RISK INDEX FOR MULTI-OBJECTIVE DESIGN OPTIMIZATION OF NAVAL SHIPS

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ABSTRACT

The naval ship concept design process often embraces novel concepts and technologies that carry with them an inherent risk of failure simply because their application is the first of its kind. Failure is recognized by gaps between actual and required measures of performance, exceeded budgets, and late deliveries. These risks can be defined and quantified as the product of the probability of an occurrence of failure and a measure of the consequence of that failure. Since the objective of engineering is to design and build things to meet requirements, within budget, and on schedule the first time, it is important to consider risk, along with cost and performance, in trade assessments and technology selections made during concept design.

To this end, this thesis presents a simplified metric and methodology for measuring the risk of ship design concepts as part of a Multi-Objective Optimization tool for naval ship concept design. The purpose of this tool is to provide a consistent format and methodology for multi-objective decisions based on dissimilar objective attributes, specifically effectiveness, cost and risk. This approach provides a more efficient and robust method to search the design space for optimal concepts than the traditional "ad hoc" naval ship concept design process where selection and assessment are often based on experience, design lanes, rules-of-thumb and Imagineering.

This thesis begins with the results of a literature and information search that investigates and describes risk, engineering systems safety, and state of the art risk analysis techniques currently in practice. Based on this background, a simplified metric and methodology is developed to calculate, quantify, and compare relative overall risk in a naval ship design optimization. To demonstrate this method, a naval ship risk register is developed for a notional ship design. This register identifies potential cost, performance, and schedule risk issues. Risk item descriptions are further defined as a function of the design parameters (DPs) considered for the notional ship. Risk Factors (RF) are calculated for each risk item based on the DP selection. Each RF is the product of a Probability of Failure Occurrence (PF) and Potential Consequence of Failure (CF). An Overall Measure of Risk (OMOR) function is developed to measure the level of overall risk for a single concept design based on DP selections. A ship design case study is performed incorporating the OMOR function and risk items into a ship synthesis model capable of calculating cost, performance, and effectiveness. This case study uses a Multi-Objective Genetic Optimization (MOGO) to identify and define a series of non-dominated cost-effectiveness frontiers for a range of risk (OMOR) values. This new method for ship design optimization provides a novel approach and consistent format for multi-objective decision-making based on three dissimilar objective attributes: effectiveness, cost, and risk.

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1. INTRODUCTION

Numerous transformational technologies such as stealth, composite materials, unmanned vehicles, computer automation, and integrated electric drive, just to name a few, are currently poised to shape the next generation of naval surface combatants. The design, construction, and lifecycle support of these ships represent hard fought tax dollars allocated to protect the interests of the nation and its citizens. Billion dollar combatant contracts maintain the national shipbuilding base and represent the lifeblood of the states, towns, and shipyards where they are built. Contract awards not only ensure jobs, but the future freedom and the security of the nation.

The end of the cold war era, however, has marked a decline in the number of new ship acquisitions. Appearing before the Senate Armed Services Committee on July 10, 2001, ADM V. E. Clark, Chief of Naval Operations, testified “Our force structure declined 41% since 1991, from 538 to 316 ships” [1]. In fact, the total number of active U.S. Navy ships is down to almost half the 1989 peak of 592 ships. Figure 1-1 shows that over the past 5 years the number of U.S. warfighting and support ships under construction annually has fallen to a low not seen since 1950. For many shipyards, new contracts have been hard to find and even harder to sustain.

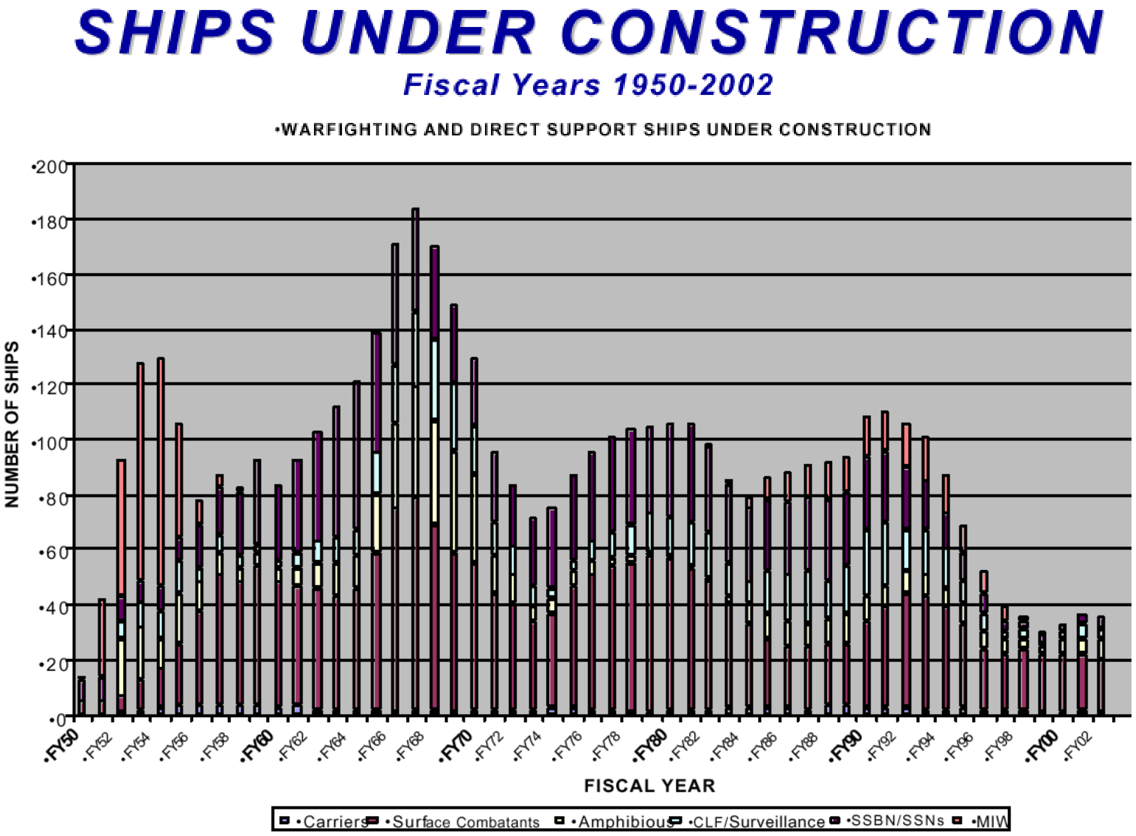


Figure 1-1. Warfighting and Support Ships under Construction 1950-2002 (1, p. 11)

To counter the political axe, system engineers and program managers are traditionally pressured to: meet performance requirements, design and build within budget, and adhere to schedule. New programs and follow-on contracts have been won, lost, renewed, or canceled based on these three principles. However, a fourth dimension is rapidly gaining importance. New programs and follow-on contracts can now be lost or canceled because they are judged not innovative enough or not transformational enough. This consideration is driving designers to "engineer" or "innovate" in the greatest possible amount of new technology.

Today's naval ship designs embrace more novel concepts and technologies than ever before, and significant innovation can be expected to continue. These innovations carry with them an inherent risk of failure simply because their application is the first of its kind. Failure is recognized by gaps between actual and required measures of performance, exceeded budgets, and late deliveries. Risks can be defined and quantified as the product of the probability of an occurrence of failure and a measure of the consequence of that failure. Since the objective of engineering is to design and build things to meet requirements, within budget, and on schedule the first time, it is important to consider risk, along with cost and performance, in trade assessments and technology selections made during concept design.

In today's arena, design teams are shaped around the concept of Integrated Product and Process Development (IPPD). Naval ships are designed by government-industry teams using Integrated Product Teams (IPTs) supported by Product Development Teams (PDTs) where risk and Total Ship System Engineering (TSSE) are both buzzwords. On a typical IPT, risk is handled by a designated risk manager. The job of the risk manager is to maintain a risk register and track risks identified by Subject Matter Experts (SMEs) in each of the supporting PDTs. The PDTs are responsible for managing the risk of their product by mitigating the probability of adverse occurrence or failure, usually through tests, trials, and modeling and simulation. Although this practice is an effective method for identifying high risks and mitigating them to lower levels, it does not treat risk as an objective attribute of the design. Further, there is no metric by which to measure an overall level or risk.

To this end, this thesis presents a simplified metric and methodology for measuring the risk of ship design concepts as part of a Multi-Objective Optimization tool for naval ship concept design.

1.1 Background

Naval ship concept design is traditionally an "ad hoc" process. Selection of design concepts for assessment is guided primarily by experience, design lanes, rules-of-thumb, and imagination. Communication and coordination between design disciplines (hull form, structures, resistance, etc.) require significant designer involvement and effort. Concept studies continue until resources or time runs out. Critical elements missing from this process are:

1. A consistent format and methodology for multi-objective decisions based on dissimilar objective attributes, specifically effectiveness, cost and risk. Mission effectiveness, cost and risk cannot logically be combined as in commercial decisions, where discounted cost can usually serve as a suitable single objective. Multiple objectives must be presented separately, but simultaneously, in a manageable format for trade-off and decision-making.

2. A practical and quantitative method for measuring effectiveness. An Overall Measure of Effectiveness (OMOE) model or function is an essential prerequisite for optimization and design trade-off. This effectiveness can be limited to individual ship missions or extend to missions within a task group or larger context.
3. A practical and quantitative methods for measuring risk. Overall risk includes schedule, production, technology performance, and cost factors.
4. An efficient and robust method to search the design space for optimal concepts.
5. An effective framework for transitioning and refining concept development in a multidisciplinary design optimization (MDO).
6. A means of using the results of first-principle analysis codes at earlier stages of design.

This thesis focuses on the third required element, a practical and quantitative measurement of risk.

1.2 Objectives

The overall goal of this research is to develop a simplified metric and methodology for measuring the risk of ship design concepts in a ship design optimization. This thesis focuses on naval combatants because they historically are highly complex and prime innovators of new technology. To accomplish the overall goal, the following specific tasks are performed:

1. Investigate state of the art risk analysis techniques currently in practice and develop a methodology for evaluating the risk of implementing new technology.
2. Develop a simplified metric and methodology to assess the relative risk of ship design concepts in a ship design optimization.
3. Develop a risk register for a notional naval ship concept design that considers emerging technologies, developing programs, systems, and applications.
4. Incorporate the risk register from Objective 3 in a multi-objective ship design optimization that implements the metric and methodology from Objective 2.

To demonstrate this method, a risk register is developed for a notional ship design. This register identifies potential cost, performance, and schedule risk issues. Risk item descriptions are further defined as a function of the design parameters (DPs) considered for the notional ship. Risk Factors (RF) are calculated for each risk item based on DP selection. Each RF is the product of a Probability of Failure Occurrence (PF) and Potential Consequence of Failure (CF). An Overall Measure of Risk (OMOR) function is developed to measure the level of overall risk for a single concept design based on all DP selections.

A ship design case study is performed incorporating the OMOR function and risk items into a ship synthesis model capable of calculating cost, performance, and effectiveness. This case study uses a Multi-Objective Genetic Optimization (MOGO) to identify and define a series of non-dominated cost-effectiveness frontiers for a range of risk (OMOR) values. This new method for ship design optimization provides a novel approach and consistent format for multi-objective decision making based on three dissimilar objective attributes: effectiveness, cost and risk.

2. LITERATURE AND INFORMATION RESEARCH & DEVELOPMENT

2.1 Introduction to Risk, Engineering & Systems Safety

It is not difficult to associate the word “Risk” with the word “Engineering.” In fact, in their text What every engineer needs to know about Risk [2, p. 12], authors Wang and Roush go as far as to define Engineering as “a profession of managing technical Risk.” So what is risk and how does it really relate to engineering?

Like many subjects, risk can be defined and measured both qualitatively and quantitatively.

Qualitatively speaking, Wang and Roush define risk as the deviation of project outcomes from a mean or anticipated value; and they define Engineering Risk as “the chance of incurring a loss or gain by investing in an engineering project” [2, p. 13]. Similar definitions are given by Modarres, Blanchard, and Molak [3; 4; 5].

In his text Fundamentals of Risk Analysis and Risk Management, Molak defines risk by stating that “Risk is a body of knowledge (methodology) that evaluates and derives a probability of an adverse effect of an agent (chemical, physical, or other), industrial process, technology, or natural process where the definition of an ‘adverse effect’, is a value judgment” [5, p. 5].

Modarres formally defines risk in his text, What every engineer needs to know about Reliability and Risk Analysis as “the potential of loss or injury resulting from exposure to a hazard” [3, p. 6]. Further stating, “When there is a source of danger (hazard), and when there are no safeguards against exposure of the hazard, then there is a possibility of loss or injury - this is referred to as risk” [p.6]. Modarres also underlines the relationship between risk and the reliability of system safeguards by saying, “In complex engineering systems, there are often safeguards against exposure to hazards. The higher the level (and reliability) of safeguards, the lower the risk” [p. 6]. However, this definition is better suited for a study of system safety and reliability than a conceptual or preliminary (ship) design.

Finally and for the purpose of this paper, risk is perhaps best defined by Blanchard in his text on Systems Engineering Management, as “the potential that something will go wrong as a result of one or a series of events…measured as the combined effect of the probability of occurrence and the assessed consequence given that occurrence” [4, p. 287].

There are many more similar definitions of Risk but no matter how risk is defined, one invariant holds true: “risk always increases as projects become more complex” [2, p.12]. Risk Engineering is a response to this invariant, and satisfies the need for an efficient way to control the identification, evaluation, and management of technical Risk.

2.1.1 Risk Engineering

Risk Engineering involves understanding system complexity and its engineering dynamics and as Wang and Roush point out, “understanding failure is critical to engineering success. Every failure is a logical result of its causes, although properly diagnosing the cause may be difficult. Engineers must get to the root causes of failures and through this understanding ensure a clear path to engineering success” [2, p. 3].

Wang and Roush characterize risk engineering as an integrated process, which includes two major parts: *Risk Assessment* (or *Quantitative Risk Analysis)* and *Design for Risk Engineering* [2, p. 15].

1. Through Risk Assessment, uncertainties are modeled and assessed, and their effects on a given decision evaluated systematically [2, p. 15].
2. Through Design for Risk Engineering, the risk associated with each decision alternative is delineated if cost-effective measures are taken to control or minimize the corresponding possible consequences [2, p. 15].

“Risk implies opportunities for improvement” [2, p. 11] and is a part of Risk Engineering.

“The objective of engineering design is to obviate failure” [2, p.11] and “convert risks into opportunities through validation, qualification, and testing” [2, p.15].

“Design for risk engineering starts from understanding the weakest link of engineering systems, and is built on the following Three Lines of Defense” [2, p. 77]:

- The First Line of Defense – Avoid or Eliminate Failure Causes
- The Second Line of Defense – Detect and Control Failure Early;
- The Third Line of Defense – Reduce the Impact/Consequence of Failures.

“Engineering risk should be eliminated and ‘designed out’ of the product or system if possible [2, p. 112]. The remaining risks should be mitigated “using measures that are introduced into system design and operation to reduce the probability or consequence of undesirable events when there are system failures” [2, p. 112].

2.1.2 Risk Analysis

2.1.2.1 A Historical Perspective

Historical perspectives on risk analysis applications in society are given by Covello and Mumpower [6] and Molak [5]:

“Modern risk analysis has roots in probability theory and the development of scientific methods for identifying causal links between adverse health effects and different types of hazardous activities. Blaise Pascal introduced probability theory in 1657, Edmond Halley proposed life-expectancy tables in 1963, and in 1972, Pierre Simon de Laplace developed a true prototype of modern quantitative risk analysis with his calculations of the probability of death with and without smallpox vaccination” [5, p. 4]

“Insurance, which started 3900 years ago in Mesopotamia, is one of the oldest strategies for dealing with risk. In 1950 BC, the Code of Hamurabi formalized bottomry contracts containing a risk premium for the chance of loss of ships and cargo. In 1583, the first life insurance policy was issued in England.” [5, p. 4]

“Actuaries (people who calculate insurance premiums, based on historical losses and estimates of the future income from premiums and losses) are probably the best risk assessors, since the failure in making accurate predictions about losses and premium income can result in the loss of the business” [5, p. 4].

“Conceptual development of risk analysis in the United States and other industrially developed countries started form two directions:

- “The development of nuclear power plants and concerns about their safety (this led to the development of the classical probabilistic risk analysis)” [5, p. 5].

- "The establishment of the U.S. Environmental Protection Agency (EPA), Occupational Safety and Health Administration (OSHA), National Institute for Occupational Safety and Health (NIOSH), and equivalent government agencies in developed countries" [5, p. 5].

Today there are a great number of individuals studying risk. "Engineers seeing risk from the technological point of view are mixing with sociologists who look at society's perception of risk. Psychologists are involved in studying how the cognitive processes analyze risk. Biologists, chemists, epidemiologists, and other medical doctors are studying how toxins from various sources, affect the body and the mortality risk. Environmentalists are studying how toxic releases affect the environment. Government regulatory agencies are involved with how the public reacts to risk information. Economists study how countries take risks and the economic effects of those risks. Politicians are asking why can't we have zero risk? Insurance companies take risk seriously and attempt to define and study it" [6, p. 201]. These different groups all approach risk analysis in different ways that can be organized and studied.

2.1.2.2 (Quantitative) Risk Analysis

Risk analysis is a complex process, interdisciplinary in nature, and with many facets. As decision-makers, engineers tend to concern themselves more with quantitative methods than qualitative methods when at all possible, and accordingly the literature and information search conducted for this manuscript was primarily focused towards understanding quantitative risk analysis (QRA).

QRA involves estimation of the degree or probability of loss, and is fundamentally intertwined with the concept of probability of occurrence of hazards or potential failures.

Both Bahr [6, p.205] and Modarres [3, p. 7] cite Kaplan and Garrick's work on the quantitative definition of risk" [8]. Bahr points out that Kaplan and Garrick define risk as three questions; Modarres points out that risk analysis consists of answers to these questions:

1. What can go wrong that could lead to an exposure to a hazard?
2. How likely is this to happen?
3. If it happens, what are the expected consequences?

Based on the definition by Kaplan and Garrick, Bahr further defines risk as the triplet: event scenario, probability of occurrence, and consequence [6, p. 205].

Wang and Roush define risk analysis as the quantification of potential failure.

"If we cannot express what we know in the form of numbers, we really don't know much about it…if we don't know much about it, we cannot expect to optimally control it…that is why we need to quantify potential failures." [2, p.4]

Wang and Roush rephrase Question 1 of the preceding page asking, "what can fail within an engineering system that could reduce effectiveness, create hazards, or cause exposure" [2, p.4]?

These questions can be customized for any specific type of system.

Determination of Risk Values

Paralleling Kaplans and Garrick's questions is a three step risk analysis triplet:

1. To quantitatively answer Question 1, a list of initiating events, Ei (or scenarios of events leading to the outcome)" is defined [3, p. 7].
2. To answer the Question 2, the likelihood of the scenarios or events materializing, Pi is estimated.
3. To answer, Question 3, an the scenario's consequence, Ci is estimated.

The concept of risk combines chance or probability for failure with the consequence caused by the failure. Probabilities are necessary to help determine the likelihood or chance of an event occurring. Sometimes, probabilities can be obtained from actual observations. However as Wang points out there are instances (e.g. such as the introduction or design and development of a new product) when the outcome is highly uncertain and there is little or no past experience to recover [2, p. 13]. According to Wang, in such cases "the engineer must make a judgment as to the probable outcome" [2, p. 13].

"Engineers must begin their design endeavor by answering what might work and what can go wrong" [2, p. 4]. However by the above definition, "Engineering designs are successful only to the extent that the designers foresee and understand how a system may fail to perform its necessary functions" [2, p. 4]. Another essential element of risk is the uncertainty or "the fact that engineers don't know exactly what failures will occur and when and where the failures will occur" [2, p. 4]. Understanding the uncertainty of a risk assessment is paramount to be able to wisely use the risk assessment as a decision tool.

"In most risk assessments, the likelihood of event E_i is expressed in terms of the probability of that event. Alternatively, a frequency per year or per event (in units of time) may be used. Consequence Ci, is a measure of the impacts of event Ei. This can be in the form of mission loss, payload damage, damage to property, number of injuries, number of fatalities, dollar loss, etc" [3, p. 301].

"The results of the risk estimation are then used to interpret the various contributors to risk, which are compared, ranked, and placed in perspective" [3, p. 301]. This process consists of two steps:

1. "Calculating and graphically displaying a risk profile based on individual failure event risks" [3, p. 302].
2. "Calculating a total expected risk value R from [3, p. 301]:

$$R = \sum P_i \times C_i \tag{2-1}$$

It is important to realize that this calculation involves uncertainties, approximations, and assumptions.

Equation (2-1) assumes:

- Independence
- Small Probabilities, i.e. Σ $P_i << 1$

Wang and Modarres stress that uncertainties must be considered explicitly [2][3].

Modarres includes two additional planning steps in a risk analysis [3, p. 301]. These steps are:

1. Identification of cost-effective risk management alternatives
2. Adoption and implementation of risk-management methods

"Using expected losses and the risk profile one can evaluate the amount of investment that is reasonable to control risks, alternative risk-management decisions to avoid risk and alternative actions to mitigate consequences" [3, p. 301].

Interpreting Results

Risk results are often shown in a general form similar to Table 2-1 [3, p. 302]. "There are two useful ways to interpret risk estimation results: determining expected risk values, Ri, and constructing risk profiles. Both of these methods are used in quantitative risk analysis" [3, p. 302].

Table 2-1. General Format of Risk Estimation Results

Undesirable Event	Likelihood	Consequences	Risk Level
E_1	P_1	C_1	$R_1=P_1C_1$

Expected Value Method

Modarres' expected value method of interpreting results is useful when the consequences C_i are measured in units measurable directly such as financial terms and equation (3) can be used to obtain the total expected loss per year for a whole set of possible events. "The expected risk value R_i associated with event E_i is the product of its probability P_i and consequence values, as described by Table 2-1. Thus if the event occurs with a frequency of 0.01 per year, and if the associated loss is $1 million, then the expected loss (or risk value) is [3, p. 302]:

$$\text{Expected loss} = .01 \text{ x } \$1 \text{ million} = \$10{,}000 \tag{2-2}$$

The expected value method assumes three things:

- Parameters not varying significantly with time.
- Low probability of multiple losses ignored over the period.
- Equal weight of all events (Ei) contributing to risk exposure.
- Independence
- Small Probabilities, i.e. $\Sigma P_i << 1$

Value factors (weighting factors) may occasionally be assigned to each event contributing to risk. When associated with the different hazardous events, these values can give a useful measure of their relative importance. "Total risk value can be interpreted as the average or "expected" level of loss over a given period" [3, p. 302].

Risk Profiles

Modarres' other method for presenting results is the construction of a risk profile. In this method, probability values are plotted against consequence values. This is accomplished using logarithmic scales or error brackets.

Risk Profiles using logarithmic scales are usually used to cover a wide range of values when discrete probabilities and consequences are known. The scales easily illustrate events with high probability, high consequence, or high uncertainty.

Risk Profiles also use error brackets [3, p. 303]. Using this method, uncertainties in the probability estimate are denoted with vertical brackets and uncertainty of consequence is denoted with horizontal brackets as shown in Figure 2-1. Complementary cumulative probability risk profiles or Farmer's curves are then created as shown in Figure 2-2 so that the low probability/high consequence risk values and high probability/low consequence risk values can be easily seen.

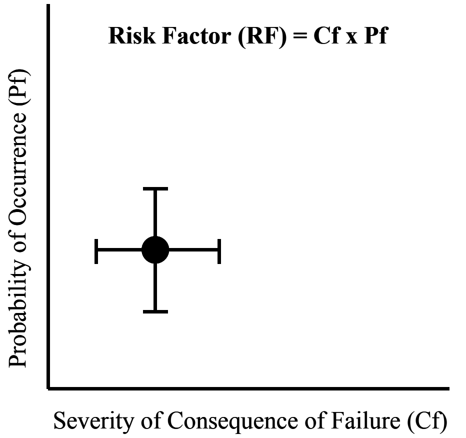


Figure 2-1. Probability and Consequence Error Brackets

Displaying Results

"Results can be presented graphically in various formats. For example, probability distributions are used to display uncertainty about scalar quantities, such as the frequency of an accident. For damage types that involve different levels of severity, complementary cumulative distribution function (CCDFs) are used to show the frequency of exceeding any given damage level. However, such CCDFs still represent only point estimates of risk, since they do not display the uncertainty about the accident frequency [9]. Uncertainty about such functions is displayed by presenting a family of possible CCDFs, possibly indexed by their probability" [5, p.70]. Graphic examples of quantitative risk assessment results are shown Figure 2-2.

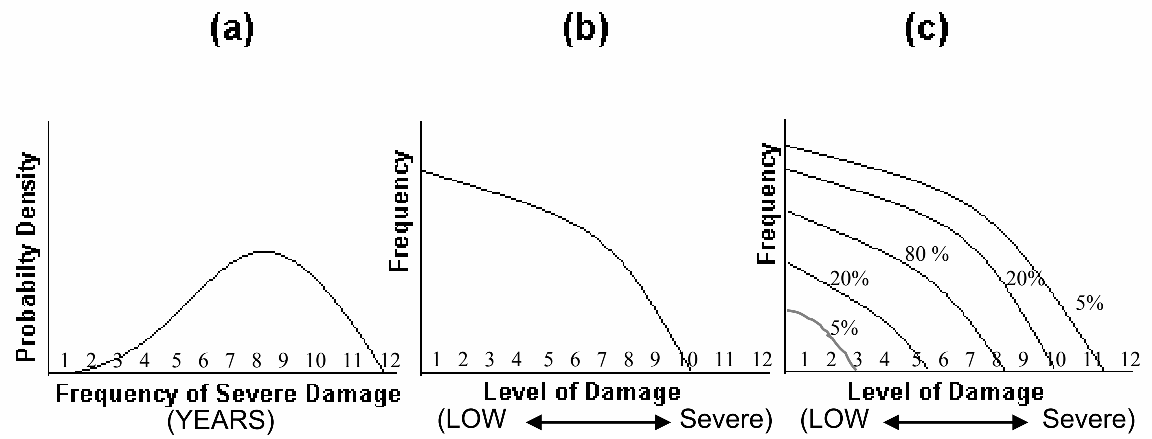


Figure 2-2. Graphic types of quantitative risk assessment results: (a) probability distribution for an accident frequency; (b) complementary cumulative distribution function; (c) Family of possible complementary cumulative distribution functions. [5, p. 70] [10]

2.1.2.3 Risk and Probability: Basic Mathematics

Risk analysis is a study of probabilities and chance. The mathematics behind probabilities are not complicated but must be understood.

The probability of an event E of set S is [3, p. 14]:

$$\Pr(E) = m(E)/\mathrm{num}(S) \tag{2-3}$$

where:

m(E) is a function that determines the number of times the event E occurs in set S.

num(S) is the total number of events in set S.

“Provided that the sample space contains N equally likely and different outcomes, n of which have an outcome E” [3, p. 15].

$$\Pr(E) = n/N \tag{2-4}$$

Risk can be assessed using one of three interpretations of probability: Classical, Frequency, or Subjective.

Classical Interpretation of Probability

Using the classical interpretation of probability, a mechanical failure, (e.g. a plant pump) is compared to the ‘equally likely’ concept of rolling a perfect die, with each side having an equal probability of 1/6 at any time. While this interpretation is fine for dice, it is not adequate for complex engineering systems. For example, if a pump fails after a start of a process, it is not clear whether all pump failures are equally likely” [3, p. 15].

Frequency Interpretation of Probability

"The frequency interpretation of probability overcomes the lack of knowledge about the overall sample space by defining the probability as the limit of n/N as N becomes large" [3, p.15]. Here probability is described as:

$$\Pr(E) = \lim_{N \to \infty} \frac{n}{N} \tag{2-5}$$

Subjective Interpretation of Probability

The subjective interpretation of probability defines Pr(E) as a measure of the degree of belief one holds in a specified event E" [3, p. 15].

"In the case where a designer believes that a change will result in a performance improvement in one out of three missions the classical interpretation is inadequate since there is no reason to believe that performance is as likely to improve as to not improve. The frequency interpretation is not applicable because no historical data exists to show how often a design change resulted in improving the system. Thus the subjective interpretation provides a broad definition of the probability concept" [3, p. 15].

