Manning and Automation Model for Naval Ship Analysis and Optimization

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ABSTRACT

The manning of a ship is a major driver of life cycle cost. The U.S. Government Accounting Office (GAO) has determined that manpower is the single most influential component in the life cycle cost of a ship. Life cycle cost is largely determined by decisions made during concept design. Consequently, reliable manpower estimates need to be included early in the design process, preferably in concept design. The ship concept exploration process developed at Virginia Tech uses a Multi-Objective Genetic Optimization to search the design space for feasible and non-dominated ship concepts based on cost, risk and effectiveness. This requires assessment of thousands of designs without human intervention. The total ship design problem must be set up before actually running the optimization. If manning is to be included in this process, manning estimate tools must be run seamlessly as part of the overall ship synthesis and optimization. This thesis provides a method of implementing a manning task network analysis tool (ISMAT, Integrated Simulation Manning Analysis Tool, Micro Analysis and Design) in an overall ship synthesis program and design optimization. The inputs to the analysis are ship systems (propulsion, combat systems, communication, etc), maintenance strategy, and level of automation. The output of the manning model is the number of crew required to accomplish a given mission for a particular selection of systems, maintenance and automation. Task network analysis programs are ideal for this problem. They can manage the probabilistic nature of a military mission and equipment maintenance, and can be used to simplify the problem by breaking down the complex functions and tasks of a ship's crew. The program builds large and complex functions from small related tasks. This simplifies the calculation of personnel and time utilization, and allows a more flexible scheme for building complex mission scenarios. In this thesis, ISMAT is run in a pre-optimization step to build a response surface model (RSM) for calculating required manning as a function of systems, maintenance and automation. The RSM is added to the ship synthesis model to calculate required manning, and a concept exploration case study is performed for an Air Superiority Cruiser (CGX) using this model. The performance of the manning model in this case study is assessed and recommendations are made for future work. This research shows that there is a difference between minimum manning and optimal manning on US Navy Ships.

DEDICATION

To

Michelle and Anna thank you for your continued love and support

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1   INTRODUCTION

1.1   Motivation and Background

Naval ship manning has a significant total ship impact in terms of space, weight, vulnerability and total ownership cost. The Government Accounting Office (GAO) states that "the cost of the ship's crew is the largest expense incurred over the ship's lifetime"[1]. A manning analysis should be conducted as early in the design process as possible because this is where the majority of the life cycle cost is formed. Figure 1 is a well known Navy chart that shows the points at which life cycle costs are locked in.

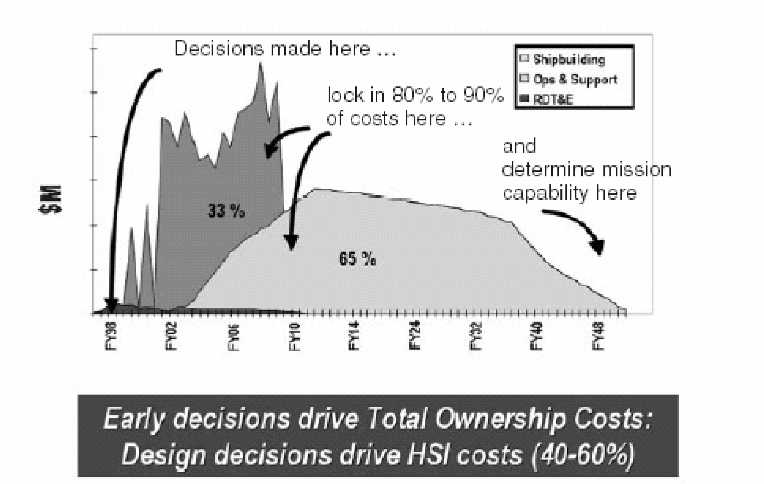

Figure 1 – Affects of early decisions on Life Cycle Costs[1]

In a report to Congress on the effects of performing manpower estimates early in the design process, the GAO had the following to say, "when applied to ships early in their development and throughout their design, human systems has the potential to substantially reduce requirements for personnel, leading to significant cost savings"[1]. There are many possible options available to ship designers to reduce the number of crewmembers onboard ship. These options include automation, changing maintenance philosophies, improving system reliabilities, revising sailor training and many others. All of these options have the possibility to reduce crew size but cost, reliability, work-life issues, and effectiveness cannot be sacrificed. Manning analyses are traditionally done by hand, one ship class at a time, late in the design process. Design optimization requires a hands-off manpower calculation that can calculate manning levels for different levels of automation and ship system configurations. Optimal manning is measured by satisfying three competing variables: total ownership cost, manning level, and ship capability. The relationship between these three variables is shown in Figure 2.

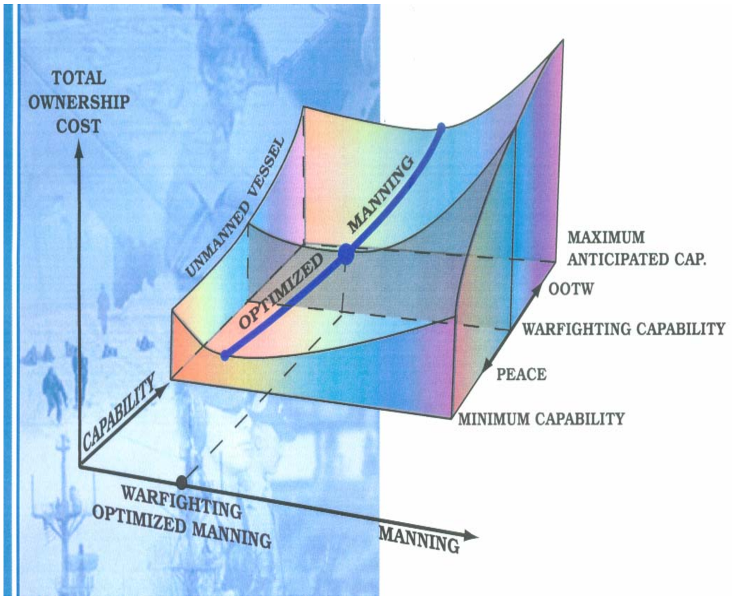

Figure 2 - Optimal Manning Curves[2]

This figure illustrates the tradeoffs that are made to create an optimal crew. Simply minimizing the number of personnel on a ship does not constitute an optimal crew. The optimal crew size is the number of personnel needed to meet the ship's capability requirement with the lowest possible total ownership cost.

Concept design is traditionally an "ad hoc" process. Selection of design concepts for assessment is guided primarily by experience, design lanes, rules-of-thumb, and imagination. Communication and coordination between design disciplines (hull form, structures, resistance, manning, etc.) require significant designer involvement and effort. Concept studies continue until resources or time runs out. In concept exploration, many (millions) of feasible designs may exist in the design space. An efficient and robust method to search the design space for optimal concepts is essential. This cannot be done by hand, one design at a time. New multi-objective optimization methods provide a solution to this problem[3-6].

Once concept exploration has narrowed the design space, technologies have been selected, and major discrete design alternatives (e.g., type of propulsion, hull form, etc.) have been chosen from the full spectrum of design choices, optimization must continue as additional ship, system and subsystem details are added and more complete analysis is performed. This is a fully multidisciplinary problem that typically must employ an array of higher fidelity, disciplinespecific computer codes to continue the optimization process while addressing the uncertainties inherent in the design. Higher fidelity codes are also required in concept exploration when significant departures are made from traditional design lanes to explore new technologies and new paradigms (high speed ships, automation, and new materials). The optimization quickly becomes computationally unmanageable when higher fidelity codes are used. New multi-disciplinary optimization methods provide a solution to this problem [3, 5, 6].

Manning and automation are critical elements that must be considered from the very beginning of the concept exploration process, and must be included in both the hands-off multi-objective and multi-disciplinary optimizations. Current tools do not support this. This problem is addressed by this thesis!

1.1.1 Multi-Objective Optimization of Naval Ships – Concept Exploration

In this thesis, a multi-objective genetic design optimization approach developed by Brown [3] is used to search the design space and perform trade-offs. This approach considers various combinations of hull form, hull materials, propulsion systems, combat systems and manning levels within the design space using mission effectiveness, risk and acquisition cost as objective attributes. A ship synthesis model is used to balance these parameters in total ship designs, to assess feasibility and to calculate cost, risk and effectiveness. The final design combinations are ranked by cost, risk and effectiveness, and presented as a series of non-dominated frontiers. A non-dominated frontier (NDF), Figure 3, represents ship designs in the design space that have the highest effectiveness for a given cost and risk compared to other designs in the design space. A non-dominated solution, for a given problem and constraints, is a feasible solution for which no other feasible solution exists that is better in one attribute and at least as good in all others.

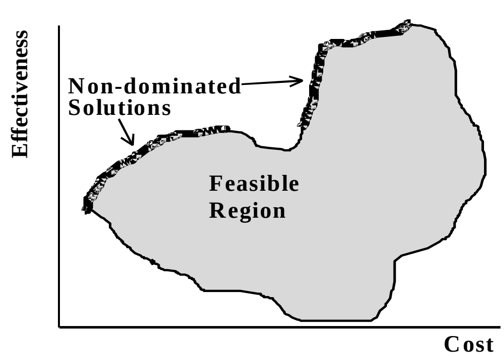

Figure 3 - Two Objective Attribute Space[3]

Concepts for further study and development are chosen from this frontier. The "best" design is determined by the customer's preferences for effectiveness, cost and risk. Preferred designs must always be on the non-dominated frontier. This preference may be affected by the shape of the frontier and cannot be rationally determined a priori. Using a graphic similar to Figure 4, the full range of cost-risk-effectiveness possibilities can be presented to decision-makers, trade-off decisions can be made and specific concepts can be chosen for further analysis. "Knees in the curve" can be seen graphically as significant changes in the slope of the frontier.

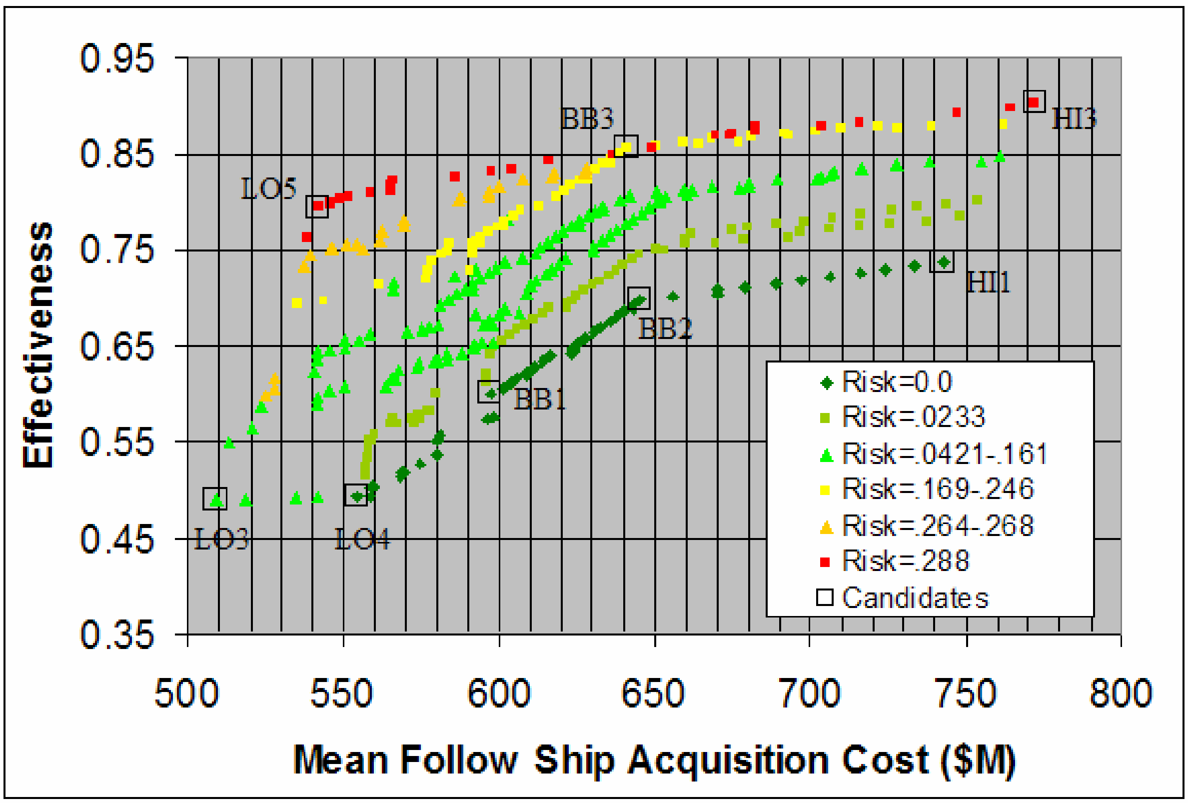

Figure 4 - Non-Dominated Frontiers

Genetic algorithms (GAs) are used in this approach because they are able to explore a design space that is very non-linear, discontinuous, and bounded by a variety of constraints and thresholds. These attributes prevent application of mature gradient-based optimization techniques including Lagrange multipliers, steepest ascent methods, linear programming, non-linear programming and dynamic programming. GAs are also ideally-suited for multi-objective optimization since they develop a population of designs vice a single optimum. This population can be forced to spread-out over the non-dominated frontier.

The multi-objective optimization is implemented in Model Center (MC). Model Center is a computer-based design integration environment that includes tools for linking design model components, visualizing the design space, performing trade studies and optimization, developing parametric models of the design space, and archiving results from multiple studies. By automating and simplifying these tasks, Model Center makes the design process more efficient, saves engineering time, and reduces the error in the design process. The manning and automation model proposed in this thesis will be used to calculate manning requirements for a ship based on the mission, ship systems and levels of automation selected by the designer or optimizer. The model will generate data to construct a simple response surface model (RSM) to estimate baseline manning. This baseline manning estimate can then be used by the overall ship design program.

