A Decision Making Framework for Cruise Ship Design

by

George P. Katsoufis

B.S. Architectural Engineering
and
B.S. Civil Engineering
University of Miami (FL), 2000

SUBMITTED TO THE DEPARTMENT OF MECHANICAL ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE IN OCEAN SYSTEMS MANAGEMENT

AND

MASTER OF SCIENCE IN NAVAL ARCHITECTURE AND MARINE ENGINEERING

AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
JUNE 2006

Signature of Author: . ...
Department of Mechanical Engineering
April 7, 2006

Certified by: ....
Dr. Clifford A. Whitcomb, Associate Professor of Systems Engineering
Naval Post Graduate School
Monterey, California
Thesis Supervisor

Certified by: ....
Dr. Henry S. Marcus, Professor of Marine Systems
Thesis Supervisor

Accepted by: ....
Professor Lallit Anand
Chairman, Committee for Graduate Students

A Decision Making Framework on Cruise Ship Design

by

George P. Katsoufis

Submitted to the Department of Mechanical Engineering on April 7, 2006 in Partial Fulfillment of the Requirements for the Degree of Master of Science in Ocean Systems Management and Naval Architecture and Marine Engineering

ABSTRACT

This thesis develops a new decision making framework for initial cruise ship design. Through review of effectiveness analysis and multi-criteria decision making, a uniform philosophy is created to articulate a framework that would enable a designer to more accurately assess what design alternatives are more important than others and how their changes affect the overall system being designed. Through a brief historical account, top-level Measures of Merit are developed and used with the framework and then applied to a requirements and effectiveness case study on initial concept development of a cruise ship. This is performed using Response Surface Methods to enable the user to visualize the design space as well as interact with it; the results and methods to visualize the design space are discussed. Finally, a Unified Tradeoff Environment is discussed, a framework that pools the aforementioned requirements and effectiveness analysis with design and technology forecasting to enable the user to make better informed requirements derivation and design selection.

Thesis Supervisor: Dr. Clifford A. Whitcomb
Title: Associate Professor of Systems Engineering

Thesis Supervisor: Dr. Henry S. Marcus
Title: Professor of Marine Systems

Page Intentionally Left Blank

ACKNOWLEDGEMENTS

This thesis would not have been possible were it not for the support and assistance of Dr. Cliff Whitcomb and Dr. Hank Marcus. Dr. Whitcomb graciously took me under his wing when no one else was willing, introduced me to this area of research, and through his academic advice over the last four years to the completion of my thesis. Dr. Hank Marcus introduced me to a world only MIT has to offer; one that I believe will resonate in my life for many years after I leave this institution. His efforts and guidance were instrumental in my graduate studies, the completion of this work, and the direction I have chosen in my life.

I owe special thanks to John Hootman, my friend and classmate, who was kind enough to allow me the use of his graduate work to lay down the foundation for my research for this thesis. Additional thanks also go out to my friends for their support, with special mention of Dr. Rick Rikoski (Jr.) who introduced me to his family when I had to return to Boston to complete my studies and had no where to stay. They were gracious enough to let me stay in their home, indefinitely, until this task was done.

Final Thanks go to my parents, whose love, understanding, and never-ending support saw me through this.

Page Intentionally Left Blank

TABLE OF CONTENTS

TABLE OF FIGURES

TABLE OF TABLES

TABLE OF EQUATIONS

NOMENCLATURE

Aerospace Systems Design Laboratory	ASDL
Analysis of Alternatives	AoA
Analytical Hierarchy Process	AHP
Cumulative Prospect Theory	CPT
Design of Experiments	DOE
Dimensional Parameters	DPs
Figure of Merit	FOM
Freight Demurrage & Defense	FD&D
Hierarchical Weighted Sum	HWS
Hull & Machinery	H&M
Insured Value	IV
International Maritime Organization	IMO
International Safety Management Code	ISM
Measures of Effectiveness	MOEs
Measures of Force Effectiveness	MOFEs
Measures of Merit	MOM
Measures of Performance	MOPs
Measures of System Effectiveness	MOSEs
Mission Tasks	MTs
Multi-Attribute Utility	MAU
Multi-Criteria Decision Making	MCDM
Overall Measure of Effectiveness	OMOE
Protection & Indemnity	P&I
Rational Decision Making	RDM
Response Surface Methods	RSM
Safety Of Life At Sea	SOLAS
Trade Disruption	TDI
Unified Tradeoff Environment	UTE
War Risk	WR
Weighted Sum	WS

CHAPTER 1: INTRODUCTION

PURPOSE

Traditional cruise ship design can be characterized as a series of tradeoffs that are often made without thorough consideration as to their overall impact to the design as a system. With the exception of ship size or displacement, the most important parameters, such as initial or acquisition cost, profitability, operational cost, operational profile, and allocation of revenue generating space, are not included in the design decision making process. Listing these considerations are often not as difficult as measuring them. As Zink *et al* observes:

> … [Measuring these factors] are dependent on the subjective opinion of the customer/user, i.e. the requirements. These requirements are often ambiguous and typically change over time. *Therefore, understanding the simultaneous impact of requirements, product design variables, and emerging technologies during the concept formulation and development stages is critically important and until now, elusive.* [Zink *et al*, 2000]

To design a modern ship, designers must be familiar with subjects normally beyond their basic discipline. They must be able to determine what, if any, external factors are critical to the design as well as understand their interactions within the super system and the design environment. They must then develop a framework to evaluate this system and come up with a viable design which meets all these requirements. This paper will, therefore, present the following:

- To summarize the collection of literature on systems approaches to effectiveness analysis.
- To summarize the collection of literature on Multiple Criteria Decision Making (MCDM) models.
- To filter the theories presented into a framework based on a consistent philosophy
- To use this to address the existing limitations in requirements and effectiveness analyses of cruise ship design.
- To conduct such an analysis on a cruise ship design case study.

The investigation of the basis for a system-level design framework for cruise ships begins with a systems approach from the naval engineering field within naval architecture and marine engineering.

SYSTEMS APPROACH

It has only been during the last 30 years that naval engineers began looking beyond traditional aspects of naval architecture and marine engineering at how the sum a vessel's parts affected its overall design as a system. Prior to this, "ship level requirements, rather than the ship's contribution to the performance of the task force, drove the design process" [Rains, 1999]. The problem created with this tactic was that:

> Organizations focused on the optimization of their products often lost sight of the overall system. Each organization perceived that their part must be optimal, using their own disciplinary criteria, and failed to recognize that all parts of a system do not have to be optimal for the system to perform optimally. [INCOSE, 2000]

To tackle this problem, systems engineering was applied to naval engineering to create, "a process which transforms an operational need into a description of system parameters and integrates those parameters to optimize the overall system effectiveness" [Tibbitts *et al*, 1993] Naval engineers have been tasked to rethink design of not just ship systems but a, "supersystem … the system that is just big enough to include everything that must be taken into account in determining the optimal (most cost-effective) ship for the mission requirements" [Hockberger, 1996].

The metrics that are used to evaluate the supersystem are generally called measures of effectiveness and are "inherent in the *mission* and *external* to the ship." [Hockberger, 1996]

> The ship's effectiveness has to do with the *change* in the [operational] situation that results from its involvement in [its operation], which is a matter of *outcomes*, and Measures of Effectiveness can thus be seen as *outputs* of an [action]... [thus] it is the synergism between the new ship or system and [its environment] that is at issue, and it is the [operational] effectiveness and ... Measures of Effectiveness that must be used as the basis for assessing and comparing the performance of each alternative. [Hockberger, 1996]

In cruise ship design it is a common practice to start with a set of vaguely defined owner's needs and desires and through the 'design spiral' synthesis process come up with a ship point design that more-or-less meets a set of requirements derived from the owner's needs and desires. This approach does not always necessarily produce the most cost-effective or revenue effective vessel. Individual systems might meet the set of requirements but no analysis has been made as to whether the ship as a whole is "optimized" to the owner's desires – as opposed to a set of feasible designs created as the naval architect interpreted them. "Further, it is often the case that the design requirements are not fixed but rather evolve through the development life of the vehicle." [Hollingsworth and Mavris, 2000] A shift in design philosophies would lead to:

> an environment in which the effects of changes in the engineering parameters are analyzed to determine their impact on overall...effectiveness. This process is accomplished by linking a conceptual...design program with a [simulation] program. Thus the linkages between design variables and [operational performance] can be more thoroughly understood, and a vehicle with the greatest overall effectiveness can be created. [Frits *et al*, 2002]

This simultaneous development of effectiveness models and engineering analysis based upon well-defined metrics would provide naval architects with a method to optimize a system, provide decision makers with appropriate information to develop appropriate requirements, and provide a traceable method between the two so that when requirements change, design impacts can be easily modeled and understood by both owner's and designers. [Hootman, 2003]

OVERVIEW

This thesis will start with a review of the cruise industry, and then survey the existing literature which will serve as a background for the development of a framework for defining and developing systems metrics for use in effectiveness analysis. It will include a literature survey of multiple criteria decision making, taking into account mathematical and practical applications. The development of a methodology to perform requirements-based tradeoffs will then be addressed. Next, a case study in cruise ship design will use what has been developed to demonstrate how to develop appropriate systems measures, how to hierarchically aggregate them, how the process is applied, and, finally, the results will be presented, followed by a discussion of the conclusions and recommendations for future work.

CHAPTER 2: A BRIEF OVERVIEW OF THE CRUISE INDUSTRY

History is a profound illustrator of how things come to be and a very useful tool to begin to understand a business. The passenger ship industry is no exception. In addition to a historical reference, a financial breakdown and a glimpse into past and current marketing philosophies will be discussed. Once these have been examined, the reader should have a better understanding of the consequent design challenges passenger ship designers and their prospective owners encounter when contemplating future new-builds and conversions; design challenges that can be resolved through a variety of newer as well as older technologies and design philosophies.

A HISTORY

The first vessels that carried passengers were designed to carry cargo. Regularly scheduled transatlantic passenger service was initiated in 1818 but ships exclusively catering to passengers did not appear until the 1840s. Early ocean going vessels were obviously not designed for passenger transport, but rather for the cargo they could carry. In 1818 the Black Ball Line in New York became the first shipping company to offer regular service for passengers from the United Stated to England onboard its freight ships, marking the beginning of the cruise industry in the sense that passenger comfort was addressed [Boyd, 1999]. It was not until the 1830's that steamships were introduced and quickly dominated the transatlantic market of passenger and mail transport; the most recognized being Samuel Cunard's British and North American Royal Mail Steam Packet Company which would later be renamed to Cunard Line. Ships did not exclusively cater to passengers until the 1850's and for the following century the foundation of the cruise industry was shaped through novel practices to lure new patrons as well as new procedures, born out of tragedy, to insure their safety while at sea [Boyd, 1999].

Cruising saw many changes in those 100 years. In addition to new steel processes, the introduction of the screw, and fabrication technologies evolving out of an American civil and two world wars, new global organizations were created to confront deficiencies in standards of construction and safety onboard ships. Born out of the now infamous tragedies of the Titanic and Lusitania disasters, organizations, such as the International Maritime Organization (IMO) and the International Convention for the Safety of Life at Sea (SOLAS) set the technical and procedural precedents that current shipping lines follow. Even pricing discrimination (in the form of classification of passenger fare) saw its inception and its eventual humane evolvement.

One constant in these past 150 years has been a transportation company's financial incentive to have those that could afford it, pay more for their fare. Passenger transport over land and sea was often brutal to those that could barely afford it. From the "steerage" class available in the 1880's where, "passengers were responsible for providing their own food and slept in whatever space was available in the hold," [Boyd, 1999] cruising's overall comfort gradually progressed due to the global enforcements of minimum safety standards onboard vessels. By the early 20th century, cruising was well on its way to becoming a staple for the affluent with ships that were increasingly being designed for comfort at sea rather than speed, resulting in larger, more stable liners. With the launch of Pan Am's trans-Atlantic flights in the late 1950's, however, came the decline of steamship transportation, paving the way for the modern-day cruise industry.

With the decrease in the role of ships for transporting people to a particular destination, companies began to create a new image for cruising; they began to emphasize the voyage itself. Instead of just going from one port to the other, multiple destinations were offered in a given period. Initially marketed for affluent customers, the idea of cruising as a mass-marketed vacation was not popularized until the late '70s by the television series, "The Love Boat." [Boyd, 1999] This heralded the gradual improvement of the quality of the cruise product and marked the beginning of a steady increase in annual passengers limited only by ship capacity, the range of its destinations from home port, and the state of the global economy. In the last thirty years, cruise ships have evolved from 40,000 ton vessels to new-builds entering the market in excess of 160,000 Gross Registered Tons (GRT). In addition to size, cruise lines also increased their numbers by adding to their respective fleets, causing many to believe that the eventual supply will exceed demand. Cruise lines, however, saw things differently.

IF YOU BUILD IT, WILL THEY COME?

They saw the U.S. as part of a largely untapped market where only 5% of Americans had ever cruised in the early '80s and, compared to other leisure markets, the potential for growth was there. Skeptics and proponents turned out to be both correct. As capacity grew so did demand, but not always at the same rate. Cruise lines addressed the problem of overcapacity with aggressive pricing. This destructive pricing led to the eventual buy-outs, bankruptcies, and mergers of underfinanced companies that had entered the industry in the early '80s by purchasing older ships. This continued throughout the '90s until 1997 where due to a strong dollar, a robust economy, warm weather, lack of shipboard incidents, and in increased interest in cruising, the industry was catapulted into another growth spurt that has continued in-spite of September 11th, albeit not as vigorously. The industry is so robust that even while the rest of the world economy was reeling in the aftermath, cruise lines maintained their occupancy levels by applying the same methods they had used the last twenty years while continuing to place orders for newer and larger vessels for the next five years. The key thinking in all of this is in understanding the marketing and money-making dynamics that differentiate the cruise industry from the rest of travel market.

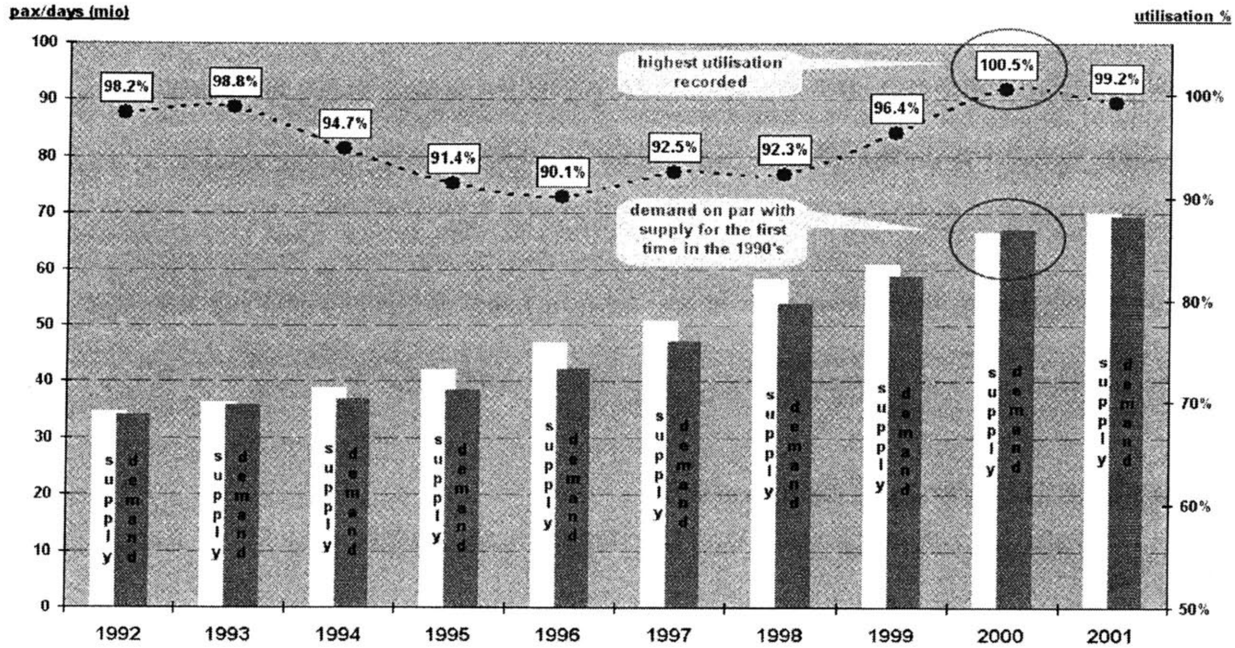


Figure 1: Historical Demand & Supply in Lower Berths and Utilization as a Percentage [DVB, 2004]

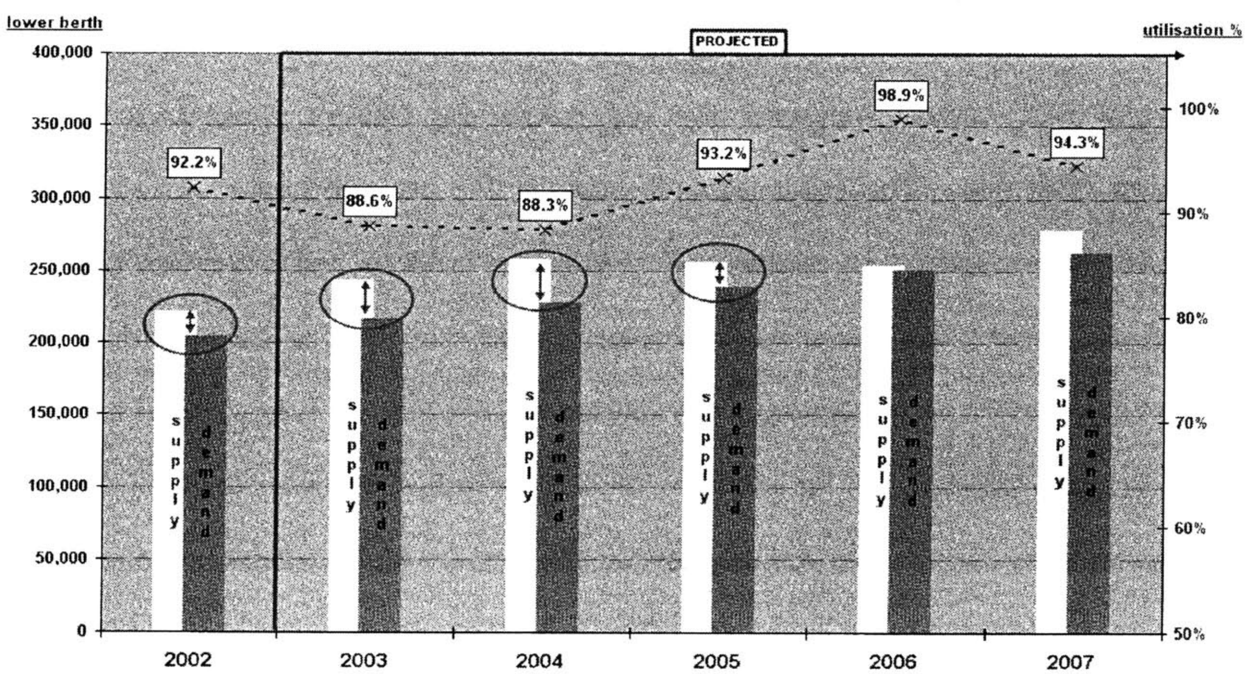


Figure 2: Projected Demand & Supply in Lower Berths (LB) and Utilization as a Percentage [DVB, 2004]

Carnival's CFO, Jerry Cahill, explains certain key points of these differentiations that have spurred this increase in capacity: [Citigroup, 2003]

> "Cruise companies collect all of the money for the cruise tickets at least 30 days before sailing. For Carnival, that is $700-$800 million in cash that the company is receiving (plus interest), rather than having to pay to borrow. Ships, unlike hotels, move, and thus this ... property can be sent to places to better match supply and demand. In addition, once the guest boards, the cruise ship holds that guest "captive" for the majority of the cruise. Thus, the cruise ship can capture every extra dollar spent at its bars, casinos, retail space, spas, and auctions. Hotels, on the other hand, cannot do nearly as much in this regard. This onboard spending is especially important in light of the growing contribution that onboard revenues make to the cruise ships, partially because price competition has kept cruise ticket prices down, but also because cruise companies have been focusing on this more, including more spas and retail space, and designing better layouts in order to entice passengers to stop into a store on the way back from dinner or the casino."

With the continual additions and the ability to reposition themselves to where their market has a need, cruise lines are becoming increasingly aggregated with respect to their target markets. From the days of segregating by class, price discrimination of the old days evolved to the Brand Positioning. Depending on which company you ask, brands can be broken down from three to five categories. The simplest breakdown contains four categories that starts with a Budget category (Day / Casino Cruises), continues to Contemporary (Carnival, Royal Caribbean, Norwegian, etc.), then to Premium (Celebrity, Holland America) and ends with a Luxury rating (Cunard, Crystal). A fifth rating, Ultra Luxury is only a recent entry and exceedingly small part of the overall market; approximately one percent of the leisure population, aged over 45 years and a gross income of $200,000. [DVB, 2004] All these brand ratings allow ships to be used to their fuller potential by providing destinations, amenities, cuisines, and services that match their target clientele so that onboard revenue can be maximized while providing incentive for those that can afford it to purchase the "superior" brand.

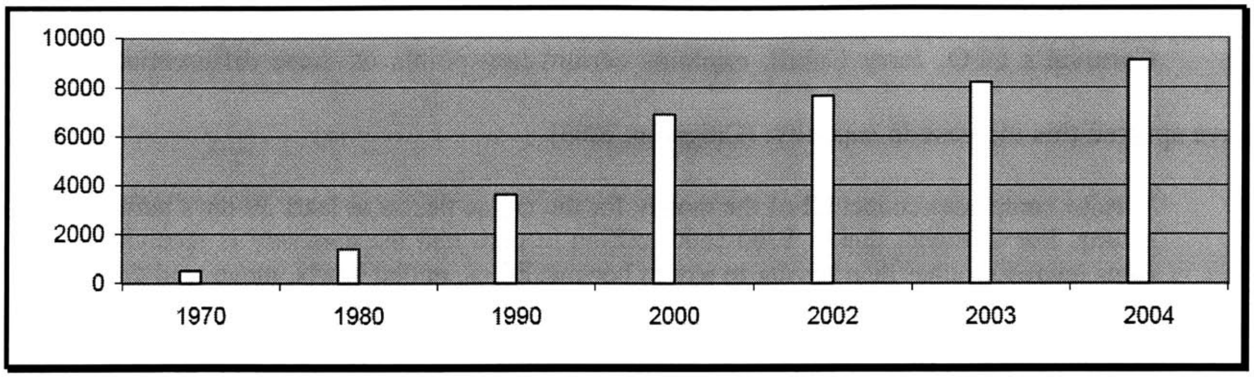


Figure 3: Annual Passenger Growth in North American Cruise Market [CLIA, 2005b]

IT'S ALL DOLLARS AND SENSE

Prior to 9/11, the cruise industry was on its way to a record year. Between the terrorist attacks, the ensuing lackluster economy, and the bad publicity of the Norwalk virus that struck in the later half of 2002, demand has waned while supply has continued to increase. [BREA, 2004] Although this has reduced revenue per passenger per day, cruise lines have remained profitable because of size, benefits from the economies of scale of their fleets and from technical/operational benefits from current mergers. One recent example is the merger battle that Carnival and Royal Caribbean had over Princess Cruise Lines. They were not only fighting for Princess' fleet but also its global reservations system which is so sophisticated that it acts more like a revenue management program than a reservation system. Client's purchase histories are monitored from time of booking, saved and then compiled to better utilize their ship's revenue potential. This is only a small example of what companies are doing to counteract the negative effect of price competition. A brief analysis of a typical income statement is needed, however, to better explain a cruise line's potential for profitability.

Income statements vary from company to company but the following example will help explain some of the differences between net and gross revenues as well as some of the generalized expenses associated with shipping. Table 1 breaks down a sample statement: [Citigroup, 2003]

Table 1: Typical Income Statement of a Cruise Line [Citigroup, 2003]

% Total Revenues	Internal Income Statement	External Income Statement
	Revenues	
70%	Ticket	
20%	Onboard	
10%	Airfare	
100%	Total Gross Revenues	Total Gross Revenues
20-30%	Less: Cost of Sales	
7-11%	Travel Agent Commissions	
10%	Airfares	
NA	Onboard (e.g. alcohol)	
70-80%	Equals: Net Revenues	
30-35%	Less: Operating Expenses	Less: Cost of Sales & Op. Expenses
NA	Payroll	
NA	Food	
2-5%	Fuel	
NA	Repairs & Maintenance	
NA	Insurance & Classification	
NA	Other	
12-15%	Less: SG&A Expenses	Less: SG&A Expenses
4-5%	Advertising	
NA	Payroll & Related	
NA	Other	
7-9%	Less: Depreciation	Less: Depreciation
19-21%	Equals: Operating Income	Equals: Operating Income

For a typical cruise line, 80% of costs are fixed while 20% are variable. A successful cruise line must find ways to reduce operational costs while increasing available revenue streams. In the example an internal and external income statement is shown, the difference being that the external income statement includes only information disclosed to the investing public while the internal is used by management. Carnival Cruise Lines believes that best way to measure profitability is to calculate operating income based on per Available Berth Day (ABD).