Bayes' Theorem

Bayes' theorem "provides a means of changing one's knowledge about an event in light of new evidence related to the event" [3, p. 17]. It is represented as:

$$\Pr(A \setminus E) = \Pr(A) * \Pr(E \mid A)/\Pr(E) \tag{2-6}$$

where:

$\Pr(A)$ is the prior probability,

$\Pr(E|A)\backslash\Pr(E)$ is the relative likelihood.

$\Pr(A|E)$ is the posterior probability [3, p. 17].

Risk Analysis for Multiple Failures

"In a complex multi-component engineering system, the possibilities of failure or the different ways in which failure of the system can occur may be so involved that a systematic scheme for identifying all the potential failure modes and their respective consequences is necessary" [2, p. 58]

To illustrate the calculation of the probability of a system failure, a system with k potential failure modes is considered where Ei is the event of failure by the ith failure mode [2, p. 55].

The probability of a system failure, P(E) is calculated by [2, p. 56]:

$$P(E) = 1 - (1 - P1)(1 - P2)\ldots(1 - Pk) \tag{2-7}$$

2.2 The Role of Risk Analysis in the System Design Process

To understand the role of risk analysis in the system design process it is important to understand what is meant by a system. “The term *system* stems from the Greek work *systema*, meaning an organized whole. In essence, a system constitutes a set of interrelated components working together with the common objective of fulfilling some designated need” (4, p. 6).

Systems are further defined by Blanchard as having the following general characteristics:

1. “System constitutes a complex combination of resources;
2. A system is contained within some form of hierarchy;
3. A system must have a purpose and be capable of meeting its stated purpose in the best way possible;
4. A system may be broken down into subsystems and related components, the extent of which depends on complexity and the function(s) being performed” (4, p. 6).

This last characteristic holds especially true for large complex systems like ships, which have been likened to “floating cities”. “Dividing the system into smaller units allows for a simpler approach relative to the initial allocation of requirements and the subsequent analysis of the system and its functional interfaces. The system is made of many different components, these components interact with each other, and these interactions must be thoroughly understood by the system designer and/or analyst. Because of these interactions among components, it is impossible to produce an effective design by considering each component separately. One must view the system as a whole, break down the system into components, study the components and their inter-relationships, and then put the system back together” (4, p. 6).

During a design, a ship is commonly broken down within some form of hierarchy into five levels of design. These levels are:

Level 1 - Ship (At this level the engineering effort typically will focus on up-front systems engineering, development of operation requirements into functional and performance requirements, and development of a System Performance Specification);

Level 2 - System (At this level the engineering effort typically will focus on the development of high level system requirements and conceptualization of design solutions for major systems such as the ship system, mission system, and support system);

Level 3 - Subsystem (At this level the engineering effort typically will focus on development of subsystem requirements and the design of system specifications for systems such as the hull, C4ISR, and logistics);

Level 4 - Component (At this level the engineering effort typically will focus on development of element component requirements and the design of system specifications for components such as bilge keels, computers, and provisioning);

Level 5 - Unit (At this level the engineering effort typically will focus on development of element unit requirements such as steel plate, computer program modules, and equipment circuit boards)

There is significant work and time between starting on Level 1 and finishing level 5. Managing this work is handled in the shipbuilding world by spreading the engineering and development effort across the first three stages of a six-stage ship lifecycle. The six stages are:

1. Conceptual design;
2. Preliminary design;
3. Detail design and development;
4. Production, fabrication, & construction;
5. Ship operations;
6. Ship retirement and disposal.

This life cycle is illustrated in Figure 2-3.

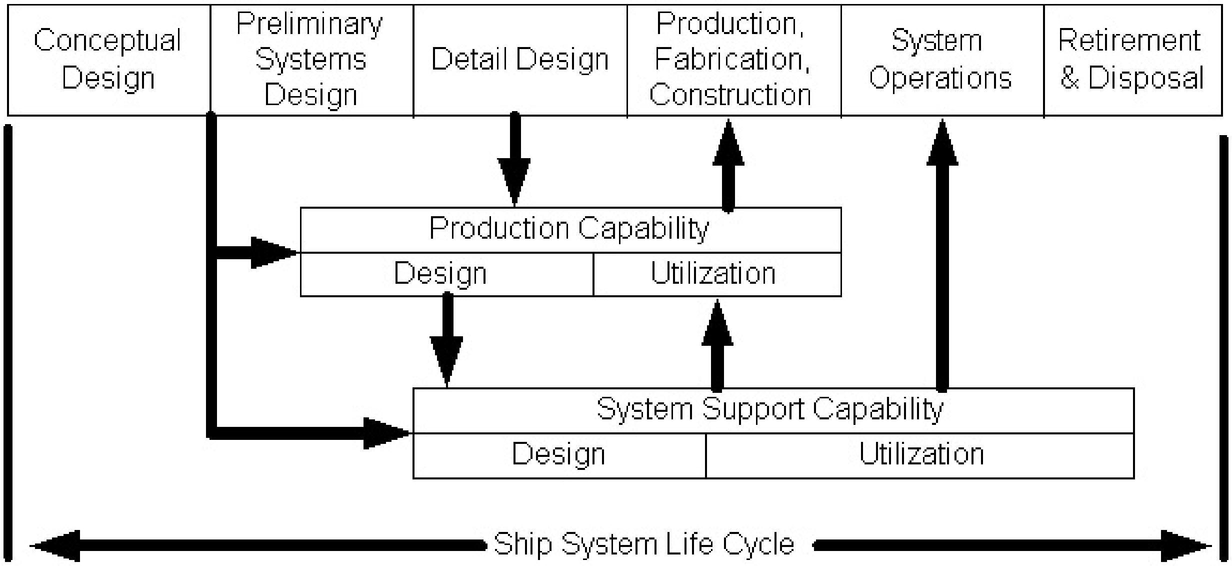


Figure 2-3. Example of a Ship System Life Cycle (modified from [4, p. 11])

Understanding the different types of engineering that are performed during the ship's life cycle and when they are performed is important because it influences what types of risk management techniques can and should be employed as the systems engineering process decomposes the ship's systems and integrates them into a ship.

During the conceptual and preliminary design phases, engineers and designers need to be concerned primarily with the risk of not meeting specified technical and program requirements like cost, schedule, and performance. Since ships have life cycles of 30-40 years, this requires thinking of everything from how the ship will be designed to how it will be disposed. This type of risk is the subject of this thesis.

Later, as the ship system designs mature, engineers need to be concerned with risks associated with specific systems and the response of these complex engineered systems to disturbances during operations. This requires identifying how they might fail and resolving specific system hazards.

As the ship is deployed into operation, more information becomes available about existing sub-systems, and at the same time, new systems are introduced into the ship system through technology refreshes and overhauls. This aspect requires risk management to continue throughout the ship's entire lifecycle.

2.2.1 Conceptual Design and the Systems Engineering Approach to Risk

Systems engineering is the orderly process of bringing a system into being. More broadly defined by Blanchard, "systems engineering is the effective application of scientific and engineering efforts to transform an operational need into a defined system configuration through the top-down iterative process of requirements analysis, functional analysis and allocation, synthesis, design optimization, test and evaluation and validation" (Blanchard, p. 12).

"The identification of technical risks is of particular interest with regard to system engineering because the fulfillment of design objectives is highly dependent on the proper and expeditious handling of these risks. In this respect, risk management should be an inherent aspect of system engineering management" [4, p. 292]

Blanchard [4] looks at Risk from the point of view of the systems engineer. His discussion is centered on building a Risk Plan and how it fits into the systems engineering (SE) process or more specifically, a Systems Engineering Management Plan (SEMP).

Blanchard warns that "the potential for risk becomes increasingly higher as complexities and new technologies are introduced in the design of systems. "Risk, as used in the context described herein, refers to the potential of not meeting a specified technical and /or program requirement; for example not meeting a requirement specified by a technical performance measure (TPM), a schedule, or a cost projection" [4, p. 287].

2.2.1.1 Risk Assessment of Technical Performance Measures and Design Parameters

Design engineering risks can be tied directly to design parameters (DPs) and technical performance measures (TPMs) such as measures of performance (MOPs) and measures of effectiveness (MOEs). These DPs and TPMs, which reflect critical factors in design and operational effectiveness, can be prioritized to reflect relative degrees of importance.

This risk management activity begins by identifying the potential areas of risk. "Although there is some degree of risk associated with any program area of activity where decisions are being made, one needs to identify those in which the potential consequences of failure could be significant! Program areas of risk may include funding, schedule, contract relationships, political, and technical. Technical risks relate primarily to the potential of not meeting a design requirement, not being able to produce an item in multiple quantities, and/or not being able to support a product in the field. [4, p. 288].

"Given the identification of performance characteristics to which the system is to be designed (i.e., those parameters that require monitoring on a regular basis), the next step is to evaluate these by indicating possible causes for failure. In the event of a failure to meet a specific design requirement, what are the possible causes and what are the probabilities of occurrence? Although the output measure being monitored may be a high-priority TPM, the cause for a possible failure may be the result of a misapplication of a new technology in design, a schedule delay on the part of a major supplier, a cost overrun, or a combination of these" [4, p. 288].

"The causes are evaluated independently to determine the degree to which they can impact the TPM(s) being monitored. Sensitivity analyses are conducted, using various analytical models as appropriate, to determine the magnitude of the potential risk. This, in turn, will lead to the classification of factors in terms of "high," "medium," or "low" risk. These classifications of risk are then addressed within the program management review and reporting structure. High-risk items are monitored to a greater extent, with a higher priority relative to initiating a risk abatement plan, than low—risk items" [4, p. 288].

The risk assessment and classification process is shown in Figure 2-4.

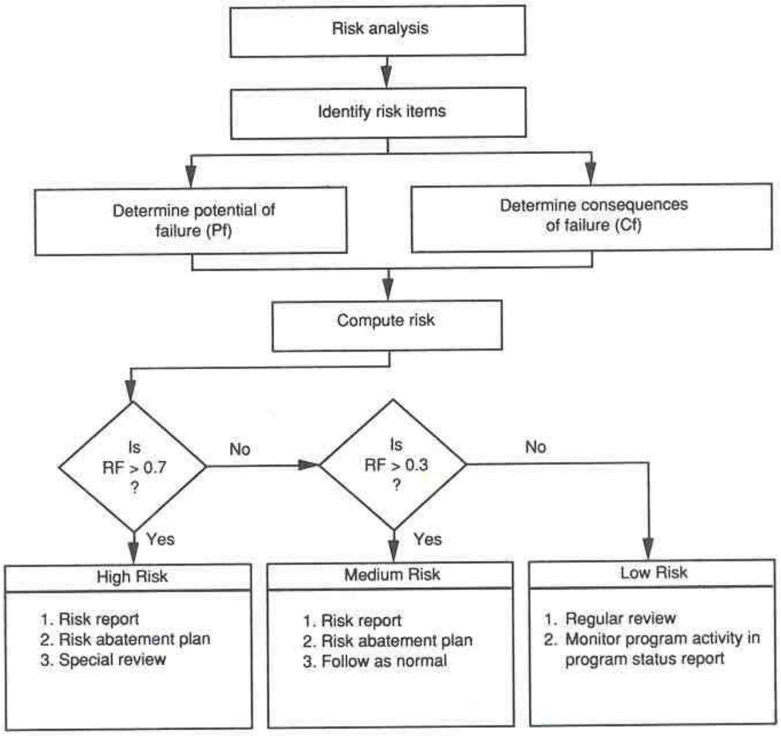


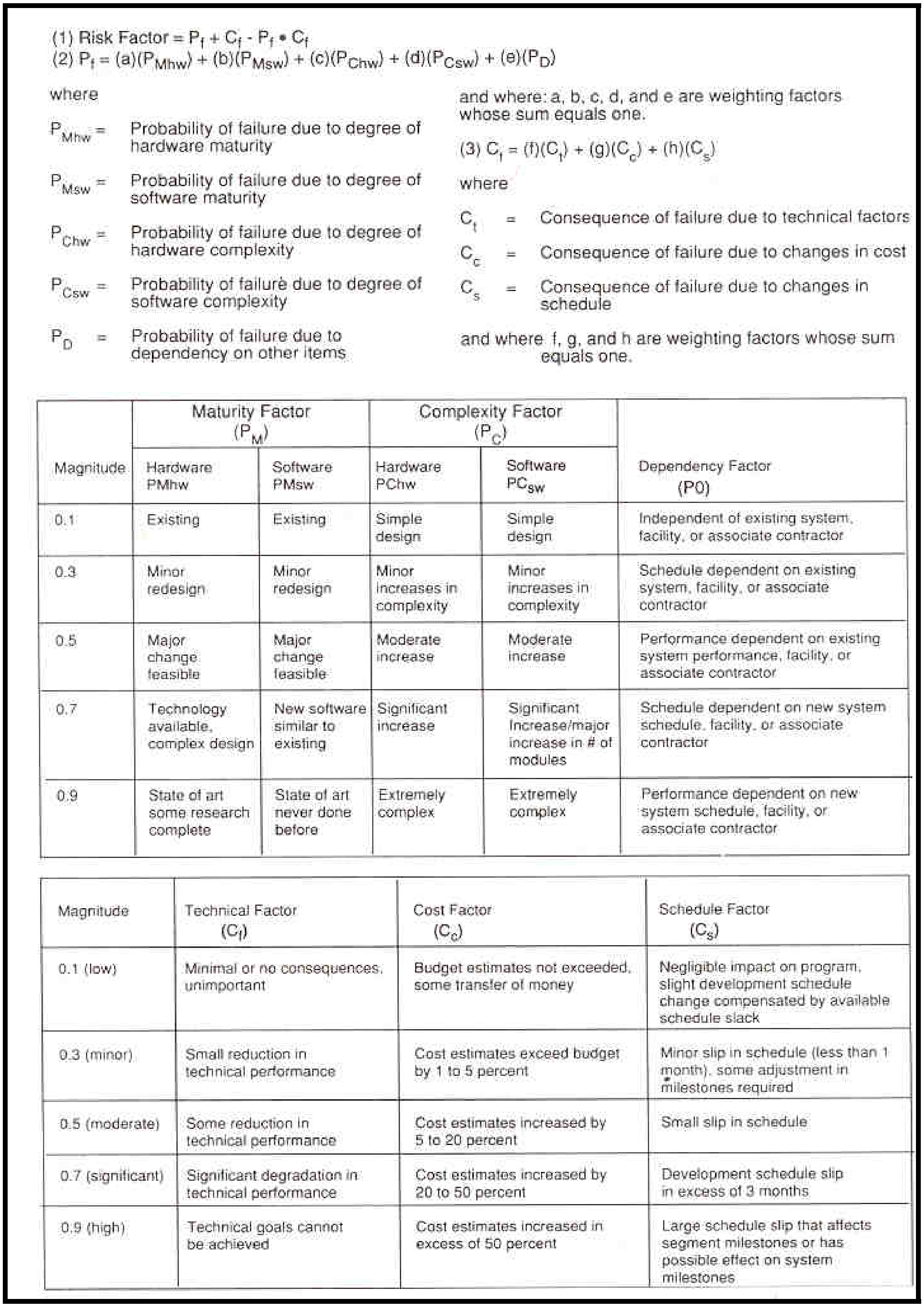
Figure 2-4. Risk Assessment and Classification Process. [4, p. 291]

To facilitate the risk assessment and classification process, Blanchard has presented a potentially useful model as an example of how to obtain a quantitative risk result. The method used in this example model derives from the equality defining risk set forth by Equation 2-1 and risk is assessed in terms of the two major variables: Probability of failure (Pf), and the Consequence of that failure (Cf). This model is shown in Figure 2-5. However, this model has two peculiarities. First the model unexplainably attempts to quantify risk by subtracting the product of Pf and Cf from the sum of Pf and CF. This is expressed as:

$$\text{Risk Factor (RF)} = \text{Pf} + \text{Cf} - (\text{Pf})(\text{Cf}) \qquad (2\text{-}8)$$

Secondly, the model attempts to structure a method that uses expert opinion to obtain a quantitative risk result through consolidation of hardware and software failure into a single PF factor and consolidation of technical, cost, and schedule consequences into a single CF factor.

Unfortunately, while this is a novel concept it may have an adverse effect of misrepresenting true risk.



(1) Risk Factor = $P_f + C_f - P_f \bullet C_f$

(2) $P_f = (a)(P_{Mhw}) + (b)(P_{Msw}) + (c)(P_{Chw}) + (d)(P_{Csw}) + (e)(P_D)$

where

P_{Mhw} = Probability of failure due to degree of hardware maturity

P_{Msw} = Probability of failure due to degree of software maturity

P_{Chw} = Probability of failure due to degree of hardware complexity

P_{Csw} = Probability of failure due to degree of software complexity

P_D = Probability of failure due to dependency on other items

and where: a, b, c, d, and e are weighting factors whose sum equals one.

(3) $C_f = (f)(C_t) + (g)(C_c) + (h)(C_s)$

where

C_t = Consequence of failure due to technical factors

C_c = Consequence of failure due to changes in cost

C_s = Consequence of failure due to changes in schedule

and where f, g, and h are weighting factors whose sum equals one.

	Maturity Factor (P_M)		Complexity Factor (P_C)		
Magnitude	Hardware PMhw	Software PMsw	Hardware PChw	Software PC_{sw}	Dependency Factor (P0)
0.1	Existing	Existing	Simple design	Simple design	Independent of existing system, facility, or associate contractor
0.3	Minor redesign	Minor redesign	Minor increases in complexity	Minor increases in complexity	Schedule dependent on existing system, facility, or associate contractor
0.5	Major change feasible	Major change feasible	Moderate increase	Moderate increase	Performance dependent on existing system performance, facility, or associate contractor
0.7	Technology available, complex design	New software similar to existing	Significant increase	Significant Increase/major increase in # of modules	Schedule dependent on new system schedule, facility, or associate contractor
0.9	State of art some research complete	State of art never done before	Extremely complex	Extremely complex	Performance dependent on new system schedule, facility, or associate contractor

Magnitude	Technical Factor (C_f)	Cost Factor (C_c)	Schedule Factor (C_s)
0.1 (low)	Minimal or no consequences, unimportant	Budget estimates not exceeded, some transfer of money	Negligible impact on program, slight development schedule change compensated by available schedule slack
0.3 (minor)	Small reduction in technical performance	Cost estimates exceed budget by 1 to 5 percent	Minor slip in schedule (less than 1 month), some adjustment in milestones required
0.5 (moderate)	Some reduction in technical performance	Cost estimates increased by 5 to 20 percent	Small slip in schedule
0.7 (significant)	Significant degradation in technical performance	Cost estimates increased by 20 to 50 percent	Development schedule slip in excess of 3 months
0.9 (high)	Technical goals cannot be achieved	Cost estimates increased in excess of 50 percent	Large schedule slip that affects segment milestones or has possible effect on system milestones

Figure 2-5. Blanchard's Mathematical Model for Risk Assessment [4, p. 289] [11]

Blanchard warns that “this model was adapted from the procedure in Defense Systems Management College, Systems Engineering Management guide, DSMC, Fort Belvoir, VA, 1866. Although the later issues of this document do cover the various aspects of risk management, this particular model has been deleted for reasons unknown” [4, p. 288].

In lieu of this warning, this model will not be used for the this thesis, however the concept of determining Pf based on maturity, complexity, and dependency factors will be adopted for use on selected systems. Hardware and software risks from failure due to maturity, complexity, and dependency will be considered, assessed, and tracked separately.

The concept of determining Cf based on technical, cost, and schedule will also be adopted with a caveat. Technical, cost, and schedule consequences will be separately considered for each Pf.

Weighting factors will not be used for consolidating hardware and software failure into a single PF factor or for consolidating of technical, cost, and schedule consequences into a single CF factor to avoid misrepresenting or understating risks related to PF or CF. The risk factor equation will be defined simply as:

$$\text{Risk Factor (RF)} = \text{Pf} * \text{Cf} \tag{2-9}$$

Table 2-2 was developed to quantify hardware and software failure probabilities due to maturity, complexity, and dependency factors.

Table 2-2. Probability of failure (Pf) due to Maturity, Complexity and Dependency

Magnitude	Hardware (HW)		Software (SW)		HW/SW
	Maturity	Complexity	Maturity	Complexity	Dependency
0.1	Existing	Simple design	Existing	Simple design	Independent of existing system, facility, or associate contractor
0.3	Minor redesign	Minor increases in complexity	Minor redesign	Minor increases in complexity	Schedule dependent on existing system, facility, associate or contractor.
0.5	Major change feasible	Moderate increase	Major change feasible	Moderate increase	Performance dependent on existing system performance, facility, or associate contractor
0.7	Technology available, complex design	Significant increase	New software similar to existing	Significant increase/major increase in 3 of modules	Schedule dependent on new system schedule, facility, or associate contractor
0.9	Beyond state of art – some research complete	Extremely complex	Beyond state of art – never done before	Extremely complex	Performance dependent on new system schedule, facility, or associate contractor

Table 2-3 was developed to quantify the technical, fiscal and schedule consequences of failure. “A similar approach can be applied in performing a risk analysis on all other applicable parameters. The net result is the development of a list of critical items, presented in order of priority that require special management attention. Risk reports are prepared at different times (i.e., frequency of distribution) depending on the nature of the risk. High-risk items require frequent reporting and special management attention, whereas low-risk items can be handled through the normal program review, evaluation, and reporting process” [4, p. 291].

This process is easily adaptable to ships and is used in Chapter 4.

Table 2-3. Consequence of Failure - Technical, Cost, and Schedule

Magnitude	Technical Consequence	Fiscal Consequence	Schedule Consequence
0.1	Minimal or no consequences, unimportant	Budget estimates not exceeded, some transfer of money	Negligible impact on program, slight development schedule change compensated by available schedule slack
0.3	Small reduction in technical performance	Cost estimates exceed budget by 1 to 5 percent	Minor slip in schedule (less than 1 month) some adjustment in milestones required
0.5	Some reduction in technical performance	Cost estimates increased by 5 to 20 percent	Small slip in schedule
0.7	Significant degradation in technical performance	Cost estimates increased 20 to 50 percent	Development schedule slip in excess of 3 months
0.9	Technical goals cannot be achieved	Cost estimates increased in excess of 50 percent	Large schedule slip that affects segment milestones or has possible effect on system milestones.

2.2.1.2 Early Risk Abatement

"Risk abatement involves the techniques and methods developed to reduce (if not eliminate) or control the risk." [4, p. 287].

"The purpose of a risk abatement plan is to highlight those areas where special management attention is required" [4, p. 292]. "For items classified under *high* and *medium* risk, a risk abatement plan should be implemented. This constitutes a formal approach for eliminating (if possible), reducing, and/or controlling risk. The accomplishment of such may involve one or a combination of the following:

1. Provide increased management review of the problem area(s) and initiate the necessary corrective action through an internal allocation or shift in resources;
2. Hire outside consultants or specialists to help resolve existing design problems;
3. Implement an extensive testing program with the objective of better isolating the problem and eliminating possible causes;

Initiate special research-and-development activities, conducted in parallel, in order to provide a *fall-back position*" [4, p. 291].

2.2.2 Current Industry Practices

2.2.2.1 Aerospace/Defense Industry

Identification of hazards early on in the aerospace/defense industry is paramount, because of the high costs of retrofitting mature systems. "The aerospace and military industries have been performing system risk and safety engineering since the 1960's. Some of the typical analysis techniques performed early on include: fault tree analysis, hazard analysis, operations and support hazard analysis, and failure modes and effects analysis" [7, p. 25]. These types of analysis will be discussed briefly in Section 2.2.3.3.

More recently, a disciplined, forward looking and continuous risk management approach has been emphasized. In 1986 the Government Accounting Office (GAO) developed five criteria “as an approach to good risk assessments” [12, p.2]. The GAO criteria are:

1. Planned Procedures – Risk management is planned and systematic.
2. Prospective Assessment – Potential future problems are considered, not just current problems.
3. Attention to Technical Risk – There is explicit attention to risk.
4. Documentation - All aspects of the risk management program are recorded and data maintained.
5. Continual Process – Risk assessments are made throughout the acquisition process; handling activities are continually evaluated and changed if necessary; and critical risk areas are always monitored [12, p.2].

These criteria “are considered important indicators of how well a risk management process is being implemented’ [12, p.2]. Currently, DoD policies and procedures that address risk management for acquisition programs are contained in the DoD 5000 series of directives [13] [14] [15] [16] [17]. “These documents contain the overall acquisition policy - with a strong basis in risk management, integrate risk management into the acquisition process, describe the relationship between risk and various acquisition functions, establish reporting requirements, and address risk and cost analysis guidance as they apply to the Office of the Secretary of Defense” [12, p.2]. Most recently, the GAO criteria and the DoD risk management policies and procedures have been described in the “Risk Management Guide for DoD Acquisition” [12].

The DoD guide prescribes risk assessment of technical performance, cost, and schedule through the identification and subsequent analysis (and prioritization) of prospective program events in terms of probability and consequences/impacts [12, p.11]. These two components of assessment are performed sequentially with identification being the first step.

While there is no standard approach (because defense industry techniques vary according to the technique employed, and the phase and nature of the program), “some top-level actions are typically common to all methods. These are grouped in Figure 2-6 into pre-risk assessment activities, risk identification activities, and risk analysis activities” [12, p.13].

An additional bullet should be added to the Risk Analysis block in this figure for multi-objective optimization (MOO). This bullet should read: Develop Overall Measure of Risk (OMOR) and use in MOO of design with Cost and Overall Measure of Effectiveness (OMOE). This will be addressed again in Chapter 4.

The DoD risk assessment process analyzes risk events by inter-relating the three risk categories (technical performance[1], schedule, and cost) to each other. For example, technical assessments include cost and schedule analysis in determining the technical risk impact. This relationship ensures integration of the assessment process through supportive analysis [12, p. 13].

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[1] Note: Technical performance risks may be further broken down into risk sub-categories. Examples of sub-categories include: threat, requirements, design, test & evaluation, simulation, technology, logistics, production, concurrency, and management. [26, p.43]

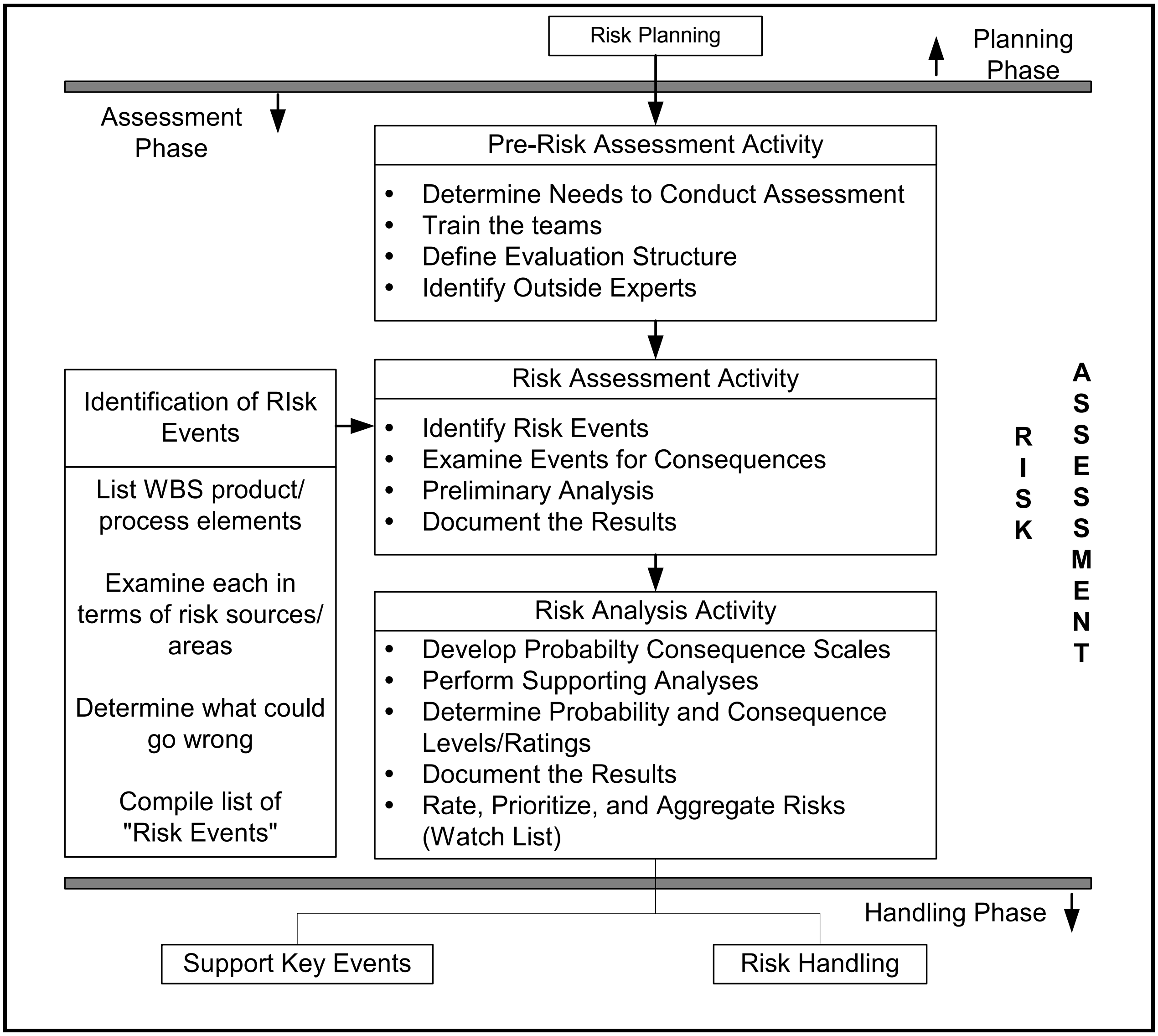


Figure 2-6. General DoD Risk Assessment Process [12, p. 12]

Pre-Risk Assessment activities may include preparing a program risk management plan, identifying team members, developing evaluation structures, and training IPTs.