1.1.2 Manning and Automation Analysis

Traditionally, manpower analyses are conducted late in the ship design process. In the U.S. Navy acquisition process, the guiding documentation for shipboard manning is a Ship Manpower Document (SMD). The Navy outlines the process to follow for the development of SMDs in OPNAVINST 1000.16J. The following are the steps to be taken when developing an SMD for a new ship or for an old ship that will be converted:

- Conduct ROC/POE analysis.
- Determine the directed manpower requirements (a directed manpower requirements is for a billet that is not directly due to the mission of the ship, the command master chief petty officer billet is an example of a directed billet.)
- Determine watch station requirements
- Develop preventative maintenance levels
- Estimate corrective maintenance workloads
- Apply approved staffing standards
- Conduct on-site workload measurement and analysis
- Consider utility tasking (Special evolutions such as underway replenishment, flight quarters, etc)

- Consider allowances (margins to account for functions not related directly to the missions of the ship. For instance, the time required for set up and stowage of equipment.)
- Conduct a fleet review of the documents.

This process is similar to what is used by newer technology but the current state of the process makes it very manpower intensive, slow, and reliant on system experts. An alternate method for manpower estimation is to conduct a Top Down Requirement Analysis (TDRA) earlier in the design. Although this process is conducted earlier in the design process, it is still conducted much later than concept exploration. The TDRA process as described by Thomas Malone is shown in Figure 4.

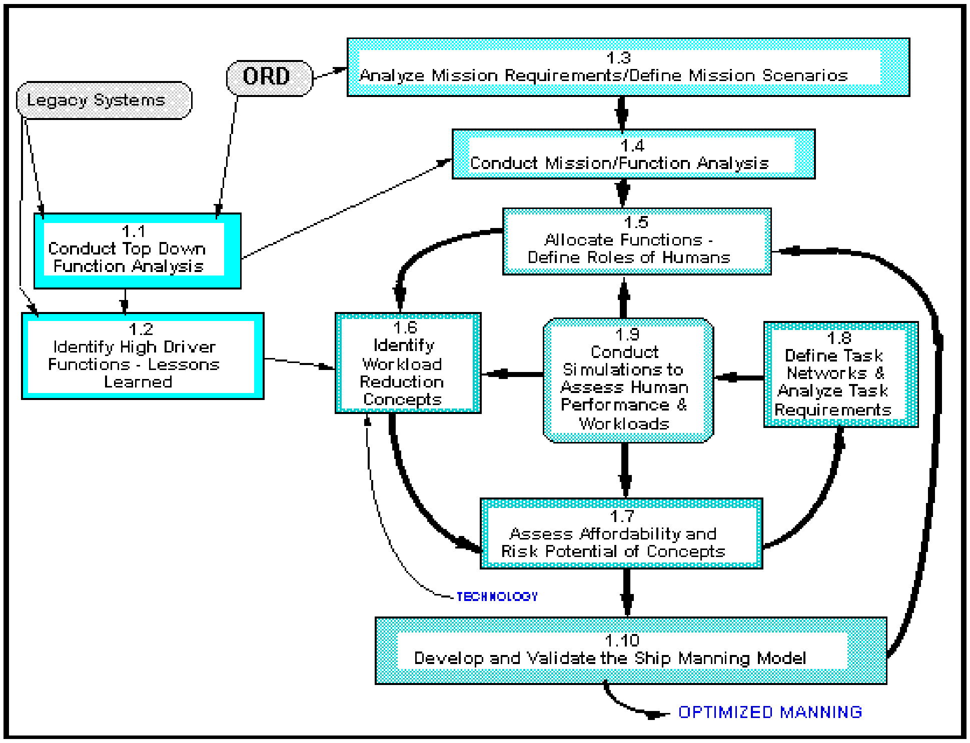

Figure 5- Top Down Requirements Analysis Flow Chart[7]

The first step of a TDRA is to analyze the mission requirements of the new asset. This analysis can be completed by studying the Mission Need Statement (MNS). From this document, various mission scenarios are developed for the ship. These mission scenarios are later used to conduct computer simulations of the manning levels to determine the effectiveness of the manning levels and the automation levels. Once the mission scenarios have been developed, the missions are decomposed into the functions that to execute the mission. This functional breakdown helps to develop mission timelines. The next step in the process is to allocate functions to humans, automation, or a combination of the two. The function allocation process is a key step in the manpower requirements design process. A Measure of Effectiveness (MOE) is created so that the different manning configurations can be compared to one another. The manning configuration is then tested by using a simulation to determine the effectiveness of the manning system. This process is similar to the method that will be used in this thesis but the manning analysis needs to be conducted much earlier in the design cycle.

1.1.3 Manpower Reduction Methods

Much research has been done on ways to reduce the number of personnel onboard ships. Some of the methods to reduce manpower include using automation to replace personnel, designing systems that have lower maintenance requirements, and reducing maintenance requirements on the ship's crew by using more shore based maintenance. Cross-training crewmembers to perform the work of other crewmembers is another suggestion that may help eliminate underutilized shipboard personnel. All of these methods should be considered at the beginning of the ship design process. The effect of each manpower reduction technique needs to be quantified. This way the designer knows how to most effectively reduce the manpower at the lowest possible cost.

1.2 Thesis Objectives

The primary objectives of this thesis are:

- Identify and assess existing tools for performing naval ship manning and automation analysis.
- Select tools.
- Propose a strategy for using these tools as part of a naval ship concept exploration and concept development design optimization.
- Develop necessary naval ship manning and automation models.
- Integrate the manning model into the Naval Ship Synthesis Model and MOGO.
- Apply this strategy and these tools in a naval ship design case study.

1.3 Thesis Outline

Chapter 1 provides an introduction and motivation for implementation of a manning estimate module in a multi-objective ship synthesis model.

Chapter 2 explores the tools and methods that are currently available for conducting shipboard manpower estimates. It also provides a description of each tool along with the advantages and disadvantages of each tool. The method and tool to be used in this thesis for determining manpower requirements in concept design is described in detail.

Chapter 3 describes the manning model developed in this research.

Chapter 4 applies the manning model to a case study.

Chapter 5 documents the results of the case study and proposes future research possibilities.

CHAPTER 2 NAVAL SHIP MANNING AND AUTOMATION ANALYSIS TOOLS AND PROCESSES

2.1 Existing Tools and Methods

As the maritime industry has realized the possible cost savings in reducing ship crew size, a number of tools have been developed to aid designers in determining the required crew size for a ship. These programs have been designed to validate different crewing strategies, maintenance philosophies and levels of automation. Advances in computer technology have also increased the ability of engineers to model the interaction between personnel and work systems. In the past, designers have used rules of thumb and taxonomies to conduct function allocation by hand. New manning philosophies were tested in large scale tests with human operators in the experiments. Theses methods were costly and took considerable time to complete. The use of discrete event simulations has assisted designers in building models to test the interaction of personnel and automation. A discrete event simulation is “one way of building up models to observe the time based (or dynamic) behaviour of a system”.[8] A discrete event simulation is run by building a network of individual tasks that must be performed together to create an event. Each of the tasks is simple by itself but the combination of the simple tasks can simulate a complicated scenario. It is easier to estimate duration and functional requirements for each task so there is less dependence on system experts. These simple tasks are connected using logic statements and probabilities which can further increase the complexity of the model. An event simulation is made of many components including, entities, logic statements, an executive, random number generators, and a data collection system. These components and their interaction with one another are illustrated in Figure 6.

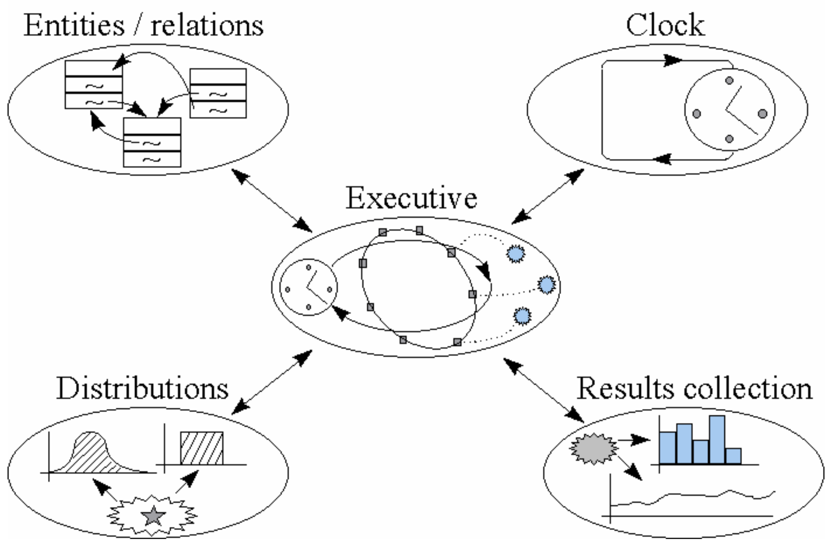

Figure 6- Discrete Event Simulation Component Interactions[8]

The entities are the building blocks in the model that can be found in the real world. For ship manning, the entities of the simulations are the personnel on the ship and the ship systems that are used to execute the ship's mission. The logical relationships link the various entities together. Dr. Peter Ball, from the University of Strathclyde, states that "the logical relationships are the key part of the simulation of the model; they define the overall behaviour of the model."[8] Since the event simulation is a time based simulation, the executive is needed to control the clock and the timing of the simulation. Random number generators and distributions are used to ensure that the models are stochastic in nature to better simulate the real world. "The variability associated with different outcome times allows for multiple executions of the network to emulate variable human response characteristics suitable for subsequent statistical analysis"[9]. Micro Saint Sharp is an example of a discrete event simulation. "Micro Saint is a discrete-event task network tool that stochastically models the impact of human interaction in system operations of varying complexity and can provide realistic outcome expectations"[9]. Micro Saint has been used by Microanalysis and Design (MAAD) on DD21 and other projects. Micro Saint or Micro Saint Sharp is the base program of most of the more refined manpower estimation tools that were explored in this research.

MAAD has developed an estimation tool known as the Total Crew Model (TCM)[10]. TCM can be effectively used to validate a watch quarter station bill and manning philosophies. This program determines whether a ship's crew can perform all of the ship's assigned missions within an acceptable level of crew fatigue. TCM is built by creating a list of crew members, a list of schedules, and a list of special evolutions using Microsoft Excel. Examples of these lists are shown in Figures 7 through 9

Billet	Name	#	Schedule	Schedule	Schedule	Note
			Condition4	GQ	CondAMIO	
0001	CrewCommand	1	5	9	5	
0002	CrewExecutive	2	5	9	5	
0201	CrewEngineer	3	5	9	5	
0301	CrewOperations	4	5	9	5	
0302	CrewDCA	5	1	8	1	OOD
0202	CrewFirstLt	6	5	9	5	
0101	CrewOPCENO	7	3	8	3	OOD
0303	CrewEMO	8	5	9	5	
0304	CrewMPA	9	2	8	2	EOW
0203	CrewCommsO	10	5	9	5	
0305	CrewWeapsO	11	5	9	5	
0102	CrewElectO	12	5	9	5	
0204	CrewAuxO	13	4	8	4	EOW
0205	CrewYeoman	14	5	9	5	
0306	CrewHST	15	5	9	5	
0307	CrewStorekeeper	16	5	9	5	
0308	CrewFS1	17	5	9	5	
0309	CrewFS2	18	6	8	6	
0311	CrewFS3	19	6	8	6	
0312	CrewFS4	20	6	8	6	
0313	CrewFS5	21	6	8	11	SecWatch
0314	CrewFS6	22	6	8	10	SecWatch
0344	CrewFS7	23	6	8	6	
0345	CrewFS8	24	6	8	11	SecWatch
0346	CrewFS9	25	7	8	7	

Figure 7 – TCM Crew List

Schedule #	TaskNumber	Name	Following Task	Task Start Time	Task End Time	Task Type	On Duty	Day in Schedule	Total Days in Schedule
			Next	StTime	EndTime	Type	Duty	SchedDay	TotSchedDays
1		Section 1							
1	1	Watch	2	0	10800	3	1	1	1
1	2	Personal Time	3	10800	11700	37		1	1
1	3	Sleep	4	11700	38700	18		1	1
1	4	Personal Time	5	38700	39600	37		1	1
1	5	Eat	6	39600	41400	17		1	1
1	6	Watch Prep	7	41400	43200	3	1	1	1
1	7	Watch	8	43200	54000	3	1	1	1
1	8	Personal Time	9	54000	54900	37	1	1	1
1	9	Normal work	10	54900	62100	34	1	1	1
1	10	Personal Time	11	62100	63000	37	1	1	1
1	11	Eat	12	63000	64800	17	1	1	1
1	12	Normal work	13	64800	75600	34	1	1	1
1	13	Personal Time	14	75600	82800	37	1	1	1
1	14	Eat	15	82800	84600	17	1	1	1
1	15	Watch Prep	1	84600	86400	3	1	1	1
2		Section 2							