This way, an entire ship's or fleet's profitability can be measured and compared to with the rest of the industry.

A quick glance at the sample statement shows three main sources of revenues: cruise tickets (70%), airfares (10%), and onboard spending (20%). Of the three revenue streams, cruise fares have been the most volatile since an empty berth is much worse than a heavily discounted one. The balance between discounting and obtaining the highest price for a cabin remains, to this date, a delicate undertaking and one that merits further discussion in this section. Thirty years ago a typical percentage for onboard revenue (compared to total income) was approximately 10%-15%. The current average has increased to roughly 20% as more amenities and opportunities to sell have been created with newer and bigger vessels. Airfares have also changed from what they once were. From a high of 60% of cruisers booking air through the cruise line 10 to 15 years ago, air bookings have declined to 15%-20% of bookings. [Citigroup, 2003] This reduction has been partially attributed to an increasing use of frequent flier miles, competition from budget airlines, and a current trend of passenger's reluctance to fly after the terrorist attacks. Today, air fare is generally a non-profit revenue source since most fares are sold at cost and are offered solely as a convenience to the consumer as a "one-stop" point of sale, leaving the cruise fares and onboard revenue as the only room to grow on.

Breakdowns of an expense report are closely guarded in this industry so there are not as many averages one can go by. As with all enterprises, costs can be split into operating and SG&A (Selling, General, & Administrative) expenses. For this thesis, operating costs will be addressed. Like many ships, operating costs are largely fixed, with the exception of food and fuel being the two variables in the general equation.

The largest operating cost for cruise lines is labor. [Citigroup, 2003] A typical employee/guest ratio on a ship can vary from 1:2.5 on budget ships to as low a 1:1 on luxury ships [Levander, 2005]. Food is the second largest cost onboard a ship and is one reason why cruise lines put a heavy emphasis on ensuring their ships sail full year round. Cost is high for food because of many specialty dining options available onboard. As opposed to the single dining room arrangement that was available only a couple of decades ago, consumers can choose to dine al fresco, in specialty restaurants, or even order room service – all free of charge.

Next is Classification and Insurance. It is a general term that is used to talk about the many policies cruise lines need to have to safeguard themselves against this unusual market. Before being able to purchase any insurance policies, all shipping companies need to be classified. Classification enables insurance companies to know that the ship that they will insure meets a certain standard of safety. This standard is a fluid one that continually changes as events like 9/11 or the Exxon Valdez happen and as new procedures, such as the International Safety Management Code (ISM), are implemented globally so does the standard. Once a ship receives its classification, its owner can purchase many different policies, the most popular being Protection & Indemnity (P&I), Hull & Machinery (H&M), Trade Disruption (TDI), Freight Demurrage & Defense (FD&D), War Risk (WR), and Insured Value (IV). The P&I is a collection of ship owners, much like a co-op, that all pay a set amount per year. The P&I cover all damages related to a crew, passengers, and salvage expenses that are not covered under H&M. These primarily include loss of life, personal effects, medical expenses, repatriations, unemployment compensation, and the liabilities incurred from an accident (loss of contract, revenue, etc.). Additionally, any port and deviation costs incurred from an accident are also covered. The P&I reimburse up to a certain amount based on the club's contract with its members and are dependent on what the claim covers (loss of life vs. repair to ship). Depending on the number of claims due to accidents, members either get a refund or a dividend at the end of their contract year. Understandably, if a member or group of members have a habitually poor record and continue to be members of a particular P&I, their fees increase dramatically. The P&I allows ship owners to mitigate expenses due to accidents by distributing the risk; allowing its members to stay active in the industry rather than going immediately bankrupt over a potentially costly accident. H&M covers exactly what its name says it does while TDI covers losses of expected profit from the interruption of a vessels business due to any casualty. FD&D covers costs and expenses from claims arising from accidents and contractual liability. Each year it becomes a little more difficult for older ships to meet the operational and maintenance requirements mandated by these insurance entities so it is an operational cost that gradually gets more expensive.

A final note on costs is on fuel. Fuel costs can vary from year to year but cost to a particular cruise line also vary. Companies have a choice of hedging fuel costs on the belief that it will be cheaper in the long run as well as flattening out its inherent volatility while others, mainly Carnival and its subsidiaries, choose not too. Their books state that their fuel expense ranges from 2%-4% of revenues even though in the first quarter of 2003 fuel hit the 6% mark. [Citigroup, 2003]

Being Pulled in Multiple Directions

All these percentages between costs are what cruise lines today are continually attempting to manipulate to not only improve their profitability but to also acquire a bigger market share. They do this by improving their economies of scale by adding to their fleet and improving the cost per passenger to operate a typical vessel. In addition to their profit making endeavors cruise lines are also subject to safety and environmental standards placed by governments and various maritime governing bodies. Figure 4 illustrates only the higher level organizations that go into managing a ship.

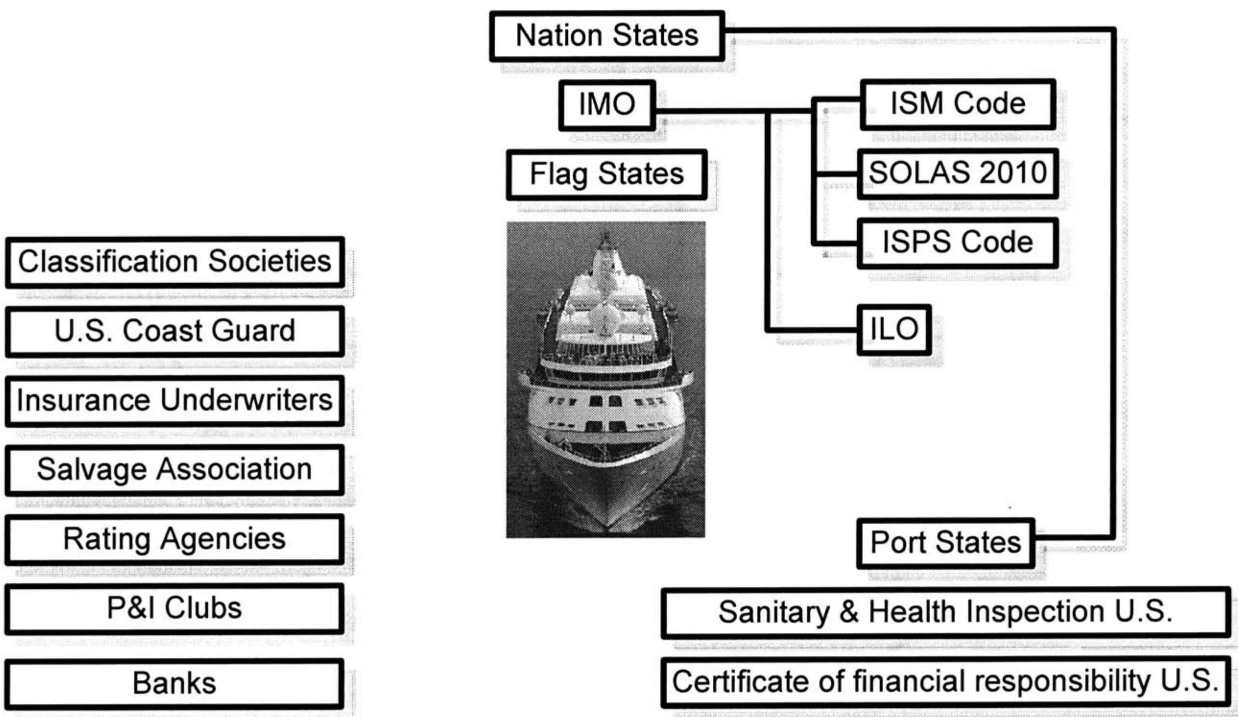


Figure 4: Various organizations involved in the management and/or owning of a cruise ship [DVB, 2004]

These safety measures and environmental restrictions encompass but are not limited to waste minimization, reuse, recycling, engine emissions, cataloguing all discharge from the vessel, and training requirements. Moreover, the industry is becoming subject to continually stricter enforcements of all these regulations, the newest being the International Ship & Port

Facility Security (ISPS) code. Following the events of 9/11, the ISPS code was developed to, "implement a ship security strategy commensurate with identified threats to security." [DVB, 2004] It brings together all security measures from every governing body to form a uniform response on all levels; whether at port, sea, dry-dock, or loading facility. Figure 5 illustrates just how many organizations are involved into creating this unified security plan. The ISPS code is still in its infancy and is bound to have a significant impact on the daily operations and costs of a cruise ship.

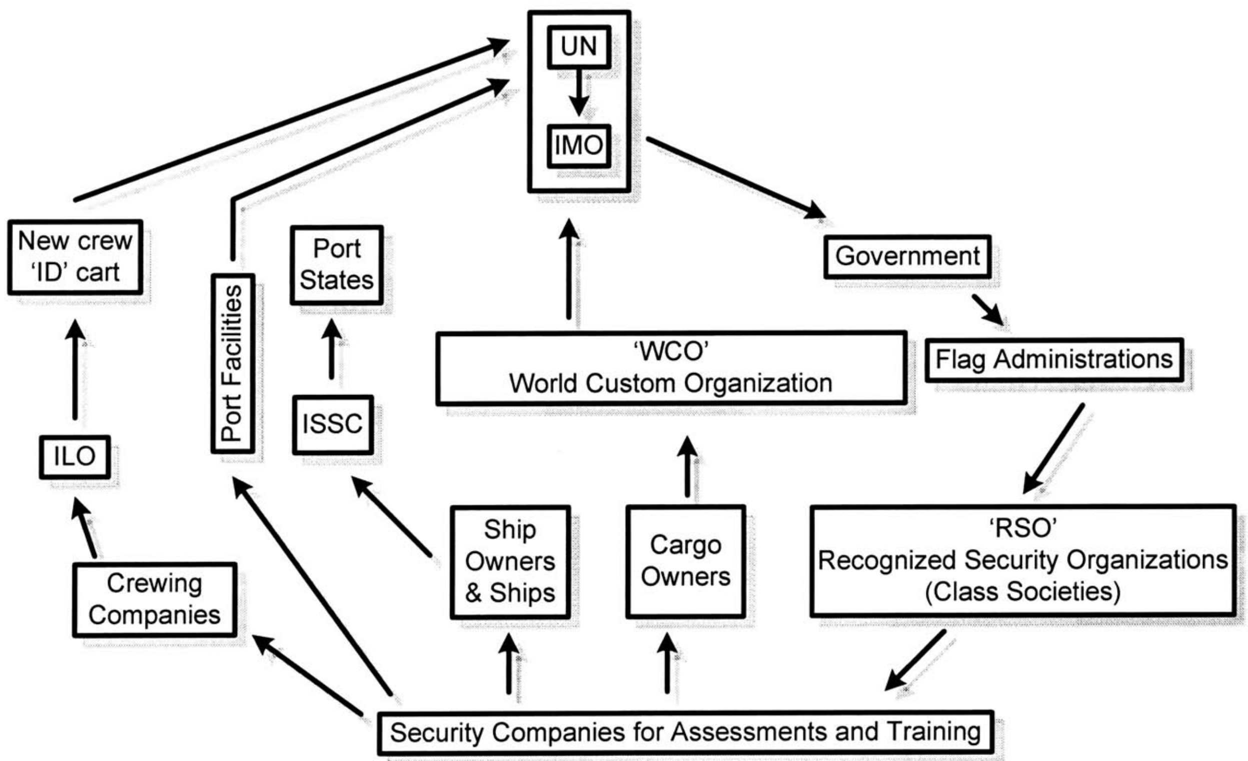


Figure 5: Organizations involved in the ISPS code [DVB, 2004]

Like any travel and leisure group, bad publicity is avoided at all cost by ensuring as best as possible that material and environmental accidents occur at a minimum. For this and for preventative liability, most cruise lines incorporate procedures and guidelines that exceed the requirements mandated or even simply recommended by governing bodies. Between these standards, the attempts of profitability by economies of scale, and physical requirements limited by waterways and ports of call, ship designers are constantly looking at the latest technology to provide prospective operators advantages over their competitors and older members of their fleet.

These design augmentations cover, but are not limited to, newer fabrication methods (to reduce cost or time of construction), propulsion alternatives (to improve speed, efficiency, maneuverability, redundancy, space limitations, etc.), and amenity alternatives (dining, shopping, exercise, individual balconies, etc.), and they don't come cheaply. On average a 2,000 berth ship can cost approximately $390 million while a 3000 berth ship goes for $500 to $650 million. [CLIA, 2005a] This correlates to an approximate 10% - 15% construction discount on a per berth basis. In addition to the discount, the operating costs of a larger ship are reduced on a per berth basis due to economies of scale. The trade-off for this increased size is a decreased mobility and limited access to ports of call, making buying decisions for cruise lines a constant tradeoff analysis of ship placement (for market penetrations), route planning, target markets, and amenity allocations. To compound the issue even further, a typical timeline for a new build is three years from start of design to delivery while the typical lifespan of a vessel is 40 to 50 years; an issue that most financial analysts bring up when all they see is continual oversupply of ships in the North American market. [Citigroup, 2003]

Larger cruise lines deal with this issue by "repurposing" their older ships to less competitive markets or they outright sell the older vessels to smaller operators who would eventually sell them for scrap metal. A few recent developments have affected this business plan as well. SOLAS passed two regulations, "that by 2005 all cruise ships be fitted with a sprinkler system throughout the vessel and by 2010 … that no part of the vessel be combustible." [DMV, 2004] Retrofitting older vessels to meet these requirements would not make any financial sense; the ship owner would not gain a newer, more marketable vessel but rather be throwing away money. Compounding the issue even further is the recent trend of scrapyards mandating the removal of asbestos and other hazardous material prior to the dismantling of the vessel, an issue that has not been mandated by the governing maritime bodies but that has been brought forth through environmentalist efforts.

Taking all these guidelines, regulations, and restrictions into consideration, a prospective ship owner is left with a quagmire of decisions that need to be made to create or maintain a successful cruise line. Marketing issues such as a ship's target demographics, areas of deployment, and brand quality all need to be addressed either through market research or awareness of the competition. Being abreast of all existing propulsion, powering, sewage treatment, water treatment, and safety technologies must also be in the purview of the owner. To add more to the mix, the owner must also bear in mind the true operational life of the vessel, taking into consideration of its marketable shelf life, the possibility of a cramped market place or poor economy, and any environmental and safety concerns that may appear in the future.

How to bring all these factors together and to make informed decisions on them is where the naval architect comes in. By developing a framework to tackle all these issues, the designer can provide the owner with a logical step-by-step breakdown of every decision in such a way that each effect can be quantified, thus affording the owner the resource of being able to quickly compare alternatives that would have not been readily available to him / her in the past. Once the process is explained in the ensuing chapter, the case study will demonstrate only the simplest of examples to show how such a myriad of factors can be broken down into quantifiable parts so that the owner can make an informed decision.

Chapter 3: Cruise Ship Systems Approach Investigation and Development

Introduction

A naval architect, as any designer of complex systems, today is faced by a multiplicity of requirements, from owner's needs and desires, engineering feasibility, imperatives of technological advancement, environmental considerations, all the way to prescribed regulations. Maritime organization requirements dictate minimum levels of redundancy in propulsion, maneuvering, electrical, and mechanical systems while mandating appropriate fire retardant materials, fire suppression equipment, general life saving equipment, and standards for damage prevention/deterrents for all classes of vessels. Additionally, markets change and the vessels that service them adapt to meet their needs. Throughout a lifecycle of a ship, its operational needs will fluctuate to meet market demands. These needs may be anticipated, to an extent, but are never able to be completely addressed in the earliest stages of design.

Introduced in 1959 by J.H. Evans ("Basic Design Concepts," *ASNE Journal*, November 1959), the design spiral is still used to characterize the ship design process. Since its inception there are many variations, but the concept remains the same, Figure 6 illustrates the cruise ship version of the typical design spiral process. Traditionally, total ship considerations such as life-cycle cost and revenue potential are often looked at in the third or fourth iteration of the design spiral process, the outcome of which is a single point design whose characteristics are not well defined in relation to the needs of all the stakeholders involved. What is needed is a comprehensive trade-off framework to consider a large and complex design efficiently so that determination of what parameters have greater impact on final design requirements than others can be accomplished in such a way as to focus the feasible design region, while simultaneously expanding the decision maker's horizons, as early on in the design process as possible.

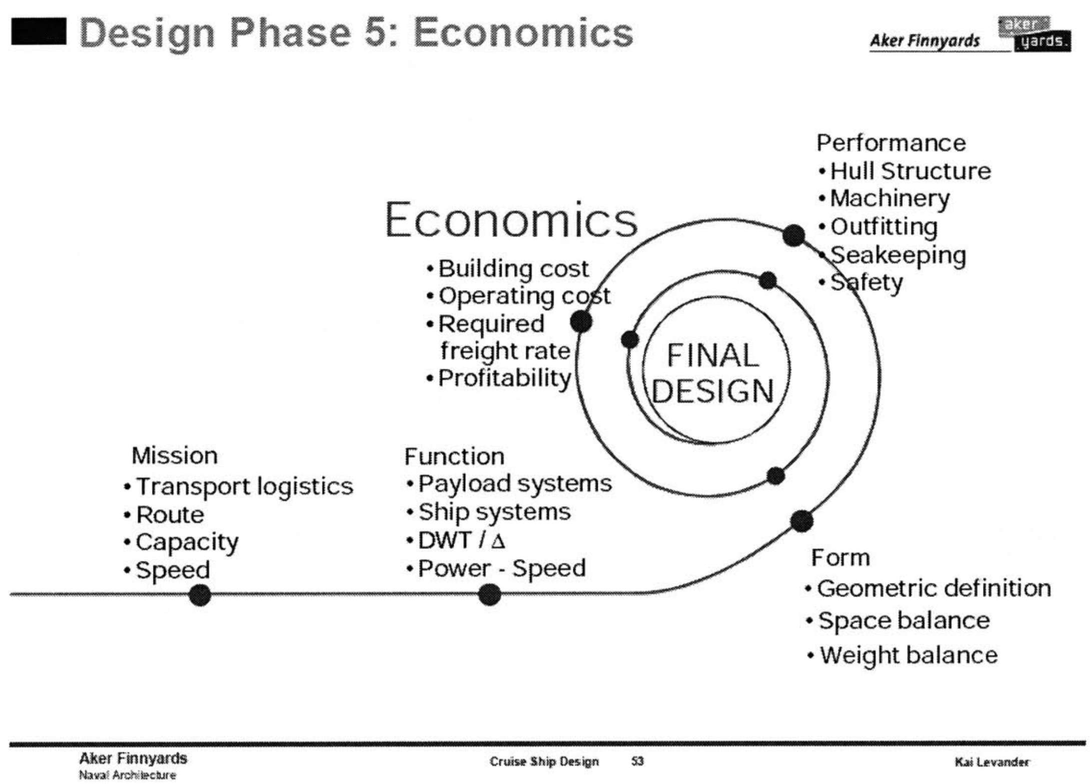


Figure 6: Typical Design Spiral [Levander, 2005]

Systems thinking and engineering methods have been used to address these perspectives in various forms over the past 30-40 years. Successes at taking a systems approach resulted in some major program successes, such as the development of the nuclear submarine, Polaris missile, and AEGIS weapon systems. With respect to the incorporation of these successes to the application of systems approaches to ship design in general, in the early 1980's the U.S. Navy started to act on what was important, an understanding that when considering a "collective whole of how a vessel was assembled: optimized parts do not necessarily create an optimized whole." [Hootman, 2003] Understandably, a cruise ship is not a naval ship; their similarities lie in their complexities of design and customizability that most other ship types do not necessarily need (Figure 7).

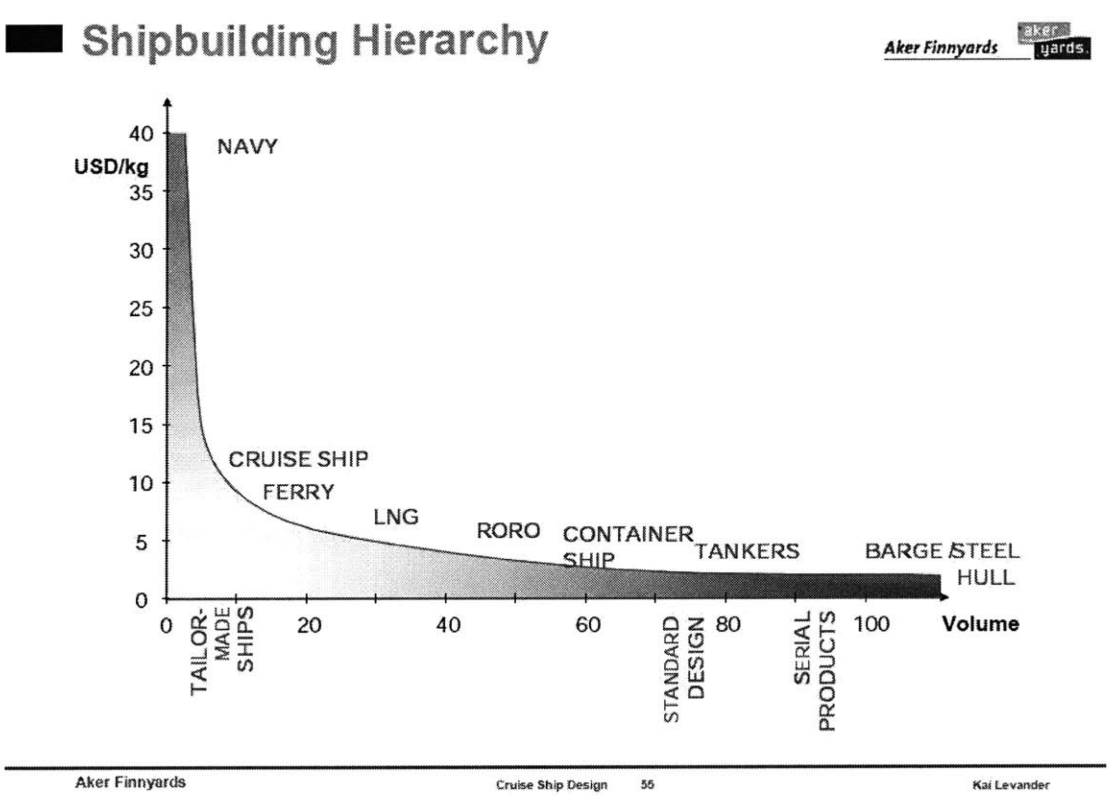


Figure 7: Shipbuilding Cost by Ship Type [Levander, 2005

Although commercial ship design does not have the same missions as naval ships do, the same philosophies can be applied to address their design issues in a more comprehensive fashion. The main deterrent to transferring this to commercial ship design is in confronting the old adage of, "if it ain't broke, don't fix it." In many naval circles one would be hard pressed to find the need to re-analyze a ship's parameters from any perspective other than the original designer's interpretation of what was deemed best. However, systems engineering is useful, and that designers "could benefit from the use of analysis to *understand* what may end up driving the [design requirements] even within the vast uncertainties" of future markets and evolving technology. [Builder, 1989] It is with this understanding that many solutions can be discarded without having to analyze them first. Cruise ship designers have only recently began to address these issues; a case in point is in the development of the Queen Mary 2:

> The genesis...was unconventional. Traditionally, when a naval architect is asked to design a newbuilding for an owner, he responds with three essential questions: How many passengers? How fast? How luxurious? But this was no conventional assignment; before providing capacity, speed, or lavishness, he needed informed guidance. Hard data would only emerge after some arduous new research. [The naval architect] was instructed to embark on an extensive study as to what form a viable and economically sound twenty-first-century ocean liner should take. ...formal research began in May 1998. [And would culminate in]...an exhaustive 2-year study. [Maxtone-Graham, 2004]

Although systems engineering can be generically defined (INCOSE Systems Engineering Handbook, INCOSE-TP-2003-016-02, Version 2a, 1 June 2004) most implementations are more domain specific. The development of cruise ships is better explained from a perspective of systems engineering with respect to product placement in the naval architecture domain. This thesis will primarily use literature based on Navy and Air Force methodologies and then will combine the most salient features with key aspects from the product placement and naval architecture domains to develop an approach for commercial cruise ship design application. The basic aspects of technical measurement, multiple criteria decision making, and experimental design are the focus of the adaptation of the developed approach.