Risk Assessment activities involve identifying risk events, examining events for consequences, and documenting results of preliminary analysis. “Risk events are those events that evaluators determine would adversely affect the program” [12, p.11]. To identify risk events, program elements are first broken down to a level where an evaluator can perform valid assessments/understand the significance of any risk and identify its causes [12, p.11]. This is done by developing a work breakdown structure (WBS) of the program. Finally, the program’s risk events are compiled by examining each product and process element in the WBS in order to identify sources or areas of risk and possible consequences. “During early phases, requirement, threat documents, and acquisition plans may be the only program – specific data available” [12, p. 14]. However, as a design is developed these risks can be extended to specific concepts.

Risk Analysis activities include developing probability and consequences scales, determining levels/ratings, performing supporting analysis, and documenting and prioritizing results. "The analysis begins with a detailed study of the critical risk events that have been identified with the objective to gather enough information about the risks to judge their probability of occurrence and their consequential impacts on cost, schedule, and performance (if the risk occurs)" [12, p.15].

Probability and Consequence/Impacts assessments, normally subjective and based on detailed information, are then performed in order to determine the probability of event occurrence and magnitude of the impact of an event, given the risk is realized. A variety of supporting analyses and techniques may support this assessment, e.g. comparisons with similar systems, relevant lessons learned, experience, test/prototype results, model/simulation data, expert judgment, document/plan analysis, sensitivity analysis, and analysis of alternatives) [12, p.15].

The last part of risk analysis, prioritization serves as the basis for risk-handling actions by ranking of risk events to determine the order of importance [12, p.11]. Risk ratings are an indication of the potential impact of risks on a program; they are often expressed as high, moderate, and low.

Table 2-4 andTable 2-5 are examples of probability/likelihood and consequence/impact criteria commonly used.

Table 2-4. Probability/Likelihood Criteria (Example) [12, p.16]

Level	**What is the Likelihood the Risk Event Will Happen?**
A	Remote
B	Unlikely
C	Likely
D	Highly likely
E	Near Certain

Table 2-5. Consequences/Impacts Criteria (Example) [12, p.16]

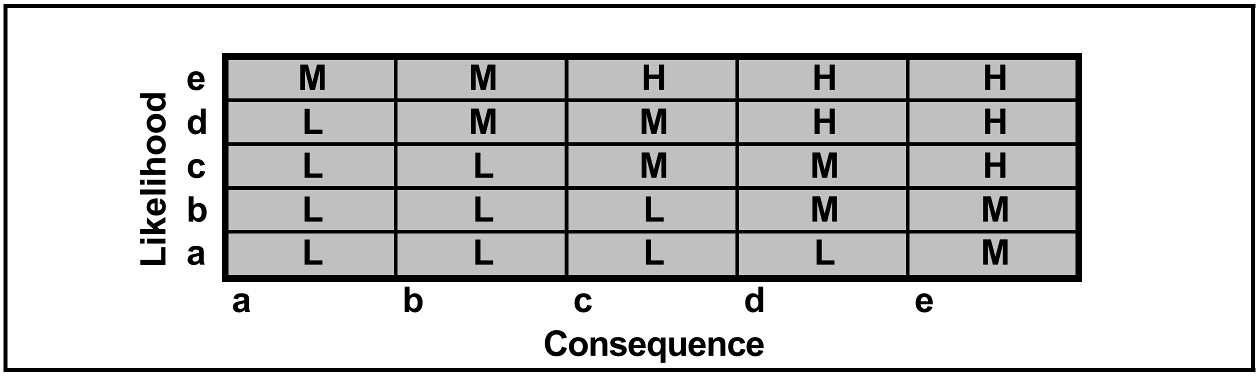
Level	**Given the Risk is Realized, What Is the Magnitude of the Impact?**		
	Performance	**Schedule**	**Cost**
a	Minimal or no impact	Minimal or no impact	Minimal or no impact
b	Acceptable with some reduction in margin	Additional resources required; able to meet need dates	<5%
c	Acceptable with significant reduction in margin	Minor slip in key milestones; not able to meet need date	5-7%
d	Acceptable; no remaining margin	Major slip in key milestone or critical path impacted	7-10%
e	Unacceptable	Can't achieve key team or major program milestone	>10%

“Table 2-6 contains an example overall risk rating criteria, which considers both probability/likelihood and consequences/impacts” [12, p.17].

Table 2-6. Overall Risk Rating Criteria (Example) [12, p.17]

Risk Rating	Description
High	Major disruption likely
Moderate	Some disruption
Low	Minimum disruption

“A simple method of representing the risk rating for risk events, i.e., a risk matrix, is shown in Figure 2-7” [12, p.17].



Likelihood

e	M	M	H	H	H
d	L	M	M	H	H
c	L	L	M	M	H
b	L	L	L	M	M
a	L	L	L	L	M
	a	b	c	d	e

Consequence

Figure 2-7. Overall Risk Rating (Example) [12, p.18]

2.2.2.2 Other Industries

Other industries put more emphasis on safety, but still offer some useful techniques.

The manufacturing and chemical industries primary interest in risk has more to do with systems safety than technical risk. Both industries are based primarily on federal OSHA regulations for worker safety and the surrounding community and environment [7, p. 23]. The manufacturing and chemical industries require “formal processes for safety analysis and hazards management” [7, p. 25]. The two most common analyses used in this industry are hazard operability analysis (HAZOP) and safety checklists [7, p. 25]. Both of these types of analysis are discussed briefly in Section 2.2.3.3.

The nuclear industry has been a leader in probabilistic safety analyses since the U.S. Atomic Energy Commission developed “the Reactor Safety Study,” WASH 1400 [19]. The WASH 1400 report lays a foundation for the use of probabilistic risk assessments or PRA. “PRA involves studying accident scenarios and ‘numerically rank[ing] them in order of their probability of occurrence, and assess[ing] their potential consequence to the public’”[7, p. 26]. PRA methods are briefly discussed in Section 2.2.4.

"The commercial airline industry was born out of the military air service, and for many years has used system safety engineering and management tools for public safety. Most airlines manage their programs using four primary analyses: hazard analysis; failure mode and effects analysis (FMEA), fault tree analysis, and zonal analysis. Zonal analysis is the verification of correct manufacture and installation. It starts by reviewing drawings and analysis and ends in the physical inspection of mockup, prototype, and production systems" [7, p. 26]. FMEA is discussed in Section 2.2.3.1.

2.2.3 Supporting Risk Analysis Techniques for Early and Later Stages of Design and Operations

Several techniques are available to engineers to help identify failure/accident scenarios of concern, the initiating events that lead to failures/accidents, and how they come about. "Depending on the particular technique and the risk being analyzed some of these supporting analyses may be necessary. In early stages of design - to provide the basis for subjective assessments, and in later stages of design – to replace them altogether and/or increase fidelity.

Failure Mode Effects Analysis (FMEA) and Criticality (CA) are two good techniques for gaining more information about failure modes and increasing design knowledge. Section 2.2.3.1 summarizes FMEA and Section 2.2.3.2 summarizes FMECA.

Initiating Events, Hazard Analysis, Checklists, and Tree methods are examples of other techniques commonly used to identify hazards and their causes. Section 2.2.3.4, contains a general review of these techniques. However, these are not described in detail because they are more oriented to reliability analysis than evaluation of technical risk.

2.2.3.1 Failure Mode Effects Analysis (FMEA)

FMEA is a bottom-up "inductive" analysis that identifies potential failures and minimizes effects of potential problems in a product, process or system design. It "is a tool used during the formal deign review stage by people who are responsible for the design, manufacture, management and maintenance of the product… to answer these fundamental questions" [2, p. 88]:

- How might this product/process potentially fail to meet its intent?
- What might be the cause and effect of such failure?
- What controls do we have in place to detect the failure?
- What safety features might prevent the failure?

The FMEA process: 1. Systematically details, on a component-by-component basis, all possible failure modes for the components of a system; 2. Identifies resulting effects on surrounding components, systems, and system of systems; 3. Attempts to predict possible sequences of events that lead to a system failure; 4. Determines the consequences of system failure (or its severity); and 5. Devises methods to minimize their occurrence or reoccurrence [20] [21, p. 109] [3, p. 158].

FMEA gives consideration to "potential failure modes and their implications to the design and manufacturing process. This allows appropriate countermeasures to be developed so that high-risk components are designed to minimize the likelihood of that failure. The product of FMEA is a table of information that summarizes the analysis of all possible failure modes" [2, p. 89].

To conduct a FMEA, an engineer starts with the components in the system and identifies the ways the components can fail as a function of the component within a system (failure modes). Next the failures are analyzed as to how they effect the system.

The “FEMA procedure consists of a sequence of steps starting with the analysis at one level or a combination of levels of abstraction, such as system functions, subsystems, or components. The analysis assumes a failure mode occurs and causes a failure. The effect of the failure is then determined as well as the causative agent for the failure, which is called the failure mechanism” [3, p. 158].

Bahr provides the following steps for FMEA:

1. Define the system and analysis scope and boundaries;
2. Construct functional block diagrams that indicate how the different system indenture levels are related;
3. Assess each functional block and determine if its failure would affect the rest of the system. If it would not, then ignore the block. If its failure would affect the rest of the system, go down another indenture level and perform the following scheme;
4. In each functional area where failures could adversely affect the system, look at the component failures. List the modes or ways that the component can fail. List the modes or ways that the component can fail. Mention what component parts would fail;
5. For each failure mode, assess the failure’s effects. Usually engineers assess the worst credible case with consequence severity and probability of occurrence, if possible;
6. Identify whether the failure is a single-point failure. A single point failure is the failure of a single component that could bring down the entire system;
7. Determine methods of corrective action. These might take the form of preventing the failure or mitigating its effects;
8. Document on the FMEA worksheet[2] [7, p. 147].

“The system schematic is the key document used to determine the ‘severity’ or effect of a failure of a specific part, in a specific failure mode. The FMEA considers each part and determines the effect that each failure mode will have on the overall system as well as the environmental impact” [2, p. 91].

“**Severity** of a potential failure is represented by the variable S and is assigned a value between 1 and 10, where 10 is the most severe. “Severity is an assessment of the seriousness of the effect (or consequence) of the potential failure mode to the next component, subsystem, system or customer if it occurs” [2, p. 93]. “Severity considers the worst potential consequence of a failure, determined by the degree of injury, property damage, or system damage that ultimately occurs [21, p. 110] [20].

“MIL-STD-1629A [20] recommends the following severity classification “ [21, p. 110]:

- Category 1: Catastrophic—A failure that may cause death or weapon system loss, i.e., aircraft, tank, missile, ship, etc.

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[2] “Typical Columns of an FMEA include: Component #, Name, Function, Failure mode, Mission Phase, Failure Effects Locally, Failure Propagation to Next Level, Single Point Failure, Risk Class, Control Recommendation” [7, p. 148].

- Category 2: Critical—A failure that may cause severe injury, major property damage, or major system damage that results in mission loss.
- Category 3: Marginal—A failure that may cause minor injury, minor property damage, or system damage that results in delay or loss of availability or mission degradation.
- Category 4: Marginal—A failure not serious enough to cause injury, property damage, or system damage, but results in unscheduled maintenance or repair.

"A reduction in the Severity Ranking index can be effected only through a design change" [2, p. 93].

2.2.3.2 Failure Mode Effects and Criticality Analysis (FMECA)

A criticality rating can be determined for each failure mode and its resulting effect and a **Criticality Analysis (CA)** is the obvious next step after an FMEA. The combination of FMEA and CA is called a FMECA.

CA as specified in MIL-STD-1629A is a procedure by which each potential failure mode identified in a FMEA is ranked according to the combined influence of severity (or consequence of failure) classification and its probability of occurrence based upon the best available data [20]. Accordingly, **Criticality** is defined as "a relative measure of the consequences of a failure and its frequency of occurrences" [20].

Availability of specific parts configuration data and failure rate data determines whether a quantitative or qualitative analysis approach is to be used. A qualitative approach is appropriate when specific failure rate data are not available, particularly in early design. Later, as parts and configuration data and failure rate data become available, criticality numbers should be calculated quantitatively and incorporated into the design.

Qualitative Approach

FEMA identifies failure modes in terms of probability of occurrence levels when specific parts configuration or failure rate data is not available. Individual failure mode probabilities of occurrence are grouped into distinct, logically defined levels. These values are based on the analyst's judgment of how often the failure mode will occur. That is to say, these are dependent on the analyst's subjective.

The failure mode probability of occurrence levels are defined as:

1. Level A—Frequent: $0.20\ P_0 < P$
2. Level B—Reasonably probable: $0.10\ P_0 < P \leq 0.20 P_0$
3. Level C—Occasional: $0.01\ P_0 < P \leq 0.10\ P_0$
4. Level D—Remote: $0.001\ P_0 < P \leq 0.01\ P_0$
5. Level E—Remote: $0.0001\ P_0 < P \leq 0.001\ P_0$

Assuming, P denotes a single-failure-mode probability for a component during operation and P_0 denotes an overall component failure probability during operation.

Quantitative Approach

The part or item failure rate data is required for the quantitative approach to Critical Analysis in order to calculate failure mode criticality and item criticality numbers. Failure rates can be derived or provided from vendor test data, in house data, or industry standards such as:MIL-HDBK-217FN2, NPRD-95, and TRS-332.

Criticality is divided into constituent parts:

- Failure effect probability (β) – The conditional probabilities that the failure effect will result in the identified criticality classification, given that the failure mode occurs.
- Failure mode ratio (α) – The probability that the part or item will fail in the identified mode.
- Part failure rate (λ) – The part failure rate concerning the failure rate of individual piece, part, or component.
- Operating time (t) – The amount of time or the number of operating cycles of the item per mission [7, p. 150].

"All of these are combined to give the failure mode criticality number (C_m) given by:

$$C_m = \beta * \alpha * \lambda * \mathrm{t} \tag{2-10}$$

or, more specifically, an item criticality number (C_r)" [7, p. 150]. This is the sum of the failure mode criticality numbers under the severity classification and is written [7, p. 151]:

$$C_r = \sum_{n=1}^{n=j} (\beta * \alpha * \lambda * t) \text{ , n} = 1,2,3\ldots \tag{2-11}$$

"This information is then compiled in a criticality matrix and the analysis ranks the items based on which is the most critical failure to the system" [7, p. 151].

\"A criticality matrix provides a means of identifying and comparing each failure mode to all other failure modes with respect to severity. The matrix is constructed by inserting item or failure mode identification numbers in matrix locations representing the severity classification category and either the probability of occurrence level or the criticality number (C_r) for the item's failure-modes. The resulting matrix display shows the distribution of criticality of item failure modes and provides a tool for assigning corrective action priorities. The further along the diagonal line from the origin the failure mode is recorded, the greater the criticality and the more urgent the need for implementing corrective action" [20, 102-3]. The example criticality matrix in Figure 2-8 was provided in MIL-STD-1629A to show how either the criticality number (Cr) or probability of occurrence level can be used for the vertical axis.

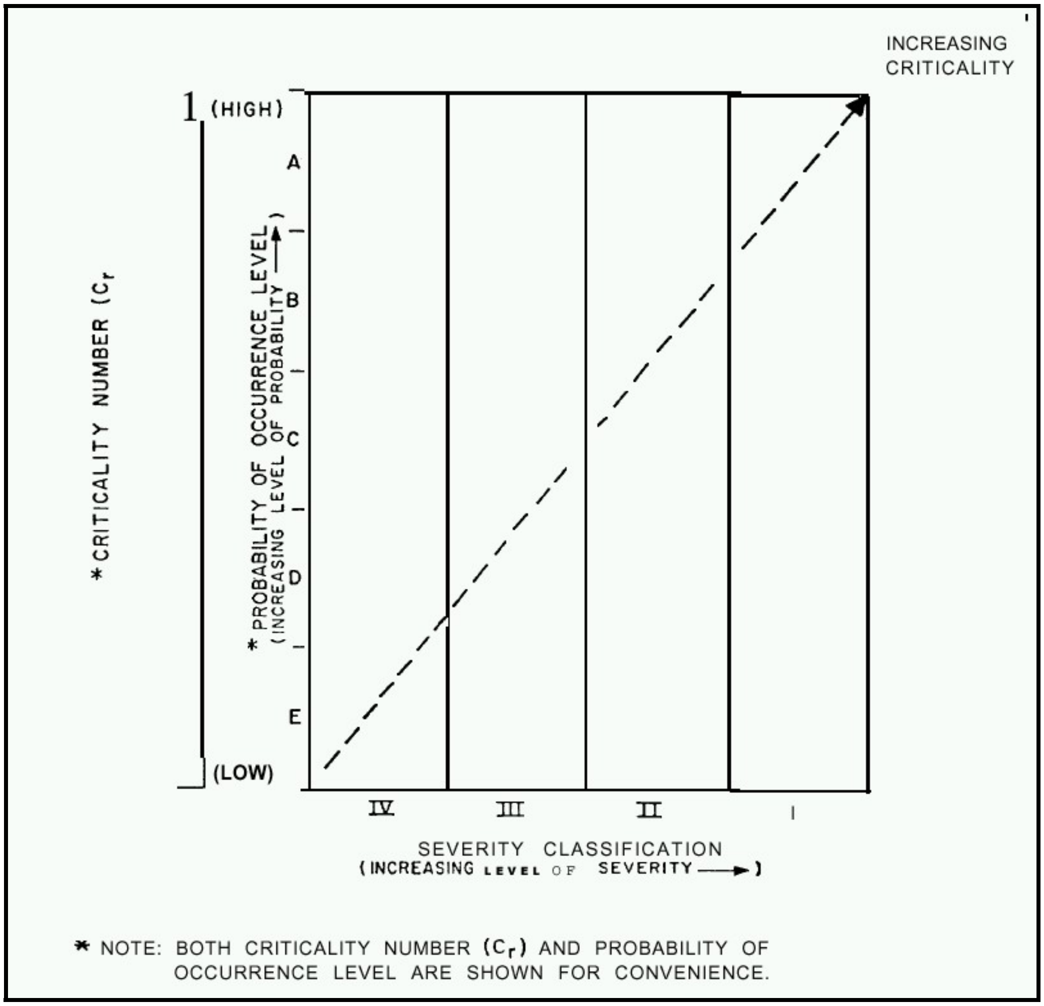

Figure 2-8. Example of Criticality Matrix (16, 102-7)

Summary

FMECA is introduced to demonstrate how inductive techniques can be used to analyze a system to assess the risk of it failing during operational use. In order to use this technique on a ship, the design of each of its systems must be extremely mature. The process itself "consists of analyzing the kinds of failure that are possible, and determining the effects that each kind of failure would have if it were to occur during operational use. The combination of likelihood and severity constitutes criticality, indicates its importance in risk analysis. The kinds of failure, or failure modes, depend on the design and the implementation of technology" [2, p. 95].

"When used in conjunction with goal tree analysis and other risk engineering techniques, FMEA (and CA) is one of the most powerful tools available for identifying reliability, safety, compliance, and product non-conformities in the design stages rather than the production process" [2, p. 95]. FMECA, however, is essentially a reliability task and provides only limited probabilistic representation of (total system or ship) reliability. It also can only be performed for one failure at a time – "This may not be adequate for systems in which multiple failure modes can occur, with reasonable likelihood, at the same time" [3, p. 158]. While the components of FMEA and CA are useful for developing a risk metric for evaluating ship concepts, FMECA itself should be considered a follow-on process to concept design that begins during the detail stage of a ship design when systems are further developed.

2.2.3.3 Risk Product Number Criticality Analysis (RPNCA)

Wang, J.X. and M.L. Roush offer an alternative approach to the Criticality Analysis (CA) established by MIL-STD-1629A. In their approach the relative importance of a failure mode is represented by its **Risk Product Number (RPN)** number which is calculated as" [2, p. 94]:

$$\text{RPN} = \text{Severity} * \text{Occurrence} * \text{Detection} \tag{2-12}$$

Severity of the effects of failure to the customer is estimated on a '1' to '10' scale according to the following ranking system [2, p. 93]:

- Unreasonable – to expect the customer to notice the very minor failure. (1)
- Low Severity – ranking. Only slight customer annoyance. (2 to 3)
- Moderate – failure causing some customer dissatisfaction. Customer annoyed. (4 to 6)
- High – degree of failure resulting in the product not working and customer angry (7 to 9)
- Very High – degree of failure. This rank indicates that the customer is at risk. Safety regulations are being infringed. (10)

"**Occurrence** is the likelihood that a specific cause/mechanism will occur. This is done by estimating the probability of occurrence on a scale '1' to '10' When estimating the occurrence raking the following two probabilities should be considered" [2, p. 92]:

1. The probability that the potential cause of the failure will occur. For this probability all current fail-safe and controls which are in place to prevent the cause of failure from occurring on the part, must be assessed
2. That once the cause of the failure has occurred, the probability will result in the indicated potential failure mode. For this estimate, it must be assumed that the cause of failure and the failure mode are not detected before the product reaches the customer.

"The engineer should mentally combine these two probabilities when estimating the occurrence ranking. The following occurrence ranking system should be used to ensure consistency" [2, p. 93]:

- Remote – probability of occurrence. Unreasonable to expect failure to occur. (1)
- Low – failure rate. Related to similar designs having low failure rates. (2-3)
- High – failure rate. Relates to failures in similar designs that have failed. (7 to 9)
- Very high – failure rate. Almost certain that failure will occur in major way. (10)

"To change the occurrence ranking for a particular design level, one of two actions must be taken" [2, p. 93]:

- Change the design to reduce the probability that the cause of failure will result in the failure mode.
- Increase or improve the fail-safe *control system* which prevent, the cause of failure from occurring.

"**Detection** is the assessment of the ability of the proposed current design controls to identify a potential cause (design weakness) before the component, subsystem or system is released for production" [2, p. 94]. Detection is assessed on a '1' to '10' scale as follows [2, p. 94]:

- Unlikely – current design controls will/cannot detect a potential design weakness, or currently there are no design controls; (10)
- Very Low – current design controls probably will not detect a potential failure cause/mechanism (design weakness); (8 to 9)
- Low – current design controls not likely to detect a potential failure cause/mechanism (design weakness); (6 to 7)
- Moderate – current design controls may detect a potential failure cause/mechanism (design weakness); (4 to 5)
- High – current design controls have a good chance of detecting a potential failure cause /mechanism (design weakness); (2 to 3)
- Very High – current design controls will almost certainly detect a potential failure cause /mechanism (design weakness); (2 to 3).

2.2.3.4 Additional Fault and Hazard Analysis Techniques

Initiating Events, Checklists, & Preliminary Hazard Analysis (PHA)

"Initiating event studies vary among industries and among companies. Initiating events are any disruptions to normal plant operation that require automatic or manual activation of plant safety systems. This includes both internal and external events" [21, p. 106]. Initiating events are used to determine which parts of a plant are more likely to pose risks than others.

There are two approaches for conducting an IE [21, p. 106]:

1. General engineering evaluation take into consideration information from previous risk assessments, operating history, and plant-specific design data. The information is evaluated and a list of initiating events is compiled.
2. The second is a more formal approach. This includes checklists: preliminary hazard analysis (PHA), failure mode and effects analysis (FMEA), hazard and operability study (HAZOPS), or master logic diagrams (MLD). These methods are not exclusively used for initiating-event identifications.

Checklists are often used in Initiating Event studies to the identify sections or components that are likely sources of an accident or initiating event [21, p. 106].

Hazard Analyses

A Preliminary Hazard Analysis or (PHA) is an extension of the Initiating Event study. “An initiating event coupled with its potential consequence forms a hazard. If the checklist study is extended in a more formal (qualitative) manner to include consideration of the event sequences that transforms an initiator into an accident, as well as corrective measures and consequences of the accident, the study is a preliminary hazard analysis [21, p. 106]:

Initiators identified in a PHA are characterized according to either their effects (e.g. Negligible, Marginal, Critical, or Catastrophic) or they are classified according to their frequencies and seventies [21, p. 106].

The hazard analysis standard is MIL-Std-822C [22] “System Safety Program Requirements” (U.S. Department of Defense, 1993)” [7, p. 84]. The ranking method in MIL-Std-822C is a very easy three-step process:

- First, hazard severity categories are assigned to each hazard;
- Second, the probability of occurrence of hazard is allocated (either qualitative or quantitative, depending on the confidence level of your data);
- Third, the two are correlated and hazards are ranked according to determine which will be addressed first [7, p. 84].

“Table 2-7 and Table 2-8 are the most commonly used hazard severity and probability of occurrence classifications used in hazard analysis” [7, p. 84]. Table 2-9 and Table 2-10 are used along with Table 2-7 and Table 2-8 to “more accurately reflect any particular system” [7, p. 84].

A hazard analysis worksheet is prepared using these tables, “taking into account: Hazard Description, Potential Causes, Potential Effects, Hazard Risk Index, Recommended Corrective Action, Effect of Corrective Action Implementation, and Hazard Control References” [7, p. 84].

Table 2-7. Hazard Severity Categories from Mil-Std –882C [22] [7, p. 84]

Catastrophic	I	Death, System loss, or severe environmental damage
Critical	II	Severe injury, severe occupational illness, major system or environmental damage
Marginal	III	Minor injury, minor occupational illness, or minor system or environmental damage
Negligible	IV	Less than minor injury, occupational illness, or less than minor system or environmental damage.

Table 2-8. Hazard Probability Levels from Mil-Std –882C [22] [7, p. 84]

Frequent	A	Likely to occur frequently
Probable	B	Will occur several times in the life of an item
Occasional	C	Likely to occur some time in the life of an item
Remote	D	Unlikely but possible to occur in the life of an item
Improbable	E	So unlikely that it can be assumed occurrence may not be experienced.

Table 2-9. Hazard Risk Assessment Matrix from Mil-Std –882C [22] [7, p. 84]

Hazard Category frequency	Catastrophic (1)	Critical(2)	Marginal(3)	Negligible(4)
(A) Frequent ($x > 10^{-1}$)				
(B) Probable ($10^{-1} > x > 10^{-2}$)				
(C) Occasional ($10^{-2} > x > 10^{-3}$)				
(D) Remote ($10^{-3} > x > 10^{-6}$)				
(E) Improbable ($10^{-6} > x$)				

Table 2-10. Hazard Risk Assessment Index from Mil-Std –882C [22] [7, p. 84]

Hazard Risk Index	Risk decision Criteria
1A,B,C 2A,B 3A	Unacceptable; stop operations and rectify immediately
1D,2C,2D,3B,3C	Undesirable; upper-management decision to accept or reject risk
1E,2E,3D,3E,4A,4B	Acceptable with management review
4C,4D,4E	Acceptable without review

2.2.3.5 HAZOP and Tree Methods

A hazard and operability study or HAZOP "is a systematic group approach to identify process hazards and inefficiencies in a system. In a HAZOP, a team of engineers methodically analyzes a system, and through the use of guide words, asks how the process could deviate from its intended operation and what the effects would be" [7, p. 112]. The team documents current safeguards and determines a risk level. If a recommendation is made, then the after risk level is indicated [7, p. 120].