Figure 8 – TCM Schedule

	Desc	Desc	Desc	Desc	Desc	Desc	Desc	Desc	Desc
	EvoType	EvoTask	EvoStart	EvoDur	Delay	RetryPeriod	Wake	Period	ModeChange
1	CmdBrf	FltOpsBrf	25200	1800			1	86400	
2	DrlBrf	ITTbrf	25200	1800	3600		1		
3	FltQts	HeloFltQts	26100	900			1	86400	
4	FltQts	VUAVFltQts	27900	900			1	86400	
5	BoatOpsL	BoatOpsL	28800	5400			1		
6	EmgDrl	ITTeDrl	28800	11700			1		
7	FltQts	HeloFltQts	36000	900			1	86400	
8	DrlDeBrf	ITTcmd	40500	1800	1800		1		
9	FltQts	VUAVFltQts	42300	1800			1	86400	
10	DrlDeBrf	ITTcrew	46800	900	1800		1		
11	FltQts	VUAVFltQts	47700	900			1	86400	
12	Boarding	Bgn4mnbrd	47700	10800			1		
13	FltQts	HeloFltQts	58500	900			1	86400	
14	FltQts	VUAVFltQts	61200	1800			1	86400	
15	FltQts	HeloFltQts	66600	900			1	86400	
16	Boarding	Bgn6mnbrd	69300	14400			1		
17	FltQts	VUAVFltQts	76500	900			1	86400	
18	FltQts	VUAVFltQts	90000	1800			1	86400	
19	DrlBrf	DCCTbrf	111600	1800			1		
20	Boarding	Bgn4mnbrd	114300	7200			1		
21	EmgDrl	DCCTdrl	115200	11700			1		
22	DrlDeBrf	DCCcmd	126900	1800	1800		1		
23	EmDest	EmDest	131400	3600			1		
24	DrlDeBrf	DCCcrew	133200	900	1800		1		
25	Boarding	Bgn4mnbrd	141300	7200			1		
26	Boarding	Bgn4mnbrd	150300	7200			1		
27	DrlBrf	CSTTbrf	198000	1800			1		
28	EmgDrl	CSTTeDrl	201600	11700			1		
29	Meetings	DptHdMtg	206100	5400	86400		1	604800	
30	Boarding	Bgn4mnbrd	211500	7200			1		

Figure 9 - TCM Scenario

Each crew member is given a base schedule. These schedules include personal time, watch standing, day working, sleeping, etc. The crew member's schedule can be interrupted to accomplish special evolutions such as general quarters, flight quarters, and other evolutions. A large strength of this program is that the daily workload on a crew member can be studied along with the overall workload on the crew member. For example, a crew member may be below the standard Navy work week of 67 hours but may have to work 24 hours straight during a certain period which is unacceptable from a fatigue perspective. One drawback for using TCM in the concept development stage is that it does not have a built in optimizer. The crew size would need to be optimized prior to using TCM. A benefit of this program is that it provides an easily used MOE, the fatigue levels of the crew. Since TCM uses Microsoft Excel it should be easy to integrate with other programs, especially Model Center. Another draw back to the program is that there is limited function allocation within the program. The function allocation would have to be conducted by the designer. The function allocation needs to be manually changed for every iteration of manning philosophy and automation philosophy. Equipment and maintenance are not directly addressed by TCM. This program is primarily used in-house by MAAD on consulting projects so there may be proprietary concerns with using this program in this thesis.

The US Navy contracted MAAD to develop other shipboard manning prediction models.

MAAD developed the Ship Manning Analysis and Requirements Tool (SMART) series of programs that allow designers to vary equipment, maintenance philosophies, and levels of automation to optimize the crew size of a ship based on various goals. The latest program in the series, SMART build 3, has effectively integrated all three parameters to conduct a manning analysis. Libraries of navy equipment and maintenance procedures are part of the software which makes constructing models easy for the user. The user develops a scenario that is used to test the ability of the crew to operate in required missions. The scenario is broken up into smaller tasks using Micro Saint. Each task in a scenario has a list of the skills required to perform the task. SMART dynamically allocates each task to a member of the crew who has the skills needed to perform the mission and is available at the beginning of the task. SMART conducts the function allocation based on taxonomies created by Dr. Edwin Fleishman and on the level of automation that is specified by the user. The built in function allocation helps to build an optimal crew. The designer does not need to spend time assigning specific tasks to the simulated crew for every scenario and iteration. The program runs a discrete event simulation to test the manning, maintenance, and automation configurations to determine an optimal crew size. The size and make up of the crew can be optimized for four different goals. The first goal is to minimize the overall cost. SMART contains a database that has the annual cost of each rank and rate in the Navy. The optimizer will try to assign a task to the least expensive operator available. The second goal is to minimize the crew size. This feature allocates functions to the fewest billets possible. The third goal is optimize the number of different jobs. This function is similar to the minimize crew size but its goal is to minimize the number of different ratings on the ship. The final option minimizes the workload on each member of the crew. This increases the size of the crew but it reduces the workload of all personnel on the ship.

MAAD's latest software for shipboard manning simulation is the Integrated Simulation Manning Analysis Tool (ISMAT). ISMAT has many similarities to SMART. They both use the same navy libraries of manning equipments, and compartment documents. ISMAT uses XML to organize the libraries of data so it is easier for a user to create their own libraries of equipment, manning, and compartment documents. This may allow the program to better interact with other software programs due to the widespread use of the XML language. ISMAT can simulate the workload on a ship's crew based on operational requirements, facilities maintenance requirements, preventative maintenance, and facilities maintenance. A strong advantage of ISMAT over SMART is the implementation of maintenance pools in ISMAT. In SMART, maintenance had to be assigned to specific personnel. This reduced the flexibility of the model and it created more front end work for the programmer. ISMAT has created maintenance pools so that any operator within a division or department can be considered for a task. ISMAT utilizes Micro Saint Sharp to run the simulations. Micro Saint Sharp is a new version of Micro Saint. It is more powerful and it is easier to organize and create simulations. Micro Saint Sharp allows the user to create subfunctions within functions and this makes it easier to cut and paste similar tasks between functions. The functions in ISMAT are contained in chart that looks similar to a Gantt Chart. The functions on the schedule can be copied and pasted for functions that occur more than once. The duration of the tasks and the start time can be altered. The ability to work with scenarios in this screen makes ISMAT user friendly for designers with limited simulation experience. ISMAT is used for all of the manpower calculations done in this research.

The Manpower Analysis and Prediction System (MAPS) was developed for Naval Surface Warfare Center (NSWC) Cadrerock Division by Multi-Media Communications Inc (MMCI). MAPS relates known billet requirements to known ROC/POEs. The designer can alter the requirements on the ship to determine the manpower requirements that will be needed to accomplish these missions. MAPs does not incorporate automation very well. This program would be good at the very beginning of concept exploration in developing the ROC/POE for a ship class and assessing how distributing the missions among various ship classes would affect manning of an individual ship class. This program does not have the level of detail that is desired for this thesis.

2.2 Top-Down Requirements Analysis utilizing ISMAT

The TDRA method used in conjunction with ISMAT is the best option for creating a manning module within the ship synthesis model. The TDRA method fits very well with the structure currently used by the ship synthesis process. There are many steps that overlap between the two processes. The inputs needed to run an ISMAT simulation are:

- Mission Scenario
- Compartments
- Ship systems and equipment
- Level of automation
- Maintenance tasks to be performed by the organic crew.
- Crew document of personnel to be considered in the automation.

The mission scenario comes from the mission analysis that is conducted at the outset of concept exploration. A library of scenarios is developed so that only a limited knowledge of discrete event simulation will be needed in future simulations. The user will only need to manipulate the scenarios to create desired levels of automaton and maintenance to be performed by the crew. During concept exploration, a list of generic compartments will be used to estimate a preliminary amount of facilities maintenance that will be required by the ship. The ship systems information will be input from the machinery module and the combat systems module of the ship synthesis model. Changing the systems that will be used on the ship will change the amount of maintenance that will be performed by the crew. The systems onboard the ship will affect both the manning and the effectiveness of the ship. If more reliable equipment or more maintainable equipment can be utilized then the size of the crew can be reduced while still having a ship with a high state of readiness. The level of automation will be determined by the designer based on a discrete scale of automation measured from level 1 (very limited use of automation) to level 4 (very high use of automation). Although automation can reduce the amount of manpower that is needed to operate the ship, it is not the only solution to the manning problem. Higher levels of automation also increase the cost and risk of a design. The affects of automation on the system, particularly the crew need to be understood and appreciated. Automation will be applied in a bottom up manner to create the overall level of automation for the ship design. The automation that is applied needs to be based on reducing workload and increasing job satisfaction and effectiveness for the operator.

2.3 Ship Design Application - Strategy

2.3.1 Concept Exploration

During concept exploration, all feasible designs should be considered. The manning model must also consider different combinations of ship systems, levels of automation, and levels of maintenance. To accomplish this, ISMAT is used with Model Center to calculate crew size for different combinations of design variables. Input files for ISMAT are created based on the design's combat systems and propulsion systems with variations for different levels of automation and maintenance. Personnel are assigned to maintenance tasks based on the systems that are in the ship and the department the technician is assigned to. A scenario is created in ISMAT so that operators can be assigned to tasks that are required to meet the design's mission requirements. Personnel are assigned to accomplish the tasks within the scenario from a pool of operators. The same scenario is used for each test. The ship will either pass or fail the scenario and therefore the design will either be feasible or not. A ship fails a scenario if there are not enough operators for the program to choose from in the manning document to complete all of the tasks in the scenario. Personnel will be selected for tasks based on the department that they are in rather than their specific specialty. Later in the design process, more detailed analyses can be conducted to determine the required number of people in specific ranks and rates. The design options are defined so that Model Center can vary the designs using a multi-objective optimization. A Visual Basic program is developed so that design options can be created and tested in ISMAT based on the inputs from MC. Model Center is then used to create a response surface model (RSM) for the manning estimate in the ship synthesis model. A RSM is an equation that is fit to the data found by the manning model. The RSM is used in the overall ship synthesis program instead of ISMAT. This is done to reduce the amount of time it takes to complete an optimization. The goal during concept design is to determine the number of personnel required for the entire crew and the total ship impact of this crew. The numbers of personnel and level of automation and maintenance are factors that are also used to determine effectiveness, cost, and risk for the design. In later phases of the design process, engineers can determine which technology to employ in the ship to implement the level of automation that was selected in concept exploration.

CHAPTER 3 NAVAL SHIP MANNING AND AUTOMATION MODEL

3.1 Model Setup and Overview

The manning model's inputs are ship systems, ship length, level of automation, and maintenance level. The model uses these inputs in a scenario to determine the number of personnel necessary to complete all mission and maintenance requirements. The output of the model is the number of personnel required in the crew. Figure 11 shows a sample block diagram of the manning module.

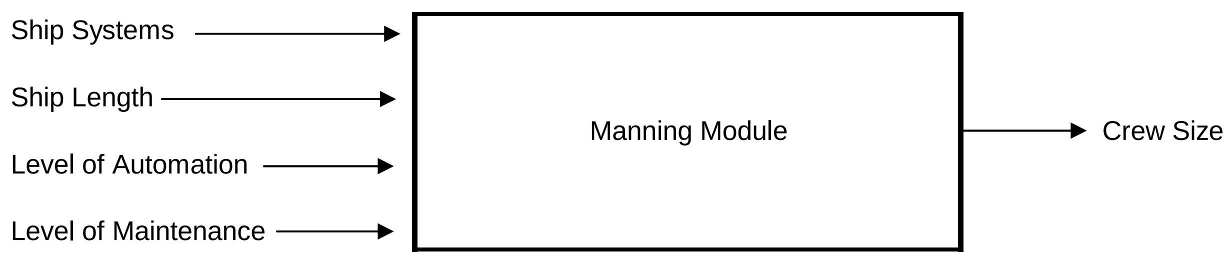

Figure 10 - Manning Module Block Diagram

The systems affect the manning levels by altering the number of personnel who are required to maintain the machinery. If there are fewer or simpler systems, the manning level will be smaller than it would be for multiple complex systems. A simpler combat system may be more advantageous than a more complex system because of the overall savings on the cost of the ship despite a slightly lower Overall Measure of Effectiveness (OMOE) for the ship. A larger ship will generally require more personnel. A larger ship has more equipment to maintain. There is also more ship that needs to be painted and cleaned. Automation is currently a very well publicized option for reducing crew size. The use of automation has many applications especially as major technological jumps are being made in information systems and controls. Automation must be carefully applied and studied prior to implementing it on a ship. Automation increases the risk and cost of a new ship design and so the use of automation should be studied to measure the number of crewmembers it will help to remove from the ship. Maintenance is often overlooked at the beginning of systems engineering. Benjamin Blanchard and Wolter Fabrycky state that "to realize the overall benefits of systems engineering, it is essential that all elements of the system be considered on an integrated basis from the beginning. This includes not only the prime mission-related elements of the system but the maintenance and support capability as well"[11]. Developing a maintenance concept early in the ship design process will help to reduce the number of operators onboard the ship or prevent the removal of personnel needed for maintenance. Although a ship can often operate with a smaller crew, the remaining crew can become overloaded by the amount of required maintenance.

The systematic process of calculating a manning estimate to integrate into an overall ship optimization is complicated and it involves the use of multiple programs. Figure 12 shows the sequence of events for conducting the manning analysis and optimization.