Systems Engineering For Product Development

Systems Engineering is based on, "iterative, top-down, hierarchical decomposition of systems requirements, supported by ... studies that record the basis for significant decisions and the options considered." [DRM, 2006] It begins by breaking down the system level requirements and continues with major subsystems, their respective subsystems, and so forth. At each level of decomposition, further "analysis, allocation, and synthesis" [DRM, 2006] is performed so that, with the assistance of other engineering disciplines, a baseline of system design is created. The end result being the allocation of systems requirements and their measure of effectiveness with respect to alternative designs; integrated within all the design disciplines and ensuring that the, "system developed meets all requirements defined in the system specification and for providing the analysis which assures that all requirements will be met." [DRM, 2006] DRM Associates, a consulting firm for product development, breaks down systems engineering in the following manner [DRM, 2006]:

> During system...requirements analysis, systems engineering analyzes and reviews the impact of operational characteristics, environmental factors, and minimum acceptable functional requirements, and develops measures suitable for ranking alternative designs in a consistent and objective manner. ...
>
> During functional analysis, systems engineering uses the input of performance requirements developed during mission [or] operational analysis to progressively identify and analyze system functions and subfunctions in order to identify alternatives to meet system requirements. It is performed in conjunction with Allocation and Synthesis activities. Systems engineering considers all specified modes of operation and support. Systems engineering then establishes performance requirements for each function and sub-function identified. When time is critical to performance of a function, systems engineering also performs a timeline analysis.
>
> During the allocation process, systems engineering allocates performance and design requirements to each system function and sub-function. These derived requirements are stated in sufficient detail to permit allocation to hardware, software, procedural data, or personnel. Systems engineering identifies any special personnel skills or peculiar design requirements. Allocation activities are performed in conjunction with Functional Analysis and Synthesis activities. Traceability of the allocated system requirements should be maintained.
>
> During synthesis, systems engineering together with representatives of hardware, software, and other appropriate engineering specialties develops a system architecture design that is sufficient to specify the performance and design requirements which are allocated in the detailed design. Design of the system architecture occurs simultaneously with the allocation of requirements and analysis of system functions. The design is documented with block and flow diagrams. ...
>
> During final configuration item or subsystem requirements definition, systems engineering uses the specifications as a mechanism to transfer information from the systems requirements analysis, system architecture design, and system design tasks. Joint sign-off's of specifications by the specification author [the ship owner] and the detailed designer [the naval architect] pertaining to systems engineering and the design engineering disciplines assures understanding and buy-in. The specifications should assure that the requirements are testable and are stated at the appropriate specification level.
>
> Specialty engineering functions participate in the systems engineering process in all phases. They are responsible for reliability, maintainability, testability, producibility, parts control, human factors, safety, and design-to-cost. Specialty engineering shall be involved in the issuing of design criteria, and the monitoring of the progress of the design and performance analysis to assure the design requirements are met.
>
> During requirements verification, systems engineering and test engineering verify the completed system design to assure that all the requirements contained in the requirements specifications have been achieved. Tests conducted to verify requirements are performed using hardware configured to the final design.

The work of Crevely, Slutsky, and Antis in their book, Design for Six Sigma in Technology and Product Development, is a greater authority on the subject of product development. From a cruise line perspective, product development is what systems engineering is about. It is what occurs when a business starts with an idea usually conceived from an observed market opportunity, develops the idea, formulates a strategy to implement it, and delivers it to the marketplace. Analyzing the operational characteristics within the framework of an entire cruise fleet and breaking it down further to a ship's level analysis is what the naval architect attempts to do in order to enable the owner in making an informed decision as to what to build and, therefore, compete in the marketplace. The keystone of this process is in the development of appropriate metrics, using these developed criteria in such a way as to make the appropriate decisions, and applying them into a unified design space so that the owner can weigh all the possible alternatives before deciding on a solution that suits his / her needs.

TECHNICAL MEASUREMENT AND MEASURES OF MERIT

One of the foundations for implementing a systems engineering approach is to implement a structured method for technical measurement. Technical measurement "is the set of measurement activities used to provide the acquirer [and designer] insight into progress in the definition and development of the technical solution, ongoing assessment of the associated risks and issues, and the likelihood of meeting the critical objectives of the acquirer." [Technical Measurement, INCOSE, 2005]. The definition of a technical measurement approach for this thesis is based upon the US Department of Defense and defense industry implementations. To begin, the following definitions will serve as the baseline for this definition [Hootman, 2003]:

Effectiveness – "Effectiveness is the condition of achieving a requirement." [Hockberger, 1996]

System Effectiveness – The "ability of a system to accomplish a mission, and achieve a favorable [mission] outcome." [Brown, 1995]

Dimensional Parameters (DPs) – "the properties or characteristics of the physical entities whose values determine system behavior and the structure under consideration even when at rest." [Green and Johnson, 2002]

Measures of Performance (MOPs) – "are the measures that characterize physical or functional attributes relating to the system operation, measured or estimated under specified testing and/or operational environment conditions." [INCOSE, 2003]

Measures of Effectiveness (MOEs) – "the 'operational' measures of success that are closely related to the achievement of the mission or operational objective being evaluated, in the intended operational environment under a specified set of conditions; i.e. how well the solution achieves the intended purpose." [INCOSE, 2003]

Measures of Force Effectiveness (MOFEs) – are a "measure of how the system, and the force of which it is a part, performs its missions" [Green and Johnson, 2002]. MOFEs may also be referred to as Measures of System Effectiveness (MOSEs) or as an Overall Measure of Effectiveness (OMOE).

Measures of Merit (MOMs) – are a general term for all measures that characterize a system under analysis, they "subsume all measures that characterize a...system" [Green and Johnson, 2002]. In this study, MOMs will refer to MOPs, MOEs, and MOFEs.

As the definitions dictate, MOMs will refer to MOPs, MOEs, and MOFEs. In the process of developing MOMs it is important that the system being analyzed is first broken down in terms of internal and external attributes because "a change in the boundaries changes the parameter set and the resulting system behavior and performance." [Green, 2001a] To better illustrate this, think of MOMs in the sense of a set of subsystems, much in the way of concentric rings (Figure 8) illustrated below.

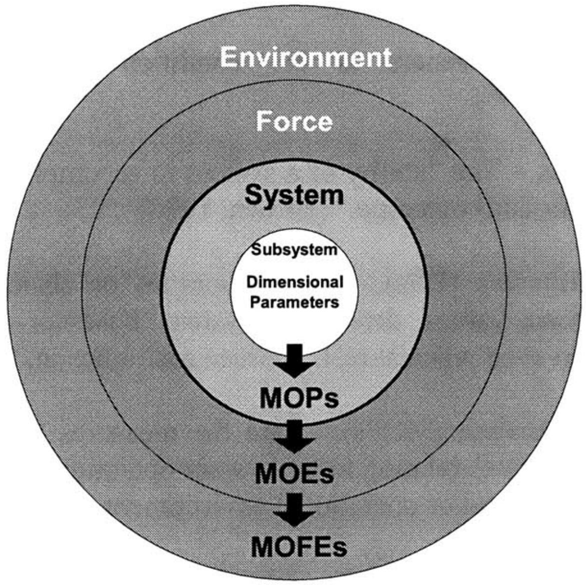


Figure 8: System Boundary Levels [Green and Johnson, 2002]

Green further clarifies that "MOEs and MOFEs are specified and measured external to the boundary" while DPs and MOPs are measured within the system (and its subsystems). Other authors similarly explain the same thinking but in a different terminology, where MOMs relate to "system performance as a function of its intended operational employment." [Leite and Mensh, 1999] This definition better explains commercial, non-mission oriented design applications, where parameters such as target acquisition effectiveness are not usually on a traditional ship owner's design requirements. Once the parameters have been defined, the consensus for developing a process model begins with four inputs: the mission, the expected threat, the environment, and potential system concepts. [Green, 2001b]

Missions of the commercial sense can relate to travel time per leg or revenue generation per leg and they should be defined in quantitative terms. [Rains, 1999] Furthermore, the literature advocates that they should be developed in parallel with system requirements because, "they help formulate [them] and it helps make the design process more efficient." [Hockberger, 1996] Leite and Mensh go on to provide a step-by-step process for developing such a model

(Figure 9) where, once it is developed, the outcomes are used as inputs to metrics for representing the previously defined MOMs. (Figure 10) [Leite and Mensh, 1999]

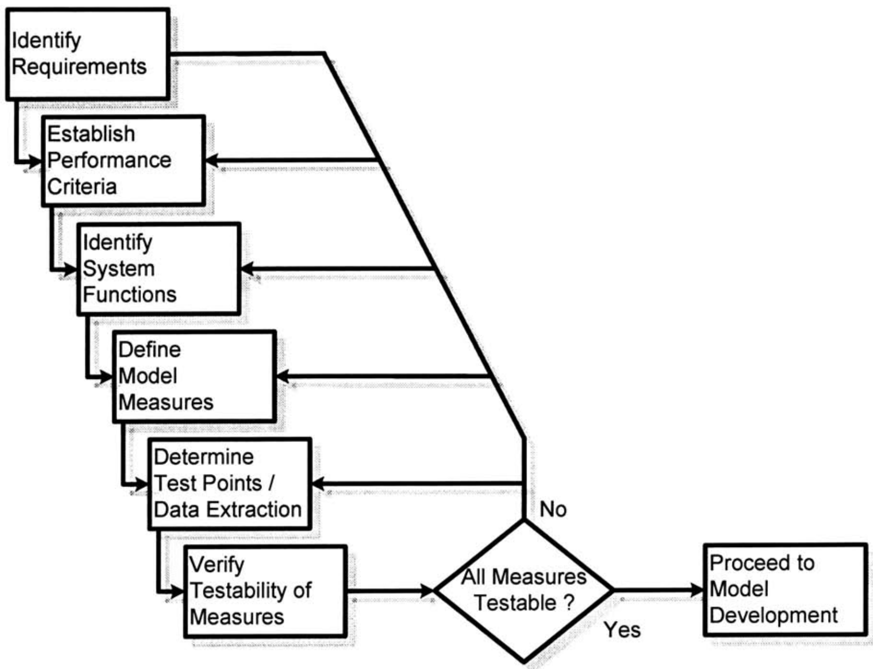


Figure 9: Model Development Process [Leite and Mensh, 1999]

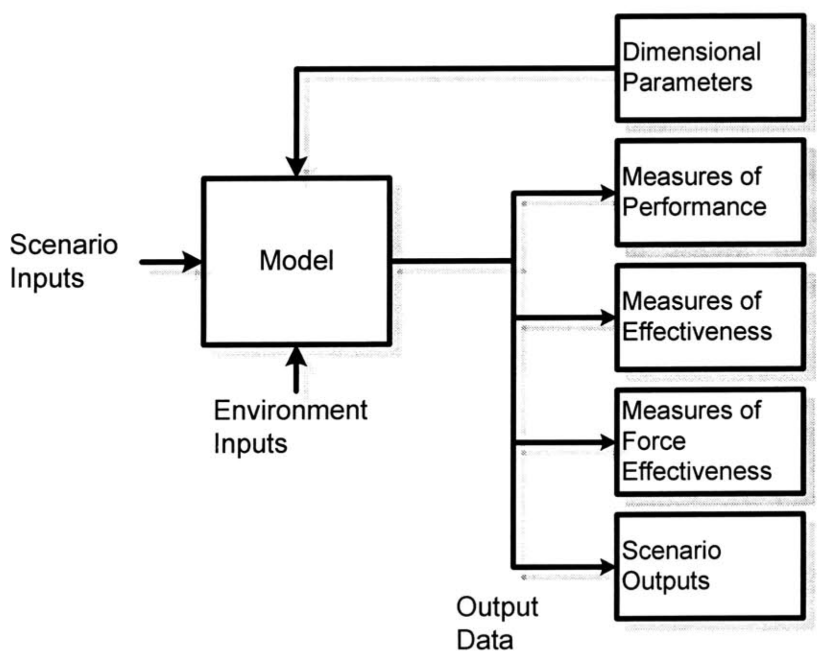


Figure 10: Relation of Models to MOMs [Leite and Mensh, 1999]

Green then continues by addressing what the literature calls the 'ilities'[1] [Hootman, 2003] and their relationship with developing a MOM hierarchy. Each author develops their process structure depending on what their subsequent impact is on the ship design. For a naval combatant as an example, one author bases the hierarchy off of a 'Cycle of Mission Accomplishment' composed of Availability, Reliability, Survivability, and Capability and relates [Brown, 1995]. However, the literature advises that the expounded measures "must be independent at the level of analysis under evaluation" [Green, 2001a]. The Air Force AoA adds that "MOEs should not be strongly correlated with one another (to avoid overemphasizing particular aspects of the alternatives)... [and that] MOEs must be independent of the nature of the alternatives, as all alternatives are evaluated using all MOEs." [OAS, 2000]

Green's solution to this approach is a balance "between those elements, both combat systems and ship systems, that are required for mission success [and that the] process model focuses on the mission goals rather than starting with a set of constraints that accept degradation in the performance of these goals as a process that must be paid." [Green, 2001b] Marud *et al* also provides a resolution through a four step process [Malerud *et al*, 2000], [Hootman, 2003]:

1. Define high-level properties through a qualitative, top-down approach.
2. Outline MOPs by first identifying DPs that characterize identified high-level properties.
3. Develop MOEs as metrics to judge system performance against user requirements.
4. MOFEs present a more unique challenge as they are often "more qualitative... [requiring] military and analyst judgment."

A good summary of characteristics of MOMs so far can be seen below on table X. Further into MOM development, the literature continues by stating that, "expressing MOPs, MOEs, and MOSEs as a probability allows us to determine if a parametric change is statistically

[1] The 'ilities' include system performance characteristics such as affordability, performability, standardability, producibility, riskability, reliability, and maintainability. [Keane, *et al*, 1996], [Shupp, 2003], [Hootman, 2003]

significant" [Green, 2001a] and that MOMs should be "efficient in the statistical sense (small variance/reasonable accuracy)" [Green and Johnson, 2002]. Green concludes that "if it can't be expressed as a probability it probably is not an effectiveness measure." [Green, 2001a] Further arguments can be read in Mason's citing of the work of Girard and Elele whose "definitions of MOEs are much more mathematically rigorous because they are expressed in probabilistic terms." [Hootman, 2003]

> In Girard's terms, an MOE is the probability of the successful accomplishment of a function, where all probabilities are conditional, and are derived from MOPS and lower level (or prior) MOEs, and where a function is a process relating in an outcome. Thus 'an MOE defined by an objective function at an upper level is a dependent variable, and is a mathematical function of the MOEs defined by objective functions at a lower level.' Ultimately, an 'audit trail' equation is generated, linking the conditional upper level MOE to measurable MOPs. Elele uses Baye's Rule to develop a similar probability based MOE definition. [Mason, 1995]

Table 2: Characteristics of MOMs [Green and Johnson, 2002]

Characteristics	Definitions
• Mission oriented	• Relates to force/system.
• Discriminatory	• Identifies real difference between alternatives.
• Measurable	• Can be computed or estimated.
• Quantitative	• Can be assigned numbers or ranked.
• Realistic	• Relates realistically to the C2 system and associated uncertainties.
• Objective	• Defined or derived, independent of subjective opinion (it is recognized that some measures cannot be objectively defined).
• Appropriate	• Relates to acceptable standards and analysis objectives.
• Sensitive	• Reflects changes in system variables.
• Inclusive	• Reflects those standards required by the analysis objectives.
• Independent	• Mutually exclusive with respect to other measures.
• Simple	• Easily understood by the user.

The final segment of MOM development is the issue of addressing cost. Although cost effectiveness is central to making tradeoffs and an integral part in the design process, the majority of literature recommends that cost should be excluded. A reasonable explanation can be found in the Air Force AoA guidebook which states that "because MTs are tasks, cost is never a MT or an MOE, and cost is never considered in the effectiveness analysis" [OAS, 2000] Furthering its belief for the need for MOM transparency it goes on to state:

> Ideally, MOEs should normally represent raw quantities like numbers of something or frequencies of occurrence. Attempts to disguise these quantities through a mathematical transformation (for example, through normalization), no matter how well meaning, reduce the information content and may be regarded as "tampering with the data." This same reasoning applies to the use of MOEs defined as ratios; a ratio essentially "hides" both quantities. [OAS, 2000]

While another source added that:

> Cost-effectiveness should not be represented as a ratio, giving values with meaningless signs or values (infinities when division by zero occurs). Rather, one plots points on a graph, with Delta-MOE on the vertical (y) axis and Delta-cost on the horizontal one (x), using the pairs of numbers for the different candidates. Now two options with the same effectiveness will be at equal altitudes, whatever their costs, and two with equal cost, whatever their MOEs, will lie above one another. The informational value one desires of a ratio is there without the confusion; and it is thus unnecessary to limit the scope of the analysis to constant cost or constant MOE. [Willard, 2002]

It goes against conventional thinking that cost should not be a consideration early on in the design process. Some literature even goes on to argue that MOEs must be defined as "numerical indicators which directly relate performance to cost" [Rains, 1999] in order to "temper results, making lower cost systems with good performance possibly the most effective for the money required." [Rains, 1994] It is not to say that cost effectiveness does not have its place, but rather it should be considered at the end of the entire design process where the prospective owner will have a few optimized solutions to his design requirements which he / she can then gauge with cost in mind. With this understanding and the fact that the majority of literature reviewed goes against using cost as a MOM, this paper will do the same in its case study by applying cost only as a final metric.

Additionally, when choosing MOMs, their long-range applicability should be considered since they are not necessarily constrained to the early stages of design. [Hootman, 2003] The logic is self-explanatory in that one would not design a ship with one specific task in mind but would put into consideration that a ship's original target market may change and would therefore take into account all of the possibilities of future use for that ship. Moreover, as the ship design gets more complex, the design process itself takes longer to complete, creating the need to factor in the design parameters that the ship meet its requirements prior to delivery and not at time of design. For more complex ships such as LNGs or passenger vessels, this may mean vital upcoming electronics or classification requirements must be forecasted early on in the development of MOMs. The Air Force AoA guidebook continues that, "if possible, MOEs should be chosen to provide suitable assessment criteria for use during later developmental and operational testing. This 'linking' of the [design process] to testing is valuable to the test community and the decision maker." [OAS, 2000]

Finally, it is should be noted that the literature acknowledges the fact the MOM development is not an exact science and that value judgments are inherent at some stage of the process. [Hootman, 2003] "A measure of effectiveness resembles a moral principle in that its validity cannot be established by reason alone...we must make a value judgment." [DARCOM, 1979] "MOMs are not just metrics from analytical model. They must also incorporate the preferences of the decision maker and customer." [Hootman, 2003] An excerpt from the Army's Handbook for Weapon Systems Analysis better illuminates:

> "In the dynamic compromise process (1) we make use of our limited understanding of the supersystem to obtain an approximate measure of the system's effectiveness, (2) adjust this measure so that it becomes possible to relate it to the system's elements, (3) we readjust the measure until it is satisfactory to the decision maker, and (4) we re-readjust it until the projected study does not exceed the time-and-effort deadline."
>
> "We are not quite finished. We must examine the resulting fourth-order approximation to see if it is close enough to the 'true' measure of effectiveness to make the study worthwhile. This can only be done by 'feel.' If we decide that the approximate measure is too far off, then, depending on the situation, we have five courses of action: (1) learn more about the supersystem, (2) learn more about the system itself, (3) talk the decision-maker into reversing his interpretation, (4) suggest an extension of the scope of the study, or (5) call the whole study off. However, in most cases, this last drastic step should not be necessary."

> "The point is that regardless of how you finally select a measure of effectiveness, this measure must be reasonably close to representing the true purpose of the system. If it is not, then all the linear programming and all the game theory in the world will not save us from optimizing auto assembly lines so as to provide the maximum number of coffee breaks per hour. And, then we would soon find that no one was willing to sponsor (such) an operations-research study…." [DARCOM, 1979]

As previously stated, the majority of the literature reviewed was military in nature. Finding published examples of MOMs for commercial applications was therefore unsuccessful and attempting to extrapolate a corresponding commercial equivalent to kill ratios, survivability, or any other uniquely military parameter is a separate paper within itself. An attempt will be made, however, to illustrate what the authors had in mind for the sake of this paper.

The military primarily determines the worth of a system in terms of military effectiveness and bases its analysis on a probabilistic framework that, depending on the author, has many formulas it can use to determine whether a specific system will perform a required mission. Commercial definitions of a mission can vary depending on ship type. For a more robust design, as in a passenger vessel, missions can consist of available dining capacity per hour, revenue generating capacity per hour, or travel times. While relatively less dynamic ship types, such as a containership, missions can be loading times or travel times. From these mission definitions, we can then gauge the ship as a system based on its performance capabilities.

Where a typical military performance category can consist of Mission Support, Readiness, and Survivability, commercial applications may be concerned with Mobility (speed, sea keeping, maneuverability, stability), Human Support (safety, health, habitability, recreation), and Survivability. [Hockberger, 1996] From that point the literature diverges and each author has his/her own way of analyzing these factors. Green proposed the following Mission Success Formula, as shown in Equation 1:

Equation 1: Green's Mission Success Formula

Mission Success = $A_O * R_M * S * MAM$

Where:

- A_O = mission availability
- R_M = mission reliability
- S = survivability = probability of ship loss
- MAM = mission attainment measure
  - $MAM=WSE=P_K*P_D*P_C*P_E*P_{WK}$
  - P_K = Ship killability (a function of vulnerability and susceptibility)
  - P_D = Probability of detection
  - P_C = Probability of control (correct identification, one track per target, etc.)
  - P_E = Probability of engagement (the ability to guide the weapon to within its acquisition cone)
  - P_{WK} = Probability of weapon kill (the ability of the weapon to achieve the desired level of kill)

Correlating this to a commercial model is not as straight forward as a mission specific task. Looking at a ship as a business model a possible alternative formula could be:

Equation 2: Possible commercial alternative to Green's Mission Success Formula

Financial Success = $A_M * R_M * S * FAM$

Where:

- A_O = Market availability
- R_M = Market reliability
- S = Survivability = probability of ship loss due to unforeseen circumstances (Acts of God, Terrorism, etc.)
- FAM = Financial attainment measure
  - $FAM=P_W*P_C*P_H*P_D*P_F$
  - P_W = Probability of inclement weather
  - P_C = Probability clients choose our product over others outside of the cruise segment
  - P_H = Probability that travel period is a good one for a vacation (i.e. on a national holiday)
  - P_D = Probability of booking on a discounted fare
  - P_F = Probability that a discounted fare is issued

It should be noted that formulas such as these are probabilistic and do not calculate discrete numbers but rather analyze fractional units instead. Although it may not be clear what it means to, say, deliver fractions of containers, it does make such an approach suitable for modeling and effectiveness analyses. [Hootman, 2003] Furthermore, these effectiveness models can be expanded in a reverse fashion. Rather than analyzing a system and its inherent subsystems, the same consideration can be put into relating a system with other systems, such as determining fleet effectiveness in a combat scenario [Crary, 1999] or in its ability to satisfy the market demands of a specific trade route.

Thus, the onus on the ship designer is, through heavy dialogue between the ship owner and his / her marketing department, to develop a set of probabilistic measurements that take not only on-board factors in mind but external elements that affect the ship as a whole as well as its passengers, crew, and sales force. Factors, for instance, that would affect the operational capability of a ship or that would affect the utilization of capacity (and therefore revenue) of a ship. For the case study, concentration on primarily internal (shipboard) MOMs will be taken into consideration while external factors will not be dealt with since marketing and environmental dynamics are beyond the scope of this thesis.

MULTIPLE CRITERIA DECISION MAKING CONSIDERATIONS

Multiple criteria decision making (MCDM), also referred to as multi-criteria decision making, is used to model the weight of various decision maker preferences and to rank alternative system solutions. With a system as complex as a ship, composed of many sub-systems that are complicated on their own right, a designer is left with many choices to meet the demands of the owner. Solving the requirements of the sub-systems alone will often not produce an ideal result; the interactions amongst the sub-systems must also be analyzed, leading to a ship design that truly is a multi-criteria decision problem. [Hootman, 2003] These MCDM methods can vary in complexity depending on not only the amount of parameters analyzed, but also how many of their interactions are thought out. In addition, subjectivity becomes a factor into determining which criteria stand out above the others. How these criteria are weighted is up to the individual method itself. This section will address the most common of the models, specifically: weighted sum (WS), hierarchical weighted sum (HWS), analytical hierarchy process (AHP), and multi-attribute utility (MAU) analysis, and discuss the concept of Pareto optimality.

WEIGHTED SUM METHOD

Of the four, the WS method is the simplest, most commonly used method. By summing the product of objective weights and attribute levels (MOEs) a figure of merit (FOM) can be obtained but has been proven to be highly inconsistent, requiring the following caveats to any potential designers [Whitcomb, 1998a]:

- Objective definitions are only defined at a single level, which impede transparency of relationships.
- The method does not attempt to mitigate or eliminate dependence between attributes.
- Risk is assessed in an overly simplistic manner.