"HAZOP can be used at any phase of a system or plant development; obviously, however, the design has to be somewhat mature to truly take advantage of the HAZOP's powers" [7, p. 118].

Tree methods are truly reliability techniques but still worth mentioning because they are commonly used for quantifying accident likelihoods and may be useful to the reader. Two tree techniques commonly used are fault trees and event trees. "Many quantitative risk assessment methods use event trees to model major plant systems and fault trees to quantify the failure probabilities of the various systems" [5, p. 67]

Two other methods also useful for reliability are goal trees and success trees. Goal trees can be used to organize complex systems and their engineering knowledge into a format suitable for problem solving and success trees can be used to show the various combinations of success events that guarantee the occurrences of a top event.

2.2.4 Probabilistic Risk Assessment (PRA) and Systematic PRA Methods

Probabilistic Risk Analysis is a systematic approach usually applied in later stages of design development and operation for transforming an initiating event into a risk profile by believing that "there can be no bad ending if there is a good beginning" [21, p. 95]. Typically applied to industrial process safety and nuclear plant safety through fault-tree and failure-tree analyses. "It is particularly appropriate for analyzing the frequencies of extremely rare events, such as core melts in nuclear reactors, for which little if any accident data will be available. " [5, p. 67].

For this reason it not directly applicable for assessing risk for ship concept design but can be useful in later stages of design and throughout its operational lifecycle as system onboard the ship is updated or refreshed through technology insertions.

According to Molak, PRAs:

1. Are generally designed to model the response of a complex engineered system to disturbances during operations;
2. Provide an integrated model of system response;
3. Identify the types and levels of damage that could result from different system responses;

4. Provide not only qualitative assessments of system performance (e.g., safe or unsafe; high, medium, or low risk), but also quantitative measure of risk;

5. Include a quantitative assessment of the uncertainty in the results;

6. Provide not only an assessment of the current level of risk, but also information on risk contributors and potential risk management actions [5, p. 68].

Once a ship is delivered, undergoes operational trials and begins its service life, a PRA can supplement more qualitative risk assessments begun during initial design and production to assess how well the ship responds to a variety of situations. In this fashion a PRA also answers the three basic questions pointed out by Kaplan and Garrick [8] [5, p.69]:

1. What can go wrong?

2. How likely is it to go wrong?

3. What will be the consequence if it does ?

"The first question is answered by a structured list of possible accident scenarios. The second question is answered by quantifying the likelihood of each scenario (including the uncertainty about that likelihood). Finally, the consequences of an accident can be assessed in terms of a variety of damage indices" [5, p.69].

"There are four phases of consequence prevention or mitigation in a PRA: initiating event prevention, initiating event propagation prevention, onsite consequence mitigation, and offsite consequence mitigation. Occurrence likelihood's of initiating events are decreased by prevention actions. An initiating event is subject to initiating event propagation prevention. If an initiating event develops into an accident, then onsite and offsite consequence mitigation's halt accident progression and mitigate consequences" [21, p. 95].

"The probability of an adverse outcome (failure of a component or a system) of a series of interconnected events is obtained by evaluating probabilities of failures of individual components. These probabilities are obtained either based on historical data or on assumptions of failure. Once a probability of failure of a process is established, one can apply (a variety) of analyses to establish the severity of consequences" [5, p. 7]. This might deal with of a release of a particular toxic substance, increased susceptibility or vulnerability to a threat, degraded operational performance, increased operational effectiveness, increased cost, or diminished return on investment.

WASH 1400, the first PRA method, is a PRA standard and was published in 1974 by the U.S. Nuclear Regulatory Commission [7, p. 206]. The WASH study includes seven basic tasks occurring in two phases that identify initiating events and identify the accident sequences using fault trees and event trees [21, p. 98]. NUREG-1150 is another standard developed as an update to WASH-1400 where initiating events are transformed into risk profiles via four intermediate products: accident-sequence groups, accident-progression groups, source-term groups, and offsite consequences. There are five steps in this process: accident-frequency analysis, accident-progression analysis, source-term analysis, offsite consequence analysis, and risk calculation. [21, p.103]. The most modern standard method for conducting a PRA that was uncovered was developed by Modarres [3]. The Modarres method is shown below in Figure 2-9.

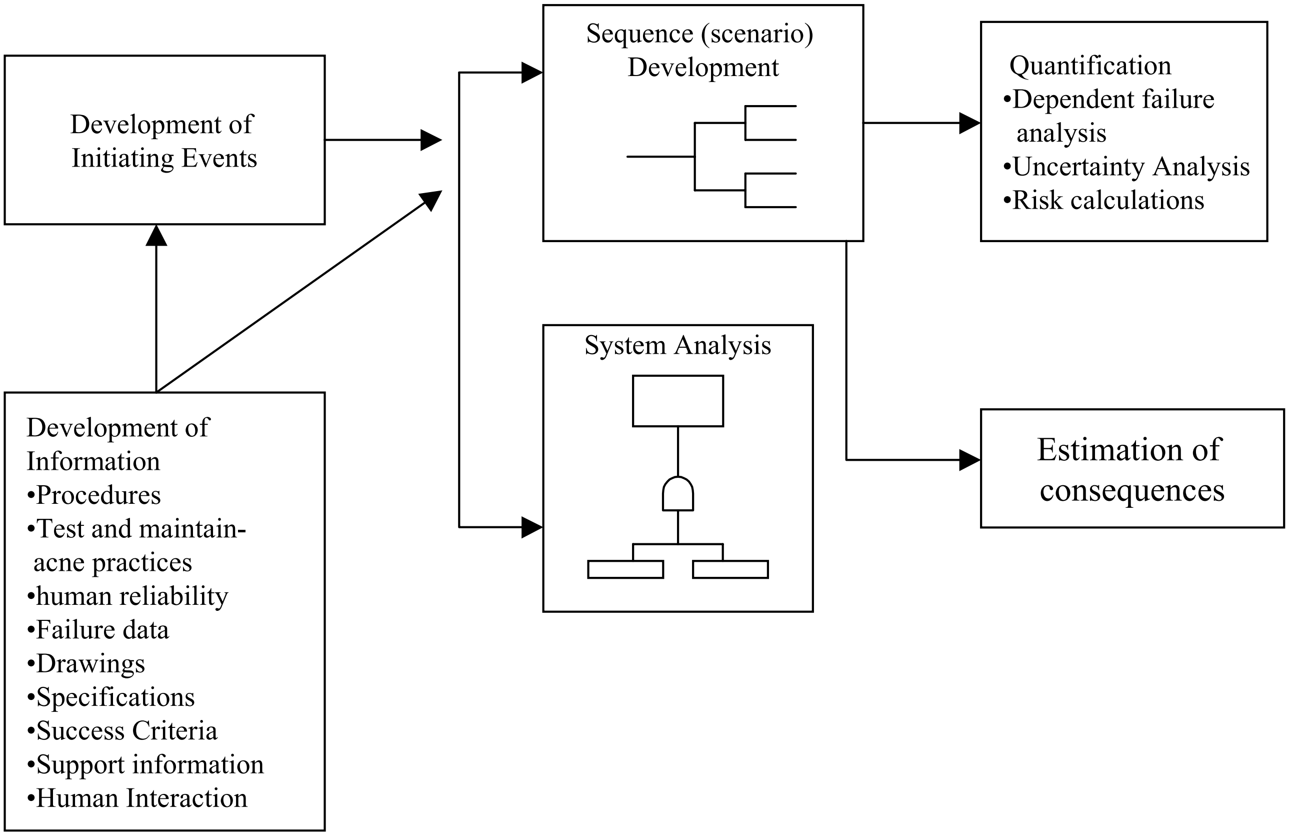

Figure 2-9. Modarres' Process for PRA [3, p. 308].

2.3 Project Risk Management

"The central features of any engineering project are to produce a result that 1. leads to customer satisfaction, 2. is accomplished on schedule, and 3. is accomplished within budgeted cost" [2, p.132]. Managing the project therefore requires control over the uncertainties in each of these features. The consequent management of risk associated with these features both limits the potential for negative consequences that may arise from their uncertainties and maximizes the possibility that results will meet or exceed requirements and goals.

"Risk Management is the process of balancing risk with cost, schedule, and other programmatic considerations. It consists of risk identification, risk assessment, decision-making on the disposition of risk, and tracking the effectiveness of the results of the actions resulting from the decisions" [2, p.137]. Good Project Risk Management will maximize the results of positive events and minimize the consequences of adverse events.

Project Risk Management is divided into two stages, Project Risk Assessment and Project Risk Control [2].

2.3.1 Project Risk Assessment

Risk assessment is used to tell us how likely it is that a thing will go wrong. It is concerned with quantities and statistical analysis and is used as an essential tool in calculating probabilities of failure to analyze these quantities.

Risk Assessment can be looked at as a way of extending Murphy’s Law: ‘If anything can go wrong, it will’ [2, p. 47]. Risk assessment provides quantitative inputs for engineering design and additional insight about how likely it is to go wrong, what it will cause as a consequence [2, p. 47].

According to Wang and Roush [2], Project Risk Assessment is the first step of Project Risk Management. Project Risk Assessment consists of the three sub-tasks shown as elements in Figure 2-10.

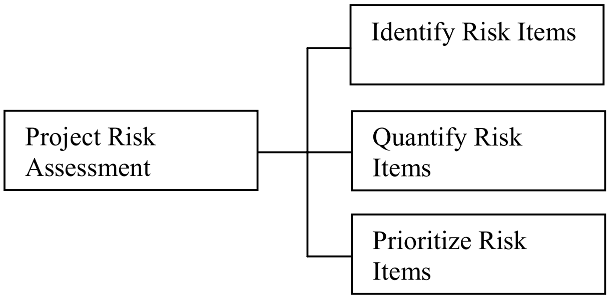

Figure 2-10. Elements of Project Risk Assessment [2, p. 137]

2.3.1.1 Identifying Risk Items

“Risk Identification requires understanding the limits of engineering designs. Every engineering design has its limitations and its breaking point. By recognizing all the possible mechanisms of failure, a robust engineering design can be developed to minimize the potential risk“[2, p. 15]. “Risk identification starts by describing the system structure and how it interfaces with operating environments” [2, p. 15].

Wang and Roush define a risk item as any uncertainty with technical performance, resource (cost), or schedule outcome. “Risk identification consists of determining which risk items are likely to affect the project and documenting the characteristics of each. Risk item identification is **not a one-time event**; it should be performed on a regular basis throughout the project” [2, p. 138].

Risk item identification should address both internal and external risks. Internal risks are things that the project team can control or influence, such as resource management and cost estimates. External risks are things beyond the control or influence of the project team” [2, p. 139].

“Risk item identification may be accomplished by identifying cause-consequence relationships and consequence–cause relationships. The former is the event tree analysis while the latter is the fault tree analysis” [2, p.139]

2.3.1.2 Quantifying and Prioritizing Risk Items

“Risk quantification involves evaluating risks and risk interactions and assessing how those areas of uncertainty can impact the performance of a project, either in duration, cost or meeting the users’ requirements. It is primarily concerned with determining which risk items warrant risk control” [2, p. 139]

“Risk item prioritization establishes which risk items should be eliminated completely, because of potential extreme impact, which should have regular management attention, and which are sufficiently minor to avoid detailed management attention” [2, p. 139].

2.3.2 Project Risk Control

According to Wang and Roush [2] Project Risk Control is the second step of Project Risk Management. Project Risk Control consists of the three sub-tasks shown as elements in Figure 2-11 mitigate risks, plan for emergencies, and measure and control residual risks [2, p. 143].

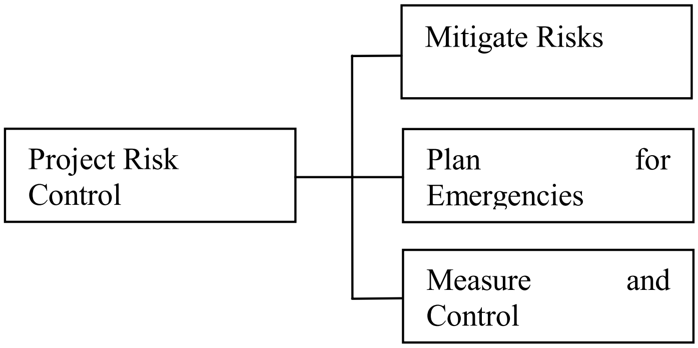

Figure 2-11. Elements of Project Risk Control [2, p. 143]

“Risk mitigation takes whatever actions are possible in advance to reduce the effect of Risk. It is better to spend money on mitigation than to include contingency in the plan. We can mitigate risks by reducing either the probability or the impact” [2, p. 143]. “Risk reduction consists of reducing uncertainties, reducing consequences, avoiding risks, and transferring risks. Transfer refers to transferring a risk to someone else” [2, p. 143]. On a naval ship design, a high risk may be transferred to the government through a contract. Reducing frequencies through risk avoidance is a common approach to risk mitigation [2, p. 143].

Planning for emergencies is a key tenet of Risk Control. Risk assessment produces the most likely areas of a project that can go wrong. “A project risk plan should include, for each identified risk, an emergency plan to recover from the risk” [2, p. 143].

Measuring and controlling residual risks requires tracking the effects of the risks identified and managing them to a successful conclusion. “The owner of each risk should be responsible to the project manager to monitor his risk, and to take appropriate action to prevent it from happening or to take recovery action if the problem does occur. Nothing can be controlled that cannot be measured. In a project there are three things that can always be measured – the schedule, the cost, and the users satisfaction. User satisfaction is not the same as whether or not the project meets the original specifications. If the project meets all three criteria, it is right to consider it a successful project.” [2, p 143].

“Risk management proposes alternatives, evaluates (for each alternative) the risk profile, makes safety decisions, chooses satisfactory alternatives to control risk, and exercises corrective actions.

2.3.3 Differences in Risk Management

Differences in risk management can vary by organization. This is especially true in the shipbuilding industry. According to Kumamoto [21], differences are acceptable as long as the following invariants hold true for a given project [21, p. 22]:

- Each outcome should be classified as a gain or loss;

- Each loss or gain must be evaluated by a significance or utility scale. Quantitatively or Qualitatively - Significance depends or cultural attributes, ethics, emotion, reconciliation, media coverage, context, litigability, etc.;
- Alternatives must be available. If only one alternative is available, it is no longer a risk;
- Risk-profile significance – because each alternative usually has two or more outcomes, these significances must be integrated into a scalar by a suitable procedure;
- Expected Utility assumes that outcome significance can be evaluated independently of outcome likelihood;
- Some outcomes are commensurable, other are incommensurable. Unification becomes far more difficult for incommensurable outcomes because of tradeoffs;
- Each Alternative has a cost (Risk/Cost trade-off) [21, p. 22].

These tenets become requirements for developing a ship concept design risk metric.

2.4 Risk Perception & Acceptability

2.4.1 Perceptions of Risk

A scientific risk metric should be free of all pre-conceived subjective opinion. However, due to the nature of ship design with many unknowns, engineers and designers often call upon past experiences to form opinions. "Perceptions of risk often differ from objective measures and may distort or politicize risk-management decisions. Subjective judgment, beliefs, and societal bias against events with low probability but high consequences may influence the understanding of the results of a risk analysis. Public polls indicate that societal perception of risk for certain unfamiliar or incorrectly publicized activities is far out of proportion to the actual damage or risk measure" [3, p. 298].

"According to Litai (1980), the risk of motor accidents compared with the risk of aviation accidents is perceived by the public to be far less than its actual value by a factor of 1000, but the risk of nuclear power accidents and food coloring is over-perceived by the public. Bias against risks tolerance thresholds accurately seem to account for public bias against risks that are: unfamiliar (by a factor of 10), catastrophic (by a factor of 30), involuntary (by a factor of 100), catastrophic (by a factor of 30), or uncontrollable (by a factor of 5 to 10), or have immediate consequences (by a factor of 30)" [3, p. 298].

In fact, "people perceived a voluntary action to be less risky by a factor of 100 than an identical involuntary action. Although the exact values of above conversion factors are debatable, they generally show the direction and the degree of bias in people's perception" [3, p. 298].

This information has been included to stress the extreme importance of rooting these types of bias out of any risk model to the greatest extent possible. Assessing early ship design risks may be especially vulnerable to bias creep as subject matter experts rely on their extensive but statistically unsound experience to make qualitative decisions. Both risk assessors and decision makers who use the results of a qualitative model should be aware of the possible danger of inadvertently skewing results by transmitting or receiving false perceptions.

2.4.2 Risk Acceptability

"Risk acceptance is a complex subject and is often subject of controversial debate. However, using the results of risk assessment in a relative manner is a common method of ranking risk-(consequence) levels.

Although regulators often strive to assess absolute levels of risk, the relative ranking of risks is a better risk-management strategy for allocating resources." [3, p. 298].

In early ship design, risk can be initially accepted or avoided through design decisions. Later, after a concept has locked certain risks into the design, the risks can be mitigated, assumed or transferred. A certain amount of risk will always be accepted from inception of the design until the ship is disposed. This risk should be minimized then controlled to the greatest extent possible, while ensuring the ship meets its cost and operational goals.

According to Wang and Roush, "Uncertainty is inherent in material strength, engineering design, manufacturing processes, and operating environments. Acceptable risk can be accomplished only through the capability of controlling uncertainties associated with each phase of the engineering life cycle" [2, p. 16].

2.5 Uncertainty, Variability, and Ambiguity in the Design Process

"Proper design calls for (correct) identification, understanding, modeling, and translation of customer requirements to the design" [23, p. 5]. However, as Mavris et. al. assert, requirements are often stated ambiguously, especially in the initial development stages and "the true impact of the customer's desires is often historically manifested in later life-cycle stages when design changes are most expensive" [p. 4].

In a complex system design "ambiguity occupies the space complement to knowledge and uncertainty arises because quantities associated with the product cannot be determined exactly (or possess degrees of variability)" [23, p. 5]. The greatest amount of ambiguity, uncertainty and variability is realized at the outset of design, but as progress is made through the life cycle, more information is learned, uncertainty is diminished, and chances for variability go away. This concept is illustrated by the knowledge curves in Figure 2-12" [23, p. 5].

Ship design and optimization must account for life-cycle issues by facilitating multi-disciplinary consideration of a system. This process requires accounting for knowledge variation and uncertainty that occurs in time through the various phases of design [23, 1]. Uncertainty is closely linked with risk; and variability is related to the potential for change that exists within the known parameters in a design.

Risk analysis was born out of the need to manage the inherent uncertainty that exists across the many levels of design, engineering and operation of complex systems. In 2.1.1, risk was defined in a systems engineering context as "the potential of not meeting a specified technical and /or program requirement" such as a requirement specified by a TPM, a schedule, or a cost projection. In this definition, the word "potential" represents uncertainty. Therefore, it can be said that by measuring risk, we are addressing uncertainty. However, this is not to say that risk takes into account all uncertainty. Much uncertainty remains. For instance, there is an uncertainty in the risk assessment itself. Uncertainty then is not the same as the probability of failure, rather it includes the degree to which the probability of failure or consequence of failure is not certain!

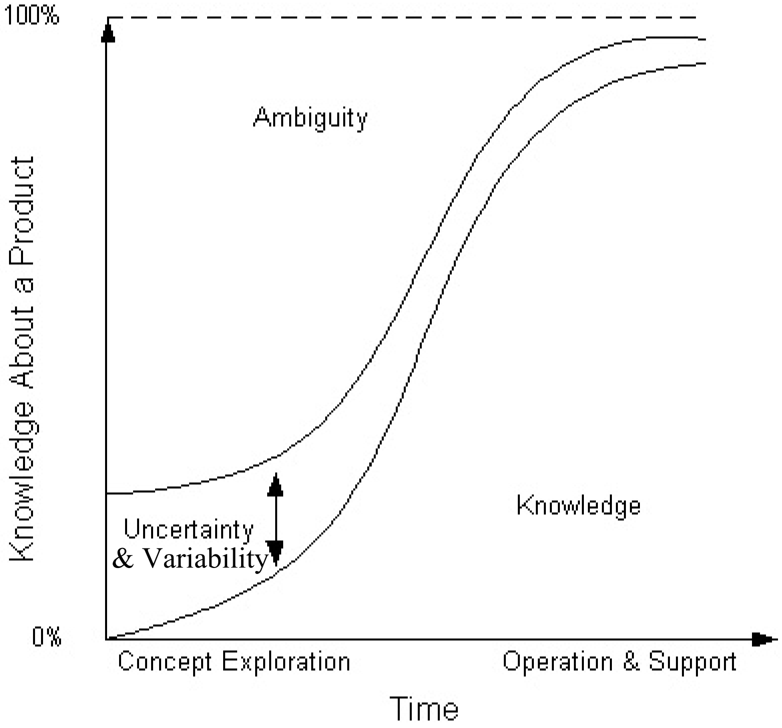

Figure 2-12. Uncertainty and Variability in Time [23, p. 5]

“Uncertainty is the combination of all other effects that lead to variations in risks, costs, schedule and technical performance for the defined population, set, or system” [5, p. 35]. Within the context of multi-disciplinary design, Mavris defines uncertainty as “an estimate of the difference between models and reality” [2]. He goes on to say that “uncertainty is manifested when quantities associated with the product cannot be determined exactly, and is a term describing the value of a variable.” More simply put, uncertainty is the range of unknown knowledge in a problem or a design.

“Variability is defined as “the measured and therefore known variation among members of a defined population or set” [5, p. 35]. In ship design synthesis, the defined population is the design parameter (DP) set defining the ship system. Variability of ship design parameters (e.g. material properties) will potentially lead to differences in risks, costs, schedule and technical performance. “Variability is found in treatment of assumptions, ambiguous requirements, code fidelity (imprecision), economic uncertainty, and technological risk” [23, 1].

A stochastic uncertainty changes with time. A process is stochastic if its response exhibits an irregular history of uncertainty over a range of time values.

According to Molak’s definition, ship concept design estimates of cost, performance and risk are stochastic because they “involve or contain a random variable or variables” or “involve chance or probability (i.e. a stochastic simulation)” [23, 2]. The fact that not all ships of the same class see identical wave loads over their life leaves a stochastic component of uncertainty. Problems having stochastic uncertainty are difficult to quantify into an exact error. In such cases, Molak pleads the importance of indicating that a stochastic component of uncertainty exists [23, 2].

2.5.1 Types of Uncertainties

According to Wang and Roush, there are four major types of uncertainties: inherent uncertainty, statistical uncertainty, modeling uncertainty, and human error [2, p. 112].

Table 2-11. Types of Uncertainty

Types of Uncertainties	Descriptions
Stochastic (Inherent) Uncertainty	Uncertainty due to variability inherent in (a system design parameter) or the environment. This type of uncertainty results from random nature of outcomes - not known or measured. Example: cycles-to-fatigue has large variability as observed in fatigue tests.
Statistical Uncertainty	Resulting from incompleteness of statistical data (small sample sizes)
Modeling (Simplification) Uncertainty	Uncertainty resulting from the simplification of nature. Models may more or less replicate reality e.g., model may only be valid over limited range. Example 1: A large number of assumptions are made in the process of estimating stress at a notch in a component given environmental conditions. Example 2: A multi-disciplinary treatment of design calls upon the integration of various analytical methods (implemented as computer codes) at different stages of the design life-cycle. The fidelity of these codes is generally not equal nor known.
Human Uncertainty & Error	Uncertainty due to differences of opinion (or subjective uncertainty) and misdiagnosis (or diagnostic uncertainty). The latter could include a breakdown in any of the following five activities that comprise a cognitive task: 1. Recollection of hypotheses (causes and their propagations) from symptoms; 2. Acceptance/rejection of a hypothesis using qualitative or quantitative simulations. 3. Selection of a goal (e.g. plant shutdown), 4. Selection of means to achieve the goal, 5. Execution of the means. Some examples of possible human breakdowns include: errors in calculation; selection of the wrong known data; inadequate design review; failure in calculating critical conditions; poor quality fabrication; use of the wrong materials; and Poor abuse/abuse by operators.

Mavris et. al. also classify Design and Operational uncertainty types. “Design uncertainty is an inability to analytically predict the outcome of an event, or the exact value of a parameter. Operational uncertainty arises as a result of what are often called noise parameters that affect the performance of a system. Hence, two distinct classes of design parameters emerge: control parameters and noise parameters.” [p. 5].

Mavris defines control parameters as “items that the designer has direct control over, while noise parameters are items that effect the design, but are beyond the control of the designer” [Mavris, p. 5]. Noise parameters exist in algorithms that interact with the control parameters to determine design characteristics, thus design results also contain noise.

“There are many distinctions between different types of uncertainty and ways of looking at uncertainty. The most important result of including uncertainties in a (risk) calculation, like the result of making the (risk) calculation itself, is not the number, but the insight that the inclusion gives to the assessor [5, p. 34].

2.5.2 Incorporating Uncertainty and Variability into Multi-Disciplinary Analysis and Design

Recent government and industry initiatives focused on system affordability as the overall decision making objective have fostered the development of many new ideas on how to design complex systems for affordability. One theme that has risen out of this paradigm shift is the desire to use synthesis models to bring more knowledge of uncertainty into earlier product design phases, where most of the cost commitment is locked in early on.

Simulation is critical to the early determination of product characteristics and recent advances in the areas of agent technologies and metamodeling have facilitated the inclusion of a variety of analysis methods into product synthesis. Now, “advanced data structures are being developed to allow stochastic parameter information to be tracked in addition to traditional deterministic values” [23, 6].

In their paper titled “a Stochastic Approach to Multi-disciplinary Aircraft Analysis and Design”, Mavris et. al., present a formulation for a framework to facilitate the paradigm shift from “deterministic, performance-based multi-disciplinary design to a stochastic formulation whose goal is maximizing affordability. [2]” The Mavris formulation, focused on aircraft design, accounts for uncertainty and incorporates physics-based disciplinary analysis to form what is termed Virtual Stochastic Life Cycle Design (VSLCD). VSLCD is described as a physics-based sizing and synthesis tool, complemented by vehicle economic and operational dynamic models, a time varying probabilistic algorithm, and advanced decision making techniques.

Similar to a ship design, Mavris’ aircraft design problem “introduces uncertainty associated with imprecise knowledge in the early phases (ambiguity, design uncertainty), analytical fidelity, operational environment, as well as uncertainty associated with new technologies” [23, 4]. VSLCD accounts for uncertainty by modeling it and quantifying its effects through the use of probabilistic models.

2.5.2.1 Modeling Uncertainty with Random Variables

Even in the best of circumstances, the uncertainty associated with various analytical methods/models (implemented computer codes) is not well known. However, Mavris contends that this uncertain information can be captured through random variables. For instance, VSLCD addresses this problem by calling for fidelity to be determined along with relationships, and linking error to operating conditions by specifying the noise parameters (defined in 2.5.1 in terms of a range and a probability distribution. “Enabling a designer to assess a design with a corresponding confidence estimate” [23, 6].

According to Mavris et. al., random variables may be used to model uncertain information about:

1. Value of a design variable,

2. Fidelity or accuracy of an objective function (modeled by computer simulation or any other engineering model),

3. Technology Risk.

The first type of uncertainty is modeled directly as a noise variable using a random variable, and fidelity can be modeled with an error term (ε) that is added to the objective function value. The third type of uncertainty, technology risk, is of most interest to this paper and “can also be modeled with random variables by recognizing the uncertain value of the metric in question, and assigning an appropriate distribution to that metric” [23, 8].

“Technology risk represents a time-varying uncertainty that is dependent on the current maturity timeline of a particular technology” [23, 7]. This type of uncertainty “arises through the inclusion of information about the readiness of new technological concepts, and their associated risk into the design process. The result of this type of analysis is a probability distribution for the objective function.” [23, 8].

