquad [24]$$

$$A_1 = {}^1/_2\,(D + D)L = DL \qquad [25]$$

$$A_1 = 10 * 100 = 1{,}000 \qquad [26]$$

$$\delta \mathrm{V}_i = \mathrm{V}_i - \mathrm{V}_0 = (BA_i) - (LBT) \qquad [27]$$

$$\delta \mathrm{V}_1 = (LBD) - (LBT) = LB(D - T) \qquad [28]$$

$$\delta \mathrm{V}_1 = 100 * 20 * (10 - 4) = 12{,}000 \qquad [29]$$

Then we calculate the centroids of both the static damage waterline and the differential volume. [30] is the generalized form for calculating the centroid of the static damage waterline relative to amidships. The result of [34] was expected due to parallel sinkage. In order to calculate the centroid for the differential volume a moment balance is used, [33].

$$C_{x_1} = {L}/{2} - {L}/{3} * {(2h2 + h1)}/{(h2 + h1)} \quad [30]$$

$$C_{x_1} = {L}/{2} - {L}/{3} * {(2D + D)}/{(D + D)} \quad [31]$$

$$C_{x_1} = {L}/{2} - {L}/{2} = 0 \quad [32]$$

$$\delta C_{x_1} = (V_i \, C_{x_1})/\delta V_1 \quad [33]$$

$$\delta C_{x_1} = 0 \quad [34]$$

[35] is the calculation of allowable floodable length. Floodable length is the differential volume divided by the cross sectional area of the barge at the centroid of the differential volume.

$$l_i = \frac{\delta V}{A_{y@\delta C_{x_i}}} \quad [35]$$

$$l_1 = {12{,}000}/{(10 * 20)} = 60 \quad [36]$$

This marks the conclusion of the first process and the identification of the first FLC ordinate. Now we repeat the process of defining the longitudinal submerged area and the differential volume for the new static damage waterline.

$$A_2 = {1}/{2}\,(D + 0.9D)L = 0.95DL \quad [37]$$

$$A_2 = 0.95 * 10 * 100 = 950 \quad [38]$$

$$\delta V_2 = (BA_2) - (LBT) \quad [39]$$

$$\delta V_2 = 19{,}000 - 8{,}000 = 11{,}000 \quad [40]$$

[38] and [40] provide the longitudinal submerged area and the differential volume for the second stage. It should be highlighted that the calculations above, [65], are for the second point without induced error.

$$C_{x_2} = {L}/{2} - {L}/{3} * {(2 * 0.9D + D)}/{(0.9D + D)} \quad [41]$$

$$C_{x_2} = {L}/{2} - {L}/{3} * {2.8}/{1.9} = 0.88 \quad [42]$$

Calculation of the longitudinal submerged centroid with no error introduced, [42].

$$\delta C_{x_2} = {19{,}000 * 0.88}/{11{,}000} = 1.52 \quad [43]$$

[44] is the allowable floodable length for the second point.

$$l_2 = {11{,}000}/{(9.5 * 20)} = 58 \quad [44]$$

This marks the conclusion of the second process. Continuation of this methodology will allow for the generation of a floodable length curve with coordinates of differential centroid versus allowable floodable length. The curve without induced error is plotted in, Figure 12 and 13 with circular data markers, the maximum observed values are also presented in Figure 13. This error envelope has been plotted with enforced commonality of the independent variable, ignoring the horizontal spreading of the data illustrated in Figure 14. Figure 12 depicts the ideal barge and FLC with the bulkhead location guides in place. Equation [47], [50], and [53] represent the line denoted as X_1X_2, X_4X_5, and X_3X_7 respectively. The hat and subscript for these equations are to assist in the differentiation of these values from other uses of allowable floodable length, l, and longitudinal position, δC_x. The position of X_2 is defined by the intersection of the FLC and line X_1X_2. Once X_2 has been located another bulkhead can be located by constructing another line with an inverse slope. This next bulkhead would be located at the intersection of line X_2X_3 and the baseline. This process is repeated until the longitudinal centerline is crossed.