Equation 3 breaks down the weighted sum method in its simplest of forms.

$$\frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i}$$

Equation 3: Weighted Sum Method

In it, w_i represents the objective weights and x_i the attribute levels. The rest of the methods addressed in this paper are all based on a hierarchical approach, which has an advantage in that it eliminates the first caveat in WS, addresses the second, and it [Whitcomb, 1998a]:

- Refines the ability to define appropriate aspects of each MOE.
- Shows objective function relationships to each other.
- Organizes the evaluation.

Hierarchical Weighted Sum

Of the remaining three, the simplest model is the hierarchical weighted sum, a "modification of the weighted sum method, using the objective hierarchy versus the single level objective sum of products formulation" that the WS method used. [Whitcomb, 1998a] Figure 11 best illustrates this. As such, rather than pooling all the objective weights together, they are segregated into their relative categories, analyzed in parts and then reanalyzed as a whole. Whitcomb formulates the HWS as follows:

> The lowest level of the hierarchy consists of the attributes, a_i, on which the alternative ship concepts are graded. A raw score, s_j, is assigned to each alternative ship concept, j for each a_i. The scoring scheme is predetermined such that s_j can have any value from 1 to 10, with 1 as the worst and 10 as the best. The raw score of an attribute is not as important as the relative score, since alternative ship concepts are rated against each other, and raw score is normalized. For k alternative ship concepts, the normalized score, s^0_j, is defined by equation 4-A.
>
> Each a_i is assigned a weighting factor, v_i. These a_i are grouped into a set of parameters, p_k, at the next level of the hierarchy. Each p_k is assigned a weighting factor, w_k. The $v_i\, s^o_j$ products are subtotaled and normalized by the sum of the weighting factors, at the respective attribute hierarchical level, to ensure that the parameter weighting is not affected by the number of attributes or the size of the attribute weights. The $w_k\ (v_i\, s^o_j)$ product is normalized at the parameter level to create a set of resulting final scores which sum to 1.0. The score for each alternative, j, is then found from equations 4-B and 4-C. [Whitcomb, 1998a]

$$s_j^0 = \frac{s_j}{\sum_{j=1}^{k} s_j} \qquad P_j = \sum_{i=1}^{m}\left(\frac{v_i \cdot \left(s_j^0\right)_i}{\sum_{i=1}^{m} v_i}\right) \qquad FOM_j = \sum_{k=1}^{r}\left(\frac{w_k \cdot \left(p_k\right)_j}{\sum_{i=1}^{r} w_i}\right)$$

(4-A) **(4-B)** **(4-C)**

Where,
P_j ≡parameter score of j^{th} alternative
m ≡number of attributes of parameter P_j
r ≡number of parameters
FOM ≡Figures of Merit

Equation 4 (Parts A, B, C): Hierarchical Weighted Sum Formulation [Whitcomb, 1998a]

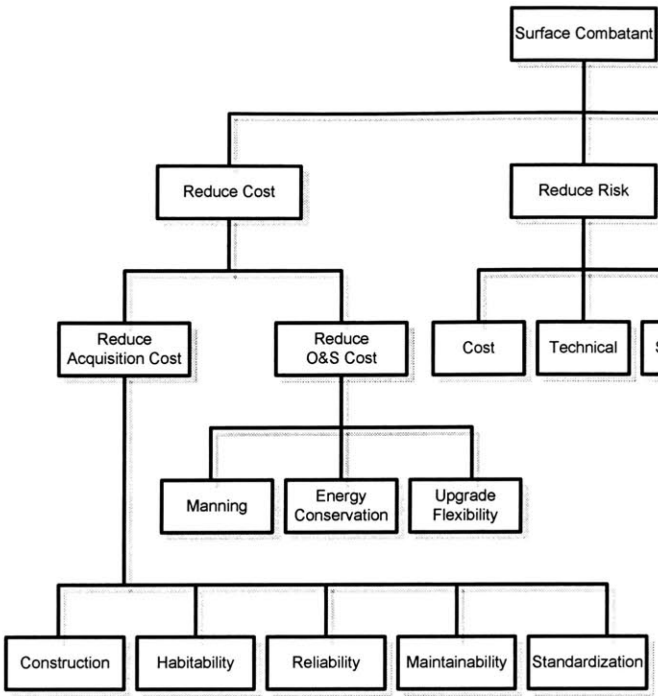


Figure 11: Whitcomb's Hierarchy Structure [Whitcomb, 1998a]

ANALYTIC HIERARCHY PROCESS

Similar to HWS is the analytic hierarchy process (AHP). AHP reflects the customer or decision maker's preferences by the use of "pairwise comparisons of every attribute at each level of the hierarchy [creating] a relative importance scale for each attribute." [Hootman, 2003] Oliver *et al* summarizes:

> The results are summarized in a matrix, and the principal eigenvector of the matrix provides the values for the priorities. If all of the effectiveness measures can be computed analytically, then these priorities are used directly as weighting factors...[however], some of the effectiveness measures may be of the type that are matters of user preference. In this case the designs are considered in pairs for each of the effectiveness measures by the individuals participating. The results are combined with the weighting factors to yield a preference for each design. [Oliver *et al*, 1997]

An additional advantage using this method is that it offers a consistency check of the pairwise comparisons; however, "as the number of attributes under consideration becomes large, approximately better than seven, decision makers may have trouble keeping the criteria straight."

[Whitcomb, 1998a] [Hootman, 2003] Islam also noted in his work of such a drawback and attempted to prove:

> Saaty's suggestion of clustering alternatives into groups according to a common attribute....In [this] procedure, the number of comparisons required is much less than is required in the unified approach and the rankings that result are sufficiently close to the standard AHP with all the pairwise comparisons. [Islam, 1997]

Multi-Attribute Utility Analysis

Leaving the direct hierarchical process of the last two methods, MAU grounds itself in the utility function, "a specific type of value function in that the units are based on an ordered metric scale and is developed under the condition of risk." [Whitcomb, 1998b] This process takes the individual utilities of singular, lower level attributes of a particular decision and combines them into a single function, the MAU function, "allowing utility to be defined with respect to any two points on the scale, which are then assigned any convenient value. The quantities for the worst and best decision outcomes can be defined, forming the basis for actual measurement of utility." [Whitcomb, 1998b]

General Method Considerations

All of the MCDM methods have challenges with their implementation, whether for ranking or weighting. The Air Force AoA Guidebook addresses the issues regarding the weighting of MOEs:

> Weighting assigns different values (weights) to different MOEs. It is a seductive idea: clearly not all MOEs are created equal. A difficulty with weighting, however, is that an analyst's weights may not be a decision maker's weights. By weighting, the analyst is proclaiming judgment superior to that of the decision-maker. Weighting is strongly discouraged. Almost invariably, weighting is an attempt, conscious or otherwise, to avoid thinking through alternative methods of presenting the results in a clearer manner. Better presentations almost always can be found; take the time to look for them. [OAS, 2000]

It points out an inconsistency with some of the more useful methods of MCDM. On one hand, weighting will allow the decision maker to deal with an appropriate amount of information but may lose some inherent properties in the analysis while, on the other hand, not weighting will provide an accurate picture at the expense of inundating the user with too much information. Hockberger does provide an interesting middle ground.

> Lower level MOEs should be calculated and combined within the model or simulation, which can determine the way each MOP of an alternative concept contributes to achieving them and how they combine to produce higher level MOEs. Human judgment and weights are only required for going the rest of the way up the tree, combining the MOEs the model yields in order to produce the overall composite MOE. [Hockberger, 1996]

Another MCDM tool was the development of the "dendritic" by Mustin whose purpose, "is to refine tasks to the point where data explicative of performance can be gathered." [Mustin, 1996]

> The dendritic is formed by focusing on overall intent of related joint tasks across levels of war and determining a question whose data supported answer will define this intent...Similarly, corresponding functional areas form critical subordinate issues that generally reflect the level at which MOEs are developed. Specific task requirements within each of the functional areas serve to formulate another level of sub issues that may determine underlying MOPs. Continued refinement of task requirements into more specific and lower levels of aggregation ultimately leads to the point where data can be gathered. [Mustin, 1996]

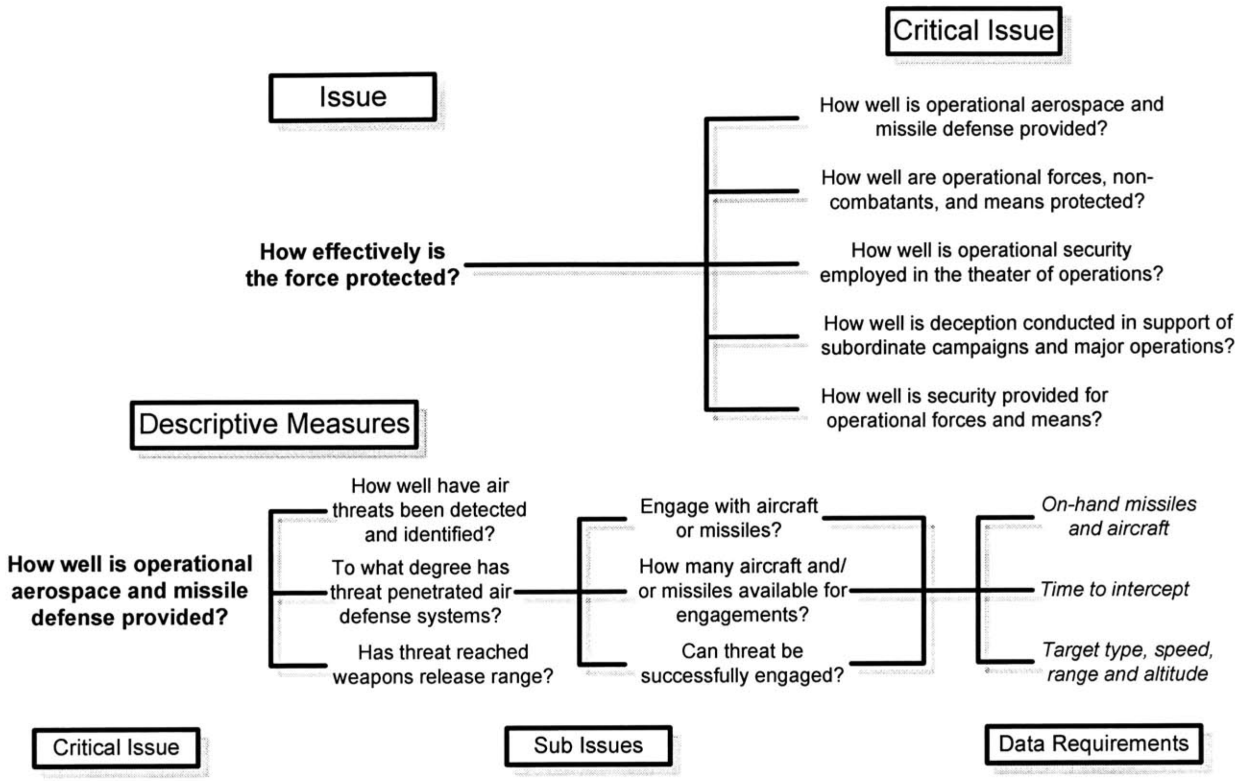


Figure 12: Mustin's Dendritic [Mustin, 1996]

Using yet another approach, breaking down all these MOMs into manageable analyses can be accomplished by a 'Goal-Question-Metric' format introduced by Kowalski *et al* that that would allow a designer to create a framework where, "all metrics [are] traceable to requirements and all requirements [are] associated with metrics." [Leite and Mensh, 1999] Figure 13 graphically demonstrates the format:

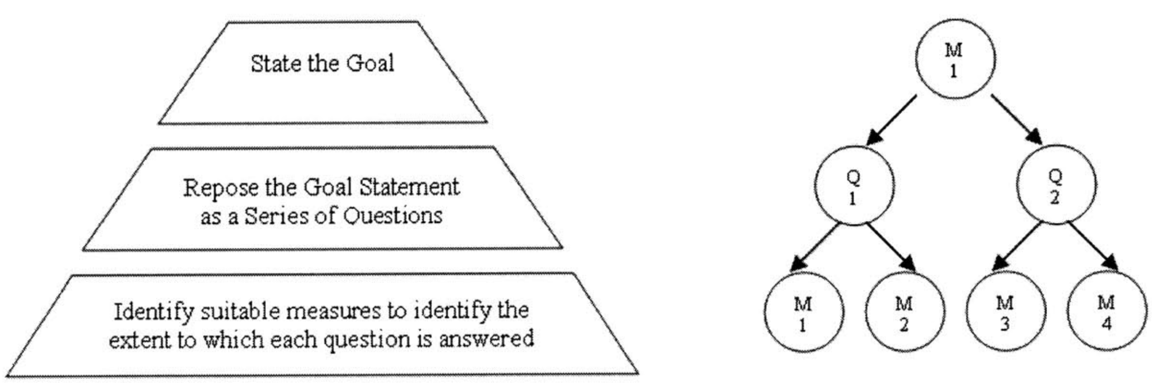


Figure 13: The Goal-Question-Metric Format [Kowalski et al, 1998]

PARETO OPTIMALITY

When dealing with MCDM situations, the concept of Pareto optimality is critical. Pareto optimality is important in situations where multiple, conflicting objectives are present in the decision – in other words, in all system cases. The MCDM cases all produce conditions where a single optimal solution cannot be defined, as in a typical single variable case where the Karesh-Kuhn-Tucker (KKT) necessary and sufficient conditions for global optimality can be mathematically defined [Introduction to Optimal Design, Arora]. The Pareto optimal solution is a set of possible solutions, a set of non-dominated solutions, in which no single objective can be improved without degrading the achievement of at least one other objective.

For systems engineering application for presentation to a set of decision makers, the designer would create a graph of two competing MOMs with one on the abscissa and the other on the ordinate and plot out the remaining designs in relation to the competing MOMs. The plot in Figure 14 additionally scales, "the values between a "Good" and "Marginal" value where the ideal is achieved at point (1, 1) and least ideal at (0, 0)." [Hootman, 2003] Using this additional method would enable the user to discern a Pareto frontier, the curved, dashed line between points A and B in the graph if there are enough designs plotted. The optimal between the two points would be determined if, "by moving away from [one] point, one MOM cannot be improved without degrading the value of the second MOM." [Hootman, 2003]

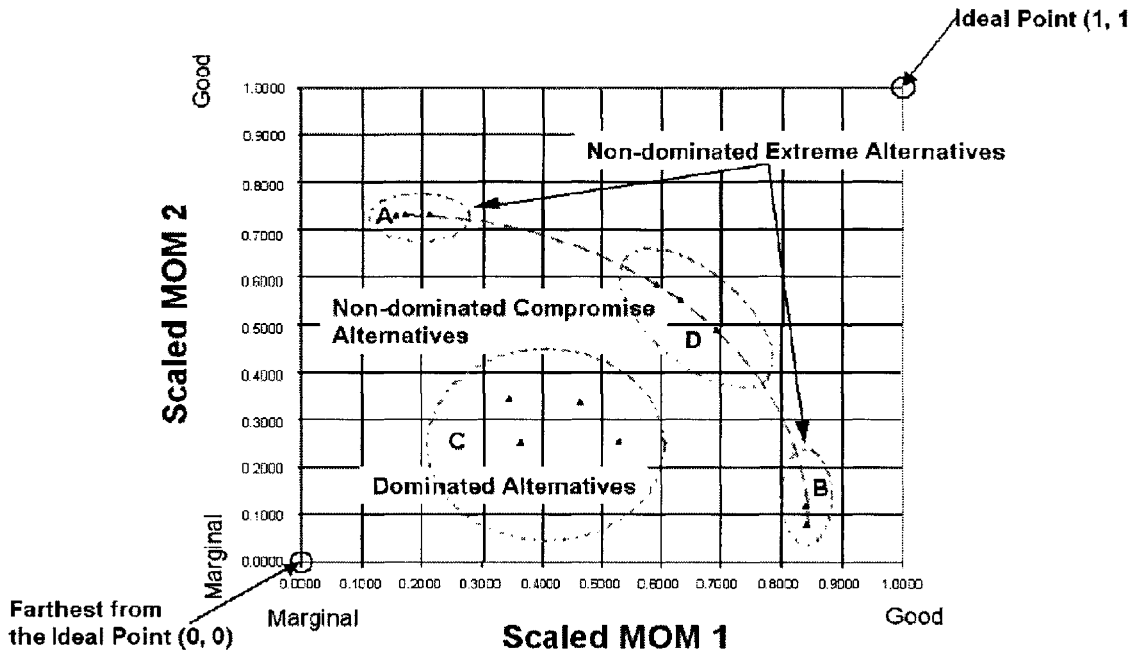


Figure 14: Example Pareto Plot [Whitcomb, XIII-A, 2001]

The solutions depicted in the figures are, "the conceptual equivalents, in multi-objective problems, of a technically efficient solution in a single objective problem," [deNeufville, 1990] and can be observed in Fig 14 by regions A, B, and D which depict the extreme Pareto optima and the compromise Pareto optima respectively. Region C represents, "all the point designs that do not fall on the frontier and [that] are…dominated by those on the frontier and are thus, inferior designs." [Hootman, 2003] A decision-maker would use this information not to find a single optimal solution but to uncover equally efficient designs to be considered for a final series of tradeoffs.

TRADE-OFF METHODOLOGY

Traditional ship design uses empirical experience, rules of thumb, and heuristics with micro-analysis of core systems to establish a feasible solution to the demands of a ship owner. With the additional impetus of technological advances and rapidly increasing building costs, design optimization has become an ever increasingly complex process. The aerospace industry has felt these similar pressures as well and has met this challenge by coupling Design of Experiments and Response Surface Methods (DOE/RSM) techniques. By identifying which of the design variables have the greatest influence in the design, they have been able, "to define the design space, conduct tradeoff studies, and facilitate better informed decision making." [Hootman, 2003]

Professor Whitcomb in the Naval Construction and Engineering Program at MIT began a Naval Research sponsored effort to translate these aerospace techniques to the field of naval combat design. The first successful application was in submarine concept exploration by Goggins [Goggins, 2001] where a response surface was generated for, "cost, submerged displacement, length, submerged speed, and OMOE." [Goggins, 2001] The OMOE was a function of test depth, submerged speed, and modular payload length. Building on Goggin's work, Price used DOE/RSM to examine, "the impacts and propagation of design parameter uncertainty at the concept design stage," [Hootman, 2003] recognizing that:

> The complexity of the ship design process leads to numerous assumptions and a great deal of uncertainty in the point designs during the concept exploration phase. While it is not feasible to eliminate this uncertainty, it is useful to explore how it affects the overall design. An analysis of the uncertainty associated with each point design provides the designer with additional information for comparing designs. [Price, 2002]

Whalen continued in the effort by using DOE/RSM to:

> develop an Optimal Deadrise Hull (ODH) that reduces mechanical shock where it first enters the boat, at the hull-sea interface. Planing boat hydrodynamics were reviewed and the mechanical shock environment was evaluated. The ODH analysis is performed on the MkV Special Operations Craft in order to determine the effects of hull deadrise on vertical acceleration. Finally, the results of the ODH analysis are used to perform a design space study of planing hulls in order to optimize the overall design for vertical acceleration based on hull deadrise, cruise speed, and payload weight. [Whalen, 2002]

In 2003, Psallidas applied DOE/RSM to assess the impact of forecasted technological improvements on system performance [Psallidas, 2003]. In order to:

> aid the decision maker in projecting the performance of future vessel concepts and in allocating the resources for technological research and development in an optimum way. The impact of technology [is] assessed through the use of technology k-factors that [are] introduced into a mathematical synthesis model [that] modify technical characteristics or cost parameters of the design. These modifications will result in changes of the technical metrics to simulate the hypothetical improvement or degradation associated with the new technology. [Psallidas, 2003]

In the same year, Hootman furthered naval DOE/RSM efforts by addressing mission analysis, within the context of a submarine's military effectiveness over a specified mission. [Hootman, 2003] The foundation of Hootman's work is the basis of this thesis as well.

DESIGN OF EXPERIMENTS (DOE)

DOE is a method by which a user can examine multiple design parameters (DP) and quantitatively understand their effect on the whole design (response). [JMP, 2002] The best implementations begin with the use of a screening experiment, followed by a response surface experiment.

A screening experiment is used prior to RSM to identify which factors are statistically significant and practically important to the overall design. Statistical significance refers to the mathematical test to distinguish between whether a design variable influences the change in the mean value of the outcome due to an effect described in the model and whether the change could have been observed in the data by chance alone. In essence, a screening experiment is a set of 2-

level factors combined to test their effect on the response output. "Given a set of k input variables (factors) to the overall design problem, a small set of designs is developed by linearly selecting two factor values over a significant range of each factor's value." [Hootman, 2003] This set of designs, n, can be demonstrated in Equation 5:

Equation 5: Required Number of DOE Designs

$$n = 2^k$$

The designer can then use statistical techniques to analyze the effects each factor has on the design, [JMP, 2002] and determine a smaller set, m, of the k factors that have a greater impact on the design.

Response Surface Method

The response surface method (RSM) is a structured process for creating a minimum set of designs based on sets of factors to enable study of an entire design space through the use of second order curve fits of desired data. By varying the values of the m factors for a minimum (the threshold), maximum (goal), and midpoint, the RSM uses a series of mathematically predefined orthogonal point designs to model the input-output relationship, which can then be used to visually represent the design space for decision making. In the following example provided in Figure 15, a three factor design ($m = 3$) is used:

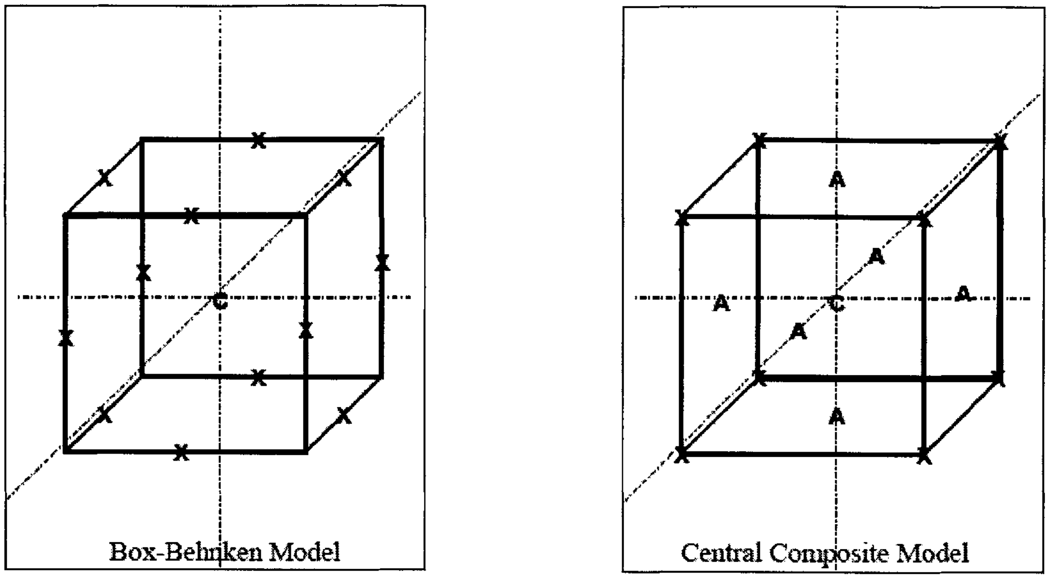


Figure 15: Three Variable Design Models

The space within these boxes represents all points of a desirable solution as mathematically good reductions of a full factorial design space, which in 3 dimensions would constitute a set of 27 point designs. Depending on which model is used either 13 points for the Box-Behnken model, or 15 points for the Central Composite model are required to be populated. Whereas the Central Composite model allows for the extremes to be a viable solution and therefore requires points for the 8 corners and the 6 in the middle of each design plane, the Box-Behnken model avoids the corners in the belief that they do not represent feasible designs and therefore requires only 13 points, 12 of which lie between each of the corner points.

Statistical analysis software packages, such as JMP, can then be used to develop and analyze the response surfaces. [JMP, 2002] JMP uses a second order interpolation (as show in Equation 6) to define the response surface, where the $b_{0,i,ii,iii}$ terms represent constants of regression, ε represents error, and the summations represent linear, quadratic, and interaction terms respectively. [JMP, 2002]

$$y = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} x_i^2 + \sum_{i=1}^{k} \sum_{j=i+1}^{k} b_{ij} x_i x_j + \varepsilon$$

Equation 6: Response Surface Equation

If the equation is determined to have a statistically accurate fit, it can then be used to apply an infinite number of variations into the design space. Additionally, JMP has a graphical interface to enable the user to visualize all possible design variants, freeing the designer from the finite number of analyses traditionally used. The naval architect can then use this graphical interface to begin to redefine the design space to additional constraints as they are presented through the interactions with the system acquirers.

To create a consistent cruise ship design framework, a uniform philosophy must be developed. For this thesis, the definitions of DPs, MOPs, MOEs, and MOMs will be used and no MOFEs will be considered due to the limited scope of the case study. For the same reason, MOMs will be made as quantitative as possible and will be developed following the steps that Malerud *et al* described while avoiding normalization, ratio, and weighting schemes. The only instance where weighting will be used is in rolling up lower level MOMs when applying AHP and Pareto analysis; the AHP model works well with hierarchy due to its inherent consistency check.