Figure 2-13 illustrates a probability distribution for Total Ownership Cost (TOC) of a notional ship design. In this example, the shaded region under the curve represents the probability that TOC will be between \$750 and \$850 million. In the graph, the total area bounded by the function curve and the x-axis is equal to unity. The exact probability that the random variable will assume a value within this interval is calculated by dividing the total area under the curve, which is equal to 1 for pdf, by the shaded region. For this notional ship, the probability that TOC will be in the specified range has been calculated to be 66%, with a mean target of \$798 million. The 66% can be termed as a confidence factor or probability of success and the interval can be termed as a confidence band.

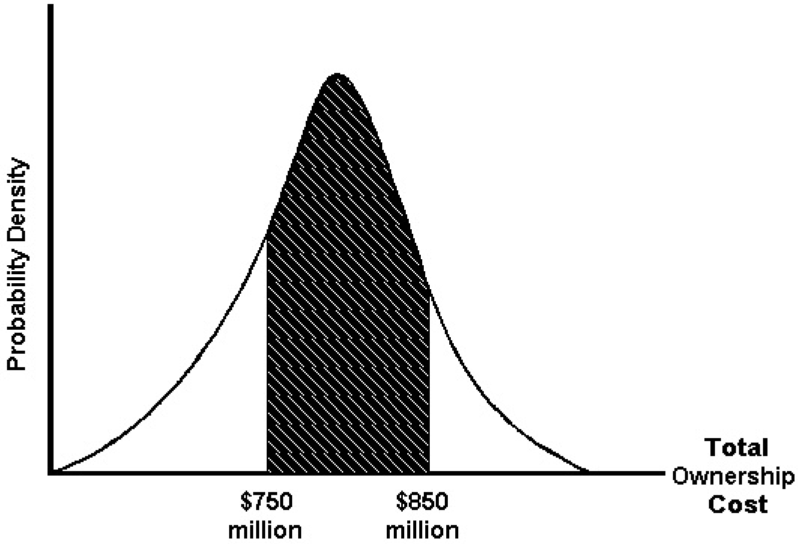

Figure 2-13. Total Ownership Cost Probability Density

In Mavris' VSLCD formulation, a method called Robust Design Simulation (RDS) is used to perform a probabilistic system level analysis that accounts for uncertainty, business practices, economics, synthesis, sizing, technology, and environmental constraints [23, 12]. RDS uses synthesis tools along with constraints and Monte-Carlo (MC) methods to perform probabilistic analysis. This probabilistic analysis, yields objective measures (e.g. cost and performance) and their associated probability distributions rather than single point design solutions in the form of an objective function response (R) mean and variance [23, 13].

2.5.2.2 Monte Carlo Methods for Probabilistic Analysis of Success or Failure

Monte Carlo methods are often used to simulate random or stochastic processes, and can be useful in analyzing risk by calculating probability distributions for objective attributes as a function of design (control) variable input. In Mavris' application, MC simulations are used to determine joint probability density functions (pdfs) of design criteria for a given set of control design variables (a given design) by performing multiple calculations that select random values for each random variable (constrained by a pre-defined range), synthesizing the behavior of the physical system, and determining objective or criterion results for each calculation. These results are collected as a joint probability distribution (pdf) for the multiple criteria. A POS is can be calculated from the pdf by integrating over a specified range of criteria values.

Four steps are required before the Monte Carlo simulation can perform the probabilistic analysis.

- First, the system must be synthesized mathematically into a single or combined synthesis model.
- Second step, "all variables that are not under the control of the designer, (i.e. their values are not known with certainty), need to be assigned probability distributions that represent the likelihood of taking on certain values" [24, p. 5]. For example, the future labor cost of shipyard welders may be estimated by applying a normal distribution with a mean of $30 an hour. "This (probabilistic analysis) element allows the subsequent simulation to evaluate a range of values rather than a single deterministic number" [24, p. 5].

- The third step in this process incorporates the probability distributions associated with each random variable into the physical system model. This is accomplished by transforming the probability distributions into probability density functions (pdfs) using basic statistics, then incorporating the pdfs into the synthesis.
- The fourth step requires fixation of the control variables. Accordingly, for each probabilistic analysis, all variables that are part of the analysis and under the control of the designer (i.e. its value is considered known with certainty) need to be held constant.

Once all the **control variables are fixed** and the random variables are described by pdfs the Monte Carlo simulation is begun and it performs multiple *trials* and collects multiple *histories*, as it runs. Effectively, this results in a statistical sample of the effect that the random variables have on the figures of merit (POS).

"Assuming that the evolution of the physical system can be described by probability density functions (pdfs), then the Monte Carlo simulation can proceed by sampling from these pdfs, which necessitates a fast and effective way to generate random numbers uniformly distributed on the interval [0,1]. The outcomes of these random samplings, or trials, are then accumulated and tallied in an appropriate manner to produce the desired result" [25,1.0]. In this application, this is not a solution of the physical problem, but rather pdfs representative of the uncertainty associated with selected figures of merit, such as cost and effectiveness.

Finally, the pdf can be superposed over an area of interest and the probability of success (POS) or confidence factor (see Figure 2-13) can be calculated from the volume under the curve. The statistical error in the average result can also be predicted once many simulations are performed by taking the desired result as an average over the number of observations (which may be a single observation or perhaps millions of observations) [25,1.0].

New methods proposed by Bandte and Mavris take this method one step further by formulating joint probability distributions and optimizing the POS. This interesting approach to probabilistic design proposes a universally applicable objective function for multi-criteria decision-making. The joint probability of success, (also based on a multivariate probability distribution in conjunction with a criterion value range of interest) allows the customer or designer to optimize a design based on the chance of satisfying all the customer's goals. **This optimization method does not result in a non-dominated frontier, but only a single design with the highest POS of being within specified ranges of particular objective or criteria values.** POS Methods are considered further in the next chapter.

2.5.2.3 Major Components of a Monte Carlo Algorithm

The calculation of POS described above assumes the following seven primary components of a Monte Carlo simulation [25, 1.1]:

- *Probability distribution functions (pdfs)* - the physical (or mathematical) system must be described by a set of pdfs.
- *Random number generator* - a source of random numbers uniformly distributed on the unit interval must be available.
- *Sampling rule* - a prescription for sampling from the specified pdfs, assuming the availability of random numbers on the unit interval, must be given.

- *Scoring (or tallying)* - the outcomes must be accumulated into overall tallies or scores for the quantities of interest.
- *Error estimation* - an estimate of the statistical error (variance) as a function of the number of trials and other quantities must be determined.
- *Variance reduction techniques* - methods for reducing the variance in the estimated solution to reduce the computational time for Monte Carlo simulation
- *Parallelization and vectorization* - algorithms to allow Monte Carlo methods to be implemented efficiently on advanced computer architectures.

Substantial information on each of the techniques associated with these components may be found in [25].

There is a great degree of uncertainty and variability in predictions of performance, cost, and risk with any ship and its design until the day it is disposed. These result from unknown variables, assumptions, and imperfect algorithms used in various calculations. The greatest amount of uncertainty and variability is realized at the outset of design. Later, as the design evolves into a ship that is built and operated, these degrees are lessened. All cycles of the ship design process follow this trend. There is more uncertainty and variability in the beginning of any cycle than at its end. As progress is made through the cycle, more information is learned, uncertainty is diminished and chances for variability go away.

2.6 Chapter 2 Summary: Inventory of Risk Techniques & Methods

In no particular order, the following list is an inventory of the methods and techniques presented in Chapter 2:

- The Modarres Method - Modarres [3] lays out a modern method for conducting risk assessment. His general process for PRA is shown in Figure 2-9.
- WASH 1400 – First PRA method, published in 1974 by the U.S. Nuclear Regulatory Commission [7, p. 206]. The WASH study includes seven basic tasks occurring in two phases that identify initiating events and identify the accident sequences using Fault Trees and Event Trees [21, p. 98].
- NUREG-1150 - Update to WASH-1400 where initiating events are transformed into risk profiles via four intermediate products: accident-sequence groups, accident-progression groups, source-term groups, and offsite consequences through five steps: accident-frequency analysis, accident-progression analysis, source-term analysis, offsite consequence analysis, and risk calculation. [21, p.103].
- Systems Risk Assessment and Management (SRAM) – Systems engineering method originally proposed by Blanchard [4] (see section 2.2.1.) that includes Risk Assessment, Risk Analysis, and Risk Abatement. SRAM relates technical/design-engineering risks to the potential of not meeting a design requirement, not being able to produce an item in multiple quantities, and/or not being able to support a product in the field and ties risks directly to design parameters (DPs) and technical performance measures (TPMs) [4, p. 288]. This method introduces Probability of failure (Pf) as a function of maturity, complexity and dependency levels of hardware and software as shown in Table 2-2. Consequence of Failure is introduced in terms of Technical, Cost, and Schedule. As shown in Table 2-3.

- DoD 5000 Risk Management Assessment Method- DoD policies and procedures are developed to assess and manage risks on DoD acquisition programs by identifying and analyzing program risks in terms of cost, schedule, and performance. The general assessment process shown in Figure 2-6 develops probability/likelihood and consequence/impacts using the criteria and rating shown in Table 2-4, Table 2-5, Table 2-6, and Figure 2-7.
- Wang's Project Risk Assessment Method - Method consisting of the three sub-tasks shown as elements in Figure 2-10: Identification of Risk Items, Quantification of Risk Items, and Prioritization of Risk Items [2, p. 137].
- (Preliminary) Hazard analysis – Techniques that go though a system methodically and identify all hazards to life and equipment [7, p. 25].
- Event Tree Analysis - Constructs Event Trees using a "deductive" or forward logic by hypothesizing an initiating event and then works forward by identifying all possible combinations of subsequent events and determining which sequences of events could cause failure of the system as a whole [5, p.73].
- Fault Trees Analysis – "Graphical technique used to identify the faults in a system and what events lead to that catastrophic event" [7, p. 25].
- Success Tree - Conceptually same as fault tree, but deductively postulates intermediate and primary events that guarantee the occurrence of a desirable event by defining the top event [3, p. 151].
- Goal Tree - "Success-oriented (techniques that) uses logic structure to organize complex systems and their engineering knowledge into a format suitable for problem solving" [2, p. 83].
- Failure Mode and Effects Analysis (FMEA) – Reliability/Safety technique appropriated to identify what causes a component to fail and what the effects or consequences will be [7, p. 25].
- Failure Mode and Effects and Criticality Analysis (FMECA) – Combines FMEA with CA procedure by which each potential failure mode is ranked according to the combined influence of severity and probability of occurrence [21, p. 110].
- Preliminary Hazard Analysis (PHA) – System Safety method that assigns severity categories to identified hazards, allocates probability of occurrence, and correlates and ranks hazards to determine which to address first. Hazard are assessed using severity and probability as shown using Table 2-7, Table 2-8, Table 2-9, and Table 2-10.
- Hazard and Operability Study (HAZOP) - Systematic "group approach" technique used to identify process hazards and inefficiencies in a system by dividing the system into nodes and using guide words that asks how the process could deviate from its intended operation and what the effects would be. [7, p. 112].
- Checklists - Technique that uses checklists "to identify, sections or components that are likely sources of an accident or initiating event" [21, p. 106].

- Master Logic Diagram - A fault-tree-based technique that decomposed and accident into subgroups characterized by initiating events, and further decomposing these into accident sequences characterized by the event-tree headings. [21, p. 114].
- Risk Product Number Criticality Analysis (RPNCA) – Wang and Roush’s alternative approach to the Criticality Analysis (CA). In their approach the relative importance of a failure mode is represented by its Risk Product Number (RPN), calculated as the product of Severity, Occurrence, and Detection rankings developed in Section 2.2.3.3.
- Mavris’ Uncertainty Methods – Mavris proposes modeling uncertainty/variability of meeting requirements (e.g. risk) by assigning probability density functions that represent the likelihood that parameters will take on certain values. Mavris incorporates this approach into a joint probabilistic decision making technique that transforms disparate objectives into a single objective function, called Probability of Success (POS) that can be optimized to maximize the likelihood of meeting all goals within specified ranges of particular objective or criteria values.

Assessment and conclusions of these methods are presented in Chapter 4.

3. SYNTHESIZING RISK: A THIRD OBJECTIVE MEASURE OR UNCERTAINTY IN COST AND PERFORMANCE

In order to successfully optimize a design, risk must be synthesized along with cost and effectiveness in a mathematical model. Using the methods described in Chapter 2, it is apparent that risk can be measured using one or a combination of the following two approaches:

- Independent-Objective Approach – Risk is treated as a third *objective measure* along with cost and performance/effectiveness by calculating an expected risk value against an index (e.g. 0-1 based on probability and consequence scales grounded against expert opinion).
- Uncertainty-Success Approach. – Risk is treated as a *measure of the uncertainty* associated with achieving cost and performance, allowing calculation of individual and joint probability that objective goals will successfully be met, i.e. Probability of Success (POS).

Taking the independent-objective approach, a total expected risk value algorithm could be added to the physical/mathematical synthesis model enabling calculation of an overall measure of risk (OMOR) from various risk contributors linked to design parameter selections. Similar to the method of Table 2-1 and Equation (2-2), various risk contributors can then be expressed in numerical terms representing probability of failure (Pi) and consequence of failure (Ci). The total expected risk factor or OMOR may then be calculated as the sum of the products of Pi and Ci for all contributors, assuming a fair and robust method has been developed to estimate Pi and Ci using qualitative and/or quantitative rules.

Taking the uncertainty-success approach, a Monte Carlo (MC) simulation consisting of the same physical/ mathematical system but with parameters described using probability distribution functions, or pdfs, may be used to simulate the physical system by random sampling from the pdfs and performing necessary supplementary computations as needed. Cost and performance/ effectiveness may then be determined by the MC simulation as random variables, described using pdfs. Risk could be measured by calculation a joint probability of success (POS) - a cumulative probability of achieving chosen cost or performance goals.

3.1 Competing Approaches

Both of the approaches described above have unique advantages and disadvantages, however the selected approach must allow:

1. Determination of objective measures and identification of non-dominated solutions.
2. Track and mitigation of risks after a concept design is chosen for further study.
3. Rapid computation (required for optimization of a ship synthesis model).

The next three sub-sections compare the two approaches by weighing the advantages and disadvantages of each relative to the criterion above for the concept design process. The conclusion is that the first approach is the “best athlete” of the two, i.e. more suitable to concept exploration. Accordingly, in the final concept exploration model proposed, risk is treated as a third objective measure and not as uncertainty in cost and effectiveness.

3.1.1 Objective Measures and Identifying Non-Dominated Solutions

The primary objective of the concept design process (as presented in Section 1.2) is to identify non-dominated[3] and feasible concepts for selection by decision-makers based on objective attributes of cost, effectiveness, and risk.

As discussed in Section 2.5.2, the uncertainty-success risk approach does not actually search for non-dominated solutions. Instead the design is optimized to maximize an objective function called the joint probability of success (JPOS). The joint probability of success, (based on a multivariate probability distribution in conjunction with a criterion value range of interest) allows the customer or designer to optimize a design based on the probability of satisfying all the customer's goals. This optimization method does not result in a non-dominated frontier, but a single design with the highest POS of being within specified ranges of particular objective or criteria values.

By contrast, the independent-objective approach treats risk as a third objective measure enabling determination of a three-objective (cost-risk-effectiveness) non-dominated solution. The non-dominated frontier can now be thought of as a surface, as illustrated in Figure 3-2. "Points on this surface represent feasible ships, and can be mapped to specific design parameters. With such a surface, the full range of cost-risk-effectiveness possibilities can be presented to decision-makers, 'knees in the curve' can be seen graphically, trade-off decisions can be made, and specific design concepts can be chosen for further analysis" [2, pg. 2].

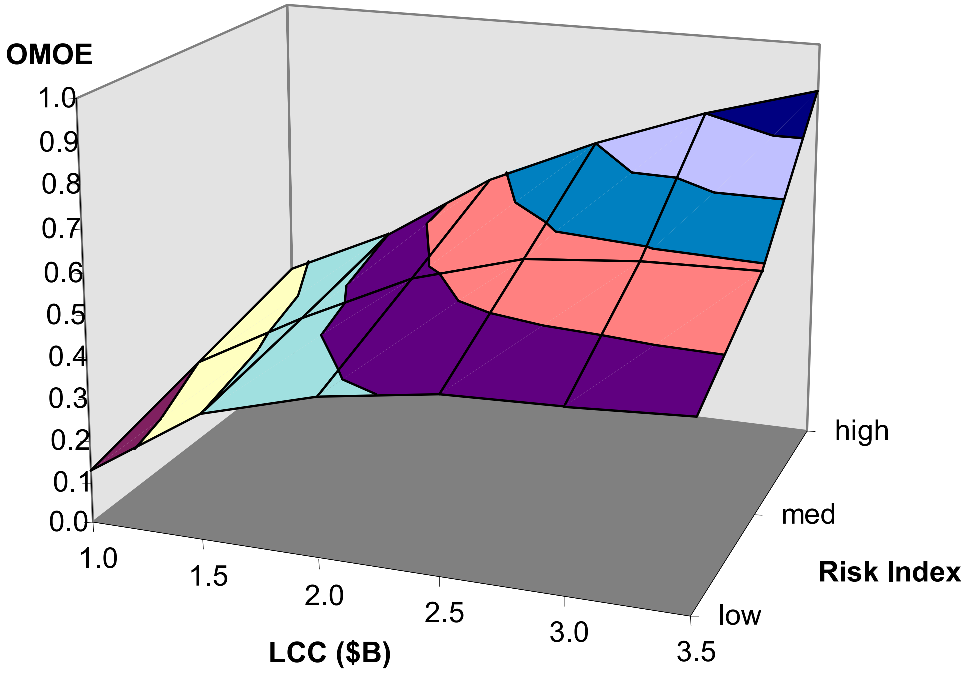

Figure 3-1. 3-D Non-Dominated Frontier [26, p. 2]

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[3] The concept of non-dominated solutions is discussed in Section 4.2.2.

Actual optimization results are shown using bands of non-dominated solutions with increasing level of risk in Figure 3-1.

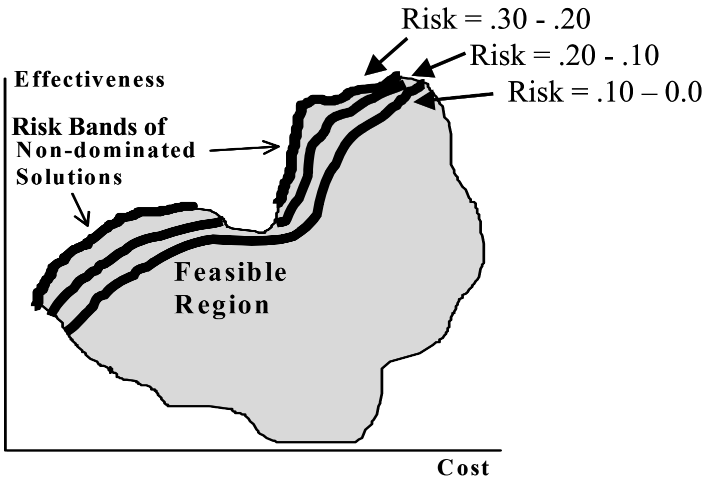


Figure 3-2. 2-D Non-Dominated Solution with Risk Bands.

3.1.2 Tracking and Mitigating Risks

Treating risk as a third objective measure is favored over the variability approach for its usefulness in tracking and mitigating risks after a concept design is chosen for further study and analysis. This is done by plotting the probability of occurrence and potential severity of consequence for each risk factor together as shown in Figure 3-3. In this plot, high, moderate and low risks are clearly visible to the designer, engineer, or program manager and can then be given necessary attention and tracked/mitigated as appropriate. This approach compliments current industry risk management practices that stem from the procedures outlined by the Department of Defense, Risk Management Guide for DOD Acquisition [12].

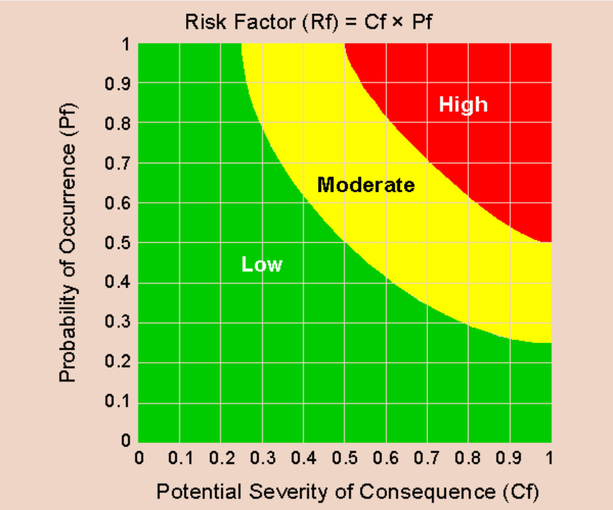


Figure 3-3. Graphical representation of Low, Moderate, and High Risks

3.1.3 Computation Time

“Ship design optimization is not a new concept, but it poses difficult problems. The ship design space is non-linear, very discontinuous, and bounded by a variety of constraints and thresholds. These attributes inhibit effective application of mature gradient-based optimization techniques including LaGrange multipliers, steepest ascent methods, linear programming, non-linear programming and dynamic programming” [26, p.8].

Rapid computation is required for optimization of a ship synthesis model. In a GA application of a ship synthesis model, input design parameters (genes) are specified in a ship design matrix (chromosome). An example is shown in Table 3-1, and design parameter descriptions are listed in Table 3-2” [26, p.7].

Table 3-1. Design Parameter Descriptions

Cp 0.61	Cx 0.82	CΔL 80	CBT 2.9	CD10 11.1
CRD 0.2	Cmanning 0.5	AAW 1	ASUW 2	ASW 1
C4I 1	MCM 4	NSFS 1	SEW 1	Weapons 1
Range 3	Stores 2	Shafts 2	CPS 1	ICR/GT 1

This is an example of a simplified ship design problem, however as presented by Brown [26], each design variant required 12.5 seconds on a 200 MHz PC to balance and evaluate. "If an exhaustive search was conducted, it would assess over ten trillion variants requiring 4 million years on this machine” [26, p.8]!

Table 3-2. Design Parameter Descriptions

Design Parameter	Description
1 - Prismatic Coefficient (Cp)	0.5-0.7; 20 increments
2 - Maximum Section Coefficient (Cx)	0.7-0.9; 20 increments
3 - Displacement to Length Ratio (C_L)	60.0-90.0; 15increments
4 - Beam to Draft Ratio (C_{BT})	2.8-3.7; 9 increments
5 - Length to Depth Ratio (C_{D10})	10.0-15.0; 10 increments
6 - Raised Deck Ratio (C_{RD})	0.0-0.4; 4 increments
7 - Manning Factor ($C_{Manning}$)	0.5-1.0; 5 increments
8 - AAW Payload	1 - Theater TBMD 2 - Area TBMD 3 - Area Defense 4 - Limited Area Defense 5 - Self Defense
9 - ASUW Payload	1 - Long Range 2 - Medium Range 3 - Short Range 4 - Self Defense
10 - ASW Payload	1 - Area Domonance 2 - Adverse ASW Environment 3 - Good ASW Environment 4 - Torpedo Defense
11 - C4I Payload	1 - Advanced 2 - Current
12 - MCM Payload	1 - Limited Clearance 2 - Mine Recon 3 - Mine Avoidance 4 - Limited Mine Avoidance
13 - NSFS Payload	1 - Advanced (VGAS, NATACMS, ATWCS) 2 - Full 3 - Medium 4 - Minimum
14 - SEW Payload	1 - Advanced 2 - Current
15 - Weapons Capacity (VLS)	1 - 128 cells 2 - 64 cells 3 - 32 cells
16 – Range or fuel capacity	1 - 10000 nm 2 - 7000 nm 3 - 5000 nm 4 - 4000 nm
17 - Stores Duration	1 - 60 days 2 - 45 days
18 - Shafts	1 or 2
19 – CPS	0 (none) or 1 (full)
20 - ICR or GT	0 (ICR) or 1 (LM2500)

Possibilities that remain include random searches, exponential random searches, and Genetic Algorithms. "Random search does not require a closed-form solution and has advantages of simplicity and insensitivity to discontinuities, but it still requires many iterations, and is computationally impractical for a large design problem. Exponential random search improves the efficiency of random search, but also requires many concept iterations. Genetic Algorithms (GA) however, offer great promise to tackle this difficult problem" [26, p.8].

"Genetic algorithms use models of natural selection, reproduction, and mutation to improve a population of individuals or variants based on the "survival of the fittest", or in the case of Pareto Genetic Algorithms (PGAs), based on the dominance and distribution of variants [27]. GAs are ideally suited to optimizing discontinuous and disjointed functions, and to optimization where no closed-form function exists (or no mathematical function at all, as with experimental data). The robustness of a particular GA depends on its exploration and efficiency qualities. Exploration refers to its ability to master the design space and consistently identify the global optima. Efficiency refers to the effort required to identify the global optima. Robustness implies an effective balance between these qualities. Genetic algorithms are very robust relative to other methods" [26, p.8].

Applying a PGA, Brown completed a search of the design space specified in Table 3-2 using Overall Measure of Effectiveness (OMOE) and Life Cycle Cost (LCC) as objective attributes. "The optimization was run for 50 generations, taking 26 hours on a 200 MHz PC" [26, p.11]. Since adding risk to the above optimization will increase its run time, it is important to try to streamline this operation.

Taking the first approach and adding a total expected risk value algorithm to the physical/mathematical synthesis model and calculating an overall measure of risk (OMOR) is much less calculation intensive than the Monte-Carlo (MC) approach.

"MC simulations estimate their probability distribution functions based on a large number of samples generated over the design space, defined by the random variable range. The use of computer tools do allow easy perturbation of MC input values. However, computation time to achieve a probabilistic result increases significantly as design complexity increases"[23, p.13]. For a ship, this can mean a substantial increase in processing time and a higher percentage of optimization program crashes.

3.1.4 Risk Metric Conclusion

The independent-objective risk approach is a better choice for ship concept design than the uncertainty-success risk approach because it:

- Allows calculation of a non-dominated frontier whereas the uncertainty-success approach does not.
- Supports tracking and mitigation of risks after a concept design is chosen for further study because each risk is assigned an individually probability of occurrence and potential severity of consequence as required by DoD guidance whereas the uncertainty-success approach does not.
- Allows for rapid computation whereas the uncertainty-success approach is computationally intensive .

3.2 Combining Approaches: Non-Dominated Frontiers and Uncertainty

The previous section competed two different approaches to risk against each other by weighing the advantages and disadvantages of each. While the independent-objective approach was concluded to be the best of the two for the ship concept design application, there is clearly a benefit to be gained if an approach could be developed that incorporated uncertainty with the ability to optimize to a non-dominated frontier. Modifying the methods evaluated in the previous section, risk could be measured by developing one of the following two approaches that combine both features.

1. Independent-Objective Approach <u>with Uncertainty</u>:
    - Incorporates probability density functions (PDFs) that represent the likelihood that parameters will take on certain values.
    - Optimizes to a three-objective (Cost-Risk-Effectiveness) non-dominated solution (Figure 3-2), but based on mean value or other attributes of the PDFs for Cost, Effectiveness, and Risk.
2. Uncertainty-Success Approach <u>with Non-Dominated Solutions</u>
    - Optimizes to a two-objective (Cost-Effectiveness) non-dominated frontier. Optimization results are shown with bands of non-dominated solutions by increasing levels of confidence in Figure 3-4.
    - Risk treated as uncertainty associated with Cost and Effectiveness.

Figure 3-4 illustrates the concept of a two-objective (cost-effectiveness), POS problem. The heavy curve represents the non-dominated solution band. The center of the circle is a single point solution on the non-dominated band. The line forming the circle and the lighter dashed curves indicate the degradation of performance and increased cost associated with different confidence levels. Treating risk as variability of cost and effectiveness predictions allows calculation of pockets of confidence surrounding each non-dominated point solution in the feasible region of the graph, as each point is the mean value of a pdf.