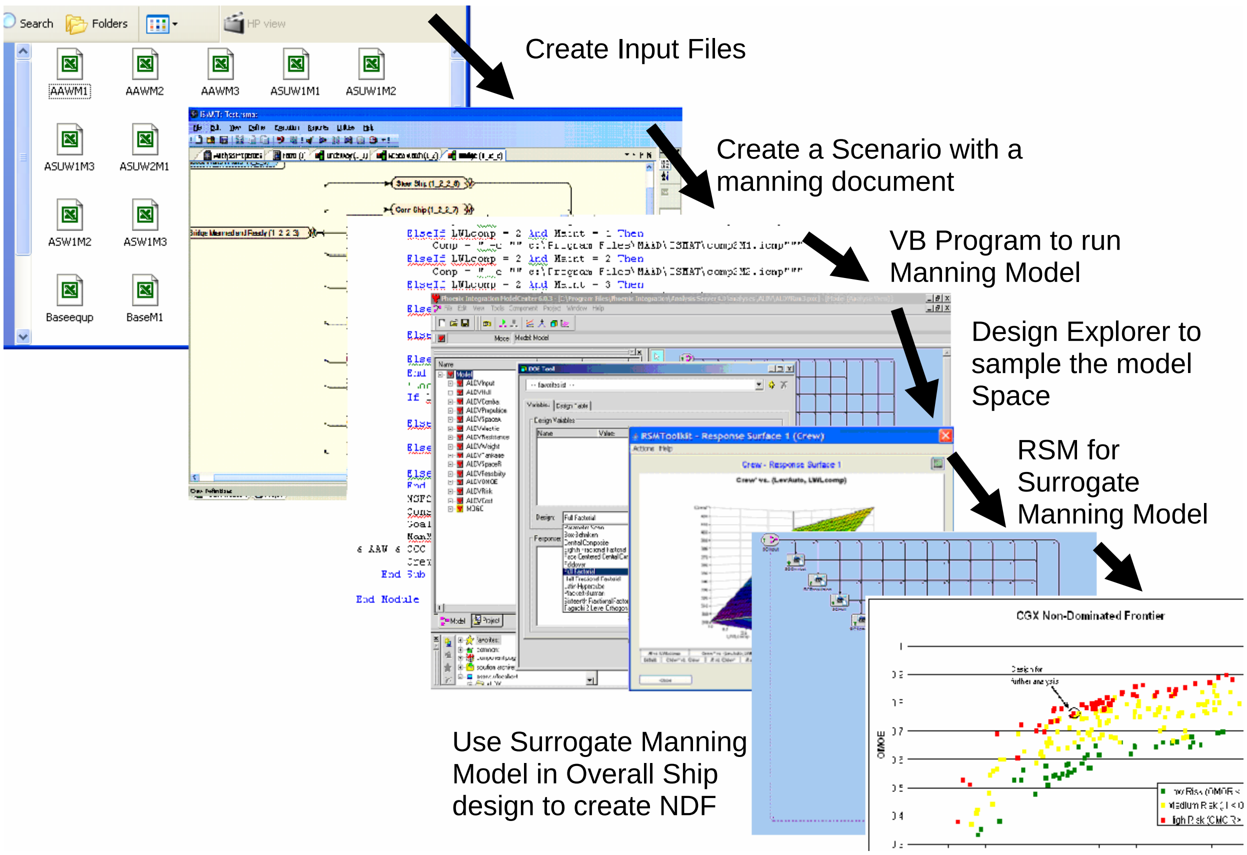

Figure 11 – Manning and Automation Analysis and Optimization Process

The manning analysis starts by creating input files for compartments and equipment. These input files contain all of the alternate equipment and compartments in the design space and all of the maintenance that is associated with them. They also include variations of the equipment files for different levels of maintenance. A scenario is created and a manning document is loaded in ISMAT. The personnel in the manning document are assigned to perform tasks within the scenario. A Visual Basic (VB) program is written that selects equipment and compartment files to add to the ISMAT model based on the particular values selected for system, automation, and maintenance design variables. The VB program will execute the simulation and the crew size is written to an output file. The Design Explorer in Model Center (MC) is used to run the ISMAT model for all of the different combinations of equipment, compartments, levels of automation, and levels of maintenance. A response surface model (RSM) is fit to the data collected by the Design Explorer to create a surrogate manning model that is used within the Naval Ship Synthesis Model (NSSM). The NSSM and MOGO are used to explore the design space for feasible ship designs and to create a non-dominated frontier of optimized design options. From the NDF, the designer can choose a ship design for further exploration and optimization. Each component of the process is explained in greater detail in Section 3.2.

3.2 Model Inputs

3.2.1 Model Scenario

The scenario is developed from the Mission Needs Statement or the Initial Capabilities Document at the very beginning of concept exploration. The scenario includes the functions and tasks that must be completed by the crew during their missions. The following is a list of functions that are common for ship missions:

- At Sea Watch- The at sea watch is responsible for keeping the ship safely moving through the water from one location to another. Some of the tasks required of the watch team are lookout, navigation, operation of machinery, and plant monitoring. These functions will always be performed while the ship is underway.
- Flight Quarters- if the ship is going to be equipped with a flight deck then it will need to have sufficient personnel to land, disembark, and refuel a helicopter or other aircraft.
- General Emergency (Fire) - if there is a fire at sea, the ship's crew must be able to contain and extinguish the fire to minimize damage and loss of life. Fires are generally not combat related and can be started by multiple sources that are found onboard ship.
- General Quarters- the primary purpose of a U.S. Navy warship is to engage an enemy force. A ship fights at general quarters. All of the weapons and sensors must be ready to be deployed. The crew must also be ready to control any damage that may be sustained from the enemy.

- Major conflagration- Due to the probabilistic nature of the scenario, a crew may never have to fight an actual fire because the automated systems in place or the rapid response team may extinguish the fire without the need of the entire damage control organization. One concern about using automation to reduce the size of the crew is the question, “will the crew be able to handle extensive damage with a high loss of life and loss of automated systems.” In this scenario, the crew will be faced with damage similar to what was inflicted on the USS STARK. Part of the ship’s crew will be become casualties and therefore unusable for the scenario. The number of personnel required to perform some tasks will be reduced. There will be penalties placed on tasks that are not done according to Navy standards but the remaining crew will still be able to perform the required tasks. The level of automation for the conflagration will not change and it will contain a very limited amount of automation.
- Depending on the specific mission of a ship, it will have other functions and tasks that will need to be incorporated into the mission scenario that is used to test the crew size during modeling.

An ISMAT analysis is constructed using a bottom-up approach. The individual tasks are linked together to create functions. The functions are then related to form a scenario. The use of a bottom-up approach helps to reduce the complexity of simulating the interaction among the members of a ships crew during the execution of the ship’s mission. Smaller tasks are easier to define and the summation of these tasks determines the amount of work that is required of the crew during an evolution. Although the construction of the scenario is a bottom-up approach, the overall process of determining the crew size is a top down process that begins with the requirements that are being imposed on the ship.

The design of a scenario starts by examining a Watch Quarter and Station Bill (WQSB) from an existing ship. The WQSB lists all of the positions that must be filled during a shipboard evolution. In the WQSB, the personnel requirements are listed but the tasks that they perform are not listed. Table 1 contains a sample WQSB for the bridge team of a Destroyer leaving port.

Table 1 - Bridge WQSB for DDG-51 IIA Class Ship

WATCH STATION	SECTION	RANK RATE	NAME
OOD UNDERWAY	1	LT	G
CONNING OFFICER	1	ENS	F
JOOD	1	LTJG	T
BMOW	1	BM3	G
HELM SAFETY BRIDGE	1	LTJG	M
MASTER HELMSMAN	1	OSSN	D
MASTER HELMSMAN U/I	1	SN	H
LEE HELM	1	GSE3	R
NAVIGATOR	1	LTJG	B
DECK LOG	1	QM2	H
NAV PLOTTER BRIDGE	1	QM2	O
BEARING TAKER	1	QM3	T
	1	QM3	F
BEARING RECORDER	1	QM1	M
FPAO	1	ENS	W
BRIDGE PHONE TALKER	1	YN1	S
BRIGHT BRIDGE OPER	1	OS3	K
TACTICAL SIGNALS/MOB	1	OSSR	F
AFT STEERING OP	1	EN2	S
AFT STEERING ELECTRIC	1	EM3	R
AFT STEERING HELM	1	BM3	M
HELM SAFETY AFT	1	LTJG	M

The analyst studies the billets that are manned and determines what tasks are being performed by each billet. The tasks that each operator performs are found in shipboard organization manuals or Commanding Officer Instructions for a particular ship. For example, the task performed by the "Master Helmsman" is to steer the ship. The "helm safety bridge" oversees the helmsman to ensure that he steers the ship in the correct direction. The helm safety officer is a redundant safety measure in the system. A separate task is not included in the simulation for each person. Instead, both personnel will be accounted for in the task "steer the ship". Once the tasks have been determined, they are entered into ISMAT. The user is able to work with the graphical user interface (GUI) in ISMAT to create the scenario. Figure 13 shows the tasks that must be performed by the bridge watch when a ship is getting underway from port.

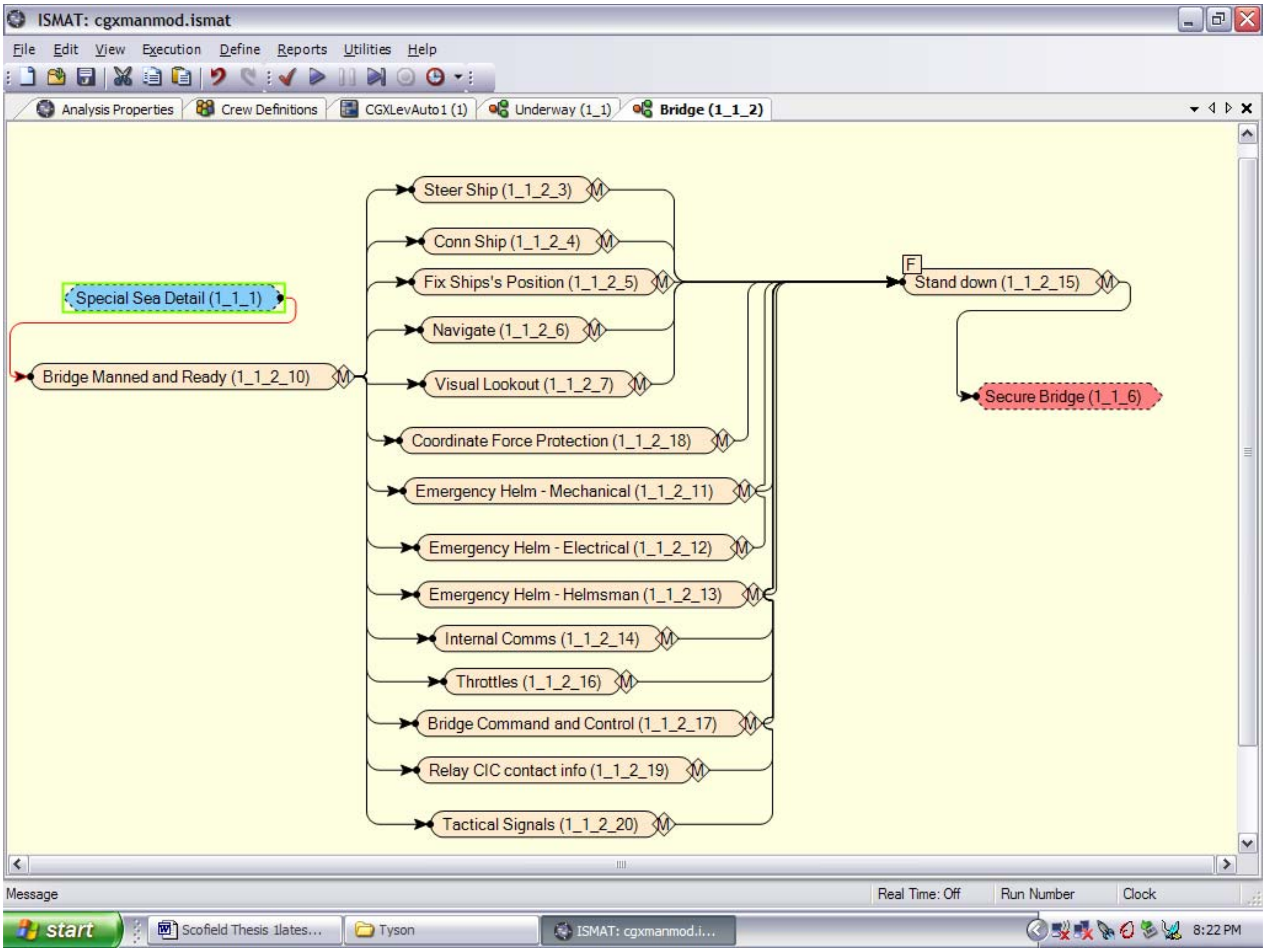

Figure 12 - ISMAT Bridge Watch Function

The duration of each task is estimated and a deviation can be applied to the task duration to make the scenario more realistic. The final task in the function, "Stand down", contains a queue that will hold personnel until all of the tasks have been completed. To set up the queue, a variable is created for each function. As each of the tasks is completed, the variable value is increased by a factor of one. When the queue variable equals the number of tasks within in the function, the queue is released and the personnel can be reallocated in the model.

The tasks can be linked together in many ways to form a function. Figure 13 shows a starting task that has multiple exit points. In this set up, each task needs to be performed every time. The crew members go from "Bridge Manned and Ready" to each of the other tasks. When they complete their tasks, they must wait in a queue until all of the other tasks have been completed. This is the same way a bridge team functions on a ship. The tactical signalman must stay in his position until the entire evolution is complete even if he is no longer sending signals to other units. He cannot be reassigned to another task on a ship or during the ISMAT simulation. If there are multiple exits from a path but the operators only need to take one path then a tactical or probabilistic decision must be made in the program. A probabilistic decision is based on the probability of the task going to either option. The chances of all of the probabilities must equal 1. Figure 14 is an example of the probabilistic decision that is used for the landing of a helicopter.