When addressing MCDM, this thesis will ensure that both MCDM and MOM hierarchies are identical and that all subjective judgments are removed. The WS and HWS models will not be used due to their simplistic nature; they would not accurately model the MCDM problem. Finally, MAU method will not be used because it is a burden to use and it produces an analysis that is too vague for the scope of this thesis.

For the case study, MOMs for the cruise industry will be first addressed and their hierarchies established. Once the MOMs are addressed, a screening experiment using a synthesis model will be done to determine which of the MOMs are statistically significant for analysis. Once these are determined, RSM will be applied to another design experiment to visualize how these key MOMs interact with each other and within the design space.

CHAPTER 4: CASE STUDY APPLICATION TO CRUISE SHIP DESIGN

One of the central points that this thesis has emphasized is the importance of analyzing a system within the framework of a predefined supersystem. In the cruising industry, the supersystem is similar to the military context in that ships serve many simultaneous purposes throughout their daily operation. In the military case, the ship is primarily assessed within a task based supersystem context, since the military mission accomplishment itself is the key decision making metric. The primary purpose of a cruise ship is to be a revenue generator, so treating the supersystem as a business model is the appropriate course of action.

A typical business model for cruise lines would be formulated around one or more demographics (family oriented, singles oriented, etc.) and a specific area of deployment (the Caribbean, the Mediterranean, etc.). How a ship is utilized is largely dependent on these two factors. From there, passenger capacity, cabin size, dining area, and general amenities are decided. Resolving what propulsion, maneuvering, and power to install, each with its own set of sub-categories that require further trade-off analysis, is performed as well.

For the purpose of the case study, the ultimate goal would be to produce a revenue generating source for a cruise line. Implementing the 'Goal-Question-Metric' method as introduced by Kowalski *et al*, this could then be broken down to a further set of questions and sub-questions, most of which would be centered on the need of accommodation and service of passengers:

- Are we purchasing a new-build or a conversion?

- What is our marketing strategy?
    - What are our intended areas of deployment?
        - Is the market saturated?
        - What cruise length do we want?
            - 3 & 4 day
            - 7 day
            - 14 day or longer
        - What ratio of days at port / days at sea do we want?
        - How many round trips before re-fueling / re-supply do we want? This can be also be asked in the form of:
            - Endurance length
            - Number of days

    - What is our intended target demographic?
        - Is the demographic saturated?
        - What does the target demographic look for in:
            - Cabin Size / Amenities?
            - Restaurant options?
                - Single or Dual Seating times
                - Types of cuisine
            - Individual Entertainment?
                - Casino
                - Game Rooms
            - Group Entertainment?
                - Types of Shows?
                - Quantity
            - Shore Excursions?

- What type of propulsion should we choose?
    - What bow/stern thrusters should we install?

- What type of power plant should we choose?

Ancillary to this question set would be the SOLAS, IMO, and environmental requirements that would also be added to the design as constraints. Examples are (but are not limited to):

- Fire retardant materials
- Life saving equipment
  - Life boats
  - Life Rafts
  - Extinguishers
- Watertight compartments
- Environmental Considerations
  - Waste Management
  - Exhaust Restrictions
- Medical Facilities
- Crew accommodations
- Crew Amenities

The context for the formulation of the problem changes with the resources available to the organization. With enough funding for market analysis, as well as an extensive empirical knowledge of existing technology, a prospective ship owner can work with a naval architect and come up with a design that fits their requirements. This would not, however, provide the owner with a full set of possible ship designs; less costly and/or higher revenue generating alternatives would also most likely be missed. Factor in the time and money needed to complete such an analysis and it becomes quickly evident that only the biggest cruise lines would be capable of funding such an analysis.

Smaller companies would use the combined experience of their personnel, what information a shipyard and naval architect can freely provide, and observations of the markets (the competition) to formulate their requirements. This would further reduce their design space, removing even more alternatives that may have worked for them. Moreover, acquisition cost would rest as one of the higher level requirements, something that larger lines do not necessarily have as a top-level requirement.

MOM development and effectiveness analysis reduce the time and funding required to develop requirements compared to traditional methods of creating a few point designs; enabling the naval architect to provide the ship owner with a set of feasible alternatives under their supplied constraints and factors for consideration. To start, a naval architect can use a synthesis model (a calculator of sorts) developed where, upon inputting the desired factors, approximate estimates can be made for general ship dimensions, volumetric calculations, powering requirements, acquisition cost, operating cost, and estimated revenue. There are many ways to produce such a calculator; whether by using sophisticated mathematical programs (CAD and CAE-based) or simple spreadsheets (MathCAD, or various typical commercial spreadsheets), the results would be the same. It is important that all the calculations used are appropriate for the specific ship being considered. For example, if one were to use propulsion characteristics of a frigate and apply it to a cruise ship there is a high probability that the propulsion (and powering) requirements would be undervalued since a frigate's hull designed for different operating characteristics than a cruise ship's hull. As such, developing a synthesis model would almost certainly have to be ship type specific. It would also require empirical data, supplied from the owner or market analysis, to accurately gauge revenue potential and operational cost.

The synthesis model used for this case study was a spreadsheet modified from a naval surface combatant analysis and to application to cruise ship design. The framework of the naval ship synthesis process was changed by regressing cruise ship information adjusted to reflect current market trends. The synthesis model has not been verified as generically acceptable to all cruise ships and was only used as a tool to demonstrate the methods brought forth in this study. The main deviations to the model are in payload area and volume relationships, propulsion calculations, acquisition cost, operational cost, and revenue generation. Due to the proprietary nature, the little data that was gathered came from anonymous sources within the industry, as well as dated financial reports. The synthesis model can be viewed in Appendix 1. Additionally, for the purpose of the case study, the following assumptions were made to reduce the scope of the required analysis:

- A new-build is considered.
- Area of deployment is not addressed.
- Target demographic is not addressed.
- Brand Quality is limited to Budget, Premium, and Ultra-Luxury; leaving out the Contemporary and Luxury categories.
- Capacity is limited from 1000 to 3000 passengers.
- Cruise Length is limited to 3 & 4 day, 7 day, and 14+ days.
  - 14+ days is considered a trans-Atlantic crossing to influence required fuel and stores in the analysis.
- Amenities for Passengers & Crew are aggregated to an average square footage per passenger or crew.
  - No correlation to demographic or area of deployment is addressed.
- Ticket and on-board revenue is aggregated on a per person basis.
  - No correlation to demographic or area of deployment is addressed.
- Occupancy rates are aggregated by brand quality only.
  - No correlation to demographic or area of deployment is addressed.
- Dual Bow thrusters are installed, no stern thrusters are considered
- A 3 ship purchase is considered for acquisition and operational cost as well as revenue generation.
- A simple discounting is applied for financial analysis; real forecasting is avoided.

The designer could always go back to the synthesis model and add more metrics for consideration. To limit the analysis scope, the following metrics were used to focus the demonstration of the application of the framework:

- Beam - for constraints such as Panamax, Supermax, etc.
- Displacement – used a check to verify that the synthesis model approximately reproduced the designs that were used create the model
- Acquisition Cost - three ships
- Operating Cost - three ships
- Revenue - three ships

Taking the set of assumptions into account, the set of factors that were studied to see their influence the possible outcomes are:

1. Brand Quality
2. Passenger Capacity
3. Cruise Type (Cruise Length)
4. Days of Stores
5. Propulsion Type
6. Number of Propulsors
7. Engine Type
8. Number of Engines

To accomplish a full factorial 2-level study would require a total of 256 (2^8) possible designs; too many for a naval architect to produce efficiently. By performing a screening experiment, the architect can quickly perform a cursory review to filter out the factors that have a greater effect on the overall design outcome responses desired.

Rather than creating 256 possible variations, a minimum set of variations can be determined to screen for factors having the largest effect and that are statistically significant. The screening experiment uses only the high and low levels of the design variables (factors) in order to specify the subset of ships to synthesize. Table 3 illustrates the threshold, middle, and goal values of each factor; with threshold and goal values used for the screening experiment generation.

Table 3: Table of Analyzed Requirements

	Values		
Factor	**Threshold**	**Mean**	**Goal**
Brand Quality	Budget	Premium	Ultra-Luxury
Passenger Capacity	1000	2000	3000
Cruise Length	3 / 4 day	7 day	14+ day
Round Trips (Endurance Length)	1	2 , 3	4
Days of Stores	7	14, 21	28
Propulsion Type	Screw	N/A	Pod
Number of Propulsion Units	2	N/A	4
Engine Type	Diesel Electric	Gas Turbine & Steam	Gas Turbine
Number of Engine Units	2	N/A	4

The design of experiments (DOE) method determines the minimum number of variations needed to conduct the experiment. In this case, 18 variations were identified (Table 4 & 5):

Table 4: Initial Set of Variations

	Screening Experiment Factor Table								
ID	**Brand Quality**	**Passenger Capacity**	**Cruise Length**	**Total Round Trips**	**Days of Stores**	**Propulsion Type**	**Number of Propulsors**	**Number of Engines**	**Power Plant Type**
1	3	1000	1	1	7	1	2	2	1
2	1	3000	1	4	7	2	4	2	3
3	2	1000	3	1	28	2	2	2	2
4	3	3000	2	4	28	2	4	4	1
5	1	1000	2	1	28	1	2	4	3
6	2	3000	1	4	28	1	4	2	1
7	2	3000	3	1	7	2	2	2	3
8	1	3000	2	4	28	1	2	2	2
9	2	1000	1	1	28	1	4	4	3
10	2	1000	2	4	7	2	2	4	1
11	3	3000	3	1	28	2	4	4	3
12	3	1000	3	4	7	1	2	2	3
13	2	3000	2	1	7	1	4	4	2
14	1	3000	1	4	28	2	2	4	1
15	3	1000	2	1	28	2	4	2	2
16	1	1000	3	4	7	1	4	2	1
17	1	1000	1	1	7	2	4	4	2
18	3	3000	3	4	7	1	2	4	2

To facilitate the software used in the analysis, non-numerical values were assigned with numerical representations. As such, for Brand Quality the Budget category was assigned the value of 1, the Premium with 2, and the Ultra with 3. Cruise Length was broken down in a similar fashion where the value of 1 was assigned to the 3 & 4 day segment, 2 was assigned for the 7 day, and 3 for the 14+ day segments. Propulsion type was assigned 1 for a traditional screw & shafting system and 2 for the newer podded system. Finally, for Power Plant Type, Diesel Electrics were assigned the value of 1, Gas Turbines with 2, and 3 for the Gas Turbines with Steam Generators. Table 5 has their corresponding responses (outputs). It should be noted that all Revenue and Cost figures are in the millions of US dollars.

Table 5: Initial Set of Responses

			Responses		
ID	**Beam**	**Displacement**	**Revenue ($M)**	**Acquisition Cost ($M)**	**Operating Cost ($M)**
1	83.8	37,142	6,827.63	1,048.14	3,581.93
2	111.5	74,719	12,048.75	1,823.59	5,668.94
3	85.0	35,882	5,341.61	1,019.24	3,680.48
4	133.6	123,626	20,482.88	2,651.09	8,495.71
5	77.2	26,764	4,016.25	861.71	2,847.26
6	124.8	106,863	16,024.84	2,294.09	7,187.55
7	119.4	101,293	16,024.84	2,211.59	6,896.82
8	116.8	81,268	12,048.75	1,943.63	6,460.27
9	83.3	34,831	5,341.61	997.83	3,266.27
10	84.0	33,317	5,341.61	1,029.60	3,430.70
11	128.3	122,345	20,482.88	2,545.66	8,115.94
12	94.1	38,768	6,827.63	1,146.38	3,774.72
13	119.2	101,269	16,024.84	2,159.91	7,248.83
14	114.5	80,904	12,048.75	1,963.24	6,112.55
15	85.0	39,613	6,827.63	1,098.39	4,009.60
16	88.9	25,487	4,016.25	957.47	3,169.65
17	74.9	24,914	4,016.25	851.01	3,167.33
18	140.3	119,442	20,482.88	2,674.66	9,123.95

Through the visualization capability within JMP, the designer can inspect individual responses to determine which of the requirements were predominately influential. Before studying the design space, however, the responses must be checked for statistical significance and practical importance. Practical importance is determined via interaction with the owner or acquirer – by reviewing the resulting impact of the factor effects on the responses, the owner can determine if any of the effects changes the resulting response enough to be considered a practically important variable in making a decision from among system alternatives. The primary indicators for the model fit and factor statistical significance are the model R^2 and the p-value. As an example, the beam response is analyzed in Figure 16:

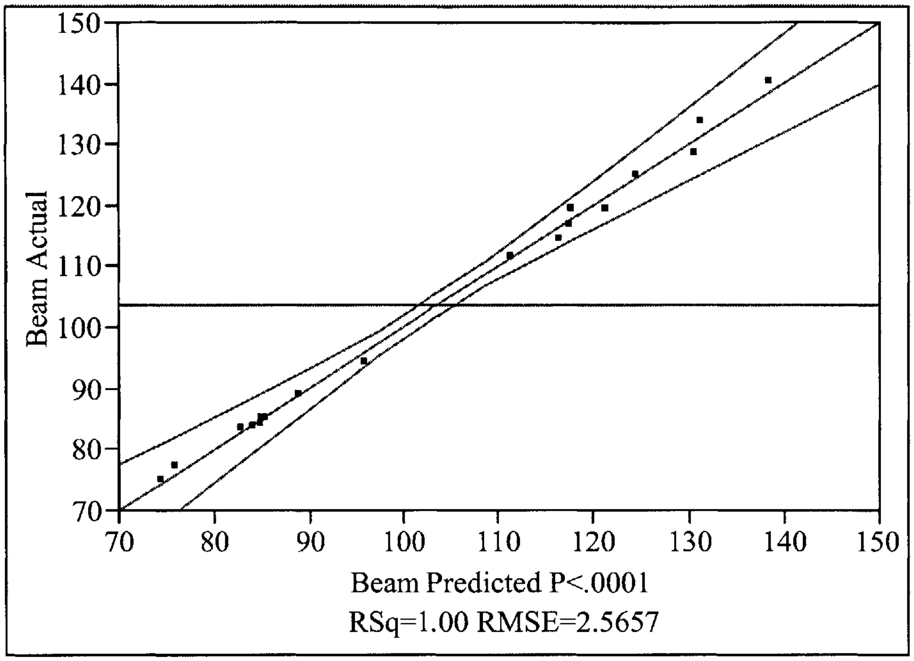


Figure 16: Actual by Predicted Plot for Beam

The R^2 test represents, "the proportion of the variation in the response that can be attributed to terms in the model rather than to random error." [JMP, 2002] All 18 variants are accounted for in this plot as data points, with the solid line indicating the least squares fit and the hashed lines indicating the 95% confidence interval. In this case, the R^2 is 1.00, indicating a very good model fit. A second check is done to make sure that the mean shift is statistically significant (not due to random chance data variation) which is true as long as the mean line is not enclosed within the 95th percentile confidence interval.

The p-value, indicated in JMP as the F Ratio, is found using 'Analysis of Variance' in JMP:

> A statistical tool to test the hypothesis that all coefficients in [Equation X: The Response Surface Equation] are zero. If the hypothesis is not true, i.e. at least one coefficient is non-zero, then the F-Ratio will be large. The "Prob > F" …is the probability of obtaining a greater F Ratio by chance alone if the specified model fits no better than the overall response mean. Significance probabilities of 0.05 or less are often considered evidence that there is at least one significant regression factor in the model. [JMP, 2002]

In other words, if the Prob > F is less than 0.05, this is equivalent to the p-value being less than 0.05, which indicates that the effects are statistically significant (Figure 17).

Response Beam

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Brand Quality	2	2	333.1606	25.3061	0.0024*
Passenger Capacity(1000,3000)	1	1	4576.7511	695.2784	<.0001*
Cruise Length	2	2	176.9345	13.4395	0.0097*
Total Round Trips	1	1	76.2824	11.5885	0.0192*
Days of Stores(10,20)	1	1	10.0950	1.5336	0.2705
Propulsion	1	1	47.2128	7.1723	0.0439*
# of Propulsors	1	1	17.6343	2.6789	0.1626
# of Engines	1	1	42.8608	6.5112	0.0512
Power Plant	2	2	18.4698	1.4029	0.3284

Figure 17: Effects Tests Report on Beam Response

Using Beam as an example, the designer can observe that five effects have p-values < 0.05:

1. Brand Quality
2. Passenger Capacity
3. Cruise Type (Cruise Length)
4. Total Round Trips (Endurance Length)
5. Propulsion Type

Graphically, the designer can use a Pareto Plot (Figure 18) to observe the relative impact of each factor effect on each of the responses.

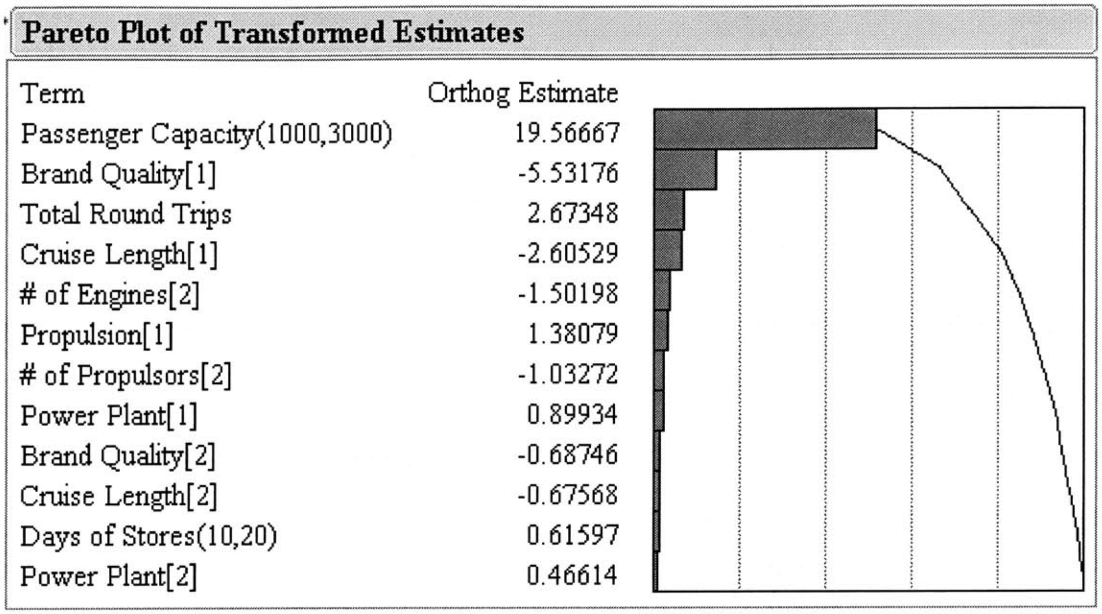


Figure 18: Pareto Plot of Beam Response

In the graph, the vertical lines represent 20% increments of the total possible 100% accumulation of each factor effect upon the response. For example, if a designer wanted to ensure that they capture 80% of all relevant factors they would have to then take Passenger Capacity, Brand Quality, Total Round Trips, and Cruise Type into consideration.

Additionally, JMP creates a 'prediction profiler' visualization that allows the designer to isolate the impact of every factor for every response (Figure 19):

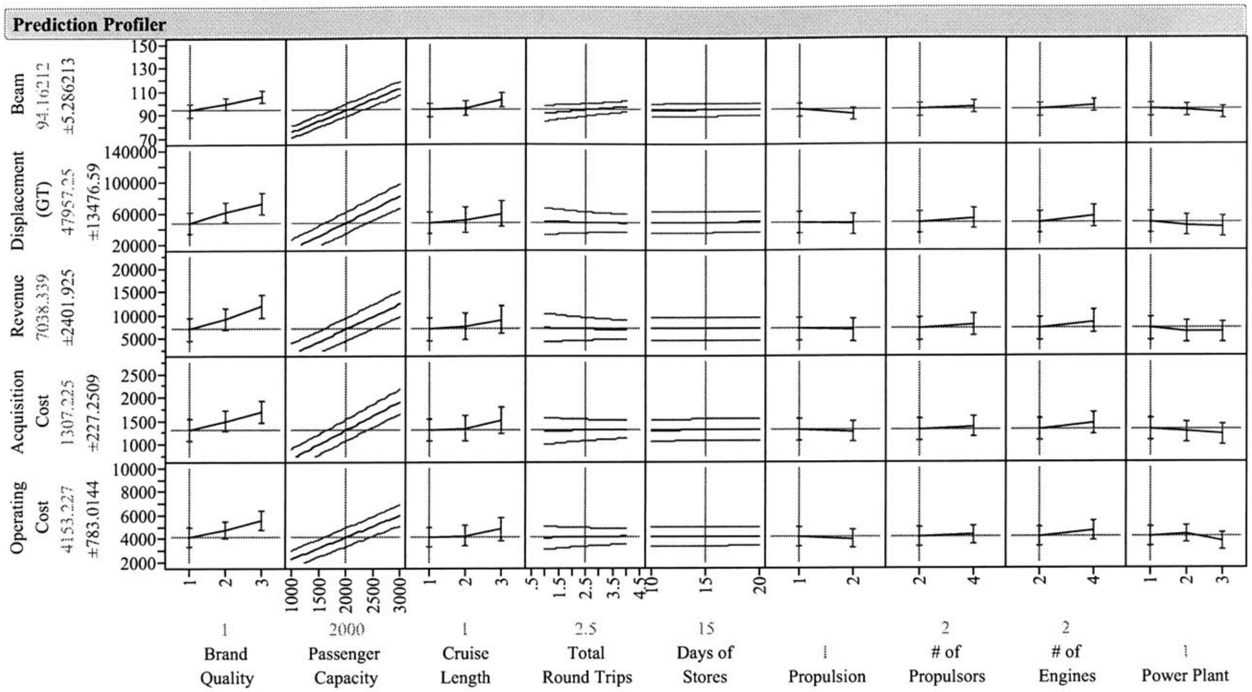


Figure 19: JMP Prediction Profiler for Top-Level MOMs

Represented as the solid line in each box, 'prediction traces' – "predicted responses as one factor is changed while holding the others constant" [Hootman, 2003] – enable the designer to visualize the effects the factors have on the responses. A flat line suggests that a specific factor has little or no impact on a specific response, while a line that has a larger slope indicates a greater influence. The threshold and goal values define the range of the factors along the x-axes. The factor effect on responses can be dynamically investigated in JMP by moving the dashed vertical lines on any prediction trace, and the designer can observe any changes the factor has on the responses. It is this prediction profiler that enables the designer to have a better understanding of what factors truly drive the responses across the entire design space.

For the case study, a cursory look at the prediction plots illustrates that the Power Plant factor has a greater effect than the Total Round Trips factor. After investigating the factor effects for all of the responses, the screening experiment indicates that five factors are both statistically significant and practically important to be used define the 3-level DOE for creation of the response surface model.

1. Brand Quality
2. Passenger Capacity
3. Cruise Type (Cruise Length)
4. Total Round Trips (Endurance Length)
5. Propulsion Type

In this case, if a designer wanted to define a full factorial 3-level experiment, this would require 243 (3^5) variations to be created for the study. Once again, a reduction in the number of variants is in order. For this case, a Box-Wilson, or Central Composite Design (CCD), DOE was chosen, which required only 27 variants to create the response surface model. Table 6 shows the resulting DOE factor table used. The synthesis model was run to generate each of the variants. The respective response results are tabulated in Table 7. The resulting Prediction Profiler is shown in Figure 20.