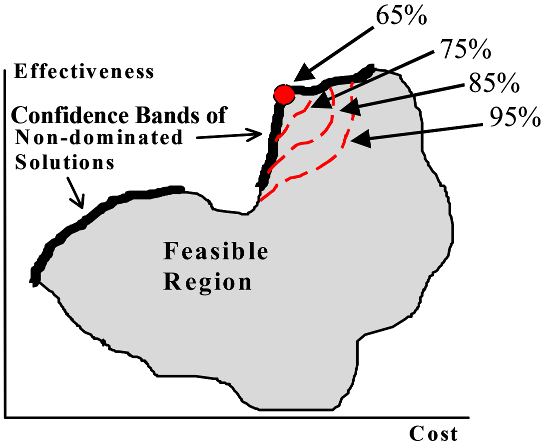


Figure 3-4. Two-Objective Attribute Space [26, p. 2]

Unfortunately both of these modified approaches prove to be computationally intensive as each design variant will require a full Monte Carlo simulation/Fast Probability Integration (FBI) [23]. For the purpose of this thesis, risk will be evaluated as a third objective measure along with cost and effectiveness, however, the combined approaches discussed above merit further study and should be considered for future work.

4. RAMS – A METHODOLODY FOR MEASURING THE RISK OF SHIP DESIGN CONCEPTS

In Chapter 2 a literature and technology search was performed to:

1. Determine how other industries defined and optimized product risk;
2. Identify methodologies and models presently used that are adaptable to naval ship design optimization.

The results of this search turned up many methodologies and models presently used for risk analysis and assessment. A study of these resulted in the following observations:

1. None of the models are directly applicable to naval ship design, but several could be adapted for an individual naval ship;
2. None of the models are specifically applicable for performing a (naval surface ship) design optimization where hundreds of concepts need to be rapidly assessed in a (ship) synthesis model.

Based on these observations, it is decided that a new quantitative risk assessment (QRA) and control methodology must be developed to model and rapidly assess the risk of a parametrically synthesized naval surface ship and enable design optimization.

The new QRA model is called RAMS (or Risk Assessment Model for Ships).

4.1 Process Development

The RAMS model is developed using the information and literature reviewed in Chapter 2, but it is influenced strongly by Blanchard (see section 2.2.1.), and DoD 5000 series *Risk Management Guide for DoD Acquisition* [12] (see section 2.2.2).

The new QRA process was developed by:

1. Reviewing and finalizing the objective of the risk analysis and establishing requirements for the risk model;
2. Collecting an inventory of possible techniques adaptable for the analysis;
3. Evaluating the resources required for adapting each analytical option.

4.1.1 Objective, Requirements and Assumptions

The objective of the risk assessment is to rapidly measure the overall risk of parametrically defined ship design concepts.

In order to accomplish this objective, the following requirements are established for RAMS:

1. RAMS shall provide a practical and quantitative method for measuring technical, schedule, and cost risks associated with producing a new ship design.
2. RAMS shall be scalable to fit different ships, design strategies, and acquisition programs
3. RAMS shall be able to address development, production, construction, test, operation, support, and disposal issues.
4. Initially, RAMS shall be probabilistic in nature only to the extent that the Probability of Failure's are estimated.
5. RAMS shall include the calculation of an overall assessment of risk for ship concept designs defined by a set of design parameters.

6. RAMS shall be adaptable for different ships with different missions
7. RAMS shall be based on the applicable information uncovered by the information search in Chapter 2.
8. RAMS shall be consistent with DoD policies and procedures that address risk management for acquisition programs as contained in the DoD 5000 series of directives [13] [14] [15] [16] [17].
9. RAMS shall be fit within the framework of the ship design process proposed by Brown and Thomas [26].
10. RAMS shall base its assessment on design parameter selections in a ship synthesis model developed based on the framework proposed by Brown and Thomas [26].
11. RAMS shall be adaptable for integration into a Multi-Objective Optimization (MOO) tool for naval ship concept design.

4.2 Ship Concept Design Framework

RAMS is required to fit within the framework of the ship design process proposed by Brown and Thomas [26]. This framework is presented in their paper, "Reengineering the Naval Ship Concept Design Process."

In this paper the authors point out missing elements in current approaches to naval ship concept design and propose a new framework for "reengineering" the design process. Whereas current approaches to naval ship concept design are described as "very much an 'ad hoc' process where selection of design concepts for assessment is guided primarily by experience, design lanes, rules-of-thumb, preference and imagination" and "where objective attributes are not adequately synthesized or presented to support efficient and effective decisions" [26].

For a naval ship, the design space is "very large, non-linear, discontinuous, and bounded by a variety of constraints and thresholds and these problems make a structured search of design space difficult" [26].

Brown and Thomas assert that a structured search is the only a rational way to "measure the optimality of selected concepts relative to the millions of other concepts that have not been considered or assessed" [26]. Their proposed framework addresses the problems associated with a traditional naval ship design by proposing a systems approach to naval ship concept design that:

1. Uses multi-attribute value theory (MAVT) and the Analytical Hierarchy Process (AHP) to synthesize an effectiveness function.

2. Uses a Pareto Genetic Algorithm (PGA) to search the design parameter space and identify non-dominated design concepts in terms of cost, effectiveness and risk.

3. Presents design concepts graphically as points on a non-dominated cost-effectiveness frontier for consideration by decision-makers.

Elements missing from current approaches to naval ship concept design are:

- "A quantitative methodology for synthesizing a manageable set of critical, but dissimilar objective attributes"
- "An efficient method to search design space for non-dominated concepts based on these attributes"
- "An effective format to present these non-dominated concepts for rational selection"

“Critical naval ship objective attributes are mission effectiveness, cost, and risk. Each of these overall attributes includes a number of specific attributes or measures such as mission-specific Measures of Effectiveness (MOEs) whose cumulative value must be synthesized in the overall measure” [26].

This approach recognizes that effectiveness, cost and risk are dissimilar attributes, and require different units of measure. “They cannot rationally be combined into a single objective attribute. They must be presented individually, but simultaneously in a manageable format for tradeoff and decision-making. Manageable implies that only a limited number of attributes can be considered simultaneously. This requires either looking at one piece of the problem at a time, or combining similar objective attributes into an overall measure or index” [26].

4.2.1 MOEs, MOPs, DPs, and PVs

An Overall Measure of Effectiveness (OMOE) index “using expert opinion to synthesize diverse inputs such as defense guidance, mission requirements, threat, war game results and experience” [26] may be calculated using MOEs, MOPs, and DPs. MOEs describe mission effectiveness in specific scenarios. Examples of MOEs are conflict duration, territory lost or gained, casualties, and targets destroyed. Measures of Performance (MOPs) define the performance of the ship system independent of mission scenarios. Examples of MOPs are sustained speed, endurance and signatures. Design parameters (DPs) provide the physical description of the ship system.

DPs determine MOPs, and MOPs determine MOEs. DPs also determine cost and risk. Ultimately, a ship design is defined by specifying millions of DPs, in thousands of drawings, and with libraries full of technical specifications and information.

Process variables (PVs) can be used to synthesize management, engineering, production, and build strategy. Cost and Risk are effected by values of PVs and DPs.

The method for calculating the Overall Measure of Risk (OMOR) is presented in this paper. The OMOR is similar to the OMOE in that its inputs are synthesized from risk factors (RFs) associated with DPs and PVs.

4.2.2 Total-System Approach

Accepting a total-system approach to ship design, “makes an already complex problem more complex” [26], however the goal of this approach is to optimize the life cycle cost-risk-effectiveness of the total ship system. This requires “an iterative and interactive process that depends on an effective concurrent engineering organization to produce a true total-system result. This system includes the ship and everything outside the ship that either affects it or is affected by it” [26].

The hierarchy of systems and subsystems included in the total-ship-system is called a "supersystem" [26] [28]. “At the bottom of this hierarchy are the detailed components and characteristics that define the ship. Many lower-level system decisions can be made at their own level or one higher. Others must be determined at the total ship level. Some compromise between global and local optimization is essential to keep the problem manageable. The number of DPs at any level must be kept to the minimum necessary to capture important interdependence. The highest level of optimization should consider only those variables that have a major impact on ship balance. Frequently combat systems, HM&E systems, and ship characteristics can be grouped into synergistic packages or suites. This reduces the number of variables that must be managed early in the design process.”

The primary objective of the concept design process (as defined here) is to identify non-dominated and feasible concepts for selection by decision-makers based on the objective attributes of cost, effectiveness, and risk [26]. Brown and Thomas prescribe a process where the selection of DPs and MOPs is without bias and where cost, effectiveness, and risk are the relevant objective attributes.

“A non-dominated solution, for a given problem and constraints, is a feasible solution for which no other feasible solution exists which is better in one objective attribute and at least as good in all others. Figure 3-2 illustrates this concept for a simple two-objective (cost-effectiveness) problem. The heavy curve represents non-dominated solutions or the Pareto-optimal frontier. The preferred design should always be one of these non-dominated solutions. Its selection depends on the decision-maker’s preference for cost and effectiveness. This preference may be affected by the shape of the frontier and cannot be rationally determined a priori” [26].

“When considering three attributes, the non-dominated frontier is a surface, as illustrated in Figure 3-1 or a series of risk curves on a 2-D plot as shown in Figure 3-3.. Points on this surface represent feasible ships, and can be mapped to specific design parameters. With such a surface, the full range of cost-risk-effectiveness possibilities can be presented to decision-makers, “knees in the curve” can be seen graphically, trade-off decisions can be made, and specific design concepts can be chosen for further analysis” [26].

4.2.3 Ship Synthesis Model

This design process equates to a sequential mapping between: 1) the mission or customer domain; 2) the functional domain; 3) the physical domain; and 4) the process domain [26] [29]. “Decisions made in each domain are mapped into the subsequent domain, moving from “what” to “how” in each mapping, and then zigzagging down hierarchies in each domain as the design is defined in increasing detail” [26]. A notional top-level design hierarchy consistent with this scheme is shown in Figure 4-1.

In this research, a simple ship-synthesis model is used to synthesize and balance designs in the physical domain, and to calculate the first level of ship MOPs. A Balance requires that the physical and functional constraints are satisfied. A genetic algorithm (GA) is used to search DP space in the physical domain, and to generate and identify concepts on the non-dominated objective attribute frontier. More sophisticated tools, models, and simulations can be used later in the design process on selected concepts to refine the designs, demonstrate feasibility, and improve MOP calculations.

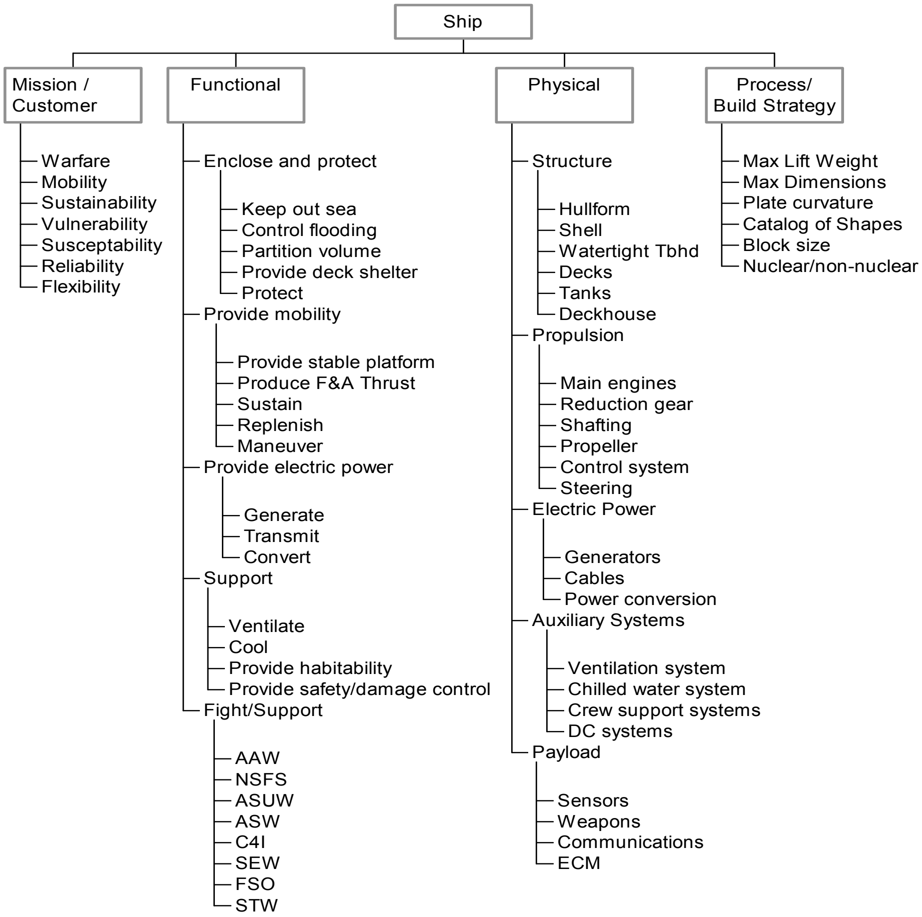


Figure 4-1. Notional Concept Design Process [26]

Analysis results are added to a design knowledge base and applied to update model parametric equations, MOP, cost and risk calculations. This provides a dynamic landscape or environment for the genetic algorithm over the course of the design process. The updated non-dominated frontier is used to reevaluate and adjust earlier top level DP decisions during the design process until further design changes are no longer cost-effective.

Design parameters define the ship in the Physical Domain. The selection, synthesis, and balance of DPs determine ship MOPs, and ultimately determine mission effectiveness. Cost and risk are determined as a function of DPs and process variables (PVs).

Brown and Thomas [26] describe several options for building the OMOE function. Expert opinion via Multi-Attribute Value (MAVT) theory [26] [30] is recommended for building the OMOE when high fidelity modeling and simulation is not feasible. The three major steps are:

1. Identify, define and bound decision attributes.
2. Build OMOE/MOP hierarchy.
3. Determine MOP value and hierarchy weighting factors.

Brown and Thomas develop the MAVT for deriving the OMOE in detail [26].

The ship synthesis model used by Brown and Thomas is based on a model originally developed by Reed (1976). Reed's model has been improved and updated [26] at MIT and Virginia Tech for over two decades by a long series of naval officer and civilian students and faculty, and specifically for use with a genetic algorithm (GA) by Shahak [31]. The author of this thesis worked with Brown and a team of undergraduates at Virginia Tech to update this model for a SWATH oceanographic research ship in 1999 [32]. The synthesis model follows the basic process shown in Figure 4-2 which Brown and Thomas describe in detail [26].

The ship synthesis model uses regression-based equations for weight, volume, area and electric power. Resistance is calculated using Taylor Standard Series. The ITTC / Thin Ship Theory was used for the SWATH model. Cost is calculated using a modified weight-based algorithm. Life Cycle Cost (LCC) calculated in the MIT model included only follow-ship acquisition cost, life cycle fuel cost and life cycle manning cost. Total Ownership Cost (TOC) was calculated in the SWATH model included lead-ship acquisition cost, life cycle fuel and manning cost, builder profits, and change order cost. Seakeeping is assessed using the McCreight Index for the MIT model or natural periods for the SWATH model.

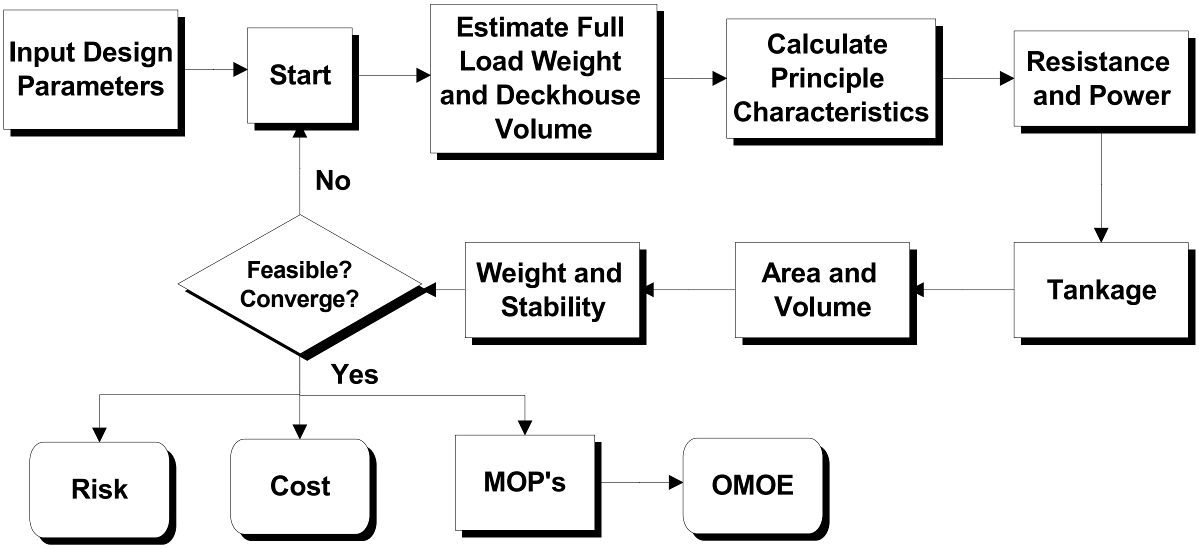


Figure 4-2. Ship Synthesis Model Process [26]

4.2.4 Design Optimization

"Genetic algorithms (GA) offer great promise for tackling ship design optimization problems" [26]. Genetic algorithms use models of natural selection, reproduction, and mutation to improve a population of individuals or variants based on the "survival of the fittest", or in the case of Pareto Genetic Algorithms (PGAs), based on the dominance and distribution of variants (Thomas, 1998).

In the GA application of a synthesis model, input design parameters (genes) are specified in a ship design matrix (chromosome). The ship is balanced and resulting MOPs, OMOE, and Life Cycle Cost (LCC) are calculated. The GA uses these results to assess fitness and breed the next generation of ship variants.

Balance requires that physical and functional constraints are satisfied. The ship must float. It must have adequate stability, volume, area, electric power, etc. It must provide required capabilities and satisfy minimum thresholds for performance.

MathCAD was used by the author to synthesize and balance SWATH research ships in a PGA [32]. The PGA was used to search the design parameter space and identify non-dominated design concepts in terms of cost, effectiveness, and risk. All important system and design trade-offs are made simultaneously as part of this ship system optimization. In this process, once the non-dominated concept frontier is identified, the baseline concept design is selected based on the customer's preference for effectiveness, cost, and risk. For two-object attribute space, the shape of the frontier may have 'knee' in the curve, or a region where there is a sharp discontinuity. The top of this knee is a *best buy region*. For a three-object attribute space, the *best buy region* will be a 'mountain peak' in the surface.

A flow chart for the pareto-genetic algorithm (PGA) used by the author [31] is shown in Figure 4-3. In the first design generation, the optimizer randomly creates 200 balanced ships using the MathCAD model to balance each ship. Each of these designs is ranked based on its fitness or dominance in effectiveness, cost and risk relative to the other designs in the population. Penalties are applied for unfeasibility and niching or bunching up in design space. The second generation of the optimization is randomly selected from the first generation with higher probabilities of selection for designs with higher fitness. Twenty-five percent of these designs are also selected for crossover or swapping of some of their design parameter values. A very large percentage of randomly selected design parameter values are mutated or replaced with a new random value. After 200 generations of evolution, a non-dominated frontier of designs is clearly defined on a cost versus effectiveness plot. Each ship located on the non-dominated frontier provides the highest effectiveness for a given cost compared to other designs in the design space.

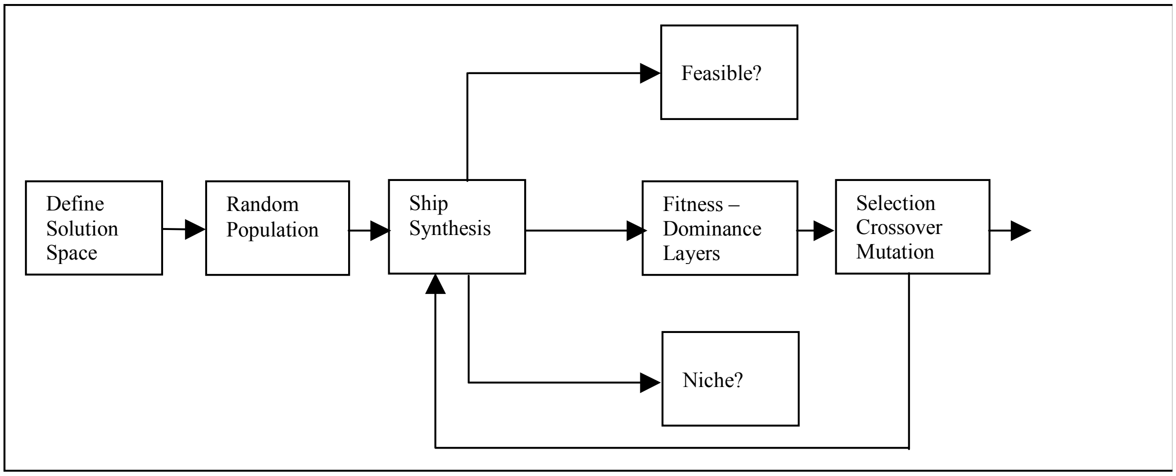


Figure 4-3. Genetic Algorithm Optimization Program

4.3 RAMS Overview

Like any good QRA process, RAMS is designed to answer the three basic questions identified by Kaplan and Garrick [8] [5, p.69]:

1. What can go wrong? (Ei)
2. How likely is it to go wrong? (Pi)
3. What will be the consequence if it does? (Ci)

The first question is answered by developing a structured list of risk events, areas and processes. The second question is answered by quantifying the likelihood the risk event will happen, and the consequences of the risks are assessed by gauging the magnitude of the impacts to performance, schedule, and cost.

RAMS takes into account the three basic types of risk associated with the development of a new ship: technical risk, program schedule risk, and program cost risk. The process that has been developed for RAMS is similar to the method presented in Section 2.2.1 (Systems Engineering Approach), where design engineering risks are tied directly to the technical performance measures (TPMs). In this process, risk is tied through the DPs to measures of performance (MOP) that describe the ships how well the ship performs independent of its mission. Some examples of MOPs are range, speed, endurance, and crew size. MOPs is used to develop the Overall Measure of Effectiveness (OMOE) for a particular set of DP values that describe a ship concept. An OMOE is calculated by synthesizing an effectiveness function from MOP value functions and weights developed using multi-attribute value theory (MAVT) and the analytical hierarchy process (AHP) [26]. However, the method used for computing the OMOE is independent of the risk process and any method may be used. Similarly high risk processes can be traded off and accounted for by using process variables (PVs). PVs allow different candidate processes that might be employed in the design, construction, maintenance, and even disposal of the ship to be counted and considered for the design by evaluating their effect on cost performance and schedule in the same fashion as DPs.

Risk is may be categorized using the primary system selection drivers (e.g. hull type, combat system, manning/automation, propulsion plant, etc.). Some DPs and PVs affect risk and some do not. Examples of DPs that don’t affect risk significantly include hullform parameters such as the Box Coefficient (C_B) and the Prismatic Coefficient (C_P).

The RAMS preliminary ship design method consists of the following steps:

1. Understanding requirements and setting effectiveness and performance metrics, goals and thresholds.

2. Defining the physical design parameters (DPs), process variables (PVs) (if considered) and their options that are needed to describe, develop, produce, and support the ship.

3. Evaluating each design parameter and process variable option and/or range of values against sources/areas of risk to determine potential risk events.

4. Assigning probabilities (P) and consequences (C) of occurrence to each risk event.

5. Selecting DP and PV values and their corresponding P and C.

6. Calculating a risk rating (R) for each Risk.

7. Calculating the overall measure of risk (OMOR) as part of ship synthesis.

8. Ship synthesis and Optimization

Steps 1-7 are described in detail in the next eight sections of this paper. Ship synthesis and optimization (Step 8.) were discussed in Section 4.2.4.

4.4 Requirements, Performance Goals and Thresholds

Understanding requirements usually means going through a requirements definition process. RAMS has been developed to be an integral part of a total ship systems engineering (TSSE) multi-objective concept design process that begins by setting objectives, goals and thresholds and ends with a three-dimensional non-dominated solution optimized for cost, risk, and effectiveness. The optimization is a concept and requirements exploration. Constraints and thresholds are set based on high level source requirements and operational concepts, but performance requirements are otherwise determined or selected as a function of cost and risk.

This process is shown in Figure 4-4.

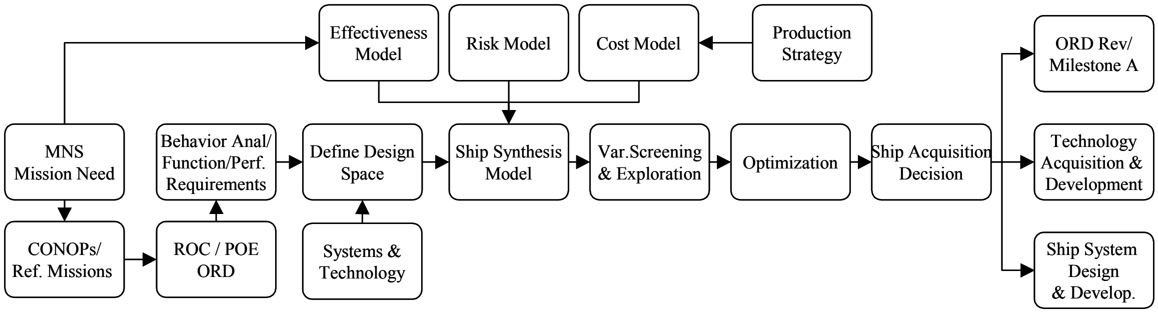


Figure 4-4. Total Ship Systems Engineering Concept Synthesis Development Process

Capturing Source Requirements

This process typically begins when a perceived need for a new or modified ship system arises and "in house" or customer or source requirements are released. Examples of customer source documents include the Mission Need Statement (MNS), Design Reference Missions (DRM), Operational Requirements Document (ORD), and Circular of Requirements (CoR). Other sources of source requirements may come from programs of record and meetings, workshops, and conversations held with the customer defining program requirements, mission requirements, and customer specified constraints.

Defining an Operational Concept

The second requirements development step is the definition of a concept of operations (CONOPS) that characterizes the mission(s) that need to be performed, e.g. Land Attack, Missile Defense, Battle Space Awareness, Command and Control, etc. Usually this is facilitated by an operational concept document (OCD). "The OCD should contain a preliminary functional diagram of the system with only the top-level functional "threads" specified" [33, p.136].

"The combination of source requirements and a CONOPS provides an initial behavioral description of the system in the context of its environment and is particularly useful in exposing mission needs and performance issues" that can be used to define measures of performance and measure of effectiveness [33, p.137]. "The primary objective is to communicate with the end user of the system during the early specification stages to ensure that operational needs are clearly understood and incorporated into the design" and decision process [33, p.137].

Defining and Deriving Functions and Measures of Performance

Once an operational concept is developed, missions are defined and functional analysis begins for each mission to decompose the top level functions (i.e. prime system operations) into sub-functions and flow diagrams. Measures of Performance (MOPs) are eventually developed to describe how well a particular system performs these required functions.

4.5 Defining DPs & PVs & Determining Potential Risk Events

Design Parameters (DPs) and Process Variables (PVs) are introduced in Section 1.2.1. DPs and PVs connect operational needs and requirements to the system solution by synthesizing quantifiable system characteristics that contribute to the total system cost, performance, and schedule.

DP values are mathematical representations of the physical characteristics of the ship system, its sub-systems, and their components that affect cost and performance. PV values are mathematical representations of management, engineering, and production processes that affect cost and schedule.

Each DP and PV represents a piece of the ship system design solution and is associated with a discrete set or bounded range of incremental values. The collective set of DP and PV options make up the solution space of the design problem. Selecting a specific value for a DP or a PV equates to a specific design choice and selecting specific values for a complete set of DPs and PVs equates to a specific design solution for total ship system.

As an example, a particular ship design problem may require the inclusion of three types of hullforms in the ship synthesis model. A design parameter called HULL then may be set up to accept the values 1, 2 & 3. For this instance, HULL=1 corresponds to a conventional displacement hullform, HULL=2 corresponds to a wave piercing tumblehome (WPTH) hullform, and HULL=3 corresponds to a catamaran multi-hull.

In the synthesis model, each HULL option is associated with a unique set of supporting optimizable DPs, such as LENGTH, BEAM, DRAFT each linked to supporting algorithms for determining cost and performance. However, each of these unique choices may also carry with them unique risks.