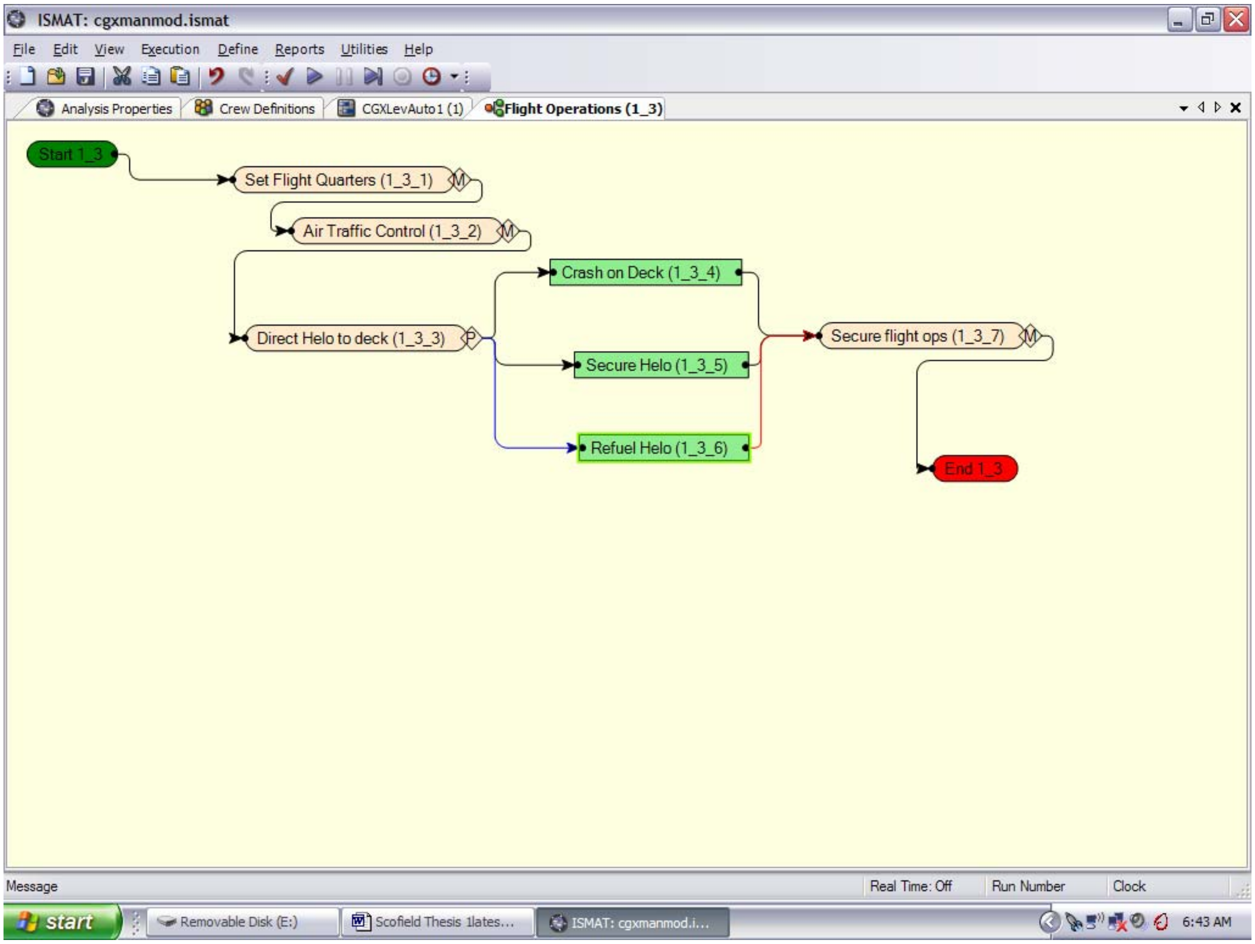

Figure 13 - ISMAT Flight Operations Function

In this scenario, the helicopter can either land and secure, fuel, or crash and catch on fire. A tactical decision in ISMAT uses a logic statement to guide the entities between tasks. Tactical decisions are very useful for recurring tasks in ISMAT. SMART is able to create recurring functions for tasks such as watches that occur every four hours during a simulation. The recurring task function in SMART had technical problems and it was removed from ISMAT and replaced with a loop task. The designer can use tactical decisions to loop the watch task so that the function “At Sea Watch” only needs to be created once but it will run for the entire scenario. Figure 15 shows the at sea watch and demonstrates how a tactical decision is used in ISMAT.

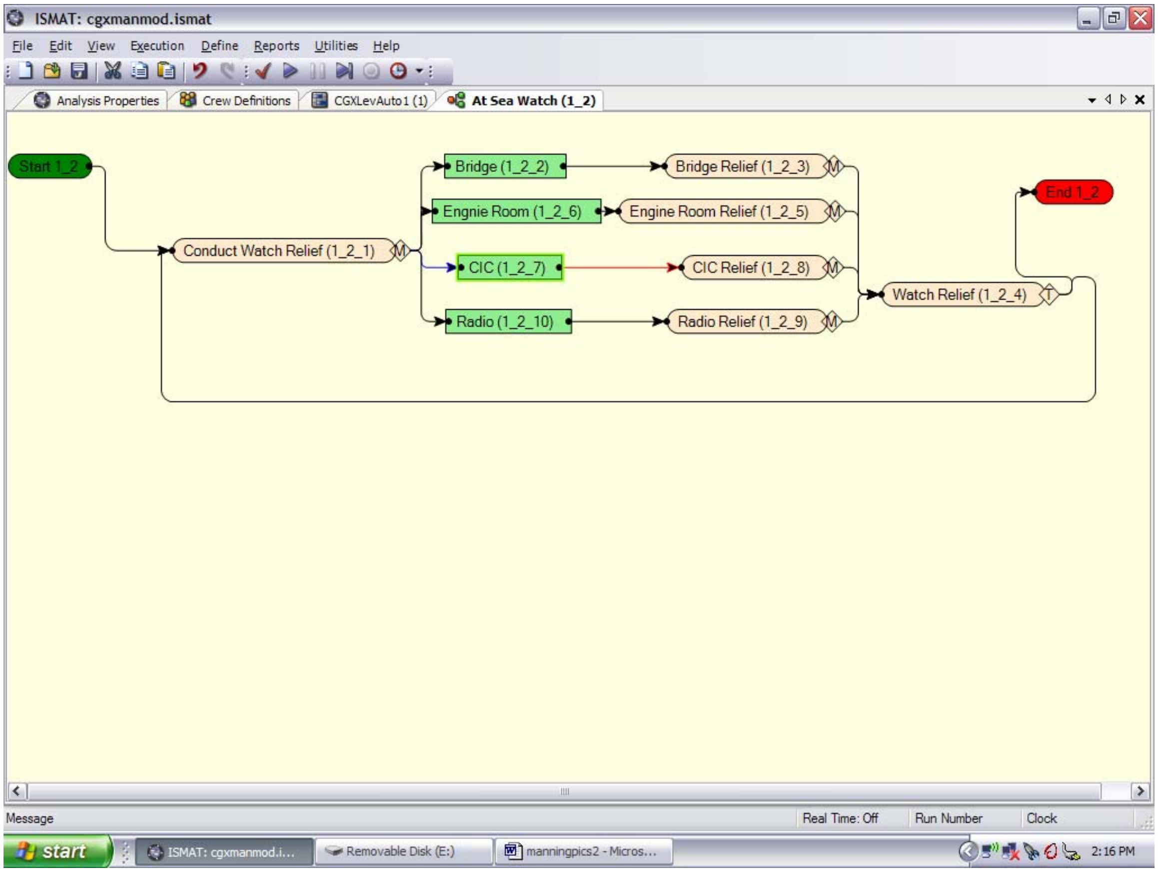

Figure 14 – At Sea Watch

The task "Watch Relief" can either exit to the end of the function or it can go to the beginning of the task and start the watch all over again. The crewmembers that are on watch are released at the task "Watch Relief" and new crewmembers are used to accomplish all of the tasks when the simulation enters the task "Conduct Watch Relief". The tactical decision is controlled by the clock in the scenario. The watch will continue to be recycled until the scenario is over.

ISMAT contains a library of the Ship Manning Documents (SMDs) for most of the ships in the US Navy. Each manning document contains the enlisted crewmembers who are assigned to the ships. Each person in the SMD has a list of skills that they posess and a measure of how well they can perform theses skills. The cost of each crewmember is also contained in the SMDs. Since officers are not contained in the SMDs, they need to be added or calculated separately. Adding officers is a simple process that is covered in the ISMAT User manual [12]. The number of officers to add to the crew can be taken from the official SMD that is created by the Navy. For this research, officer categories were limited to "division officers" and "department heads". The officers are needed in the scenario to fill watch stations and billets during special evolutions. The Command Cadre of a ship consists of the Commanding Officer and the Executive Officer and these individuals are on all Navy ships regardless of the design variables. These two officers are considered when the number of officers is calculated in Section 3.3.4.

The number of personnel needed to perform each task is entered into ISMAT after the tasks have been created. The WQSB is used as a guideline for the number of operators required. ISMAT can be used to specify all of the skills that are needed to perform a task. A list of operators who meet the skills required to perform a task is created and the analyst chooses which of the crew members can be used to complete the task. For the purposes of this thesis, the skills required to perform tasks are not considered, this would be an excellent avenue for further research. As was stated earlier, the personnel that may be considered for each task is based on the department in the ship which they are assigned to. Tasks are assigned to departments based on the current operating procedures of the U.S. Navy. Figure 16 shows the crew allocation menu that is used to assign personnel who can be considered for the task “Steer Ship”.

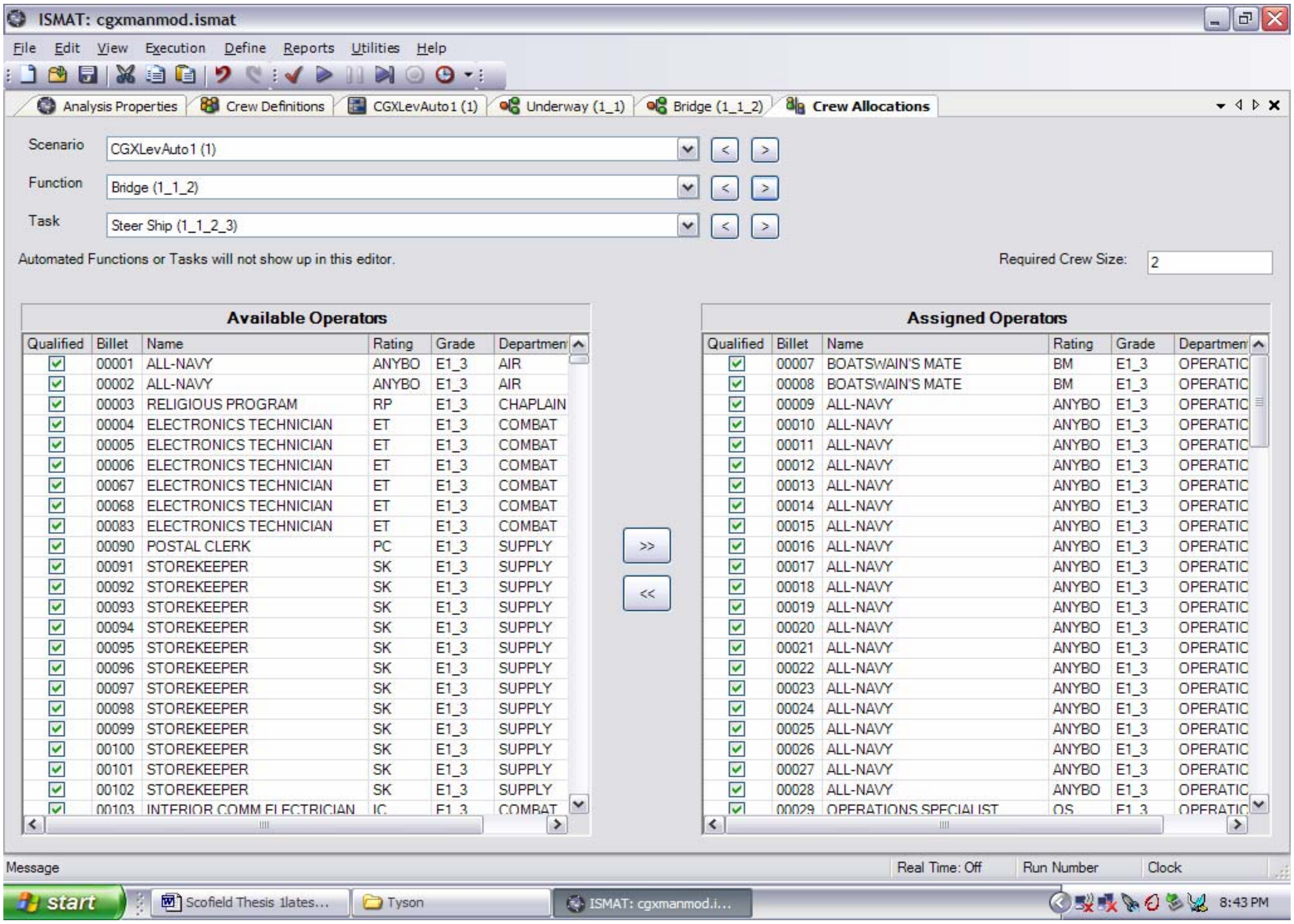

Figure 15 - Crew Allocation Screen for “steer ship”

The “available operator” list includes all of the members of the crew who are qualified to perform the task. The “assigned operators” list contains all of the crew members assigned to the task by the program during the simulation. Two personnel in the “assigned operators” list are assigned to steer the ship based on the objective of the optimization during the simulation. All of the personnel in the “assigned operators category are members of the Operations Department which is responsible for maneuvering the ship.