Table 6: Central Composite Design Factors

	CCD Factor Table				
ID	**Brand Quality**	**Passenger Capacity**	**Cruise Type**	**Propulsion Type**	**Plant Type**
1	1	2000	2	2	2
2	2	2000	3	2	2
3	2	2000	2	2	3
4	1	3000	3	1	1
5	3	3000	1	3	3
6	3	1000	3	3	3
7	1	3000	1	3	1
8	3	3000	1	1	1
9	2	2000	2	2	2
10	1	1000	3	1	3
11	3	1000	1	1	3
12	2	2000	2	3	2
13	3	3000	3	1	3
14	3	1000	3	1	1
15	1	1000	1	1	1
16	3	3000	3	3	1
17	1	1000	1	3	3
18	2	2000	2	1	2
19	1	3000	1	1	3
20	2	1000	2	2	2
21	3	2000	2	2	2
22	1	1000	3	3	1
23	3	1000	1	3	1
24	2	3000	2	2	2
25	2	2000	2	2	1
26	2	2000	1	2	2
27	1	3000	3	3	3

Table 7: Central Composite Responses

	CCD Responses				
ID	**Beam**	**Displacement**	**Acquisition Cost**	**Operating Cost**	**Revenue**
1	99.3	54,439	1,450.81	4,936.79	8,032.50
2	113.6	72,113	1,785.43	6,018.77	10,683.23
3	105.6	71,169	1,684.30	5,279.10	10,683.23
4	119.4	81,621	2,001.46	6,207.62	12,048.75
5	128.7	122,136	2,538.52	8,079.84	20,487.88
6	87.2	41,369	1,139.13	3,734.03	6,827.63
7	112.7	80,669	1,941.62	6,027.66	12,048.75
8	129.0	121,926	2,506.86	8,103.09	20,482.88
9	106.2	71,303	1,683.86	5,712.94	10,683.23
10	85.6	28,838	950.09	3,073.29	4,016.25
11	87.6	41,391	1,110.29	3,669.14	6,827.63
12	106.1	71,244	1,682.26	5,691.84	10,682.23
13	134.9	123,479	2,605.29	8,278.63	20,482.88
14	94.3	41,970	1,196.89	3,962.04	6,827.63
15	80.0	28,295	907.78	3,025.75	4,016.25
16	136.9	123,502	2,705.48	8,624.10	20,482.88
17	79.1	28,457	918.04	2,981.08	4,016.25
18	107.0	71,323	1,659.89	5,649.03	10,683.23
19	113.0	80,788	1,898.49	5,848.38	12,048.75
20	85.3	36,663	1,054.75	3,779.46	5,341.61
21	111.3	81,317	1,864.21	6,439.73	13,655.25
22	86.3	28,749	994.33	3,244.63	4,016.25
23	87.4	41,460	1,151.58	3,831.47	6,827.63
24	123.9	106,750	2,308.99	7,671.05	16,024.84
25	106.0	71,301	1,699.49	5,395.59	10,683.23
26	105.3	71,123	1,675.90	5,686.38	10,683.23
27	118.6	81,472	2,026.03	6,172.66	12,048.75

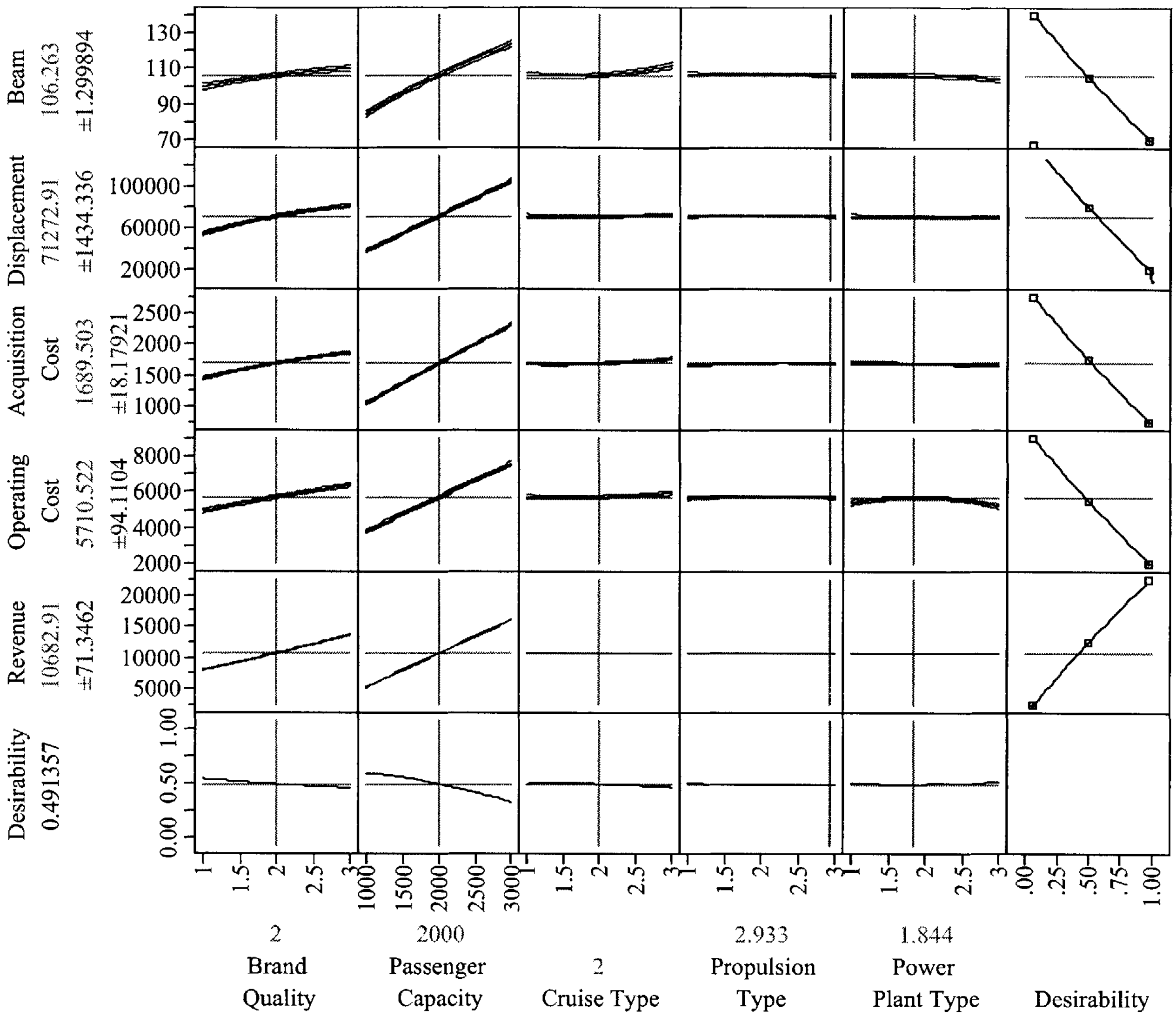


Figure 20: Prediction Profiler for Central Composite Design

The factors were all found to be statistically significant and practically important for use in the RSM. The factors Brand Quality and Passenger capacity have the most leverage on the responses, but all of the factors have enough practical importance to warrant keeping them in the model. By reducing the number of factors, the naval architect can reduce the effort required to define the design space to investigate the impact on the owner's requirements. Additionally, the Prediction Profiler in JMP allows the user to find the factor levels that produce the maximum overall desirability for the response outcome. The Desirability column defaults to a linear scale but can be adjusted by the user to highlight or diminish any particular response. The response optimizer then can be invoked to determine the level of factors.

In order to allow the designer to investigate all possible outcomes, JMP has another graphical interface, called the Contour Plot, which shows the response surface with respect to any two factors, two at a time.

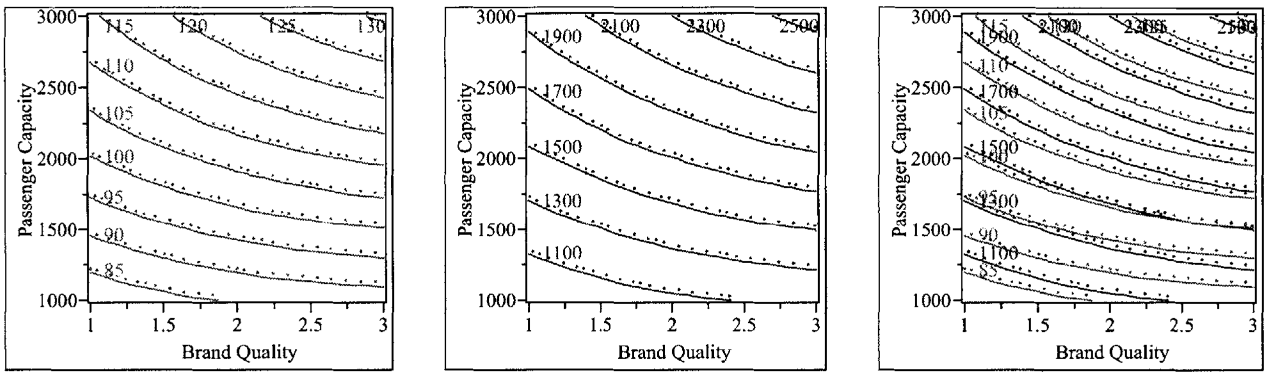


Figure 21: Contour Plot of Beam (left), Acquisition Cost (middle), and Combined (right)

As an example, Figure 21 shows the incremental contours of the Beam and Acquisition Cost response surfaces with respect to Passenger Capacity and Brand Quality. Plotted side by side, these enable the designer to visualize the impact of changing input variables and seeing the resulting outcome on the owner's requirements. To further the designer's ability to explain the design possibilities to the owners, regions in the contour plot can be excluded by setting limits to the feasible region. In Figure 22, a 105 foot beam has been set as the upper limit (goal) to represent the Panamax requirement while a \$1.2 billion lower limit (threshold) and \$1.8 billion upper limit for the Acquisition Cost of three ships has been set. The white, un-shaded, region represents the constrained feasible design space; combining the two requirements provides the user with a new, constrained feasible region.

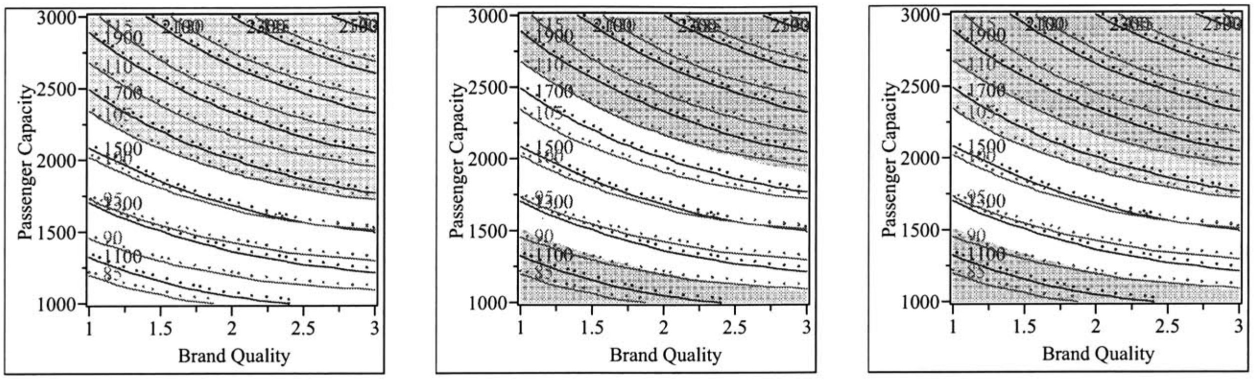


Figure 22: Threshold and Goal Limits on Contour Plots

It is with these steps that a designer can break down a plethora of data to singular regions of analysis; enabling the decision makers (owners, prospective investors) to better understand their preference impact to the overall design. Furthermore, it is with this information that a ship owner can decide on which path to take to make their business a more competitive one.

Each contour can be set to represent an edge to a variable that is used for decision making. For example, in Figure 22, if a decision maker were limited to a 105 foot beam and $1500 Million acquisition cost, it can be seen that the feasible region for decision making is the white space in the plot – which is the region over which the Brand Quality and Passenger capacity can be varied to look for alternative designs.

The Pareto optimal set of solutions is that which is along the response surface contour line that constrains the feasible region, and it is this line that defines the subset of feasible solutions to use in the decision making process – thus reducing an large, multi-dimensional design space to a small number of possible outcomes along a line in that space. Any combination of Brand Quality and Passenger Capacity that maps to a point along the contour defines a possible solution that is equally optimal to any other solution along that same line – they all have the same acquisition cost, but there are variations in the BQ and PC that achieve that end. The naval architect can be confident that each possible design in the space is technically feasible, and the decision maker can select from many possible alternatives of variables and be confident of staying with a set of equally optimal outcomes from the perspective of the outcome of interest. The naval architect, interacting dynamically with the owners, can work out a final solution that can be checked against all outcomes simultaneously, and with the knowledge that each outcome is optimal. The process continues until the owners are satisfied that they have all of their concerns met, and that they have defined their preferred solution.

Page Intentionally Left Blank

CHAPTER 5: CONCLUSIONS

The case study demonstrated a straightforward alternative to the traditional design spiral that, paired with a practical graphical interface like JMP, allows the user to evaluate multiple points in a design space at any time. Through a common framework established with the literature presented in chapter 3, a designer can identify and consider every aspect of a design simultaneously in such a way as to visualize their individual influence to the system as a whole.

Previously, a naval architect had to use empirical intuitive processes at the beginning of the design and continue in a linear step-wise spiral progression to ensure that all requirements are met. Shortcomings of this method stem from the owner supplied requirements and the inability to visualize how these prerequisites define the feasible design space. MOM development paired with RSM analysis allow the user to properly develop appropriate metrics and provide potential insights into what metrics actually matter and how they play into the complete system being considered.

For the cruise industry, this process is as much a marketing tool as well as a design tool. While the asset, a ship in this case, and its target demographic are used to drive the marketing strategy, this method allows marketing and design to go hand in hand in such a way that all factors are tweaked to maximize the goal at hand – whether it be to dominate market penetration, raise profit margins, lower operational expenses, or a combination thereof.

APPLICATIONS FOR IMPLEMENTATION

The case study used the simplest of examples to demonstrate the ease of use of this methodology. The system was, at best, a microcosm of existing market and demographic trends; it was intentionally chosen because the particular data was relatively readily available and was used as a check for the synthesis model. In practicality, design requirements for the cruise industry are much more complicated. Applying this framework to a more sophisticated design set will be discussed. Additionally, Rational Decision Making and Uncertainty considerations will be addressed.

UNIFIED TRADEOFF ENVIRONMENT

The heart of a cruise line operation deals with the understanding of their clientele, what ports they wish to visit, and what amenities they wish to have while doing so. Existing and emerging technology continually affects the design of a ship with respect to construction and on-board amenities. To apply response surface methodologies to the entire cruise system, three groups of factors must be incorporated: "concept design variables, requirements, and technology K-factors." [Hootman, 2003] The first two have been previously discussed, K-factors have not. Inserted, "into the engineering model to represent a predicted notional degradation or improvement to various technologies [and market trends] based on future research and development," [Hootman, 2003] K-factors address the effect of future advances in technological capability and market awareness. The Unified Tradeoff Environment (UTE) is a term coined by the ASDL to describe the combination of these three groups of factors. It can be best illustrated by placing three prediction profilers (one for each group) side by side (Figure 23):

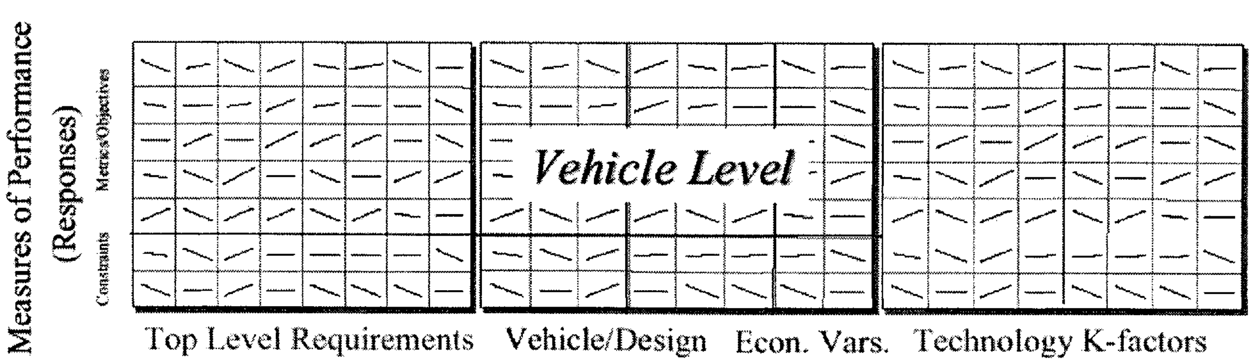


Figure 23: The Unified Tradeoff Environment [Soban and Mavris, 2000a]

By examining the design alternatives in such a way, it enables the user to simultaneously observe the effects of each factor set on the system constraints and responses. To develop the UTE, the designer must first create a baseline set of each of the factors. By holding the K-factors and design variables constant at their baselines, the requirements space is formulated. To develop the design variable space, the user would hold the K-factors and requirements at baseline. For the K-factor space, the design variables and requirements would be held at their baselines.

> The three sets of regression equations are then aggregated into an overall expression for changes in desirements as a function of requirements, design/economic variables, and technology improvements...For the purposes of visibility and creation of decision support tools, it is assumed that the three sets of RSE inputs are independent (and thus un-correlated) from each other. Thus, their contributions are considered to be additive. However, subsequent confirmation testing is employed to check the validity of this assumption. If some variables are dependent, one possible solution is to identify mixes of design variables, requirements, and technology factors that are independent and then create three "mixed" sets of RSEs. [Mavris and DeLaurentis, 2000]

UTE sets the groundwork for developing an expanded effectiveness analysis. The designer can develop a UTE set for every facet of the system and combine each set within the other in a hierarchical fashion, creating a 'system of systems' approach (See Figure 24). For the cruise line, one UTE set would be formulated to address areas of deployment (Theater Level); taking into consideration available ports, their dimensions, their ability to absorb an influx of tourists, available tourist attractions, weather, etc. The next set would be demographics (Mission Level), where various requirements depending on the age bracket of the client are considered. Finally, once these two sets are developed, the ship UTE (Vehicle Level) can be created. This is where the environmental, safety, and design constraints are applied.

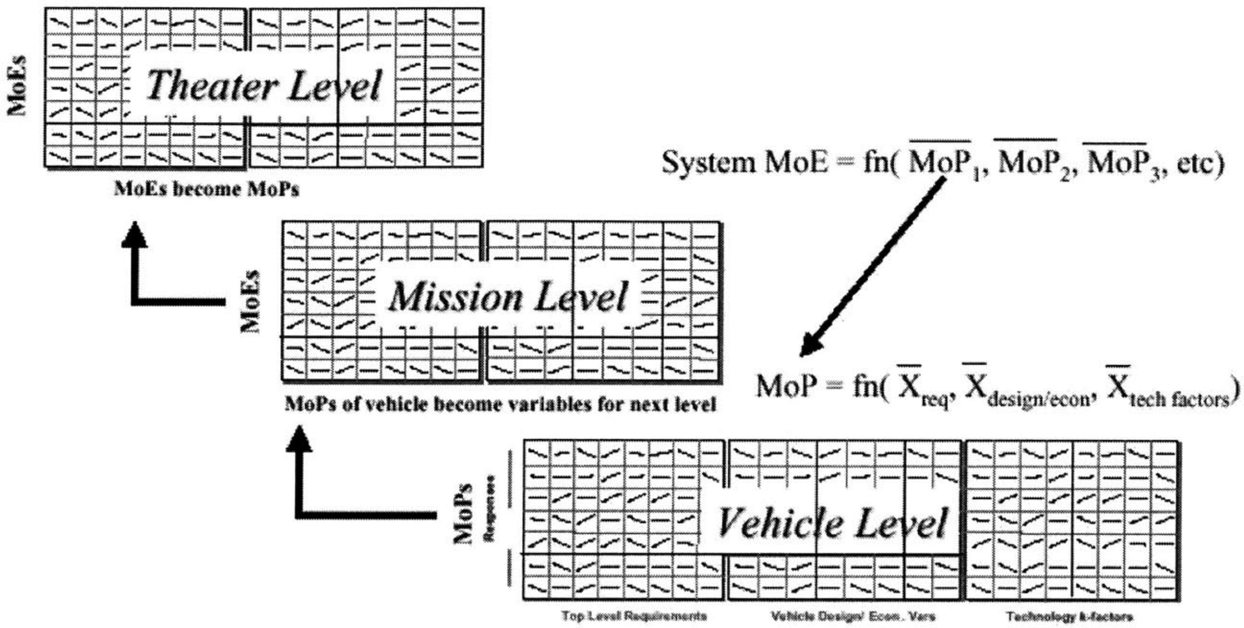


Figure 24: Systems of Systems Approach [Soban and Mavris, 2000a]

All these UTE sets are not easily quantifiable and, in most cases, are based on human preference. When the human condition is taken into consideration, design analysis takes on a different dynamic. Kahneman and Tversky, two Nobel Prize winning researchers in the area of RDM, will be extensively used to address the human equation.

RATIONAL DECISION MAKING AND GROUPS

They have exhibited in their research that illogical human behavior can occur in systematic patterns. They developed the Prospect Theory, an "alternative theory of choice…which value is assigned to gains and losses rather than to final assets and in which probabilities are replaced by decision weights." [Kahneman and Tversky, 1979] In this theory, they brought to light the human tendency, "to overweight outcomes that are considered certain, relative to outcomes which are merely probable." [Kahneman and Tversky, 1979] Coined the 'certainty effect' they noted that:

> In the positive domain [positive outcomes, i.e. gains], the certainty effect contributes to a risk averse preference for a sure gain over a larger gain that is merely probable. In the negative domain [negative outcomes, i.e. losses], the same effect leads to a risk seeking preference for a loss that is merely probable over a smaller loss that is certain. [Kahneman and Tversky, 1979]

They concluded that people demonstrate, "risk aversion for gains and risk seeking for losses of high probability... [and] risk seeking for gains and risk aversion for losses of low probability." [Kahneman and Tversky, 1979] Conversely, they also observed the 'reflection effect' whereby changing positive prospects to zero (reflecting the gains into losses), the user preference is reversed. Implying that, "risk aversion in the positive domain is accompanied by risk seeking in the negative domain.' [Kahneman and Tversky, 1979] The last item of their research worth noting is their proposal that decisions are better modeled as being reference dependent.

> The carriers of value are changes in wealth or welfare, rather than final states. This assumption is compatible with basic principles of perception and judgment. Our perceptual apparatus is attuned to the evaluation of changes or differences rather than to the evaluation of absolute magnitudes. [Kahneman and Tversky, 1979]

Years later, they revised their findings into the 'Cumulative Prospect Theory' modifying the mathematical formulation of their model to a continuous model. Composed of, "a value function that is concave for gains, convex for losses, and steeper for losses than for gains...[and] a nonlinear transformation of the probability scale, which overweighs small probabilities and underweighs moderate and high probabilities." This value function exhibited the following characteristics [Kahneman and Tversky, 1979]:

- Reference Dependence – "the carriers of value are gains or losses defined relative to a reference point"
- Loss Aversion – "the function is steeper in the negative than in the positive domain; losses loom larger than corresponding gains"
- Diminishing Sensitivity – "the marginal value of both gains and losses decreases with their size"

The diminishing sensitivity characteristic "drives the weighting function to be more concave near zero and move convex near one." [Hootman, 2003]

> ...the impact of a given change in probability diminishes with its distance from the boundary. For example, an increase of .1 in the probability of winning a given prize has more impact when it changes the probability of winning from 0.9 to 1.0 or from 0 to 0.1 than when it changes the probability of winning from 0.3 to 0.4 or form 0.6 to 0.7. [Kahneman and Tversky, 1979]

All three properties are best shown in the following figure:

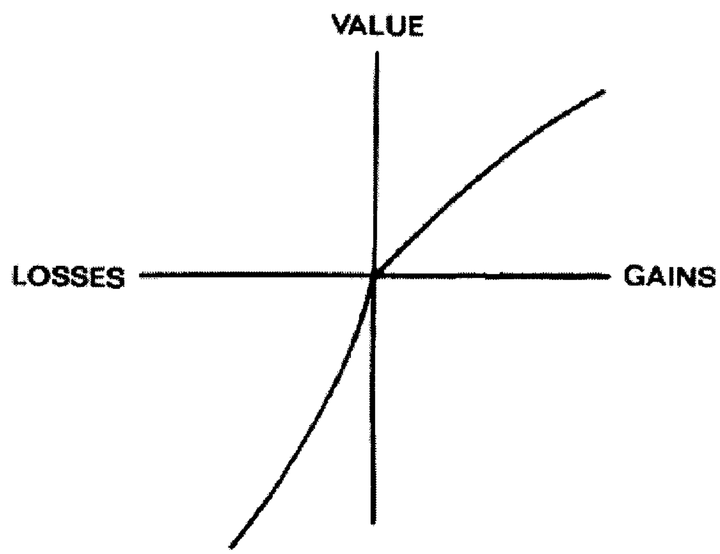


Figure 25: Prospect Theory Value Function [Kahneman and Tversky, 1979]

In the subject of heuristics, Kahneman and Tversky observed that people rely on a limited number of principles to help them solve complex operations by reducing them to simpler discernable tasks. Identifying the following primary heuristics [Hootman, 2003]:

- Representativeness - insensitivity to prior probability of outcomes, predictability, and sample size
- Availability - biases of retrievability of circumstances, imaginability, and illusory correlation
- Adjustment and Anchoring - insufficient adjustment "usually employed in numerical prediction when a relevant value is available" [Kahneman and Tversky, 1979]

They concluded that most people failed, "to infer from lifelong experience such fundamental statistical rules as regression toward the mean, or the effect of sample size on sampling variability." [Kahneman and Tversky, 1979]

It should also be noted that all of their research was based on individuals making decisions which is not normally the case. The design of a system is more often than not a group decision which adds yet another dynamic to RDM. Group decision making presents the unusual dilemma in that there, "is no way to define a group utility function, either by combining individual utilities or by assessing group preference as a whole, as shown by Arrow's Impossibility Theorem." [Whitcomb, 1998b] Arrow's Theorem states that [Sage, 1977]:

> **Axiom 1:** Any two alternatives must be comparable, i.e., between alternatives x_1 and x_2 either x_1 is preferred over x_2 or x_2 is preferred over x_1, or both x_1 and x_2 are equally acceptable.
> **Axiom 2**: All comparisons between alternatives x_1, x_2 and x_3 are transitive, that is, given x_1 is not preferred over x_2 and x_2 is not preferred over x_3, then x_1 is not preferred over x_3.