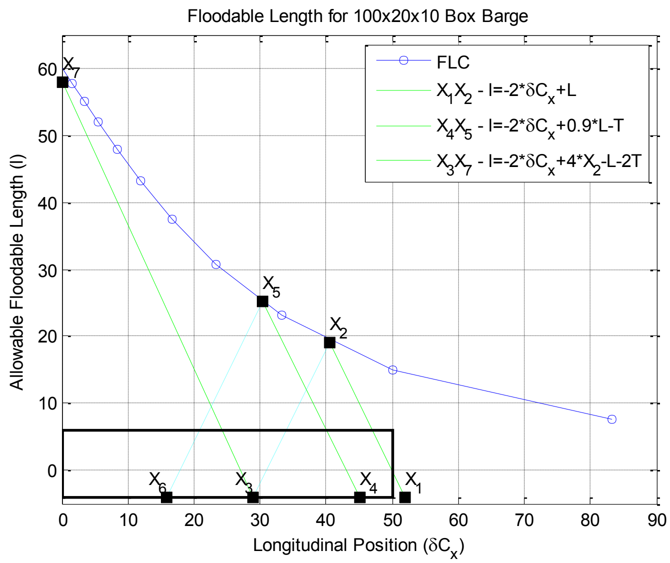

Figure 12 - Deterministic Bulkhead Placements

$$\hat{l}_1 = -2\widehat{\delta C}_1 + b_1 \quad [45]$$

$$@\ \widehat{\delta C}_1 = 0.5L;\ \hat{l}_1 = 0 \quad [46]$$

$$\therefore b_1 = L \rightarrow \hat{l}_1 = -2\widehat{\delta C}_1 + L \quad [47]$$

$$\hat{l}_2 = -2\widehat{\delta C}_2 + b_2 \quad [48]$$

$$@\ \widehat{\delta C}_2 = 0.45L;\ \hat{l}_2 = -T \quad [49]$$

$$\therefore b_2 = 0.9L - T \rightarrow \hat{l}_2 = -2\widehat{\delta C}_2 + 0.9L - T \quad [50]$$

$$\hat{l}_3 = -2\widehat{\delta C}_3 + b_3 \quad [51]$$

$$@\ \widehat{\delta C}_3 = X_1 - 2(X_1 - X_2);\ l_1 = -T \quad [52]$$

$$\therefore b = 4X_2 - L - 2T \rightarrow \hat{l}_3 = -2\delta C_{x_3} + 4X_2 - L - 2T \quad [53]$$

[54-61] are the x-axis location of key feature points displayed on Figure 12. [62] represent the intercept points of a third order polynomial estimation of the floodable length curve and [47], [50], and [53] respectively. The x-value of

the apex points are represented as a ratio of their location to the total length. This ratio has been labeled as γ_i, it has been introduced to facilitate the compact development of the observation transformation matrix, [64].

$$X_1 = 0.5L + 0.5T \quad [54]$$

$$X_2 = \gamma_1 L \quad [55]$$

$$X_3 = X_1 - 2(X_1 - X_2) \quad [56]$$

$$X_4 = 0.45L \quad [57]$$

$$X_5 = \gamma_2 L \quad [58]$$

$$X_6 = X_4 - 2(X_4 - X_5) \quad [59]$$

$$X_7 = \gamma_3 L \quad [60]$$

$$X_8 = X_3 - 2(X_3 - X_7) \quad [61]$$

$$\therefore [X_2 \quad X_5 \quad X_7] = [\gamma_1 \quad \gamma_2 \quad \gamma_3]L \quad [62]$$

With the designated bulkhead locations given by [63], an observation transformation matrix can be developed in terms of L and T, [64].

$$Bulkheads = \begin{bmatrix} \cdots & X_1 - 0.5T & \cdots \\ \cdots & X_4 & \cdots \\ \cdots & X_3 = X_1 - 2(X_1 - X_2) & \cdots \\ \cdots & X_6 = X_4 - 2(X_4 - X_5) & \cdots \\ \cdots & X_8 = X_3 - 2(X_3 - X_7) & \cdots \end{bmatrix} \quad [63]$$

$$[C]_{11} = \left[\begin{matrix} 0.5 & 0 & 0 & 0 \\ 0.45 & 0 & 0 & 0 \\ 2\gamma_1 - 0.5 & 0 & 0 & -0.5 \\ 2\gamma_2 - 0.45 & 0 & 0 & 0 \\ 2\gamma_3 - 2\gamma_1 + 0.5 & 0 & 0 & 0.5 \end{matrix} \middle| \, 0_{5x11} \right] \quad [64]$$

$$\overrightarrow{y_{11}} = [C]_{11} \, \overrightarrow{x_{11}{}^{o}} \quad [65]$$

So at the conclusion of total process the state vector is a 15 element vector. The first four are the barge dimensions, while the last eleven are the ordinates of the curves calculated by the corresponding process in the chain. However since the state vector grows at each successive step the transmission matrix must grow to match, so this matrix will start as a 4x4 matrix and complete the process as a 15x15 matrix. Although for the purposes of this first case study, an error due to transmission has been limited to overall barge length exclusively; all other base variables remain unaltered.