3.2.2 Shipboard Systems

The combat systems and propulsion system modules are used to test different systems during the concept exploration of the ship. These modules help to define the manning requirements of the ship. Ship equipment data is contained in XML files with an .ieqd extension. The equipment file contains the equipment information and the maintenance information for every system on the ship. There are equipment files for most of the ships currently in the U.S. Navy, although combat system information is somewhat limited. The equipment files are created from NAVSEA PMS data CDs. The easiest way to add equipment is to obtain copies of these PMS CDs for newer equipment and follow the instructions of the ISMAT User’s Manual[12]. The other option is to write the new equipment into the file using XML code. The process is simple for small amounts of equipment, especially if there is no NAVSEA guidance for the system yet. Figure17 shows an example of an equipment file for a GMLS design option.

```xml
<?xml version="1.0"?>
<EquipmentDocument xmlns:xsd="http://www.w3.org/2001/XMLSchema"
xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance" HullClassSymbol="VT SHIP
SYNTHESIS MODEL" Name="VTX" ID="VTX">
  <EntryList>
    <Entry Name="VLS Magazine Blowout Ventilation Closures" ID="VLS Magazine Blowout
Ventilation Closures" Cost="0" Redundant="false">
      <PMs>
        <PM Name="Clean, Inspect, Lubricate, and Test Operate VLS Magazine Vent
Closure Operator and Remote Operating Gear." ID="B9XT" MRC_MIP="5121/004/B9XT"
MeanTime="1" StdDev="0" MRPA="0.15" NumSup="0" NumNoSup="1" RR="1 GMM/E5"
EffortLevel="100" PerformEvery="1" PerUnit="Year">
          <Allocs />
          <Skills />
        </PM>
        <PM Name="Test VLS Magazine Blowout Ventilation System." ID="B9XU"
MRC_MIP="5121/004/B9XU" MeanTime="1" StdDev="0" MRPA="0.15" NumSup="0" NumNoSup="1"
RR="1 GMM/E5" EffortLevel="100" PerformEvery="1" PerUnit="Year">
          <Allocs />
          <Skills />
        </PM>
        <PM Name="Clean, Inspect, and Test Operate VLS Magazine Motorized Blowout
Ventilation Closures." ID="B9XV" MRC_MIP="5121/004/B9XV" MeanTime="1" StdDev="0"
MRPA="0.15" NumSup="0" NumNoSup="1" RR="1 GMM/E5" EffortLevel="100" PerformEvery="1"
PerUnit="Quarter">
          <Allocs />
          <Skills />
        </PM>
        <PM Name="Test Operate VLS Magazine Blowout System." ID="B9XW"
MRC_MIP="5121/004/B9XW" MeanTime="1" StdDev="0" MRPA="0.15" NumSup="0" NumNoSup="1"
RR="1 GMM/E5" EffortLevel="100" PerformEvery="1" PerUnit="Quarter">
          <Allocs />
          <Skills />
        </PM>
      </PMs>
      <CMs />
      <AllocationList />
      <PMAllocationList />
      <CMAllocationList />
      <OpPools>
        - <Pool Grade="E1_3" GradeRateRating="ANYBODY" Department="COMBAT SYSTEMS"
Division="ANY">
          <UtilString>B9XT,1,B9XU,1,B9XV,1,B9XW,1</UtilString>
        </Pool>
      </OpPools>
    </Entry>
  </EntryList>
</EquipmentDocument>
```

Figure 16 - GMLS Equipment File

The latter process is used in this thesis to create each of the equipment input files. The base equipment file is created using the installed CG-47 equipment file. All of the systems that are contained in the design option input files (propulsion, combat systems, communications, etc) are removed from the base equipment file. The design option input files are:

- Propulsion (PSYS)
- Anti-Air Warfare (AAW)
- Anti-Submarine Warfare (ASW)
- Anti-Surface Warfare (ASuW)
- Communications, Control, and Communications (CCC)
- Naval Surface Fire Support (NSFS)
- Guided Missile Launching System (GMLS)
- Self Defense Systems (SDS)

These equipment files are created by cutting and pasting all of the information for every piece of equipment that is contained in the system option. The equipment information can be obtained from the equipment files for any of the ships that are contained in ISMAT. If a system under consideration is not currently in use in by the navy, then the designer must enter all of the equipment information using existing equipment information as a template. All of the equipment information must be correctly entered into the file for the simulation to work properly. Each of the equipment files is saved as the name of the system and the option number. For instance, PSYS1 corresponds to the first option of the propulsion system. The configuration of the equipment files in ISMAT requires that all of the design variables in the manning model be discrete variables. Most of the information in the .ieqd file is maintenance information for the equipment. The maintenance information is further discussed in Section 3.2.3. The level of maintenance is created by modifying each of the baseline equipment files to account for different maintenance tasks being performed by the ship's crew. Table 3 in Section 3.3.1 contains all of the equipment files and compartment files.

3.2.3 Compartments

The size of a ship is another driver for the required crew size. A smaller ship will have less people onboard because there is less ship for the crew to maintain and operate. The size of the ship and the size of the crew become a very cyclical issue. As the ship gets larger, more people are needed for the maintenance. If there are more people, the ship needs to be larger to accommodate the larger crew which in turn creates even more maintenance. In ISMAT, compartments are handled in a very similar fashion to system equipment. Compartment information is contained in XML files that have an .icmp extension. The compartment files contain all of the maintenance that is required to be done in the space. The designer can modify the XML code for the compartment files using notepad or any other text writer. Figure 17 shows one compartment entry from the file comp1M1.icmp.


```
<?xml version="1.0" ?>
<CompartmentDocument xmlns:xsd="http://www.w3.org/2001/XMLSchema"
xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance" Name="FM Data for SMART3.txt">
  <CompartmentList>
    <Entry Name="AFFF LOCKER #1 (OV)" ID="0.5-060-1-A" CompartNumber="0.5-060-1-A">
      <FMDataHash>
        <FMData Name="CLEAN MACHINERY" ID="0" MeanTime="0.07" StdDev="0" MRPA="25" NumSup="0"
NumNoSup="1" EffortLevel="0" PerformEvery="1" PerUnit="Month">
        </FMData>
        <FMData Name="PAINT MACHINERY        " ID="1" MeanTime="0.781" StdDev="0" MRPA="25" NumSup="0"
NumNoSup="1" EffortLevel="0" PerformEvery="1" PerUnit="Year">
        </FMData>
        <FMData Name="PAINT OVERHEAD    " ID="10" MeanTime="0.087" StdDev="0" MRPA="25" NumSup="0"
NumNoSup="1" EffortLevel="0" PerformEvery="1" PerUnit="Quarter">
        </FMData>
        <FMData Name="SWEEP DECK        " ID="2" MeanTime="0.002" StdDev="0" MRPA="25" NumSup="0"
NumNoSup="1" EffortLevel="0" PerformEvery="1" PerUnit="Day">
        </FMData>
        <FMData Name="SWAB DECK (DAMP MOP)        " ID="3" MeanTime="0.003" StdDev="0" MRPA="25" NumSup="0"
NumNoSup="1" EffortLevel="0" PerformEvery="1" PerUnit="Week">
        </FMData>
        <FMData Name="SCRUB DECK        " ID="4" MeanTime="0.01" StdDev="0" MRPA="25" NumSup="0"
NumNoSup="1" EffortLevel="0" PerformEvery="1" PerUnit="Week">
        </FMData>
        <FMData Name="PAINT DECK        " ID="5" MeanTime="0.111" StdDev="0" MRPA="25" NumSup="0"
NumNoSup="1" EffortLevel="0" PerformEvery="1" PerUnit="Quarter">
        </FMData>
        <FMData Name="DUST &amp; SPOT WIPE BULKHEAD - PAINTED        " ID="6" MeanTime="0.104" StdDev="0"
MRPA="25" NumSup="0" NumNoSup="1" EffortLevel="0" PerformEvery="2" PerUnit="Month">
        </FMData>
        <FMData Name="SCRUB BULKHEAD - PAINTED    " ID="7" MeanTime="0.38" StdDev="0" MRPA="25"
NumSup="0" NumNoSup="1" EffortLevel="0" PerformEvery="1" PerUnit="Month">
        </FMData>
        <FMData Name="PAINT BULKHEAD        " ID="8" MeanTime="1.378" StdDev="0" MRPA="25" NumSup="0"
NumNoSup="1" EffortLevel="0" PerformEvery="0.5" PerUnit="Year">
        </FMData>
        <FMData Name="DUST AND SPOT WIPE OVHD - ACOUSTIC PANEL       " ID="9" MeanTime="0.022" StdDev="0"
MRPA="25" NumSup="0" NumNoSup="1" EffortLevel="0" PerformEvery="2" PerUnit="Month">
        </FMData>
      </FMDataHash>
      <AllocationList />
      <OpPools>
        - <Pool Grade="E1_3" GradeRateRating="ANYBODY" Department="ANY" Division="ANY">
          <UtilString>0,1,1,1,10,1,2,1,3,1,4,1,5,1,6,1,7,1,8,1,9,1</UtilString>
        </Pool>
      </OpPools>
    </Entry>
  </CompartmentList>
</CompartmentDocument>
```


Figure 17 - Sample Compartment File

To create the file comp1M2, all of the maintenance tasks with a “PerUnit” of one year are removed. All maintenance items with a “PerformEvery” value of greater than 12 months is also removed from the baseline compartment file. Each compartment in ISMAT has its own identification based on its location on the ship and its function. The compartment identification scheme is the same as the scheme that is currently used for naval vessels. For this study, the number of compartments is made a function of the length of the waterline. ISMAT contains a compartment file for CG-47. The number of compartments in this file was divided by the length of the waterline (LWL) to determine a relationship between the number of compartments and LWL. CG-47 was considered to be the baseline size for a cruiser. Three discrete design points are needed to build a response surface model so three compartment files were created. Compartments are added to the baseline compartment file to create two larger ships. The compartments that are added to the compartment files are fan spaces, passageways, workshops, berthing areas, and sanitary spaces. Similar to the equipment files, the design variables for the compartments need to be discrete. The maintenance for the compartment is further explained in 3.2.2.

3.2.4 Maintenance Philosophies

The maintenance that is performed by the crew can be altered to change the workload on the crew. The maintenance in ISMAT is based on the current US Navy system. There are three types of maintenance: facilities maintenance, preventative maintenance, and corrective maintenance. Facilities maintenance is the upkeep of the compartments on the ship. Some of the maintenance items include painting and cleaning the spaces. By using longer lasting coatings or hiring outside contractors to clean and paint the ship, the facilities maintenance workload can be reduced. Although personnel will be reduced from the crew, the cost of the higher quality coating or outside painters will affect the overall lifecycle cost of the ship.

The preventative maintenance in ISMAT is time-based work done to equipment to keep it operational. Examples of preventative maintenance are regularly scheduled oil changes and inspections. Some of the workload associated with preventative maintenance can be eliminated by contracting maintenance tasks. The navy currently schedules maintenance on a hourly, daily, monthly, quarterly, or annual basis. These maintenance intervals are used to determine the level of maintenance that will be performed by the ship’s crew. For the manning model, the maintenance levels below are used.

- Maintenance Level 1: The crew performs all of the maintenance that is listed for each piece of equipment. There is no work done by outside contractors and there is no work that is eliminated due to better technology.
- Maintenance Level 2: The crew performs all tasks except for tasks which have a period of occurrence greater than one year. These tasks may be contracted or eliminated based on their importance to the operation of the ship.
- Maintenance Level 3: The ship performs all monthly tasks and below. Ships generally deploy for 6 months at a time. This will hinder the ability for outside personnel to conduct maintenance on the ship on a monthly, daily, or weekly basis. The quarterly tasks and above can be scheduled around port calls or can be delayed until the ship has returned to port.

These maintenance levels help to eliminate some technicians from the ship's crew. In an ISMAT simulation, operator pools are created in the equipment files. A separate equipment file is needed for each level of maintenance. The levels of maintenance are created by the user opening each equipment file and deleting all of the maintenance tasks that will not be performed by the crew for the level being considered.

The program determines which operator to use based on the optimizer goal. The method for programming the maintenance pools is shown in Figure 19.

```
<PM Name="Test Operate VLS Magazine Blowout System." ID="B9XW"
MRC_MIP="5121/004/B9XW" MeanTime="1" StdDev="0" MRPA="0.15" NumSup="0"
NumNoSup="1" RR="1 GMM/E5" EffortLevel="100" PerformEvery="1"
PerUnit="Quarter">
  <Allocs />
  <Skills />
  </PM>
<OpPools>
    - <Pool Grade="E1_3" GradeRateRating="ANYBODY" Department="COMBAT SYSTEMS"
Division="ANY">
      <UtilString>B9XT,1,B9XU,1,B9XV,1,B9XW,1</UtilString>
    </Pool>
  </OpPools>
```

Figure 18 - Maintenance Pool Code

For the code in Figure 19, the maintenance pool consists of all of the personnel in the Combat Systems Department. The maintenance item "Test Operate VLS Magazine Blowout System" is performed once every quarter. One technician is required to perform the maintenance and it will take one hour to perform the maintenance. The "utilstring" designates the maintenance item that needs to be performed and the number of people that are required to perform it. Each maintenance item has a specific ID number that identifies it in the "utilstring".

“B9XW” corresponds to “Test operate VLS magazine blowout system”. For concept exploration, a general method of assigning maintenance is sufficient to get an initial estimate of crew size at the department level. During Concept Development, a more thorough maintenance analysis can be completed to ensure that each division has the correct number of qualified technicians in each pay grade. For newer systems, maintenance plans have not been developed by the Navy. To test the maintenance load of new equipment, research is conducted to find other organizations that use the same equipment or similar equipment. The US Navy has very limited information on Integrated Propulsion Systems(IPS) and there is no maintenance information available yet. However, the U.S. Coast Guard has two ships that use IPS. The Coast Guard was contacted to obtain their maintenance information for the IPS and the information was used in ISMAT to model the maintenance requirements of a propulsion system that utilized IPS. Further refinement of the maintenance for an IPS will need to be done during concept development and detail design to ensure that an adequate level of maintenance is considered by the manning model.

Corrective maintenance is the work that must be performed when a piece of equipment fails. ISMAT contains a list of corrective maintenance tasks for each piece of machinery. The corrective maintenance tasks are based on the Mean Time Between Failure (MTBF) for the equipment that is under consideration. ISMAT then takes the amount of time a piece of equipment is being used in the simulation and it creates casualties in a probabilistic way for the crew to handle.

In order to select the appropriate level of maintenance for a ship system, a variable Maint is added to the ship synthesis model. The value of Maint determines which maintenance strategy is employed during the simulation. A file is saved with an “M#” at the end of the file. This “M#” indicates which maintenance level is to be used. An example is “BaseshipM1.ieqd”, which is the file for the baseline equipment with a maintenance level of 1.