And must satisfy five conditions summarized as [French, 1988] [Sage, 1977]:

1. Basic conditions
2. Positive association of social and individual values
3. Independence of irrelevant alternatives
4. Condition of citizens' sovereignty
5. Condition of nondictatorship

As mentioned earlier these requirements, "prove to be mutually exclusive, thus preventing the determination of utility function that satisfies all stakeholders when more than one decision maker is involved." [Hootman, 2003]

One particular problem that arises through the use of these methods for group decision making is the possible violation of Arrow's Impossibility Theorem; however, when used pragmatically, the major benefit of this is, "the ability to incorporate the decision maker's nonlinear preferences towards each of the objectives into the decision process." [Whitcomb, 1998a]

Some RAND studies used the 'Delphi Method' to address this possible group decision making problems. "Intended to minimize the effects of dominant individuals, irrelevant communications, and group pressure encouraging conformity," [Don, 2002] the Delphi Method uses the following key features for obtaining guidance and judgment from groups:

- Group opinion is defined as an appropriate statistical aggregate of the individual opinions in the final round.
- The opinions of the members of the group are obtained in such a way that the responses are anonymous.
- Iterations are obtained by conducting systematic controlled feedback between decision rounds. [Hootman, 2003]

One concern with this method is that it is possible that none of the decision makers would approve of the outcome. Additionally, although aggregation of data does allow the decision maker to compare choices with a smaller number of measures, it also adds the risk that some information, along with what may be weaned by it, might be lost in the process.

To deal with this specific problem, the Air Force AoA Guidebook recommends using the Delphi Method only when it meets the following [OAS, 2000]:

- The aggregation arises naturally from relationships among the MOEs.
- The significance of the aggregates is clear.
- The aggregates tell a clearer story than the individual MOEs.

UNCERTAINTY CONSIDERATIONS

In the case of decision weights, "given [their] subjective and abstract nature..., there is no attempt to seek [a] definitively "right" set of weights, but rather to explore how different assumptions and weightings affect the relative ranking of options." [Zanini, 2002] For the cruise industry, these decision weights are highly subjective and in no means easily forecasted. Ship owners have used their years of historical data to provide ship amenities that mitigate the myriad of incompatible preferences that many passengers have. Some passengers want rest and relaxation, others music, fun and sun, while others want games and activities. For limited spaces this leads to an overlapping that can potentially conflict if the improper demographic is chosen for the design requirements of the ship. Uncertainty comes into this foray to allow the designer to take marketing data (requirements) and use it in the entire concept design framework where the goal is not to develop one single optimum but to illustrate the relationships that have the greatest impact on the design so that they can be used to create a better design.

Monte Carlo simulations are commonly used to introduce uncertainty into the analysis. Randomly selecting values for variables by giving each variable a probability distribution over a specified range, the simulation performs at least 1,000 to 10,000 iterations with inputs chosen, "at a frequency consistent with the probability distribution to simulate the probability distribution well." [Crystal Ball, 2000] Understandably, this process can be very resource intensive and has not been used until recently with the proliferation of high power desktop computers. As such, in earlier work, probabilistic analyses were used arguing that, "the underlying assumption in all of the analyses presented is that probability results are useful and meaningful." [Rains, 1994]

Another method used is the real options approach. "Real options involve the 'right but not the obligation' to take a course of action," [Gregor, 2003] providing the option of reevaluation as uncertainties are resolved. This leads to determining, "the value of these options and...the best types and amount if flexibility to design into naval systems in order to maximize the value of the system over time under uncertain conditions." [Gregor, 2003]

Summary of Applications

Taking into consideration all the methods described in this research, this thesis has laid a foundation for a decision making framework for initial cruise ship design. A method for the development of appropriate metrics (MOMs) with uncertainty analysis also needing to be considered has been proposed. A method of how to visualize (and therefore analyze) these metrics (RSM) has been demonstrated. Developing a new framework of what a true design space (systems and super-systems) has also been discussed. By integrating all these processes into one super-framework the designer is given the freedom and flexibility to define and continually develop the system, super systems, and all pertinent metrics simultaneously.

Recommendations for Future Work

To further improve on this thesis many avenues can be explored, starting with a serious analysis of the UTE framework in the cruise ship industry. Traditional market research has relied on target demographics' preferences of ship amenities and destinations without much analysis on where their needs fit in the overall design system. Because of the robust nature of the cruise market and relative untapped markets worldwide, there has not been much need to do so. Those days are fast approaching to a close as markets begin to be saturated. A systematic analysis on a global scale could be worked on, such that metrics could be developed to gauge marketability of every available port of call based on local and foreign tourism and the travel time needed to meet a ship at these ports. Concurrently, each port of call could be gauged with additional metrics such as pricing for fuel, water, and food as well as their ability to store parts and their access to any repair facilities. The idea being that downtime due to unforeseen circumstances can be mitigated if there are enough ports of call that can support a ship sufficiently on a moment's notice, an issue that is beginning to surface as bigger ships with newer technology are entering in the marketplace. Organizing all these metrics together would provide a prospective ship owner a true gauge of the desirability of each port of call based on how much a demographic is interested in it as well as what the real and potential cost of sailing to it might be.

Furthermore on the UTE framework would be how a ship is managed during its voyages. Currently segregated into Hotel, Deck, and Engine functions, not much analysis has been placed on how these three functions correlate within a ship system; mainly due to the fact that a ship's organization has not really changed that much in the last 100 years. The only new developments have been in the increases in ship size and the implementation of the computer for the day to day operations of a ship. Many cruise companies have not delved into data mining the way casinos have. Ironically, ships have more of a captive audience than most casino chains do and yet the casinos have a much better understanding of what attracts their clientele. Data mining can be implemented to develop better metrics such that interior design and amenities can be better tailored for passenger enjoyment (and greater spending) while maintaining the strictest of safety standards.

Taking both global and internal metrics in hand, the UTE framework can help the owner decide what ship to build based on what market he / she wishes to enter. Add this to the dynamics of a cruise fleet and the potential that economies of scale would afford a large cruise operator is the luxury of mitigating many of the risks taken by smaller operators. Conversely, a smaller operator would have a better market placement and would also mitigate some of the risks associated with a smaller fleet.

Finally, one major weakness in this case study was in the lack of an appropriately designed synthesis model due to the highly proprietary information needed to develop it. Newer vessels are designed not with a specific hull form in mind; rather, once the basic layout has been agreed upon, the hull is manipulated around the space. Due to the availability of powerful computers, hulls now have shapes that were not available even 10 years ago; allowing for designs of similar gross registered tonnage to be quicker, more nimble, and more fuel efficient. A naval architect, through the help of the shipyard, can better develop the synthesis model so, as newer technology is developed, it can more accurately provide statistical measurements that would facilitate the quantification of the desired metrics by the designer and ship owner.

Works Cited

"Crystal Ball 2000 Users Manual," Decisioneering Inc. [Crystal Ball, 2000]

"JMP: The Statistical Discovery Software," 2002 SAS Institute Inc. [JMP, 2002]

Boyd, Lydia. Brief History of the Passenger Ship Industry. 1999. John W. Hartman Center for Sales, Advertising, and Marketing History, Duke University. Date of Access: March 31, 2006 http://scriptorium.lib.duke.edu/adaccess/ship-history.html [Boyd, 1999]

Brown, Kevin W., "Measuring the Effectiveness of Weapons Systems in Terms of System Attributes," Naval Postgraduate School Thesis, 1995. [Brown, 1995]

Builder, Carl H., "The Masks of War: American Military Styles in Strategy and Analysis," RAND, 1989. [Builder, 1989]

Business Research & Economic Advisors. "The Contribution of the North American Cruise Industry to the U.S. Economy in 2003." Exton: August 2004. [BREA, 2004]

Crary, Michael A., "Measuring Surface Combatant Fleet Effectiveness," Naval Postgraduate School Thesis, September 1999. [Crary, 1999]

Cruise Lines International Association. "Cruise Lines International Association 2005 Spring Overview." New York City: 2005. [CLIA, 2005b]

Cruise Lines International Association. "2005 Cruise Industry Source Book." New York City: 2005. [CLIA, 2005a]

DARCOM, "Engineering Design Handbook, Army Weapon Systems Analysis, Part Two," DARCOM P 706-102, October 1979. [DARCOM, 1979]

deNeufville, Richard, "Applied Systems Dynamics," McGraw-Hill, 1990. [deNeufville, 1990]

Don, Bruce W., Thomas Herbert, and Jerry Sollinger, "Future Ground Commanders' Close Support Needs and Desirable System Characteristics," RAND, MR-833-OSD, 2002. [Don, 2002]

French, S., "Decision Theory: An Introduction to the Mathematics of Rationality," Elis Horwood Limited, Great Britain, 1988. [French, 1988]

Frits, A., N. Weston, C. Pouchet, A. Kusmik, W. Krol, Jr., and D. N. Mavris, "Examination of a Torpedo Performance Space and its Relation to the System Design Space," American Institute of Aeronautics, 2002. [Frits *et al*, 2002]

Goggins, David A. "Response Surface Methods Applied to Submarine Concept Exploration," MIT Thesis, 2001. [Goggins, 2001]

Green, John M., "Establishing System Measures of Effectiveness," Proccedings of the AIAA Biennial National Forum on Weapon System Effectiveness, March 2001. [Green, 2001a]

Green, John M., "Modeling the Ship as a Weapon System," 69th MORS Symposium, Annapolis, MD, June 2001. [Green, 2001b]

Green, John P. and Bonnie W. Johnson, "Towards a Theory of Measures of Effectiveness," 2002 Command and Control Research and Technology Symposium, Monterey, CA, June 11-13, 2002. [Green and Johnson, 2002]

Gregor, Jeffrey Allen, "Real Options for Naval Ship Design and Acquisition: A Method for Valuing Flexibility Under Uncertainty," MIT Thesis, June 2003. [Gregor, 2003]

Han, Suk, Jill Krutick, and Elizabeth Osur. "Carnival Corp (CCL): First through Fourth Smith Barney Tutorial; Demystifying the Cruising Cost Structure." Citigroup Investor Update. New York: 8 May 2003. [Citigroup, 2003]

Hockberger, William A., "Total System Ship Design in a Supersystem Framework," *Naval Engineers Journal*, May 1996. [Hockberger, 1996]

Hollingsworth, P., Mavris, D.N., "A Method for Concept Exploration of Hypersonic Vehicles in the Presence of Open & Evolving Requirements," 5th World Aviation Congress and Exposition, San Diego, CA, 2000. [Hollingsworth and Mavris, 2000]

Hootman, John C. "A Military Analysis and Decision Making Framework for Naval Ship Design and Acquisition." MIT Thesis, 2003. [Hootman, 2003]

International Council on Systems Engineering, "Systems Engineering Handbook, Version 2.0," International Council on Systems Engineering, July 2000. [INCOSE, 2000]

Islam, R., M. P. Biswal, and S. S. Alam, "Clusterization of Alternatives in the Analytic Hierarchy Process," Military Operations Research, Vol. 3, No. 1, 1997. [Islam, 1997]

Kahneman, Daniel, and Amos Tversky, "Prospect Theory: An Analysis of Decision Under Risk," Econometrica, Vol. 47 Issue 2, 263-292, 1979. [Kahneman and Tversky, 1979]

Kowalski, Norman w. *et al*, "Open Systems Engineering Effectiveness Measurement," Software Technology Conference, April 1998. [Kowalski *et al*, 1998]

Leite, M. J., and D. R. Mensh, "Definition of Evaluation Criteria for System Development Acquisition Modeling and Simulation," *Naval Engineers Journal*, January 1999. [Leite and Mensh, 1999]

Levander, Kai. "Cruise Ship Design." Class notes, TKK luento: December, 2005 [Levander, 2005]

Malerud, Stein, *et al*, "Assessing the Effectiveness of Marine C2 Systems – Measures of Merit," 2000 Command and Control Research and Technology Symposium, Monterey, CA, 2000. [Malerud *et al*, 2000]

Mason, Douglas, "Identifying Measures of Effectiveness for Marine Corps C4I Systems," Naval Postgraduate School Thesis, 1995. [Mason, 1995]

Mavris, D. M., and D. DeLaurentis, "Methodology for Examining the Simultaneous Impact of Requirements, Vehicle Characteristics, and Technologies on Military Aircraft Design," 22nd Congress of the International Council on the Aeronautical Sciences (ICAS), Harrogate, England, August 27-31, 2000. [Mavris and DeLaurentis, 2000]

Maxtone-Graham, John. "Queen Mary 2: The Greatest Ocean Liner of Our Time." New York: April 28, 2004 [Maxtone-Graham, 2004]

MIT Naval Construction and Engineering Program (XIII-A), "Lecture #2: Effectiveness Estimating," Principles of Naval Ship Design Class Notes, 2001. [XIII-A, 2001]

Mustin, John B., "Evaluating Carrier Battlegroup Anti-Air Warfare Capability in a Computer Aided Exercise," Naval Postgraduate School Thesis, September 1996. [Mustin, 1996]

OAS – Office of Aerospace Studies, "AoA Handbook: A Guide for Performing an Analysis of Alternatives (AoA)," Office of Aerospace Studies, Air Force Materiel Command (AFMC) OAS/DR, June 2000. [OAS, 2000]

Oldendorf, Sven. "The Cruise Industry and its Outlook 2004-2007: Innovation is the story." DVB Research & Consulting. Netherlands: January 2004. [DVB, 2004]

Oliver, David W., Timothy P. Kelliher, and James G. Keegan, Jr., "Engineering Complex Systems with Models and Objects," McGraw-Hill, 1997. [Oliver *et al*, 1997]

Price, Shelly L., "Integrating Response Surface Methods and Uncertainty Analysis into Ship Concept Exploration," MIT Thesis, 2002. [Price, 2002]

Psallidas, Konstantinos, "Forecasting System Level Impacts of Technology Infusion on Conventional Submarine Design," MIT Thesis, 2003. [Psallidas, 2003]

Rains, Dr. Dean A., "Fleet Mix Mission Effectiveness Analysis," *Naval Engineers Journal*, January 1999. [Rains, 1999]

Rains, Dr. Dean A., "Methods for Ship Military Effectiveness Analysis," *Naval Engineers Journal*, March 1994. [Rains, 1994]

Roedler, Garry J. and Cheryl Jones. "Technical Measurement – A Collaborative Project of PSM, INCOSE, and Industry." INCOSE-TP-2003-020-01: December 27, 2005 [INCOSE, 2005]

Sage, A. P., "Methodology for Large Scale Systems," McGraw-Hill, New York, 1977. [Sage, 1977]

Soban, Danielle S., and Dimitri N. Mavris, "Formulation of a Methodology for the Probabilistic Assessment of System Effectiveness," Aerospace Systems Design Laboratory, Georgia Institute of Technology, 2000. [Soban and Mavris, 2000a]

Systems Engineering Process. DRM Associates. Date of Access: March 31, 2006 <http://www.npd-solutions.com/se.html> [DRM, 2006]

Whalen, Todd, "Optimal Deadrise Hull Analysis and Design Space Study of Naval Special Warfare High Speed Planing Boats," MIT Thesis, 2002. [Whalen, 2002]

Whitcomb, Cliff, "A Prescriptive Production-Distribution Approach for Decision Making in Product Design Engineering," University of Maryland PhD Thesis, 1998. [Whitcomb, 1998b]

Whitcomb, Cliff, LCDR, USN, "Naval Ship Design Philosophy Implementation, *Naval Engineers Journal*, January 1998. [Whitcomb, 1998a]

Willard, Daniel, "Army – Cost-Effectiveness, CAIV, and Knee of the Curve," Defense Acquisition Deskbook, Defense Acquisition University, 2002. [Willard, 2002]

Zanini, Michele, "Italy's All-Volunteer Army: An Analytical Framework for Understanding the Key Policy Issues and Choices During the Transition," RAND, RGSD-162, 2002. [Zanini, 2002]

Zink, P.S., Mavris, D.N., Raveh, D.E., "Integrated Structural/Trim Optimization for Active Aeroelastic Wing Technology," 8th AIAA/NASA/USAF/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Long Beach, CA, 2000. [Zink *et al*, 2000]

Works Consulted

"Genesis of a Queen – one year on." The Naval Architect January, 2002: 5-9.

Ackerman, Brian M. "Modular Gas Turbine Propulsors: A Viable Alternative for Today's Merchant Fleet." Marine Technology. 40.2 (2003): 106-125.

Bretz, Elizabeth A. "Super Conductors on the High Seas: New ship motors propel a quiet revolution." IEEE Spectrum January, 2004: 60-67.

Brown, Alan and Juan Salcedo, "Multiple-Objective Optimization in Naval Ship Design," *ASNE Day 2002*, April, 2002.

Business Research & Economic Advisors. "The Contribution of the North American Cruise Industry to the U.S. Economy in 2004." Exton: August 2005.

Chauvel, Alain-Michel. Managing Safety and Quality in Shipping. London, England: 1997

Creveling, C.M., J.L. Slutsky and D. Antis Jr. Design for Six Sigma in Technology and Product Development. Upper Saddle River: Bernard Goodwin, 2003.

Defense Systems Management College, "Systems Engineering Fundamentals," Defense Acquisition University Press, December 2000.

Garin, Kristoffer A. "Devils on the Deep Blue Sea – The dreams, schemes and showdowns that built America's cruise-ship empires." New York: 2005

Garzke, William H., Jr. and George Kerr, "A New Warship Design Strategy – A Perspective," *SNAME Transactions*, 1985.

General Accounting Office, "Best Practices: Better Matching of Needs and Resources Will Lead to Better Weapon System Outcomes (GAO-01-288)," United States General Accounting Office, March 2001.

Goode, Erica, "On Profit, Loss and the Mysteries of the Mind," *The New York Times Online*, 11/04/02.

Grier, James B., MAJ, USAF, LCOL T. Glenn Bailey, USAF, and COL Jack A. Jackson, USAF, "Response Surface Modeling of Campaign Objectives Using Factor Analysis," Military Operations Research, Vol. 4, No. 2, 1999.

Hämäläinen, Ramo and Jaap van Heerd. "Hydrodynamic Development for a Large Fast Monohull Passenger Ferry." Kvaerner Masa-Yards, Inc. & Maritime Research Institute report. 2005

Institute of Aeronautics, 2002.

Ito, Hideto, "A Study of the Measures of Effectiveness for the JMSDF AEGIS Destroyer In a Littoral, Air Defense Environment," Naval Postgraduate School Thesis, 1995.

Kahneman, Daniel, Jack L. Knetsch, and Richard H. Thaler, "Anomalies: The Endowment Effect, Loss Aversion, and Status Quo Bias," The Journal of Economic Perspectives, Vol. 5, Issue 1, 193-206, 1991.

Keane, Robert G., Jr. and Barry F. Tibbitts, "A Revolution in Warship Design: Navy-Industry Integrated Product Teams," *SNAME Journal of Ship Production*, November 1996.

Keeney, R., and Raiffa, H., "Decisions with Multiple Objectives," Wiley, New York, 1976.

Keus, Hans A., "A Framework for Analysis of Decision Processes in Teams," 2002 Command and Control Research and Technology Symposium, Monterey, CA, June 11-13, 2002.

Klein, Ross A. Cruise Ship Blues - The underside of the cruise industry. Gabriola Island, Canada:2002

Knox, Jennifer. "Chapter 38: Ferries." Ship design and construction /written by an international group of authorities. Ed. Thomas Lamb. Jersey City, New Jersey: SNAME, 2003-2004 Pages 1-31.

Koch, Patrick N., Dimitri Mavris, and Farrokh Mistree, "Multi-Level, Partitioned Response Surfaces for Modeling Complex Systems," American Institute of Aeronautics, 1998.

Leopold, Reuven, "U.S. Naval Ship Design: Platforms vs. Payloads," *U.S. Naval Institute Proceedings*, August 1975.

Levander, Kai. "Chapter 37: Passenger Ships." Ship design and construction /written by an international group of authorities. Ed. Thomas Lamb. Jersey City, New Jersey: SNAME, 2003-2004 Pages 1-39.

Meyer, Jan, "A Risk-Based Approach to Optimal Margins in Ship Design," MIT Thesis, 2002.

Mine Warfare Center, "MCM Measures of Effectiveness (MOE'S) and Measures of Performance (MOP'S)," Unclassified, A-2G-2758.

Miorelli, Joseph. "Site Team Management for Construction of a Large Modern Cruise Ship." Marine Technology. 40.3 (2003): 189-200.

Odlyzko, Andrew. "Privacy, Economics, and Price Discrimination." University of Minnesota: July 27, 2003.

Pace, Dale K., Dr., "Scenario Use in Naval System Design," *Naval Engineers Journal*, January 1986.

Rains, D. A., "An Assessment of Naval Combatant Propulsors Using Ship Sensitivity and Military Effectiveness Analysis," *SNAME's Propellers '88 Symposium*, September 1988.

Rains, Dr. Dean A, "A Systems Engineering Approach to Surface Combatant Design Issues," *Naval Engineers Journal*, May 1990.

Rains, Dr. Dean A., "Combatant Ship Design Guidance Through Mission Effectiveness Analysis," *Naval Engineers Journal*, May 1984.

Saaty, T., "The Analytical Hierarchy Process," University of Pittsburgh, 1988.

Shupp, Jeffrey K., "The Mission Analysis Discipline: Bringing Focus to the Fuzziness about Attaining Good Architectures," Proceedings of the 13th Annual International INCOSE Symposium, June 2003.

Soban, D.S., Mavris, D.N., "Methodology for Assessing Survivability Tradeoffs in the Preliminary Design Process," 5th World Aviation Congress and Exposition, San Diego, CA, 2000.

Soban, Danielle S., and D. N. Mavris, "Use of Probabilistics in Campaign Analysis," SAE, 2001.

The Steamship Mutual Underwriting Association (Bermuda) Limited. 2005/2006 Rules – Classes 1 & 2 and List of Correspondents. Hamilton, Bermuda: 2005

Thaler, Richard H., Amos Tversky, Daniel Kahneman, and Alan Schwartz, "The Effect of Myopi and Loss Aversion on Risk Taking: An Experimental Test," The Quarterly Journal of Economics, Volume 112, Issue 2, 647-661, 1997.

Thompson, George E., "Combat Search And Rescue (CSAR) Aircraft Effectiveness," Military Operations Research, Vol. 4, No. 4, 1999.

Tibbitts, Barry, Edward Comstock, Philip M. Covich, and Robert G. Keane Jr. "Naval Ship Design in the 21st Century," *SNAME Transactions*, 1993.

Turban, Efriam, and Morton L. Metersky, "Utility Theory Applied to System Effectiveness Evaluation," *Management Science*, Volume 17, Issue 12, Aug 1971.

Tversky, Amos and Daniel Kahneman, "Judgment Under Uncertainty: Heuristics and Bias," Science, Vol. 185, Issue 4157, 1124-1131, 1974.

Tversky, Amos and Daniel Kahneman, "Loss Aversion in Riskless Choice: A Reference- Dependent Model," The Quarterly Journal of Economics, Vol. 106, Issue 4, 1039-1061, 1991.

Tversky, Amos and Daniel Kahneman, "The Framing of Decisions and the Psychology of Choice," Science, Vol. 211, Issue 4481, 453-458, 1981. [Tversky and Kahneman, 1981]

Tversky, Amos, and Daniel Kahneman, "Advances in Prospect Theory: Cumulative Representation of Uncertainty," Journal of Risk and Uncertainty, 1992.

Tversky, Amos, Paul Slovic, and Daniel Kahneman, "The Causes of Preference Reversal," The American Economic Review, Vol. 80, Issue 1, 204-217, 1990.

Washburn, Alan R., "Search and Detection, 3rd Ed.," Institute for Operations Research and Management Sciences, 1996.

Whitcomb, Cliff and Gerard McHugh, "Asymetric Impacts of Evolving SSK Technologies on Future Naval Deployments," RINA Warship 99, Naval Submarines 6, 1999.

Zentner, Jack, P. W. G. De Beats, and D. N. Mavris, "Formulation of an Integrating Framework for Conceptual Object Oriented Systems Design," SAE International, 2002.