To account for these risks, the RAMS process requires an evaluation of DP and PV options against sources/areas of risk to identify potential risk events.

DP and PV risk identification is a process of transforming uncertainties, issues, threats, and opportunities into distinct risks that can be described and measured. Identification focuses on technology and process selections (e.g. hullform type) and requires answering the following questions:

- “What is the state-of-the-art of the technology proposed for use” [12, p.41]?
- What development/manufacturing/production capabilities are required to develop and produce the selected design choices (including experience, tools, processes, etc.) as compared to the capabilities of the potential contractors?

DoD 4245.7-M [25] is a good guide to help tailor a set of questions to a specific project. Table 4-1 (from DoDs Risk Management Guide) highlights some of the specific areas or sources for risk identification. It includes a number of areas (threat, requirements, design, etc.) that have been shown through experience to contain risk events that tend to be more critical than others" [27, p.41]. All of these sources and areas of risk should be considered during a concept design and development project. However, some areas (e.g. requirements, logistics, management, etc.) should be considered and dealt with independently since they do not having a bearing on the system solution once the requirements have been defined.

Table 4-1. Significant Risk Events by Critical Risk Areas

Risk Area	Significant Events
Threat	• Uncertainty in threat accuracy. **• Sensitivity of design and technology to threat.** **• Vulnerability of system to threat and threat countermeasures.** • Vulnerability of program to intelligence penetration.
Requirements	• Operational requirements not properly established or vaguely stated. • Requirements are not stable. • Required operating environment not described. • Requirements do not address logistics and suitability. • Requirements are too constrictive—identify specific solutions that force high cost.
Design	• Design implications not sufficiently considered in concept exploration. **• System will not satisfy user requirements.** **• Mismatch of user manpower or skill profiles with system design solution or human-machine interface problems.** • Increased skills or more training requirements identified late in the acquisition process. **• Design not cost effective.** **• Design relies on immature technologies or "exotic" materials to achieve performance objectives.** **• Software design, coding, and testing.**
Test & Evaluation	• Test planning not initiated early in program (Phase 0). • Testing does not address the ultimate operating environment. • Test procedures do not address all major performance and suitability specifications. **• Test facilities not available to accomplish specific tests, especially system-level tests.** **• Insufficient time to test thoroughly.**
Simulation	• Same risks as contained in the Significant Risks for Test and Evaluation. • M&S are not verified, validated, or accredited for the intended purpose. • Program lacks proper tools and modeling and simulation capability to assess alternatives.
Technology	**• Success depends on unproved technology for success.** **• Success depends on achieving advances in state-of-the-art technology.** **• Potential advances in technology will result in less than optimal cost-effective system or make system components obsolete.** **• Technology has not been demonstrated in required operating environment.** **• Technology relies on complex hardware, software, or integration design.**

Risk Area	Significant Risks
Logistics	• Inadequate supportability late in development or after fielding, resulting in need for engineering changes, increased costs, and/or schedule delays. • Life-cycle costs not accurate because of poor logistics supportability analyses. • Logistics analyses results not included in cost-performance tradeoffs. • Design trade studies do not include supportability considerations.
Production/ Facilities	• Production implications not considered during concept exploration. • Production not sufficiently considered during design. • Inadequate planning for long lead items and vendor support. **• Production processes not proven.** • Prime contractors do not have adequate plans for managing subcontractors. **• Sufficient facilities not readily available for cost-effective production.** • Contract offers no incentive to modernize facilities or reduce cost.
Concurrency	• Immature or unproven technologies will not be adequately developed before production. • Production funding will be available too early—before development effort has sufficiently matured. • Concurrency established without clear understanding of risks.
Capability of Developer	**• Developer has limited experience in specific type of development.** **• Contractor has poor track record relative to costs and schedule.** • Contractor experiences loss of key personnel. • Prime contractor relies excessively on subcontractors for major development efforts. • Contractor will require significant capitalization to meet program requirements.
Cost/Funding	• Realistic cost objectives not established early. • Marginal performance capabilities incorporated at excessive costs-satisfactory cost-performance tradeoffs not done. • Excessive life-cycle costs due to inadequate treatment of support requirements. **• Significant reliance on software.** • Funding profile does not match acquisition strategy. • Funding profile not stable from budget cycle to budget cycle.
Schedule	• Schedule not considered in trade-off studies. • Schedule does not reflect realistic acquisition planning. • APB schedule objectives not realistic and attainable. **• Resources not available to meet schedule.**
Management	• Acquisition strategy does not give adequate consideration to various essential elements, e.g., mission need, test and evaluation, technology, etc. • Subordinate strategies and plans are not developed in a timely manner or based on the acquisition strategy. • Proper mix (experience, skills, stability) of people not assigned to PMO or to contractor team. • Effective risk assessments not performed or results not understood and acted upon.

Note 1. Areas and sources of risk that should be considered when evaluating each DP and PV option are shown in **bold** in Table 4-1.

Note 2. The risks shown in Table 4-1 are not intended to serve as a simple checklist that one should apply directly, then consider the DP or PV option risk-free if none of the listed risks are present. They should instead be considered a point of departure to help in identifying different risk areas that might apply to different systems.

RAMS determines risks by examining DP and PV options in terms of risk areas. If a WBS has been developed, risks may be determined by first examining WBS element products and processes in terms of risk areas, then allocating the risks to DP and PV options.

"Process areas are specifically addressed in DoD 4245.7-M [36]. They are general in that areas of risk can be present on any project from either source (product or process) and they are intended as 'top-level' risk sources that will focus attention on a specific area" [12, p.41].

Lower levels and supporting DPs and PVs are also analyzed to ensure that all potential risks are identified, accounted for and documented. DPs/PVs, options and risks are documented in a RAMS spreadsheet. Table 4-2 displays a RAMS spreadsheet with DP options and risks for a notional ship's main gun system.

Table 4-2. Sample DPs, PVs & Potential Risk Event Spreadsheet

Risk Category	RISK ID	DP/PV	DP/PV Option	DP/PV Option #	Risk Event Title	Risk Description
Armament	1	Main Gun	Novel Gun System	1	Use of a Novel Gun System/ Projectile - Projectile Performance	Not meeting range and accuracy requirements will result in warfare objectives will not be met.
Armament	2	Main Gun System	Novel Gun System	1	Use of a Novel Gun System - Gun Magazine Performance	Not meeting magazine rate-of-fire requirements will result in a reduction in warfare effectiveness.
Armament	3	Main Gun System	Novel Gun System	1	Use of a Novel Gun System - Upper Gun Performance	Upper gun components not withstanding required energy levels will result in gun redesign and schedule delays.
Armament	4	Main Gun System	Novel Gun System	1	Use of a Novel Gun System - Barrel Life	If barrel life does not meet the projected performance, then a(o) requirements may not be met
Armament	5	Main Gun System	Novel Gun System	1	Use of a Novel Gun System Availability	If the gun can not meet its Availability Requirement, then the ship may not meet the Ship Availability Requirement.
Armament	6	Main Gun System	Novel Gun System	1	Use of a Novel Gun System - Capability	If the novel gun system capability cannot be developed within projected schedule and budget, then mission performance will not be achieved.
Armament	7	Main Gun System	Novel Gun System	1	Use of a Novel Gun System - Projectile Availability	If funding for novel projectile development availability will not be met.
Armament	8	Main Gun System	Legacy Gun A	2	Use of Legacy Gun A - Production Run affect on Ship Delivery Cost & Schedule	If supplier ends the production run sooner then expected the gun may not be available for follow class ships resulting in schedule delays and inflated costs.
Armament	9	Main Gun System	Legacy Gun A	2	Use of Legacy Gun A - Production Run affect on O&S Cost	If supplier ends the production run sooner then expected gun replacement components may not be available throughout the entire life of the ship(s) resulting in inflated O&S costs and possible gun replacement.
Armament	10	Main Gun System	Legacy Gun B	3	Use of Legacy Gun B - Barrel Life affect on a(0)	If barrel life is not improved to meet the projected performance, then a(o) requirements may not be met
Armament	11	Main Gun System	Legacy Gun B	3	Use of Legacy Gun B - Barrel Life affect on a(0)	If upper gun components can not withstanding required energy levels the gun will have to be rejected or redesigned

In the RAMS spreadsheet, identified risks are grouped by DP/PV and their options. DPs/PVs are also grouped by risk categories to assist later tracking, mitigation and management.

Risk categories are based on the level 3 "ship" elements in the work breakdown structure for ship systems as specified in Appendix E of the DoD work breakdown structure handbook [35]. The categories are: Hull Structure, Propulsion Plant, Command and Surveillance, Auxiliary Systems, Outfit and Furnishing, Armament, Integration/Engineering, and Ship Assembly & Support Services.

Each row in the spreadsheet corresponds to a separate risk unique to each DP option. The spreadsheet also has seven columns. The first column specifies the risk category. The second column specifies the risk ID number. The third column specifies the name of the DP or PV. The fourth column specifies the name of the DP or PV option. The fifth column specifies the title of the risk event, and the six column contains a detailed description of the risk.

4.6 Assigning Probabilities (P) and Consequences (C) of Risk Occurrence

Once DP and PV options have been analyzed and entered into the RAMS spreadsheet, each risk event is rated by determining the probability/likelihood of an event occurring (P) and the consequences/impacts of the event (C). RAMS risk ratings are an indication of the potential impact of risks on the system.

RAMS risk ratings must be assigned by one or more experts, who are familiar with each risk source/area and DP/PV option.

A simple rating criterion is chosen for RAMS that establishes levels of probability/likelihood and consequences/impacts. The criteria combines both Blanchard's and DoD techniques to provide a range of possibilities large enough to distinguish differences in risk ratings and calculate a risk factor (R) for each DP and PV option.

Table 4-3. RAMS Probability/Likelihood Criteria

Level	What is the Likelihood the Risk Event Will Happen?
0.1	Remote
0.3	Unlikely
0.5	Likely
0.7	Highly likely
0.9	Near Certain

Table 4-4. RAMS Consequences/Impacts Criteria

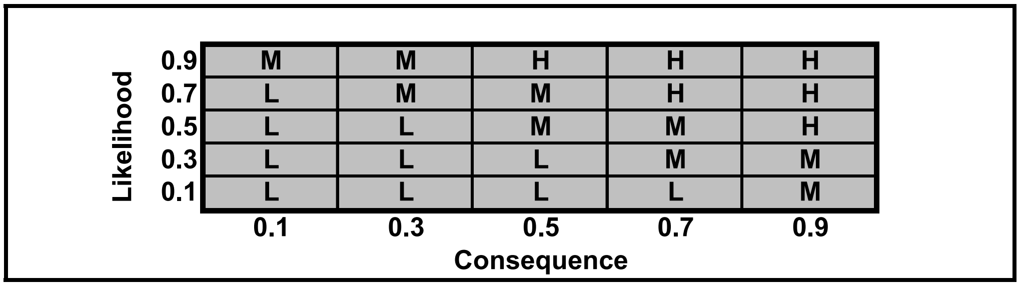
Level	Given the Risk is Realized, What Is the Magnitude of the Impact?		
	Performance	Schedule	Cost
0.1	Minimal or no impact	Minimal or no impact	Minimal or no impact
0.3	Acceptable with some reduction in margin	Additional resources required; able to meet need dates	<5%
0.5	Acceptable with significant reduction in margin	Minor slip in key milestones; not able to meet need date	5-7%
0.7	Acceptable; no remaining margin	Major slip in key milestone or critical path impacted	7-10%
0.9	Unacceptable	Can't achieve key team or major program milestone	>10%

“For each risk event, the probability/likelihood that the event will happen must be determined [12, B-16]. As shown in Table 4-3, there are five levels (0.1-0.9) in the RAMS risk assessment process, with the corresponding subjective criteria of Remote, Unlikely, Likely, Highly Likely, and Near Certainty. “If there is zero probability/likelihood of an event, there is no risk” [12, B-16].

Consequence/impact is determined for each risk area identified by answering the following question: “Given the event occurs, what is the magnitude of the consequence/impact?” [12, B-16].

As shown in Table 4-4, there are five levels of consequence/impact (0.1-0.9). “Consequence/impact is a multifaceted issue” [12, B-16]. RAMS uses three areas to evaluate risk events when determining consequence/impact: technical performance, schedule, & cost. “At least one of the three consequence/impact needs to apply for there to be risk; if there is no adverse consequence/impact in any of the areas, there is no risk” [12, B-16].

Using the RAMS criteria, risk events are determined to be High (H), Moderate (M), or low (L). The RAMS risk matrix is shown in Figure 4-5.



Likelihood	0.1	0.3	0.5	0.7	0.9
0.9	M	M	H	H	H
0.7	L	M	M	H	H
0.5	L	L	M	M	H
0.3	L	L	L	M	M
0.1	L	L	L	L	M
	Consequence				

Figure 4-5. Overall RAMS Risk Rating Matrix

RAMS adapts definitions from the DoD Risk Management Guide to define High, Medium and Low risk [12, p.B-17]. However, these definitions only come into play after design optimization has been performed and a ship has been selected from the non-dominated solution for further study. The definitions are:

HIGH – Unacceptable. Major disruption likely. Requires major mitigation efforts or a different approach is required. Priority management attention is also required.

MODERATE – Some disruption. Requires significant mitigation efforts or a different approach may be required. Management attention may be needed.

LOW – Minimum impact. Minimum mitigation effort and oversight needed to ensure risk remains low.

4.7 Calculating Risk Factors and Overall Measure of Risk

Once possible risk events are identified, a probability of occurrence, P_i, and a consequence of occurrence, C_i, are estimated for each event using Table 4-3 and Table 4-4 and a Risk Factor (R_i) is calculated for each risk.

Three types of risk events are considered in the RAMS risk calculation: performance, cost and schedule. The initial assessment of risk is performed in concept exploration. After the ship's missions and required capabilities are defined and technology options identified, these options and other design parameters are assessed for their potential contribution to overall risk.

The OMOR is calculated directly using weights, probabilities, and consequences using Equation (4-1). To calculate OMOR, risk events do not need to be organized in a Risk hierarchy similar to the hierarchy used to calculate the OMOE. However, the analytical hierarchy process (AHP) and expert pair-wise comparison can be used to calculate OMOR hierarchy weights W_{perf}, W_{cost}, $W_{sched,}$ wi, w_j and $w_{k.}$ Weight parameters W_{perf}, W_{cost}, W_{sched} are available to relate different probability and consequence criteria tables to each other. This weighting option has been included in the OMOR equation to accommodate varying levels of interest in each of the three risk areas and to allow for adaption/tailoring of novel probability and consequence criteria tables that might better fit a particular problem.

$$OMOR = W_{perf}\sum_i w_i P_i C_i + W_{\cos t}\sum_j w_j P_j C_j + W_{sched}\sum_k w_k P_k C_k \tag{4-1}$$

Once the OMOR parameters have been determined, the OMOR function is used as the third objective attribute in the MOGO.

5. PRELIMINARY DESIGN OPTIMIZATION OF CUVX

The RAMS method has been implemented on concept exploration and development of an unmanned combat air vehicle carrier (CUVX) for the United States Navy. The CUVX design, completed in a two-semester ship design course by students at Virginia Tech, incorporates the OMOR function and a CUVX risk register into a ship synthesis model capable of calculating cost, performance, and effectiveness for CUVX. Application of a Genetic Algorithm (GA) with the ship synthesis allows the student design team to develop a population of non-dominated ship design solutions for the cost-effectiveness frontier in risk bands. This CUVX design optimization provides a novel and consistent format and methodology for multi-objective decision making based on the three dissimilar objective attributes: effectiveness, cost and risk.

5.1 Background of the CUVX Design

The Virginia Tech design team choose to adopt the RAMS approach and employ a total system approach for the CUVX design process in order to achieve a structured search of design space based on the multi-objective consideration of performance effectiveness cost and risk. The scope of the CUVX design project includes the first two phases in the ship design process, Concept Exploration and Concept Development.

A multiple-objective design optimization is used to search the CUVX design space. Concept Exploration considers various combinations of hull form, propulsion systems, weaponry and automation within the design space using mission effectiveness and acquisition cost as objective attributes. A ship synthesis model is developed, validated by rough order of magnitude calculations, and finally employed to balance these parameters in total ship designs. The complete model assesses feasibility and calculates cost, risk and effectiveness.

5.2 CUVX Design Requirements and Constraints

The following missions, requirements and constraints were identified for the CUVX by the Virginia Tech student design team.

The CUVX is expected to perform the following missions:

1. Intelligence, Surveillance, and Reconnaissance (ISR)
2. Suppression of Enemy Air Defenses (SEAD)
3. Anti Submarine Warfare (ASW)
4. Anti Surface Ship Warfare (ASuW)
5. Electronic Countermeasures (ECM)
6. Mine Warfare (MIW)
7. Time-sensitive Air and Missile Strikes.

CUVX will operate primarily in littoral areas, depending on stealth, high endurance, minimum external support, low cost and low manning. It will support 20-30 UCAV’s and UAV’s, providing for takeoff and landing, fueling, maintenance, weapons load-out, planning, and control. CUVX will operate independently or in conjunction with small Surface Attack Groups (SAG). It will be capable of performing unobtrusive peacetime presence missions in an area of hostility, and immediately respond to escalating crisis and regional conflict.

CUVX is likely to be forward deployed in peacetime, conducting extended cruises to sensitive littoral regions. It will provide its own defense with significant dependence on passive survivability and stealth. As a conflict proceeds to conclusion, CUVX will continue to monitor all threats. It will likely be the first to arrive and last to leave the area of conflict.

UAV's will provide surface, subsurface, shore, and deep inland surveillance, reconnaissance, and electronic warfare. UCAV's and LAMPS will provide the initial/early conflict ASW, ASuW, SEAD, and MIW.

CUVX must minimize life cycle costs through the application of producibility enhancements and manning reduction. The design must minimize personnel vulnerability in combat through increased automation.

Average follow-ship acquisition cost shall not exceed \$650M (\$FY2005), not including aircraft with the expectation that 30 ships of this type will be built with initial operating capability (IOC) in 2012.

The concept design must also satisfy several physical constraints necessary for feasibility. These constraints, which are built into the ship synthesis model include:

- Weight = displacement
- Arrangable area > required arrangable area
- Hangar area > required hangar area
- Deckhouse area > required deckhouse area
- Sustained speed > required sustained speed = endurance speed = 20 knots (for CUVX)
- SSG rated power > required SSG power
- Machinery box height > required machinery box height
- GM/B ratio between .07 and 0.2
- Flight deck length > required flight deck length
- Flight deck breadth > required flight deck breadth

The optimization program uses these constraints to eliminate unfeasible ships from the concept exploration design space. In addition, all design parameters must be within their prescribed range and all measures of performance (MOPs) must be above threshold values.

5.3 CUVX Design Parameters and Trades

In order to support the required CUVX missions functional capabilities are developed and measured by explicit Measure of Performance (MOP). Available technologies and concepts necessary to provide required functional capabilities are next identified and defined in terms of performance, cost, risk, and ship impact (weight, area, volume, power). Trade-off studies and design space exploration are performed by a Multi-Objective Genetic Optimization (MOGO) using a Pareto Genetic Algorithm (PGA). Through this process all trade-off alternatives are considered in the total ship design.

The following technologies and concepts are described with parameters and explored by the MOGO in the CUVX trade space: Hull forms, aircraft, weapons and consumable storage capacities, Propulsion and Machinery Plants, Aircraft Launching and Arresting Systems (EMALS, AAG, EARS), Weapons Paths, LO/Signature Control Technologies (AMES, LOMFS), UCAV Weapons, and Combat Systems for AAW, ASuW, ASW, SEW and MCM.

A sampling of some high risk trade items considered is offered in Table 5-1.

Table 5-1. Sample of High Risk Trades Items

High Risk Trade Item	Justification
WPTH Hullform	High risk because no large WPTH have yet been built and remain unproven.
Single Shaft Propulsion	High risk because this choice provides both poor maneuverability and zero level redundancy leading to a larger risk of total propulsion loss and increased vulnerability.
EMALS	The Electromagnetic Aircraft Launching System has yet to be proven on U.S.Naval ships.
AEMS/LOMFS	Advanced Enclosed Mast Sensor System and the The Low Observable Multi-Function Stack both also have yet to be proven on U.S. Naval Ships.

Using a survival of the fittest approach, the MOGO creates a population of CUVX concepts by selecting values for the 21 CUVX design parameters presented in Table 5-2. Design-parameter values are selected by the optimizer from the range indicated and input into the ship synthesis model where the ship is balanced, checked for feasibility, and ranked based on risk, cost and effectiveness.

Table 5-2. Design Parameters

DP	Description	Metric	Range	Increments
1	Hull form	type	General monohull, LPD-17, WPTH	3
2	Prismatic coefficient	ND	.6-.8	20
3	Max section coefficient	ND	.9-.99	9
4	Displacement to length ratio	lton/ft2	50-90	20
5	Beam to Draft Ratio	ND	3-5	20
6	Length to Depth Ratio	ND	6-8	20
7	Aircraft launch deck?	y/n	0,1	2
8	Deckhouse volume ratio	ND	.05-.3	25
9	AAW system	alternative	1,2	2
10	LAMPS helos	#	2,4	2
11	Endurance range	nm	4000,8000,12000	3
12	Stores duration	days	60,90,120	3
13	Propulsion system	alternative	1-14	14
14	Ship manning and automation factor	ND	.5-1.0	5
15	Hull structure type	type	Conventional, ADH	2
16	CPS	extent	None, partial, full	3
17	UAVs	#	5-20	15
18	UCAVs	#	10-30	20
19	Aviation manning and automation factor	ND	.5-1.0	5
20	Ship aircraft fuel	lton/UCAV	30.-60.	10
18	Ship aircraft weapons	lton/UCAV	5.-15.	10

5.3.1 Overall Measure of Effectiveness (OMOE)

Figure 5-1 illustrates the process used to develop the CUVX OMOE and OMOR.

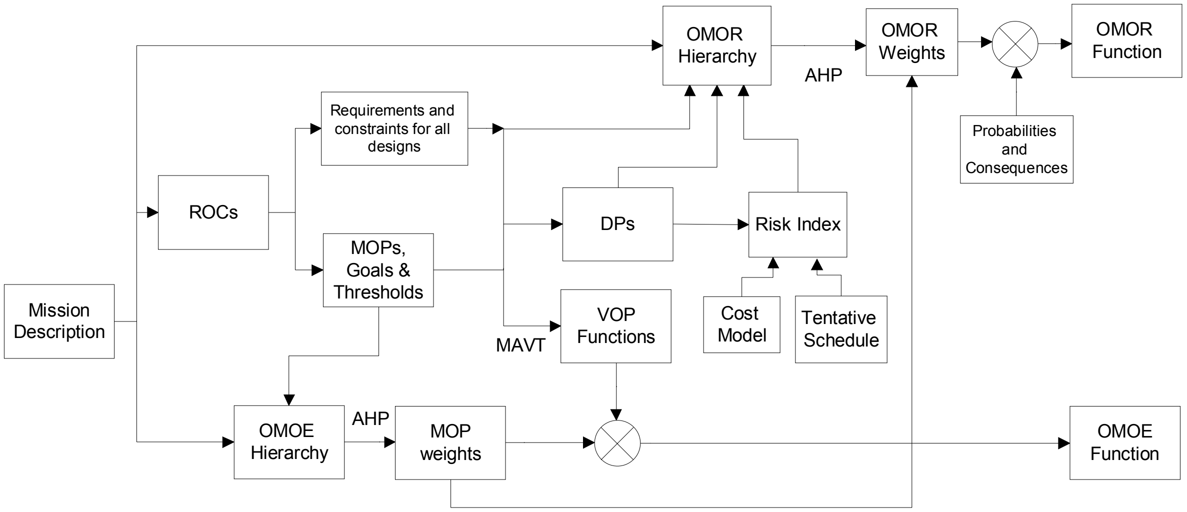


Figure 5-1. OMOE and OMOR Development Process

An OMOE function is developed for CUVX to assess overall effectiveness of ship concepts. The OMOE is developed as a single figure of merit that portrays how well a CUVX concept performs all CUVX missions. The OMOE is developed as a Multi-Attribute Value (MAV) function [26] using CUVX MOPs and Values of Performance (VOPs).

MOPs are specific ship or system performance metrics independent of mission (speed, range, number of missiles). Measures of performance (MOPs) are specified for those capabilities that will vary in the designs as a function of the ship design variables (DPs). A VOP is a figures of merit index (0-1.0) specifying the value of a specific MOP to a specific mission area for a specific mission type. VOPs are developed from expert opinions using the Analytical Hierarchy Process (AHP).

The OMOE function is presented as Equation (5-1).

$$OMOE = g\left[VOP_i\left(MOP_i\right)\right] = \sum_i w_i VOP_i\left(MOP_i\right) \tag{5-1}$$

Figure 5-2 illustrates the OMOE hierarchy for CUVX. Separate hierarchies are developed for each mission or condition (pre-conflict, conflict and post-conflict) for CUVX. MOPs are grouped into six categories (ship combat, sustainability, mobility, vulnerability, susceptibility and airwing combat) under each mission.

MOP weights calculated for CUVX using expert opinion are compared in Figure 5-3.

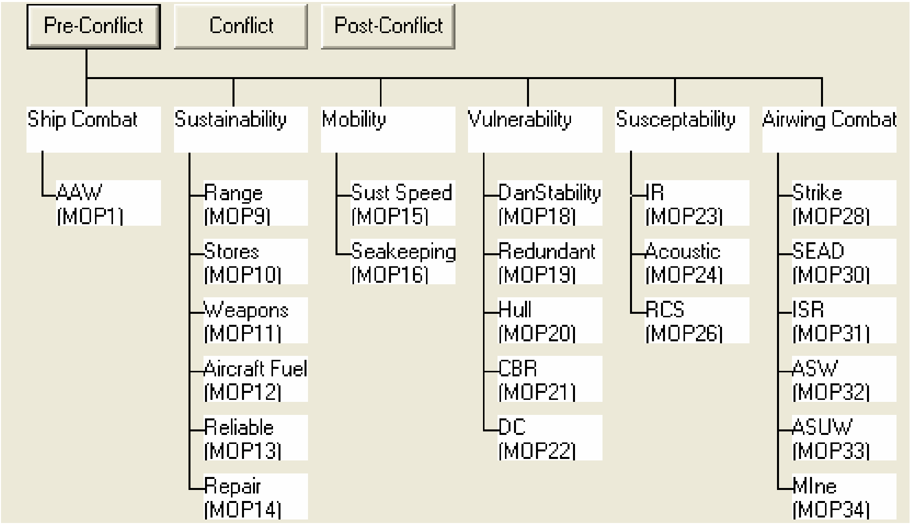


Figure 5-2. OMOE Hierarchy

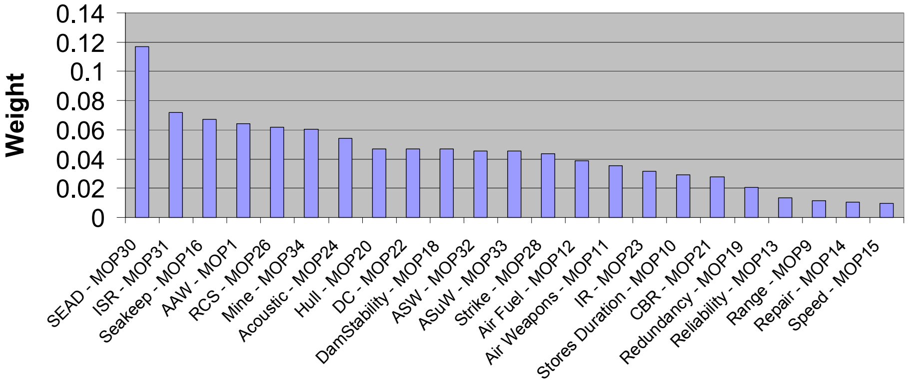


Figure 5-3. MOP Weights

5.3.2 Overall Measure of Risk (OMOR)

Three types of risk events are considered in the CUVX risk calculation: performance, cost and schedule. The initial assessment of risk is performed in concept exploration. Referring to Figure 5-1, after the ship's missions and required capabilities are defined and technology options identified, these options and other design parameters are assessed for their potential contribution to overall risk. MOP weights, tentative ship and technology development schedules and cost predictions are also considered. Possible risk events identified for CUVX are listed in the risk register developed for CUVX in Table 5-3. To calculate an OMOR, weight parameters W_{perf}, W_{cost}, W_{sched}, w_i, w_j and w_k are all nominally set to 1. Once possible risk events are identified, a probability of occurrence, P_i, and a consequence of occurrence, C_i, are estimated for each event using Table 5-4 and Table 5-5. The OMOR is calculated with these weights, probabilities, and consequences as:

$$OMOR = W_{perf}\sum_i w_i P_i C_i + W_{\cos t}\sum_j w_j P_j C_j + W_{sched}\sum_k w_k P_k C_k \tag{5-2}$$

Once the OMOR parameters have been determined, the OMOR function is used as the third objective attribute in the MOGO.