3.2.5 Level of Automation

The use of technology and automation is a way to reduce the number of personnel onboard a ship. Technology can be a very effective way to reduce the manning, but it must be used cautiously. Since a single crewmember does multiple jobs onboard a ship, there is not a one to one correlation between automating job tasks and removing personnel from the ship’s crew. The growth of technology and automation has spawned research in the area of human factors engineering. Methods for determining how to allocate tasks between humans and machines have been presented by many authors. One of the first approaches was created by Fitts and it is a list of tasks that are better performed by humans and tasks that are better performed by machines. This allocation method is known as a “Fitts List”. These lists became the basis of function allocation between humans and machines. These list are helpful, but should not be considered the sole basis of function allocation.[13] The “Fitts List” is a useful guideline, but a more comprehensive strategy for creating levels of automation is needed for the shipboard manning model. Mica Endsley created a taxonomy of ten levels of automation while researching situational awareness of human operators in various psychomotor and cognitive tasks[14]. Endsley’s levels of automation are used as a guideline for the levels of automation that are used in the manning model. Endsley’s taxonomy was chosen because the information that she found on situational awarness and risk is valuable to the designer as levels of automation are chosen. Further more, although only four levels of automation are currently being used, in the future, it may be more desirable to use different levels of automation that were selected for this research of designers may want to consider more than four levels of automation. Table 2 contains the 10 level taxonomy that was created by Endsley.

Table 2 - Taxonomy of Automation Levels[14]

	Roles			
Level of Automation	**Monitoring**	**Generating**	**Selecting**	**Implementing**
1- Manual Control	Human	Human	Human	Human
2- Action Support	Human/Computer	Human	Human	Human/Computer
3- Batch Processing	Human/Computer	Human	Human	Computer
4- Shared Control	Human/Computer	Human/Computer	Human	Human/Computer
5- Decision Support	Human/Computer	Human/Computer	Human	Computer
6- Blended Decision Making	Human/Computer	Human/Computer	Human/Computer	Computer
7- Rigid System	Human/Computer	Computer	Human	Computer
8- Automated Decision Making	Human/Computer	Human/Computer	Computer	Computer
9- Supervisory Control	Human/Computer	Computer	Computer	Computer
10- Full Automation	Computer	Computer	Computer	Computer

The tasks are assigned to a human or to automation based on the type of task that is being performed. The roles, the action being performed during a task, are monitoring, generating, selecting, and implementing. Monitoring is the task of ensuring that systems are functioning properly. This involves analyzing data to ensure that systems are operating within acceptable ranges. Generating is creating ideas and strategies for achieving desired system outcomes. Selecting is determining the option from “generating” to execute. Implement is the execution of the decision from the "selecting" task[14]. These functions can be assigned to either humans, machines, or both. Four of these levels are used in the scenarios of the manning model. The four highlighted levels are used at the levels of automation currently in the manning model although any of the 10 could be chosen. Level 1 and Level 4 were not chosen for evaluation because they are not practical. The US Navy currently uses some automation on it ships and it will not go back to a system that is strictly manual. The Navy has begun to experiment with unmanned vessels but these vessels much smaller than a cruiser. The following is a description of the four selected levels of automation.

- LevAuto1 - Action Support: The human will generate and select the course of action for the system but the automation will help the operator in monitoring the system and implementing the decision.
- LevAuto2 - Shared control: The human still has full control of decision making but the system will help to generate solutions and continues to help monitor the system and implement decisions.
- LevAuto3 - Rigid System: The operator is limited to monitoring the system and choosing the solution from a list that is presented by the computer.
- LevAuto4 - Supervisory Control: The human only monitors the system to ensure that it is functioning properly. The computer will monitor for problems, generate solutions, select a solution and implement it without any action from the human operator.

Endsley found in his research that the middle two options had the lowest amount of risk. Involving the operator with the task at hand was important for the operator to maintain situational awareness, but the workload of the operator should not be exceeded or the operator would not be able to keep track of everything that is happening. Decreasing automation or human involvement led to an increase in risk.

The task level of ISMAT is where the use of automation is specified. In ISMAT, automation means that a human is not required to perform a task. The method of performing the task does not need to be specified. A task can be automated because a machine is doing the task or the number of personnel can be reduced by conducting job redesign. In a damage control scenario, the size of the fire party can be reduced using technology to eliminate the need for messengers, phone talkers, and damage plotters. Job design can also be used to reduce the hierarchy of the fire party by eliminating an attack team leader and using the nozzlemen on the hoses to perform this task in conjunction with applying water to a fire. Tasks can either be allocated to personnel only, automation only, or the system can decide which to use based on the optimization being run. The designer will chose where a automation is used and where humans are used for the manning model. Figure 15 shows the menu in ISMAT for designating automation in a task.

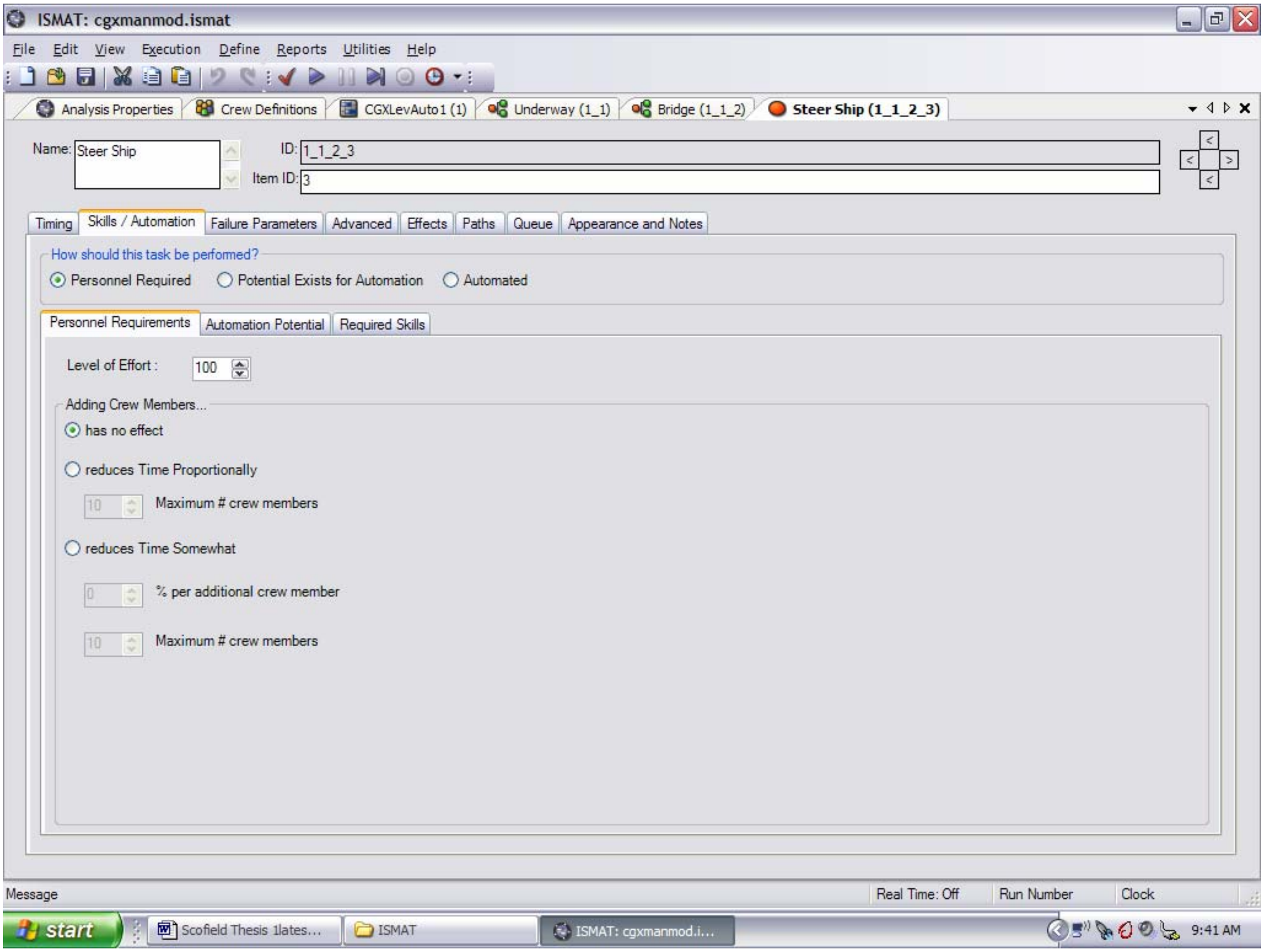

Figure 19 - ISMAT Skills/Automation Screen

The designer chooses whether the task will be automated or not by using the menu "How should this task be performed" in the figure above. If personnel are required, the analyst can allow the optimizer to use more people to finish a task faster, if possible. The "Required Skills" tab is used to specify what skills are needed to perform the task. The levels of automation for the model are created in ISMAT by automating tasks. The tasks are the same for each scenario but the automation for the tasks is different between the various scenarios. Figure 21 shows bridge watch for a ship getting underway with a level of automation of 1. Figure 22 shows the bridge watch of a ship getting underway with a level of 4. The red tasks are the automated tasks. For the first scenario, there is no automation used other than what is currently found onboard ships. In the second figure, automation is used for most of the tasks. Humans are still used as the visual lookouts due to maritime law. The tasks of "Conn Ship", "Coordinate Force Protection", and "Bridge Command and Control" are all forms of monitoring tasks so they are allocated to humans. The humans are kept in the emergency repair billets as a redundant feature in case there is a failure in the automation.