Page Intentionally Left Blank

APPENDICES

Page Intentionally Left Blank

APPENDIX 1: Synthesis Model (Partial)

INPUTS

Description	Variable	Value	Units	Input/Calc/ Constant	Equation/Source
Brand Quality	BRAND	1		Input	Budget:1, Premium:2, Ultra:3
Desired Number of Ships	NS	3		Input	
<u>People</u>					
Ratio of PAX / CREW	R_{PC}	2.285		Calc	Budget: 2.285, Premium: 2, Ultra: 1.4
Desired Amount of Passngrs	N_{PAX}	3000	people	Input	
Required Lower Berths	N_{LBERTH}	2520	berths	Calc	N_{PAX} * 84%
Required Crew	N_{CREW}	1103	people	Calc	N_{LBERTH} / Ratio
	N_T	4103	people	Calc	$N_T = N_P + N_C$
<u>Gross Characteristics</u>					
Ratio of GT / PAX	RGP	32		Calc	Budget:32, Premium:45, Ultra:52
Initial Dsplcmnt (Weight)	W_{DI}	49000	lton	Input	Estimate
Initial Deadweight Fraction	F_P	0.16		Constant	Empirical Estimate - range from 0.15 -0.19
Prismatic Coefficient	C_P	0.61		Input	Empirical Estimate
Midships Sctn Coefficient	C_M	0.95		Input	Empirical Estimate
Beam to Draft Ratio	C_{BT}	4.13		Input	Empirical Estimate
Displcmnt Length Quotient	C_{Disp-L}	74.8	lton / ft^3	Input	Empirical Estimate
Average Deck Height	H_{DK}	11	ft	Input	Avg height including overhead
Freebrd Depth @ midships	D_{MID}	58	feet	Input	Height at Freeboard
<u>Target Velocities</u>					
Maneuvering	V_M	6	kn	Input	
Low Speed	V_{LS}	12	kn	Input	
Intermediate Speed	V_{IS}	15	kn	Input	
Cruise Speed	V_{CS}	20	kn	Input	
Service Speed	V_{SS}	24	kn	Input	
Trial Speed (Full Power)	V_{TS}	25	kn	Input	
Cruise Type		3		Input	1 for 3/4 day itinerary, 2 for 7 day itinerary, 3 for maximum speed/range
<u>Operational Profile</u>					
Harbor	T_H	0	hours	Input	
Maneuvering <6kn (M)	T_M	0	hours	Input	
Low Sp At Sea ~12kn (LS)	T_{LS}	0	hours	Input	
Intermediate Sp At Sea ~15-16kn (IS)	T_{IS}	0	hours	Input	

INPUTS

Description	Variable	Value	Units	Input/Calc/ Constant	Equation/Source
Cruise Speed (CS)	T_{CS}	0	hours	Input	
Service Speed (SS)	T_{SS}	168	hours	Input	
Total (Should = 168 hours)		168	hours	Calc	
Amount of Round Trips	Trips	3	Trips	Inputs	
<u>Operational Range</u>					
Maneuvering <6kn (M)	OPMR	0	kn x hr	Calc	
Low Sp At Sea ~12kn (LS)	OPLSR	0	kn x hr	Calc	
Intermediate Sp At Sea ~15-16kn (IS)	OPISR	0	kn x hr	Calc	
Cruise Speed (CS)	OPCSR	0	kn x hr	Calc	
Service Speed (SS)	OPSSR	12,096	kn x hr	Calc	
Total Range	OPTOTR	12,096	kn x hr	Calc	
<u>Stores</u>					
Stores Period	T_S	28	days	Input	
<u>Machinery</u>					
Type of Propulsion	PRPLSN	3		Input	1 for Podded, 2 for Screw
Number of Propulsion Units	N_{PU}	2		Input	
Number of Auxiliary Propulsion Units	N_{APU}	2		Input	
Number of Propulsion Engines	N_{PENG}	2		Input	
Engine Type	ENG	3		Input	1 for Diesel 2 for Gas Turbine 3 for Combo (GT & Steam)
<u>Cost Constraint</u>	C_{CN}	519.08	M$	Input	C_{CN} = ((NPAX*RGP) + 50000) / 262.

Note: Linear for rule of thumb.

GROSS CHARACTERISTICS

Description	Variable	Value	Units	Input/Calc/ Constant	Equation/Source
<u>Hull Principal Characteristics</u>					
Length on Waterline	L_{WL}	868.49	feet	Calc	$100 \times (W_{D1} / C_{Disp\text{-}L})^{1/3}$
Beam	B	118.63	feet	Calc	$(C_{BT} \times V_{FL} / (C_P \times C_M \times L_{WL}))^{1/2}$
Draft	T	28.72	feet	Calc	B / C_{BT}
Depth from lifeboat deck	D_{MID}	58.00	feet	From Inputs Sheet	
<u>Hull Coefficients and Ratios</u>					
Prismatic Coefficient	C_P	0.61		From Inputs Sheet	
Midship Section Coefficient	C_M	0.95		From Inputs Sheet	
Displacement Length Ratio					
Speed Length Ratio	R_{VL}	0.85		Calc	$V_{TS} / L_{WL}^{1/2}$ (From Trial Speed Requirement)
Volumetric Coefficient	C_V	0.0026		Calc	V_{FL} / L_{WL}^3
Length to Beam Ratio	C_{LB}	7.32		Calc	L_{WL} / B
Beam to Draft Ratio	C_{BT}	4.13		From Inputs Sheet	
Length to Depth Ratio	C_{LD}	14.97		Calc	L_{WL} / D_{MID}
Displacement Length Quotient	$C_{Disp\text{-}L}$	74.8	lton / ft^3	From Inputs Sheet	
<u>Complete Principal Characteristics</u>					
Displacement (Weight)	W_{D1}	49,000	lton	From Inputs Sheet	
Displacement (Volume)	V_{FL}	1,715,000	ft^3	Calc	$V_{FL} = W_{D1} \times 35\ ft^3/lton$

DESIGN SUMMARY

Principal Characteristics			Weight Summary	
			Description	**Weight (lton)**
LWL	868.5	ft	Structure	20138.2
Beam	**118.6**	**ft**	Propulsion	721.0
Depth, Midships	58.0	ft	Command	313.0
Draft	28.7	ft	Aux Systems	7356.5
GMT	25.4	ft	Outfitting & Furnishings	6006.7
GM/B Ratio	0.214		Summary	34535.4
CP	0.61			
CM	0.95			
Trial Speed (Full Power)	25.0	knt	Design Margin	3453.5
Service Speed	24.0	knt	Lightship Weight	37989.0
Range	12096	nm	Loads	10890.9
			Full Load Weight	**48,880** **ltons**
			Full Load KG	31.79 ft
Number Main Engines	2			
Main Engine Rating	47000	hp		
SHP / Shaft or Pod	47000	hp		
Propeller Diameter	29.4	ft	Fuel Weight	6101.7 lton

			Manning	
			Crew	1103
			Passengers	3000
Maximum Margined Electrical Load	17120	kW	Total	4103
Total Area	847905	ft^2	**Total Volume**	**9,326,951** **ft^3**
			Total GT	**81,472** **GT**

Cost		
Total End Cost	701.15	M$
Total Lead Ship Acquisition Cost	712.69	M$
Total Follow Ship Acquisition Cost	656.67	M$
Total Acquisition Cost	**2,026.03**	**M$**
Total Life Cycle Cost (Undiscounted)	**6,172.66**	**M$**
Revenue		
Ticket Price	100	$/pax/day [Budget:100 (100% occ), Premium:140 (95% occ), Ultra:200 (85% occ)]
Total Yearly Sales	107.1	M$
Total Life Cycle Revenue (Undiscounted)	9639	M$
OnBoard Revenue	25	$/pax/day [Budget:25, Premium:35, Ultra:50]
Total Yearly Sales	26.775	M$
Total Life Cycle Revenue (Undiscounted)	2409.75	M$
Total Life Cycle Revenue (Undiscounted)	**12,048.75**	**M$**

Page Intentionally Left Blank

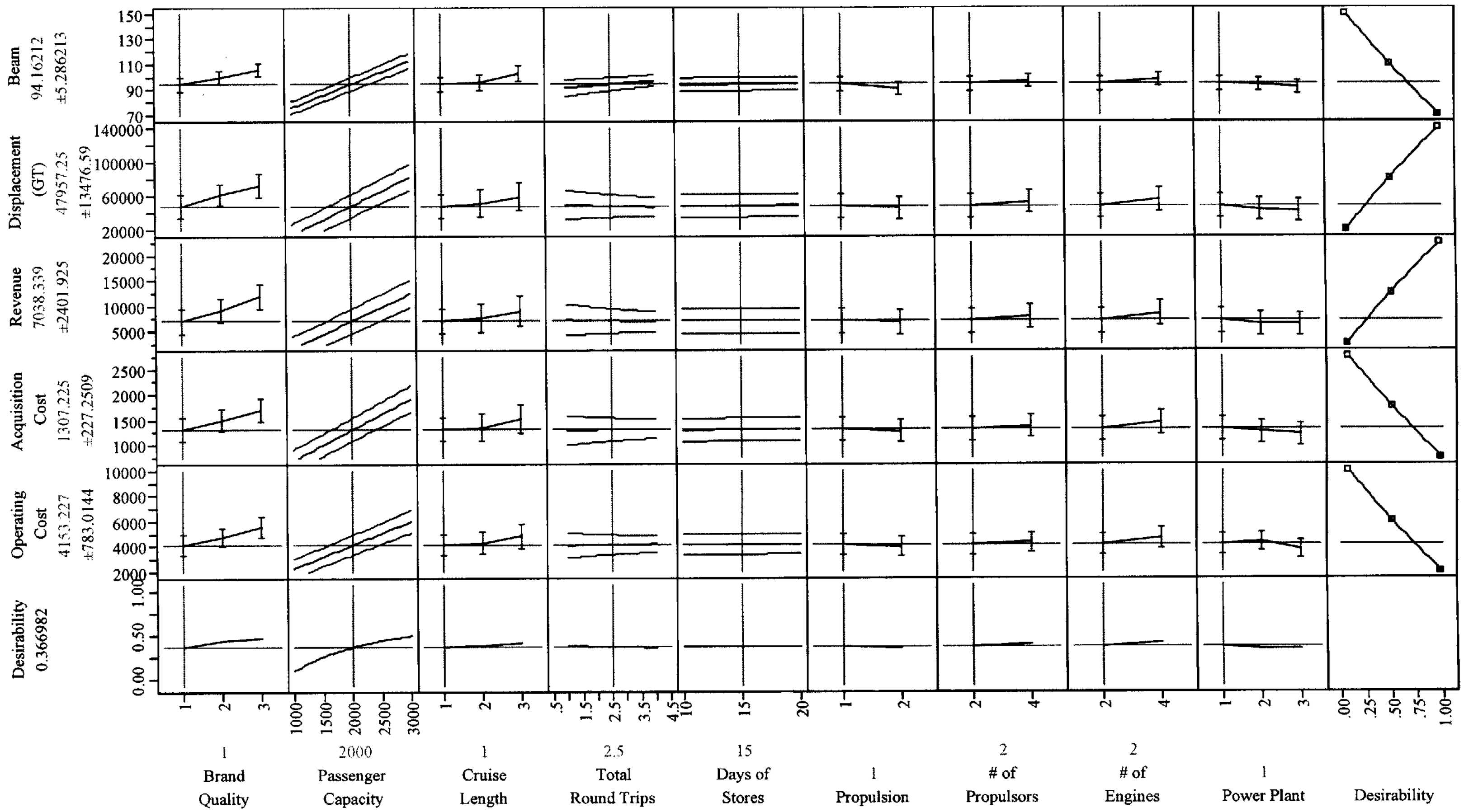
APPENDIX 2: JMP Screening Experiment Inputs

Brand Quality	Passenger Capacity	Cruise Length	Total Round Trips	Days of Stores	Propulsion	# of Propulsors	# of Engines	Power Plant	Beam	Displacement (GT)	Revenue	Acquisition Cost	Operating Cost
3	1000	1	1	7	1	2	2	1	83.8	37142	6827.63	1048.14	3581.93
1	3000	1	4	7	2	4	2	3	111.5	74719	12048.75	1823.59	5668.94
2	1000	3	1	28	2	2	2	2	85	35882	5341.61	1019.24	3680.48
3	3000	2	4	28	2	4	4	1	133.6	123626	20482.88	2651.09	8495.71
1	1000	2	1	28	1	2	4	3	77.2	26764	4016.25	861.71	2847.26
2	3000	1	4	28	1	4	2	1	124.8	106863	16024.84	2294.09	7187.55
2	3000	3	1	7	2	2	2	3	119.4	101293	16024.84	2211.59	6896.82
1	3000	2	4	28	1	2	2	2	116.8	81268	12048.75	1943.63	6460.27
2	1000	1	1	28	1	4	4	3	83.3	34831	5341.61	997.83	3266.27
2	1000	2	4	7	2	2	4	1	84	33317	5341.61	1029.6	3430.7
3	3000	3	1	28	2	4	4	3	128.3	122345	20482.88	2545.66	8115.94
3	1000	3	4	7	1	2	2	3	94.1	38768	6827.63	1146.38	3774.72
2	3000	2	1	7	1	4	4	2	119.2	101269	16024.84	2159.91	7248.83
1	3000	1	4	28	2	2	4	1	114.5	80904	12048.75	1963.24	6112.55
3	1000	2	1	28	2	4	2	2	85	39613	6827.63	1098.39	4009.6
1	1000	3	4	7	1	4	2	1	88.9	25487	4016.25	957.47	3169.65
1	1000	1	1	7	2	4	4	2	74.9	24914	4016.25	851.01	3167.33
3	3000	3	4	7	1	2	4	2	140.3	119442	20482.88	2674.66	9123.95

Page Intentionally Left Blank

APPENDIX 3: JMP Screening Experiment RSM Report (Partial)

Prediction Profiler



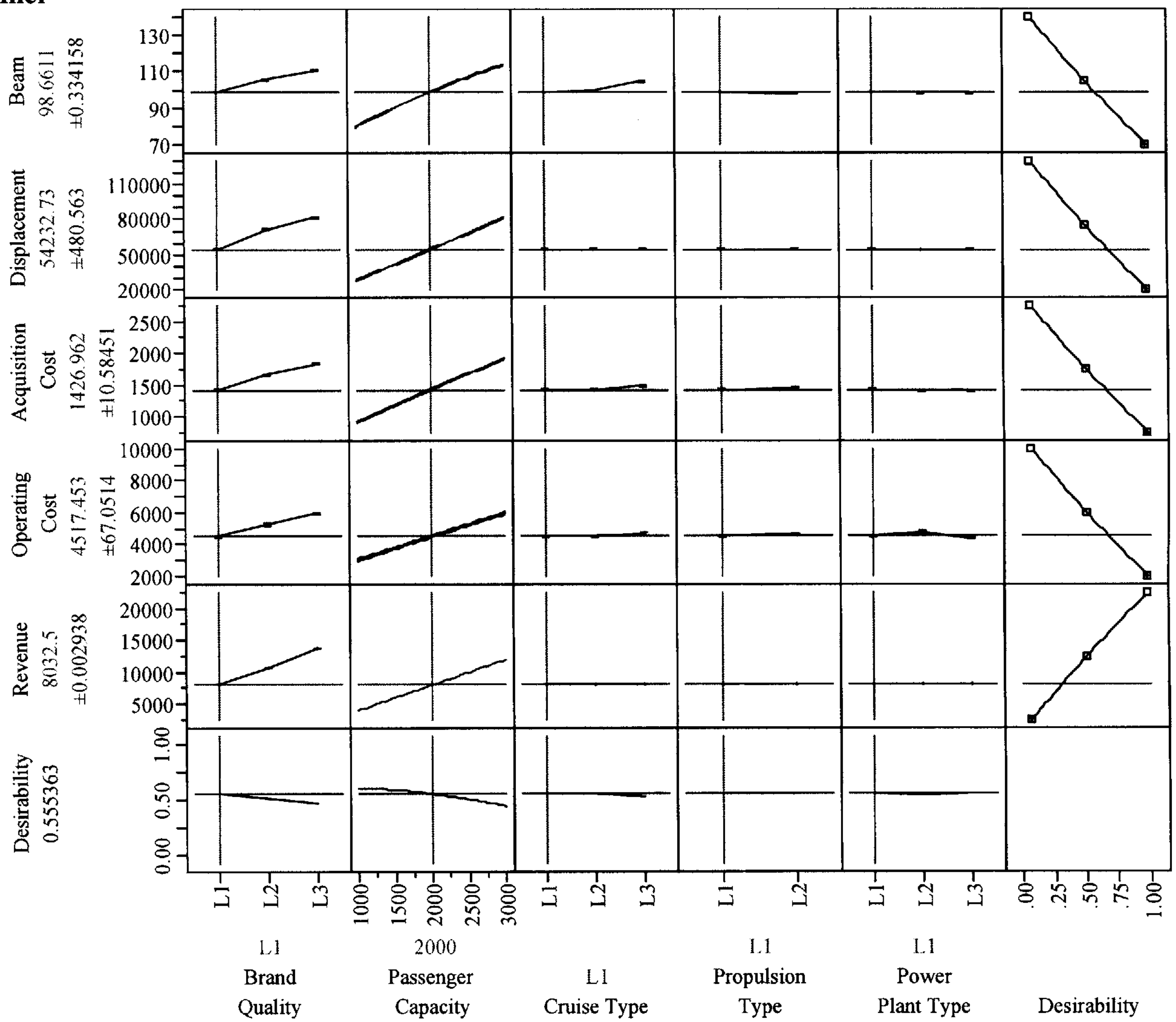
APPENDIX 4: JMP Custom Design Inputs

Brand Quality	Passenger Capacity	Cruise Type	Propulsion Type	Power Plant Type	Beam	Displacement	Acquisition Cost	Operating Cost	Revenue
L2	1000	L2	L1	L3	85	34956	1008.75	3656.47	5341.61
L1	3000	L1	L2	L3	113	81578	1939.32	5963.85	12048.75
L2	2000	L3	L1	L2	112.7	71393	1731.87	5870.18	10683.23
L1	3000	L2	L2	L1	114	81102	1959.46	6101.21	12048.75
L3	1000	L1	L2	L3	86.5	39728	1115.76	3698.55	6827.63
L2	3000	L3	L2	L1	130.1	108677	2443.83	7596.27	16024.84
L3	3000	L2	L2	L2	130.5	123140	2576.17	8767.17	20482.88
L1	3000	L3	L2	L2	121.8	82786	2070.2	6825.92	12048.75
L1	2000	L2	L2	L2	99.3	54439	1450.81	4936.79	8032.5
L2	2000	L1	L1	L3	105.4	71131	1651.8	5182.71	10683.23
L2	1000	L1	L1	L2	84.2	35692	1008.16	3650.55	5341.61
L1	1000	L2	L1	L1	80.2	27445	902.51	3014.48	4016.25
L1	1000	L2	L2	L3	78.8	26647	899.04	2957.04	4016.25
L3	3000	L1	L1	L3	129	121926	2503.53	8002.28	20482.88
L1	3000	L1	L1	L2	113.6	80813	1896.94	6317.97	12048.75
L1	1000	L3	L1	L2	87.3	27922	954.21	3454.94	4016.25
L3	1000	L2	L1	L2	88.7	40622	1111.31	4046.78	6827.63
L1	1000	L1	L1	L3	79.1	27373	884.8	2904.94	4016.25
L2	3000	L2	L1	L2	123.9	107621	2270.82	7566.26	16024.84
L2	1000	L1	L2	L1	83.5	35644	1046.36	3467.42	5341.61
L1	1000	L1	L2	L2	78.7	27340	900.76	3299.33	4016.25
L2	1000	L3	L2	L3	89.7	36095	1098.21	3536.75	5341.61
L3	3000	L1	L2	L1	128.9	122369	2561.76	8252.99	20482.88
L1	1000	L3	L2	L1	86.1	27851	990.7	3258.09	4016.25
L3	1000	L2	L2	L1	88	40767	1148.57	3849.22	6827.63
L1	2000	L1	L2	L1	97.9	54221	1447.19	4596.63	8032.5
L1	3000	L2	L1	L3	113.8	81241	1908.82	5876.62	12048.75
L2	1000	L3	L1	L1	90.8	37007	1098.99	3591.91	5341.61
L2	2000	L3	L2	L2	113.6	72113	1785.43	6018.77	10683.23
L3	1000	L3	L1	L3	92.9	40961	1154.31	3788.3	6827.63
L2	2000	L2	L2	L1	106	71186	1698.58	5393.77	10683.23
L2	3000	L3	L1	L3	128	107660	2338.53	7220.88	16024.84
L2	3000	L1	L1	L1	122.5	106524	2263.66	7101.76	16024.84
L2	1000	L2	L2	L2	85.3	36663	1054.75	3779.46	5341.61
L1	2000	L2	L1	L2	99.6	54370	1421.6	4856.36	8032.5

Brand Quality	Passenger Capacity	Cruise Type	Propulsion Type	Power Plant Type	Beam	Displacement	Acquisition Cost	Operating Cost	Revenue
L1	2000	L1	L1	L1	98.8	54306	1430.94	4539.96	8032.5
L1	2000	L1	L1	L1	98.8	54306	1430.94	4539.96	8032.5
L3	1000	L1	L1	L1	88	41418	1126.57	3776.32	6827.63
L3	2000	L1	L2	L2	110.3	81169	1848.94	6394.78	13655.25
L2	3000	L1	L2	L2	122.2	106793	2280.08	7584.37	16024.84
L3	3000	L3	L1	L2	137.2	123399	2646.02	9009.02	20482.88
L3	2000	L3	L1	L1	116.7	81991	1910.3	6181.87	13655.25
L2	3000	L2	L2	L3	122.6	106613	2292.93	7103.14	16024.84
L3	3000	L2	L1	L1	130.3	122625	2537.14	8182.64	20482.88
L1	3000	L3	L1	L1	119.4	81621	2001.46	6207.62	12048.75
L1	2000	L3	L2	L3	104	54816	1509.46	4689.75	8032.5
L3	3000	L3	L2	L3	135.6	123230	2677.54	8471.91	20482.88
L3	1000	L3	L2	L2	96	42097	1223.78	4371.72	6827.63
L3	2000	L2	L1	L3	110.9	81271	1827.59	5876.36	13655.25

APPENDIX 5: JMP Custom Design RSM Report (Partial)

Prediction Profiler



APPENDIX 6: JMP Central Composite Design Inputs

Pattern	Brand Quality	Passenger Capacity	Cruise Type	Propulsion Type	Power Plant Type	Beam	Displacement	Acquisition Cost	Operating Cost	Revenue
a0000	1	2000	2	2	2	99.3	54439	1450.81	4936.79	8032.5
00A00	2	2000	3	2	2	113.6	72113	1785.43	6018.77	10683.23
0000A	2	2000	2	2	3	105.6	71169	1684.3	5279.1	10683.23
-++--	1	3000	3	1	1	119.4	81621	2001.46	6207.62	12048.75
++-++	3	3000	1	3	3	128.7	122136	2538.52	8079.84	20487.88
+-+++	3	1000	3	3	3	87.2	41369	1139.13	3734.03	6827.63
-+-+-	1	3000	1	3	1	112.7	80669	1941.62	6027.66	12048.75
++---	3	3000	1	1	1	129	121926	2506.86	8103.09	20482.88
00000	2	2000	2	2	2	106.2	71303	1683.86	5712.94	10683.23
--+-+	1	1000	3	1	3	85.6	28838	950.09	3073.29	4016.25
+---+	3	1000	1	1	3	87.6	41391	1110.29	3669.14	6827.63
000A0	2	2000	2	3	2	106.1	71244	1682.26	5691.84	10682.23
+++-+	3	3000	3	1	3	134.9	123479	2605.29	8278.63	20482.88
+-+--	3	1000	3	1	1	94.3	41970	1196.89	3962.04	6827.63
-----	1	1000	1	1	1	80	28295	907.78	3025.75	4016.25
++++-	3	3000	3	3	1	136.9	123502	2705.48	8624.1	20482.88
---++	1	1000	1	3	3	79.1	28457	918.04	2981.08	4016.25
000a0	2	2000	2	1	2	107	71323	1659.89	5649.03	10683.23
-+--+	1	3000	1	1	3	113	80788	1898.49	5848.38	12048.75
0a000	2	1000	2	2	2	85.3	36663	1054.75	3779.46	5341.61
A0000	3	2000	2	2	2	111.3	81317	1864.21	6439.73	13655.25
--++-	1	1000	3	3	1	86.3	28749	994.33	3244.63	4016.25
+--+-	3	1000	1	3	1	87.4	41460	1151.58	3831.47	6827.63
0A000	2	3000	2	2	2	123.9	106750	2308.99	7671.05	16024.84
0000a	2	2000	2	2	1	106	71301	1699.49	5395.59	10683.23
00a00	2	2000	1	2	2	105.3	71123	1675.9	5686.38	10683.23
-++++	1	3000	3	3	3	118.6	81472	2026.03	6172.66	12048.75

Page Intentionally Left Blank

APPENDIX 7: JMP Central Design RSM Report (Partial)

Prediction Profiler