It is necessary in this example to fully calculate the floodable length curve once before the measurement matrix can be developed. Therefore the measurement matrix is a 5x15 matrix that operates on the end dimensions after the effects of cumulative error have been realized. This implies that the output state vector of station 10 would be multiplied by the measurement matrix to define the bulkhead locations for that run. It is important to realize that each run will have a unique error signature, polynomial fit, and bulkhead locations.

RESULTS

The process describe above was executed 1,000 times. This generated 1,000 unique floodable length curves and corresponding bulkhead locations. Figure 13 outlines the maximum and minimum values obtained at each station. This graphic provides a contextual image of how error accumulates as the process progresses and the total bandwidth of the error. The width of this error envelope is directly related to the variable perturbation. Therefore if the allowable deviation was reduced from this max-min band would also subsequently reduce.

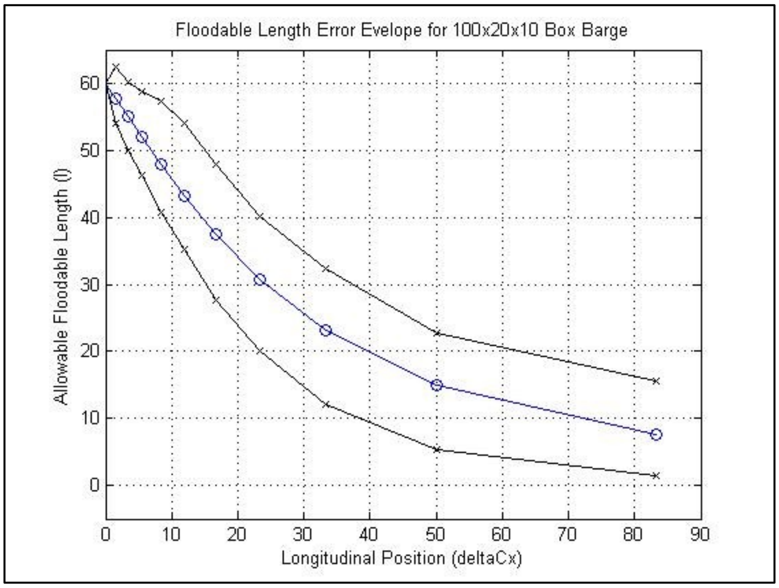

Figure 13 - Floodable Length Error Envelope

Figure 14 presents similar information in a different manner. This graphic plots all of the generated curves on top of the ideal curve. The error band depicted in Figure 13 can also be visualized in Figure 14. However what is more interesting is the trend of the actual curve ordinate shifting as the error is accumulated. While early in the process and the accumulated error is small there is little to no lateral movement of the ordinates. As the error accumulates through the process the ordinates become more skewed from vertical, indicating that the results may be less reliable in a majority of cases. This corresponds with personal experience that error early is less problematic initially, but small error compounded across the entire effort equates to enormous error at the end of the effort.