Table 5-3. CUVX Risk Register

SWBS	Risk Type	Risk ID	DP#	DP Description	DP Value	Risk Event E_i	Risk Description	P_i	C_i	R_i
Armament	Performance	1	DP_{10}	Peripheral VLS	1	Failure of PVLS/AVLS EDM tests	Will require use of VLS or RAM with impact on flight deck and hangar deck area and ops	0.3	0.5	0.15
Hull	Performance	2	DP_1	WPTH hull form	2	Unable to accurately predict endurance resistance	Will over-predict endurance range.	0.2	0.3	0.06
Propulsion	Performance	3	DP_{20}	Integrated power system	>5	Development and use of new IPS system	New equipment and systems will have reduced reliability	0.4	0.4	0.16
Hull	Performance	4	DP_1	WPTH hull form	2	Unable to accurately predict sustained speed resistance	Will over-predict sustained speed.	0.2	0.5	0.1
Hull	Performance	5	DP_1	WPTH hull form	2	Unable to accurately predict WPTH seakeeping performance	Seakeeping performance will not be acceptable	0.5	0.5	0.25
Hull	Performance	6	DP_1	WPTH hull form	2	Unable to accurately predict WPTH extreme motions and stability	Damaged stability performance will not be acceptable	0.7	0.7	0.49
Hull	Performance	7	DP_8	Separate launch deck	1	Concept doesn't work preventing simultaneous launch and recovery for SEAD mission	Unforeseen problems with dedicated launch deck (launch, fuel, weapons)	0.4	0.8	0.32
Hull	Performance	8	DP_8	Separate launch deck	1	Concept doesn't work preventing simultaneous launch and recovery for Strike mission	Unforeseen problems with dedicated launch deck (launch, fuel, weapons)	0.4	0.9	0.36
Propulsion	Schedule	9	DP_{20}	Integrated power system	>5	Development and integration of new IPS system will be behind schedule	Unexpected problems with new equipment and systems	0.3	0.3	0.09
Propulsion	Cost	10	DP_{20}	Integrated power system	>5	Development and integration of new IPS system will have cost overruns	Unexpected problems with new equipment and systems	0.3	0.6	0.18
Auxiliary	Schedule	11	DP_{20}	EMALS	>5	Development and integration of new EMALS system will be behind schedule	Unexpected problems with new equipment and systems and integration with IPS pulse power	0.5	0.4	0.20
Auxiliary	Cost	12	DP_{20}	EMALS	>5	Development and integration of new EMALS system will have cost overruns	Unexpected problems with new equipment and systems and integration with IPS pulse power	0.5	0.6	0.3
Armament	Cost	13	DP_{10}	Peripheral VLS	1	PVLS EDM test and development system will have cost overruns	Unexpected problems with new equipment and systems	0.2	0.4	0.08

SWBS	Risk Type	Risk ID	DP#	DP Description	DP Value	Risk Event E_i	Risk Description	P_i	C_i	R_i
Armament	Schedule	14	DP_{10}	Peripheral VLS	1	PVLS EDM test and development will be behind schedule	Unexpected problems with new equipment and systems	0.2	0.2	0.04
Hull	Schedule	15	DP_1	WPTH hull form	2	Delays and problems with WPTH testing	Unexpected problems or unsatisfactory performance of new hull form	0.5	0.7	0.35
Hull	Cost	16	DP_1	WPTH hull form	2	Delays and problems with WPTH testing	Unexpected problems or unsatisfactory performance of new hull form	0.5	0.6	0.3

Table 5-4. Event Probability Estimate

Probability	What is the Likelihood the Risk Event Will Occur?
0.1	Remote
0.3	Unlikely
0.5	Likely
0.7	Highly likely
0.9	Near Certain

Table 5-5. Event Consequence Estimate

Consequence Level	Given the Risk is Realized, What Is the Magnitude of the Impact?		
	Performance	Schedule	Cost
0.1	Minimal or no impact	Minimal or no impact	Minimal or no impact
0.3	Acceptable with some reduction in margin	Additional resources required; able to meet need dates	<5%
0.5	Acceptable with significant reduction in margin	Minor slip in key milestones; not able to meet need date	5-7%
0.7	Acceptable; no remaining margin	Major slip in key milestone or critical path impacted	7-10%
0.9	Unacceptable	Can’t achieve key team or major program milestone	>10%

5.3.3 Cost

Lead ship acquisition cost, and to a lesser extent, follow ship acquisition cost are particularly important for getting the concept of a CUVX carrier “off the ground”. Two separate multi-objective optimizations are performed for CUVX, the first using lead ship acquisition cost, and the second using mean follow-ship acquisition cost. Life cycle cost were not addressed and postponed for later analyses.

CUVX construction costs are estimated for each SWBS group using primarily weight-based regression equations adapted from an early ASSET cost model and US Navy cost data. Historical costs are inflated to the base year using a 2.3% average annual inflation rate from 1981 data. The CUVX base year is assumed to be 2005. Figure 5-4 illustrates total lead ship acquisition cost components calculated in the model.

Basic follow-ship costs for SWBS groups 100-600 are equal to lead ship costs, but reduced by a learning factor and inflated to the follow-ship award year. A learning rate of 98%, total ship acquisition of 30 and production rate of two ships per year are assumed for calculating CUVX follow-ship acquisition costs.

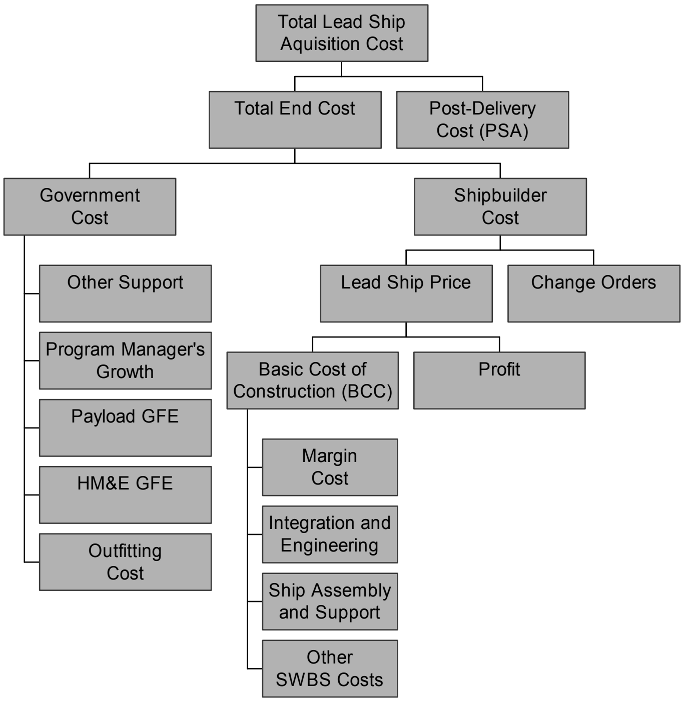


Figure 5-4. Naval Ship Acquisition Cost Components

5.4 Optimization Results

Figure 5-5 and Figure 5-6 show the non-dominated (ND) frontiers calculated for CUVX. Figure 5-6 is based on lead ship acquisition cost and Figure 5-6 is based on mean follow ship acquisition cost. Each point on the ND frontier represents a specific ship design. Designs of particular interest include curve knees (BB1, BB2, BB3, LO5) and extreme or near extreme highs and lows (LO1, LO2, LO3, LO4, HI1, HI2, HI3). Characteristics of these candidate designs for CUVX are listed in Table 5-6. Curve knees, called best buys (BB), represent points where the change in effectiveness for a given change in cost or risk increases or decreases sharply. Knees where sharp decreases occur represent good marginal selections for the customer if they are within acceptable risk and cost thresholds.

All ND ships in the lead ship acquisition cost optimization, Figure 5-5, are LPD-17 modified-repeat designs. This is a result of substantially lower Group 800 and 900 costs for the modified repeat. New monohull or WPTH monohull designs require more lead ship effort for engineering (detailed design) and production support. These costs are reduced in a modified-repeat. Since Figure 5-5 represents only the LPD design, its ND risk curves are much more uniform than in Figure 5-6 where all three hull forms are represented. Reading from low to high cost, the first straight upward slope in all curves adds UAVs (from threshold to goal), the second adds UCAVs, and the third adds ship UCAV weapons capacity. Increases in risk between curves add IPS, EMALS, launch deck, peripheral VLS, advanced double hull, and WPTH hull form in various combinations.

ND ships in the follow-ship acquisition cost optimization include all three hull form types (Table 5-6). Since the LPD modified-repeat requires a specific displacement (+/- 2%), low end ships with displacements less than 25000 MT, and high-end ships with displacements greater than 25000 MT are either general monohulls or WPTH. Many of the ships in the middle (LPD) region are on both lead ship and follow ship ND frontiers.

No high automation / low manning ships are included in either frontier because the risk of low manning variants is too high. All other technology options are included in some variants. Displacements range from 21000 lton – 29000 lton. Low end (cost) variants have one shaft; high end variants have two shafts.

The CUVX student teams choose to continue concept development of the high cost and risk alternatives, HI2 and HI3 based on educational value, interest, and challenge even though they are well above the customer’s cost threshold. The low end variants, however, are also above the original acquisition cost thresholds and the ND frontier results, MOP thresholds, and design alternatives will be discussed with the customer prior to proceeding with concept development on lower cost alternatives. If the customer is able to compromise on his cost threshold, the optimization results show LO1 and BB2 to be very cost/risk effective alternatives for CUVX. Either way, the CUVX design optimization demonstrates the value of the RAMS method and provides a novel approach and consistent format and methodology for multi-objective decision making with the three dissimilar objective attributes: effectiveness, cost and risk.

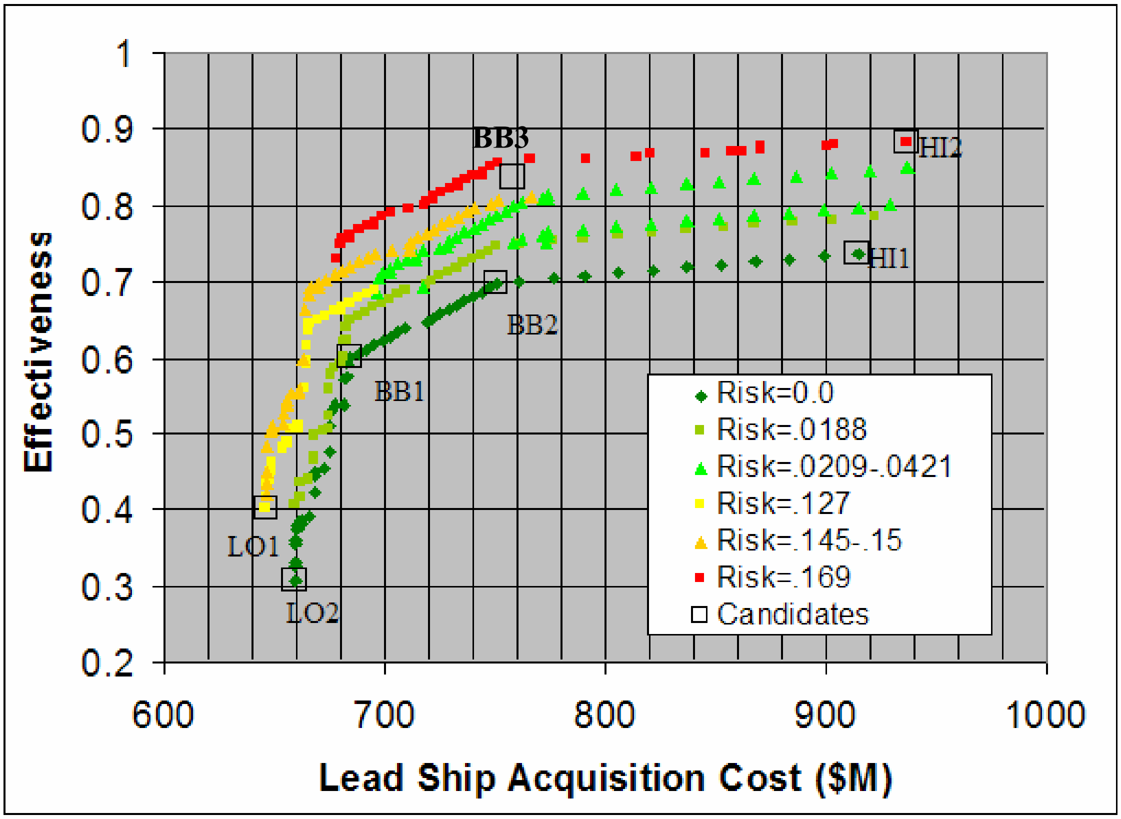


Figure 5-5. Non-Dominated Frontier based on Lead Ship Acquisition Cost

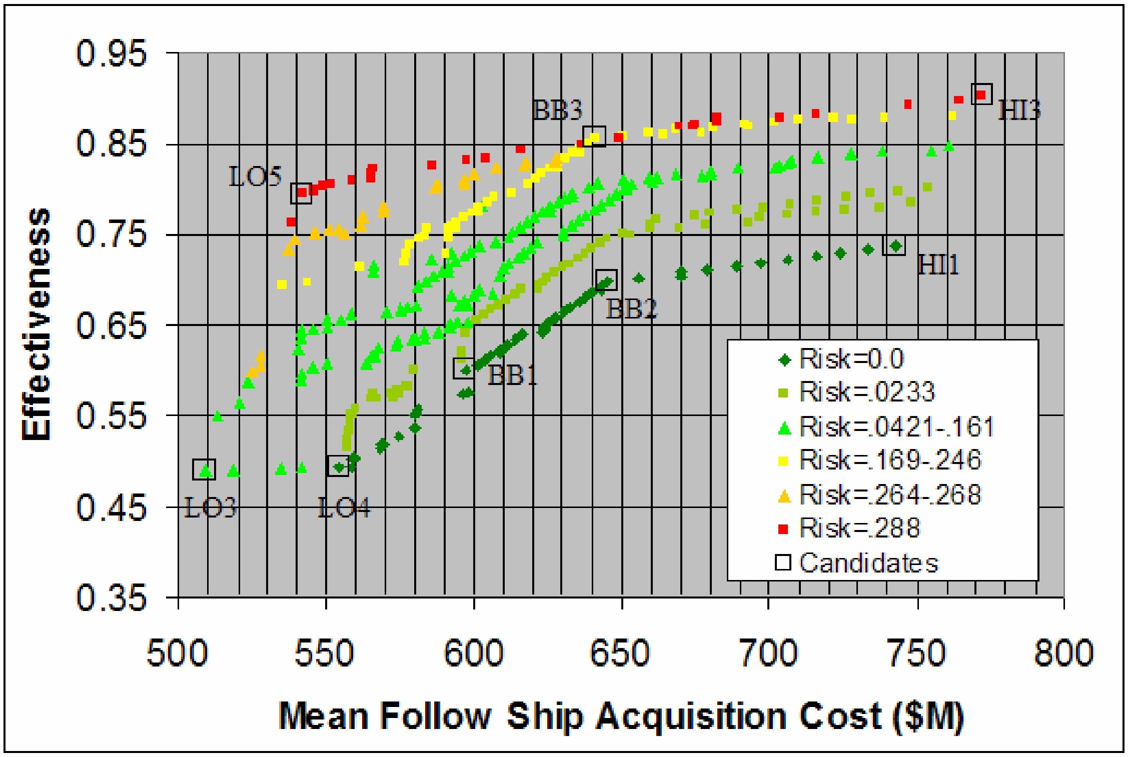


Figure 5-6. Non-Dominated Frontier based on Average Follow Ship Acquisition Cost

Table 5-6. Non-Dominated Design Candidates

	Team 4						**Team 4**			**Team 1**	**Team 2**
	LO1	**LO2**	**LO3**	**LO4**	**LO5**	**BB1**	**BB2**	**BB3**	**HI1**	**HI2**	**HI3**
Cfol ($M)	562.60	574.82	509.21	554.67	542.18	597.10	645.44	641.39	742.49	760.29	772.24
Clead ($M)	641.93	654.56	770.79	840.10	822.39	682.55	750.92	751.79	914.55	937.07	1192.30
OMOR	0.1271	0.0000	0.1185	0.0000	0.2877	0.0000	0.0000	0.1692	0.0000	0.1692	0.2877
OMOE	0.4003	0.3055	0.4889	0.4931	0.7946	0.6005	0.6977	0.8553	0.7367	0.8820	0.9021
Hullform	LPD	LPD	WPTH	MH	WPTH	LPD	LPD	LPD	LPD	LPD	WPTH
Δ (lton)	25711.1	25295.7	20412.9	22495.8	21412.2	25143.8	25873.0	25880.4	25170.8	25294.6	28995.6
LWL (ft)	656.17	656.17	614.46	629.96	634.05	656.17	656.17	656.17	656.17	656.17	696.01
Beam (ft)	96.92	96.92	74.20	82.21	89.96	96.92	96.92	96.92	96.92	96.92	94.12
Draft (ft)	23.23	22.85	20.61	22.22	21.94	22.72	23.38	23.38	22.74	22.85	22.96
D10 (ft)	87.37	87.37	83.04	82.89	88.06	87.37	87.37	87.37	87.37	87.37	96.67
Cp	0.647	0.647	0.800	0.720	0.630	0.647	0.647	0.647	0.647	0.647	0.710
Cx	0.941	0.941	0.950	0.950	0.950	0.941	0.941	0.941	0.941	0.941	0.950
Cdl (lton/ft3)	90.012	90.012	88.000	90.000	84.000	90.012	90.012	90.012	90.012	90.012	86.000
Cbt	4.220	4.220	3.600	3.700	4.100	4.220	4.220	4.220	4.220	4.220	4.100
CD10	7.510	7.510	7.400	7.600	7.200	7.510	7.510	7.510	7.510	7.510	7.200
NLaunDk	0	0	0	0	1	0	0	1	0	1	1
Cvd	0.080	0.080	0.290	0.140	0.180	0.110	0.110	0.120	0.110	0.210	0.150
Range (nm)	12000	12000	12000	12000	8000	12000	8000	4000	4000	4000	4000
Duration (days)	120	120	120	120	120	120	120	120	120	120	120
NCPS	3	3	3	1	1	1	1	1	1	1	1
PSYS	8	1	1	1	12	4	4	12	4	11	12
Shafts	1	1	1	1	2	2	2	2	2	2	2
PSYStype	IPS	Mech	Mech	Mech	IPS	Mech	Mech	IPS	Mech	IPS	IPS
AAW	2	2	2	2	1	2	2	1	2	1	1
ADHull	0	0	0	0	1	0	0	0	0	0	1
Nhelo	2	2	4	4	4	4	4	4	4	4	4

	Team 4						Team 4			Team 1	Team 2
	LO1	**LO2**	**LO3**	**LO4**	**LO5**	**BB1**	**BB2**	**BB3**	**HI1**	**HI2**	**HI3**
CManShip	1	1	1	1	1	1	1	1	1	1	1
NUAV	13	9	20	18	20	20	20	20	20	19	18
NUCAV	10	10	10	10	11	10	28	29	30	30	28
CManAir	1	1	1	1	1	1	1	1	1	1	1
WFUCAV	45.0	45.0	42.0	42.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0
WWUCAV	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	15.0	15.0	14.0
W1	10835.0	10761.1	7036.2	8636.5	8697.0	10823.4	10853.2	10926.3	10857.6	10922.0	13061.8
W2	1963.9	773.3	759.5	766.8	2130.1	1093.5	1093.5	2138.9	1093.5	1172.9	2143.0
W3	634.9	712.1	585.5	668.9	598.4	848.7	895.7	745.6	901.1	778.6	816.7
W4	301.2	301.2	247.0	270.4	270.0	302.1	302.1	313.5	302.1	316.2	328.8
W5	3355.7	3469.9	2813.5	3152.6	2909.1	3552.2	3633.5	3539.1	3642.6	3599.2	3739.9
W6	1406.0	1399.4	1118.1	1239.2	1208.1	1452.8	1730.0	1760.6	1776.1	1810.6	1838.8
W7	29.9	29.9	29.9	29.9	42.4	29.9	29.9	42.4	29.9	42.4	42.4
Wp	933.1	912.2	1070.9	1060.5	1162.3	1070.9	2179.8	2271.3	2603.0	2627.7	2451.2
Δ LS (lton)	20379.3	19191.5	13848.7	16240.8	17440.7	19912.9	20391.7	21413.1	20463.1	20506.1	24168.5
KG (ft)	30.73	30.17	27.38	28.10	32.28	31.36	33.90	34.89	35.35	35.62	38.81
GM/B=	0.186	0.190	0.105	0.133	0.131	0.177	0.154	0.144	0.136	0.133	0.084
Vs (knt)	20.95	22.63	22.14	22.62	21.92	21.28	21.28	20.95	21.28	24.63	20.18
McC	46.88	46.55	40.66	43.47	40.82	46.48	47.13	47.18	46.68	46.78	53.14
Manning	476	481	496	490	514	523	863	880	901	917	901

6. CONCLUSION

The naval ship concept design process often embraces novel concepts and technologies that carry with them an inherent risk of failure simply because their application is the first of its kind. Failure is recognized by gaps between actual and required measures of performance, exceeded budgets, and late deliveries. These risks are defined and quantified as a product of the probability of an occurrence of failure and a measure of the consequence of that failure. Since the objective of engineering is to design and build things to meet requirements, within budget, and on schedule the first time; it is important to consider risk, along with cost and performance, as trade assessments and technology selections are made during conceptual design.

To this end, a simplified metric and methodology for measuring the risk of ship design concepts has been developed and integrated into a Multi-Objective Optimization tool for naval ship concept design. The purpose of this tool is to provide a consistent format and methodology for multi-objective decisions based on dissimilar objective attributes, specifically effectiveness, cost and risk. This approach provides a more efficient and robust method to search the design space for optimal concepts than the traditional "ad hoc" naval ship concept design process where selection and assessment are often based on experience, design lanes, rules-of-thumb and imagineering.

This literature and information search presented in this paper investigates and identifies Risk, Engineering Systems Safety, and state of the art risk analysis techniques currently in practice. Based on this information search, a simplified metric and methodology referred to as the Risk Assessment Method for Ships (RAMS) was developed to calculate, quantify, and compare relative overall risk in a ship design optimization, defined and synthesized in a math model based on variation of parametric design parameters. In this method, a risk register is developed for the a notional ship. The register identified potential cost, performance, and schedule risk issues. Risk item descriptions are further defined against design parameters (DPs) considered for the notional ship. Risk Factors (RF) are calculated for each risk item based on DP selection. RF is calculated as the product of Probability of Failure Occurrence (PF) and Potential Consequence of Failure (CF). An Overall Measure of Risk (OMOR) function is developed to measure the level of overall risk for a single concept design based on DP selections.

The methodology was exercised in the concept design of CUVX, and unmanned combat air vehicle carrier by incorporating the OMOR function and risk items into a ship synthesis model capable of calculating cost, performance, and effectiveness. Applying a Genetic Algorithm (GA) to the CUVX ship synthesis, a population of ship design solutions is developed that spreads across the two-dimensional, non-dominated, cost-effectiveness frontier in risk bands. This new model for ship design optimization provides a novel approach and consistent format and methodology for multi-objective decision-making based on the three dissimilar objective attributes: effectiveness, cost and risk.

6.1 Discussion of Limitations

It is important to realize that different assumptions yield different sets of scenarios and sources of risk. “While risk assessment is a useful tool to evaluate and compare relatively simple risks (e.g. equipment failure, or damage in a particular scenario) with alternative risks if different choices are taken (e.g., replacement of technology), it may be dangerous to apply it to more complex phenomena in order to derive a definitive risk ranking” [5, p. 8]. This danger also exists when trying to represent an overall measure of risk for a complex ship. Thus, risk assessment should be applied with caution to the real-life problems, keeping in mind its limitations.

Risk assessment can be used to justify design choices and is useful for pointing out the dangers of pursuing one or another course of action. However, these decision may be based on some rather questionable numerical values, and the most important thing is to always make risk assessment transparent with all the assumptions and parameters clearly stated.

“The thought process that goes into evaluating a particular risk is more important than the application of some sophisticated mathematical technique or formula, which may be based on erroneous assumptions or models of the world” [5, p. 9].

6.2 Future Work

The debate in Chapter 3 argued that risk is best considered as a third objective measure along with cost and performance/effectiveness by calculating expected risk values against an index. The RAMS methodology presented in this paper was developed based on that argument. However, alternative ways of considering risk bear further study. Chapter 3 discussed the possibility of incorporating uncertainty into the non-dominated frontier. Although, two approaches were presented, both proved to be computationally enormous. However if more efficient techniques can be developed this idea may become more feasible. Fast Probability Integration (FBI) and Fuzzy Logic both show promise of increased efficienty. More reasearch should be applied in this area towards developing non-dominated solutions in association with confidence factors or probability of success (POS). Future research should also focus on developing models for other ship types and development of generic risks that would apply for all ship types.

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8. VITA

Timothy Stephen Mierzwicki was born July 28, 1977 in Baltimore, Maryland and he is the youngest of two sons of Cheryl and Edward Mierzwicki Jr. His early love of being on the water led him to attend Virginia Tech, where he graduated with a Bachelor of Science degree in Ocean Engineering in May of 1999. During his time at Virginia Tech, Tim participated in the student-faculty Human Powered Submarine Program where he eventually served as Vice President. Also during this period he gained vauluable engineering, design, analysis, and test experience working for J.W. Russell Mechanical, General Dynamics Electric Boat, and Henry DuPont Preservation Shipyard. Since graduating in 1999, Tim has worked for Northrop Grumman Ship Systems (NGSS) as a Naval Architect and Systems Engineer, He has completed his graduate studies as a distance learning student, first from Northrop Grumman's Ingalls shipyard in Pascagoula, MS then later from the NGSS Washington D.C. office after accepting a transfer in November 2002.

Tim was a naval architect on the DD21 Gold Team responsible for design, calculations, analysis, and tests leading to the development of DD21 and DD(X) technical proposal baselines. His efforts in the areas of Hydrodynamics, Weight Control, Stability, Maneuvering, Model Tests, Arrangements, Mobility Effectiveness, Survivability, Design Optimization & Simulation helped Northrop Grumman Ship Systems secure the Design Agent contract for DD(X). Tim has worked with both the Hull Technical and Noise Shock and Vibrations scientific groups at Northrop Grumman's Ingalls Shipyard supporting production evolutions and at sea tests on DDG and LHD class ships. He has provided in yard and at sea engineering support for airborne noise tests, translations, launches, surveys, and inclining experiments on DDG and LHD vessels. In 2001 Tim helped stand up the Systems Engineering Department at NGSS along with a core group of cross-disciplined engineers. He continues to work on developing corporate wide SE processes and procedures and has worked on various proposals and ship development efforts at NGSS. Tim has supported DD21 aviation systems integration and has help develop the Systems Test Engineering program for DD21 and DD(X) including T&E, System Verification, and Certification plans and procedures. In addition to providing general SE process support to DD(X), Deepwater, & FMS; and he was the NGSS ship architect for JCC(X). Tim was the lead NGSS engineer to BIW and Dassault Systems leading to the custom development of a CATIA shipbuilding software package supporting Conceptual Ship Design & Arrangement, and Structural Design & Analysis.

Upon receiving his Master of Science degree in Ocean Engineering in May of 1998, he will continue with Northrop Grumman Ship Systems in his current capacity in Washington D.C. Currently, Tim is the lead systems engineer for the DD(X) Systems Test Engineering (STE) team and provides systems engineering support on various developmental programs.