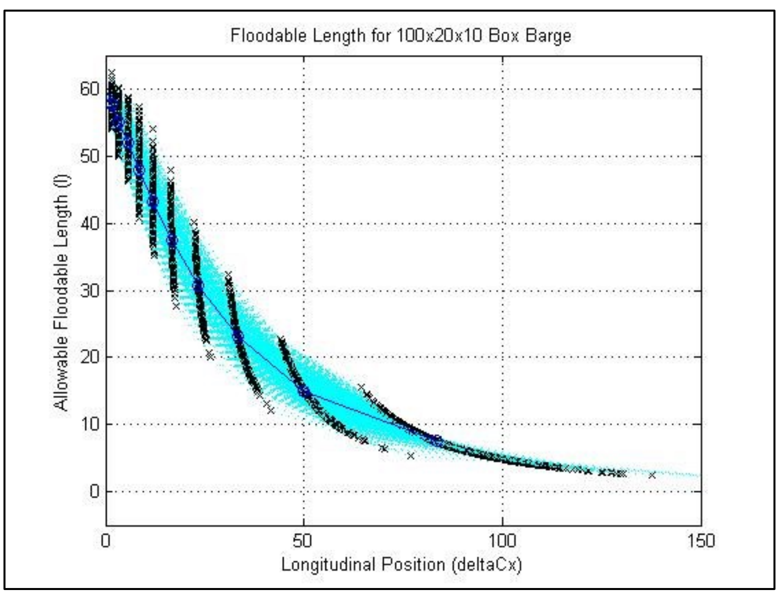

Figure 14 - Floodable Length Composites

Figure 14 represents 1,000 iterations of a floodable length curve developed in accordance with this section. For each of these curves a series of bulkhead locations were generated base on the perturbed floodable length curve. These values where deducted from the ideal positions generated without error and normalized by the ideal values in order to determine a percent difference. The values of this differencing scheme have been plotted in Figure 15. Each distribution is the percentage error that resulted in the calculated position from ideal. As expected the means remained centered around the nominal value but the variance increases in each successive calculation.

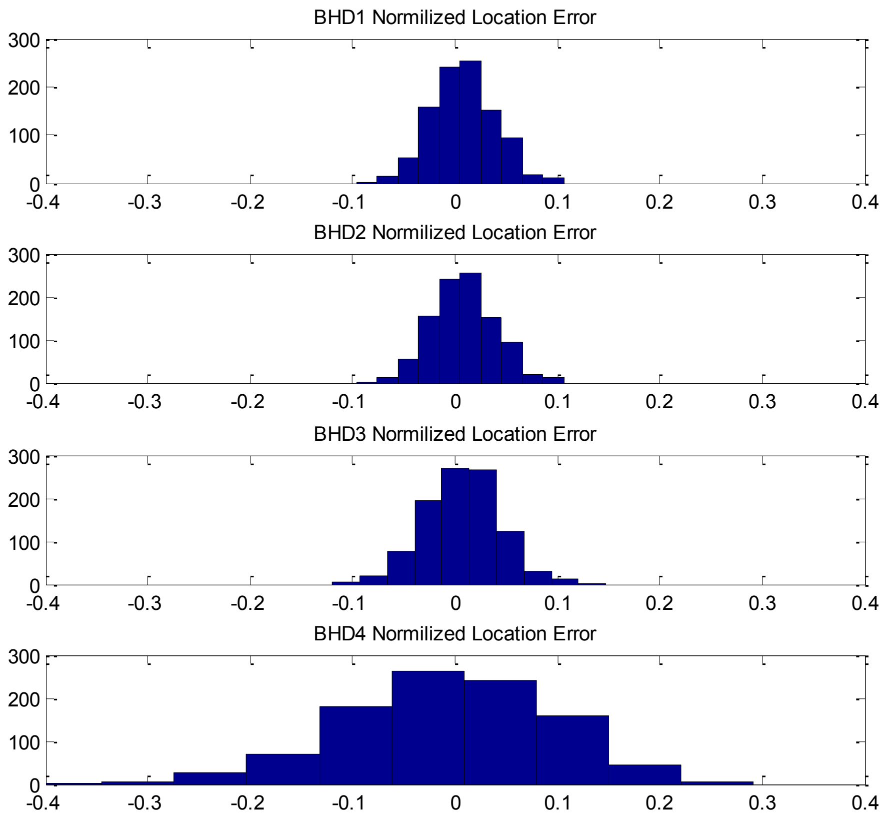

Figure 15 - Bulkhead Location Distributions

SUMMARY

The ship design problem is a wicked problem – David Andrews. This is largely due to the characteristics of such a problem. (Rittel & Webber, 1973) Most notably the iterative nature of the effort and the lack of clearly defined stopping criteria. This is an environment that is further complicated by the actual participants of the design activity and is not mathematically deterministic. This provides an excellent opportunity for the application of a technique which forecasts the potential results. While the proposed technique does not remove the iterative process it does begin to define stopping criteria for an effort. This would allow for the 'taming' of our wicked problem.

The single biggest problem in communication is the illusion that it has taken place. – George Bernard Shaw. Communication is an art and imprecise at best. This is compounded with technical jargon, geographical idioms, slang, gender bias, and generational bias. As design team become more decentralized and remote the potential for a miscommunication increases. The current model has utilized a normally distributed random variable for each successive perturbation. There may be a case for event based communication error as well, meaning a higher likelihood of miscommunication between specific designers or design communities.

The floodable length example presented only perturbed one element of the state vector, and included only the communication or transmission error. The new results can be contrasted against the initial findings in order to get a rough idea of the effect of cognitive error within this model. After the cognitive error component has been incorporated the effect of perturbations to multiple elements of the state vector will be evaluated. Additional assumptions for the application of the error in a logical fashion will be developed such that results can be evaluated against a baseline.

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