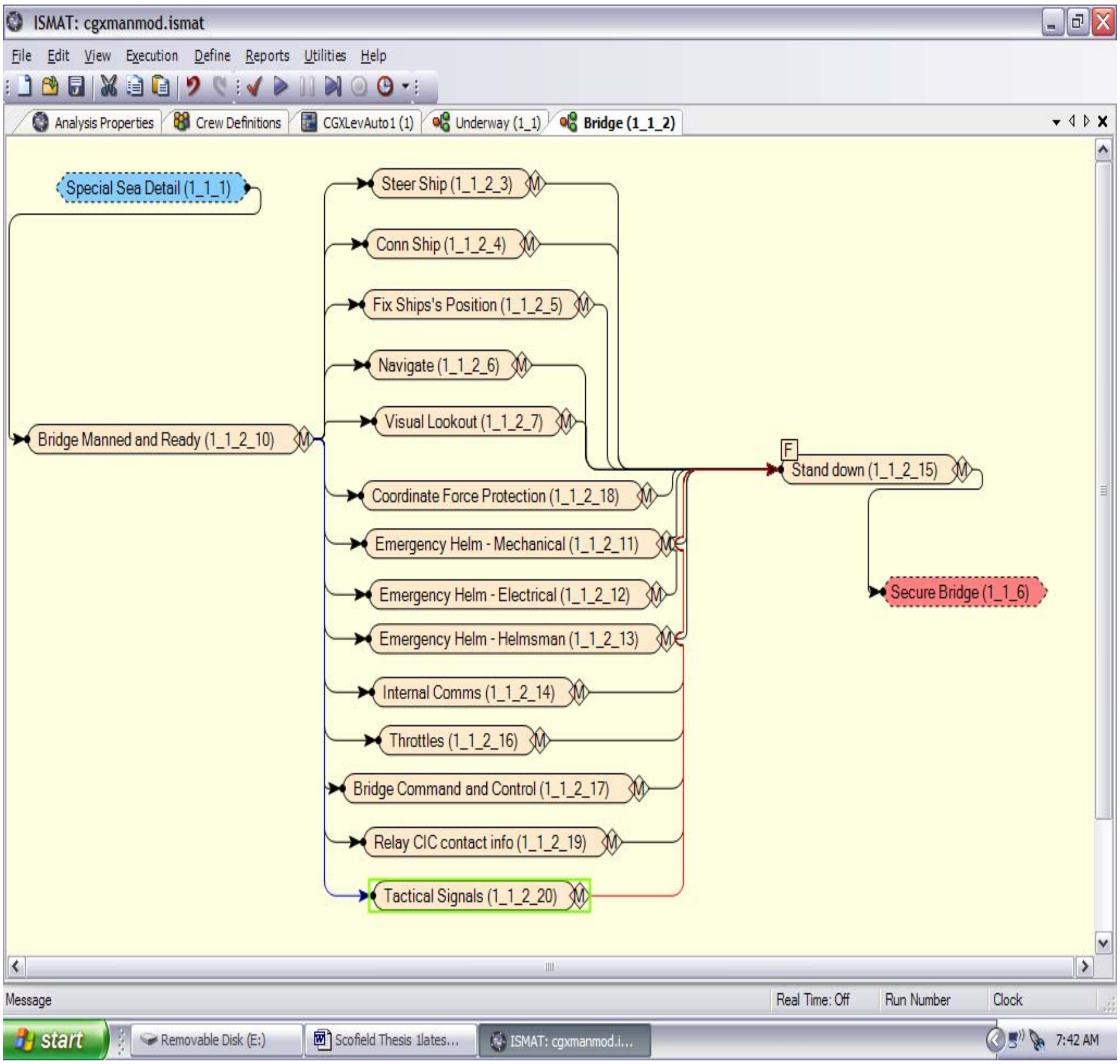

Figure 20 - Underway Bridge LevAuto 1

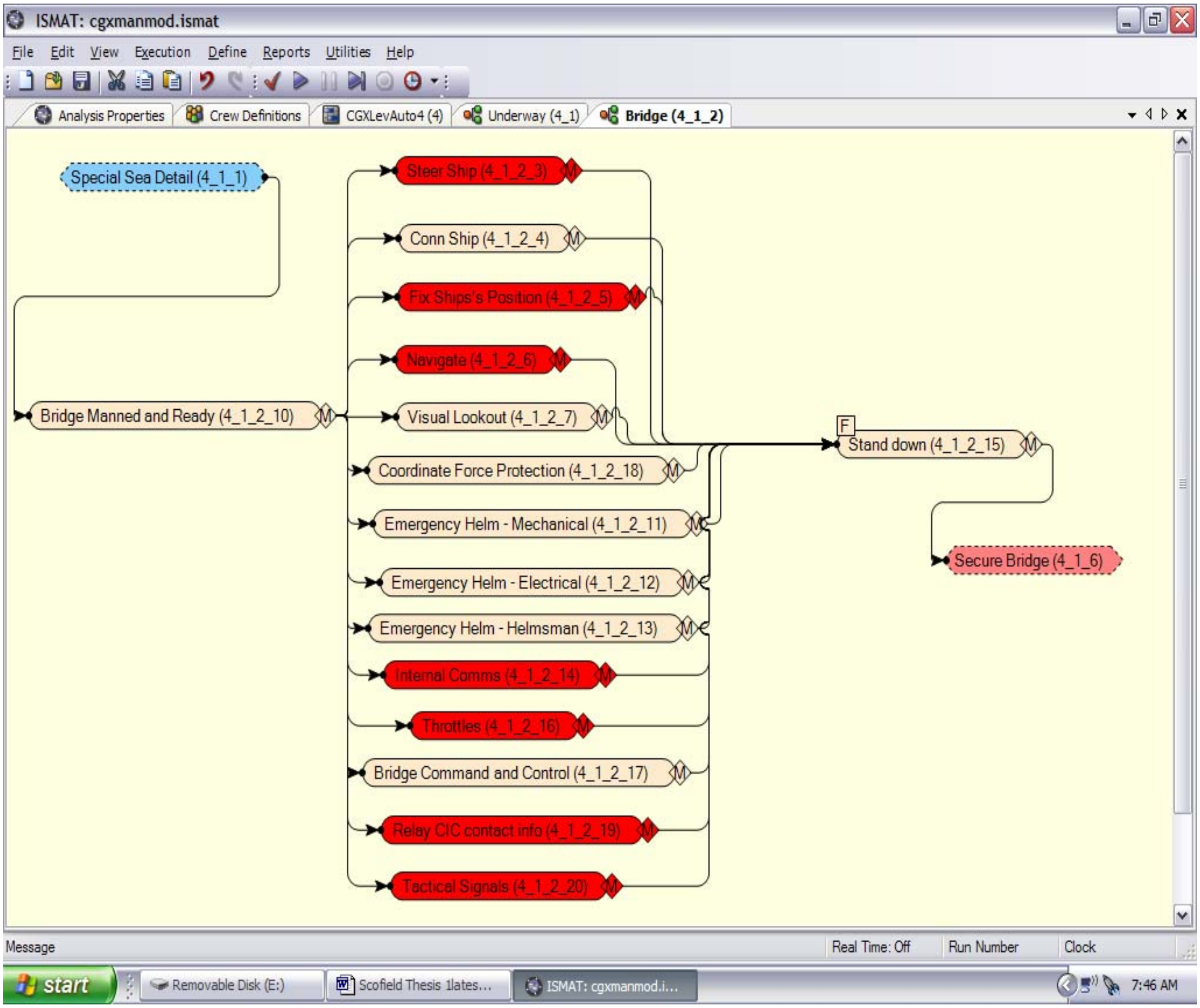

Figure 21 - Underway Bridge LevAuto 4

When the simulation is run, a command from the visual basic program is used to specify which level of automation is being implemented for the run.

3.3 Model Execution

Once all of the components of the ISMAT simulation have been created, an entire simulation can be run. The simulation must be able to be run from an outside program multiple times with multiple configurations. MAAD has modified ISMAT so that it can be run as a console application. A program has been written to take the inputs from Model Center to populate ISMAT and then run the simulation. After the simulation is complete, ISMAT writes the required crew number to an output file that is opened by Model Center to retrieve the data.

This allows the user to conduct multiple runs automatically and to create a response surface model (RSM) for the design space of the manning model.

3.3.1 Console ISMAT

ISMAT was originally created to use a graphical user interface (GUI) for building, executing, and reviewing simulations. This is a very good setup for single simulations with only one set of design variables. However for a project that has multiple design variables that come from other programs and must be run as part of a DOE or MOGO without human intervention, a different system is needed. The process of changing variables is needed so that a DOE can be parametrically run to define the relationship between manning, ship systems, ship length, automation, and maintenance. With the GUI configuration, an operator is required to sit in front of the computer and enter the data for each design option, run the simulation, and record the results. This would be very time consuming. A console version of ISMAT allows the analysis to be built and executed from the command line. The following command line is required to build and run an ISMAT simulation:

MAAD.ISMAT.Console.exe –f {filename of simulation} –e {equipment file} –c {compartment file} –s {number of the scenario to run} -g {goal for the function) –k (kills the program upon completion of the scenario) {True\False}

The console version of ISMAT contains all of the functionality of ISMAT but it is accessible without having to use the GUI. This set-up makes it possible to integrate ISMAT with other programs. Multiple equipment files can be loaded so that the configuration of the ship can be broken down by systems rather than having to create large input files. The equipment files are added to the simulation by stringing together the “-e {file name}” argument string. The level of maintenance is considered in the equipment and compartment files. Table 3 lists all of the equipment and equipment files and the levels of maintenance that were created for the manning model.

Table 3 – Manning Model Equipment files

		Maintenace Level 1	2	3
AAW Opton	1	AAWM1	AAWM2	AAWM3
	1	ASuW1M1	ASuW1M2	ASuW1M3
ASuW Options	2	ASuW2M1	ASuW2M2	ASuW3M3
	1	ASW1M1	ASW1M2	ASW1M3
ASW Options	2	ASW2M1	ASW2M2	ASW2M3
Base Option	1	Base1	Base2	Base3
	1	CCC1M1	CCC1M2	CCC1M3
CCC Options	2	CCC2M1	CCC2M2	CCC2M3
	1	COMP1M1	COMP1M2	COMP1M3
	2	COMP2M1	COMP2M2	COMP2M3
Compartment Options	3	COMP3M1	COMP3M2	COMP3M3
GMLS Options	1	GMLSM1	GMLSM2	GMLSM3
NSFS Option	1	NSFSM1	NSFSM2	NSFSM3
	1	PSYS1M1	PSYS1M2	PSYS1M3
	2	PSYS2M1	PSYS2M2	PSYS2M3
PSYS Options	3	PSYS3M1	PSYS3M3	PSYS3M3
SDS Option	1	SDSM1	SDSM2	SDSM3

One disadvantage of using the console version of ISMAT is that the GUI cannot be utilized for building the equipment and compartment files. The user must open and manipulate the equipment files and compartment files using a text editor. The manning document is loaded, using the GUI, prior to running the simulation because the pool of personnel that is considered for the simulation is not a design variable. The ISMAT optimizer determines the number of personnel required to complete the scenario regardless of how large the operator pool is. For the manning model, the objective of the optimizer is to minimize the size of the crew. Personnel are assigned to tasks before the scenario is run to eliminate the amount of required programming. Since the program automatically assigns crewmembers, the GUI can be utilized for the crew assignment functions. The level of automation is reflected in the scenario that is written, so scenario 1 has LevAuto of 1 and scenario 4 has a LevAuto of 4. Each scenario ID corresponds to the level of automation. In the console run line, the user specifies what scenario to run with the "-s" command. This executes the scenario with the proper level of automation. All of this can be used to run ISMAT from the command prompt or it can be programmed into an executable which will run the simulations automatically.

A method for outputting the results of a simulation is also required. To accomplish this, MAAD developed a function to record the number of crew members who are utilized during a simulation. These operators may be used for maintenance, operations, or a combination of the two. This number is written to a variable in the output file, manning.out. The code that is required for this process is found in Appendix A. This code is written into the "Finalization Code" section of the "Execution Settings" found in the tree view of ISMAT. The MC wrapper opens the file manning.out and reads the number of crew numbers into the MC data explorer for building an RSM.

3.3.2 Interfacing Model Center and ISMAT

Once a command line version of ISMAT was created, a method of interfacing ISMAT and Model Center was required. Visual Basic (VB) is used as a code to interface Model Center and ISMAT. VB was chosen because it is a good program for reading input and running outside programs. Model Center uses a wrapper file to create an input file for the VB executable to read, to run the executable, and to write the input from ISMAT back into Model Center. The file wrapper code is contained in Appendix B. The input variables from Table 3 that are under consideration for an analysis are written into manning.in. The executable manning.exe reads the input file and uses the input to select the necessary compartment and equipment files to load into ISMAT. Based on the inputs from Model Center, manning.exe creates strings for each system in the simulation that will load the correct equipment file into ISMAT. Equipment strings are concatenated with other strings to create the entire command and argument statement that is needed to run the ISMAT simulation for a particular design and maintenance level. The "shell" command in VB is used to run ISMAT. The "shell" command from manning.exe is:

```
Crew = Shell(ManModel, AppWinStyle.MinimizedNoFocus, True, -1)
```

The shell command runs the command and arguments that are contained in the string "ManModel". The console screen is minimized and not in focus so it will not be the seen on the screen while the simulation is running. The last two commands tell the executable to wait until the ISMAT simulation has run until the executable moves forward. Once the simulation is complete, the executable is finished and the Model Center wrapper file will look for the output from the simulation and write the crew size into Model Center. The complete code for Manning.exe is found in Appendix C

3.3.3 Design of Experiments and Response Surface Model

After the wrapper and the executable are complete, the wrapper is loaded into Model Center to create a manning module. A Design of Experiments (DOE) is used in Model Center to create a data sample relating total crew size to the input variables that are representative of the entire design space. This data is used to build a Response Surface Model (RSM) surrogate for the manning model. This is done because it is not practical to run the manning module directly in Model Center as part of the ship synthesis model and optimization. It currently takes approximately 20 seconds for Model Center to run a single ship design and over 6 hours to run an entire optimization. The ISMAT model takes approximately 1 minute to run a manning simulation. The increase in the amount of computing time would be unacceptable for the total optimization. The full factorial method DOE in Model Center Design Explorer (MCDE) was used for this analysis since the design space was fairly small. The full factorial method tests every design variable in the design space. The designer must specify how many samples of each design variable are taken. The default in MCDE is to test each variable at the lower and upper limit. For the manning model, the full factorial needs to sample each variable four times so that it finds data points for all values of LevAuto and MAINT. Once the crew data has been collected for the manning design variables, a RSM is created to fit an equation to the data using the RSM toolkit plug-in found in MC. This equation is added to one of the existing ship synthesis modules in Model Center to calculate manning for each design. A further benefit of this method is that it allows the designer to treat the discrete values as representative of a continuous function. A level of automation of 1.5 may be more desirable in a ship design and the use of an RSM allows continuous values between the integer values used in the full factorial DOE and RSM development. Once concept exploration is complete, the designer can revisit the automation levels and decide where to blend the different levels of automation so that the technology is optimal.

3.3.4 Integrating the Manning Module with the Overall Ship Synthesis Model

Within MC, there are two ways to implement a RSM. The first method of integrating the manning calculations into the ship synthesis model is to write the RSM equation into one of the FORTRAN modules that are already contained in the ship synthesis program. Currently a crew size equation is contained in the electrical module. This equation is based on a simple regression analysis of US Navy ships performed a number of years ago and a generic crew reduction factor. The RSM equation from the manning model can simply replace the existing equation to calculate manning. The FORTRAN code and the wrapper code for the electrical module are altered to provide the proper variables to the FORTRAN code for the manning calculation. The same variable names for the ship synthesis and the manning model are used to minimize rewriting of the code.

The second method creates a new module in MC based on the RSM that can be linked directly into the ship synthesis model as an additional module. This method is good because there is no additional coding required in FORTRAN. The user only needs to drag the module into the MC design environment and ensure that the variables are linked to the proper modules. A downside to this approach is that the variables used in the manning model must be compatible with the ship synthesis model. The ship synthesis model currently estimates risk and cost based on the variable CMan which is the manning factor used in the past. Although “CMan” and “LevAuto” perform very similar functions and their cost and risk are analogous, they cannot be interchanged because “CMan” has a range from .5 to 1 where .5 is the highest level of automation and 1 is the lowest. “Levauto” ranges from 1 to 4 where 1 is the lowest level of automation and 4 is the highest. Additionally, the ship synthesis model requires the number of officers and enlisted personnel on the crew to calculate the space required for the crew, not just the total crew size.

We chose to replace the current manning equation in the Electrical Module with the equation from the Manning Model RSM. This allows the variables that are currently being used in the ship synthesis model to remain unaltered. Changes required to map CMan into LevAuto and to calculate the number of officers are coded directly in the Electrical Module. The FORTRAN code for the electrical module is found in Appendix D.

The crew and the “CMan” that are used in the manning model need to be added into the cost and risk modules because they are affected by manning and automation. The Naval Ship Synthesis Model (NSSM) uses a weight based analysis to determine the acquisition cost of a design. An increase in automation will lead to the increase in cost of the command and control weight group (W4) of the ship. Since the cost of automation will not increase linearly with the weight of the automation, a ratio is needed to increase cost based on the level of automation that is being used. Figure 23 contains the code that is used to account for the increase in cost due to automation.

```
        KN4=1./CMan                                        ! command and control complexity factor
        !
           CL1=.03395*Fi*KN1*W1**.772              ! SWBS 100 lead ship construction cost
           CL2=.00186*Fi*KN2*Pbpengtot**.808        ! SWBS 200 lead ship construction cost
           KN3=1.0                                            ! electrical complexity factor
           CL3=.07505*Fi*KN3*W3**.91                        ! SWBS 300 lead ship construction cost
           CL4=.10857*Fi*KN4*W4**.617              ! SWBS 400 lead ship construction cost
```

Figure 22 – Cost Module Code

The highest level of automation is when CMan=.5. This results in the cost of the command and control weight group being doubled. The cost of personnel is considered directly in Life Cycle Cost but, not directly in ship acquisition cost. The size of the crew affects the size of the ship that is needed and that is where manning influences the acquisition cost of the ship. The technology risk associated with using increased levels of automation must also be estimated. This is accomplished in the risk module, the code for calculation risk based on automation if demonstrated in Figure 24.

```
PerfRiskAuto=.42*(1.0-CMan)
           CostRiskAuto=.25*(1.0-CMan)
           SchedRiskAuto=.35*(1.0-CMan)
!
           PerfRisk=(PerfRiskDHMAT1+PerfRiskDHMAT2+PerfRiskTH+PerfRiskIED+PerfRiskICR+&
                     PerfRiskPod1+PerfRiskPod2+PerfRiskSPY+PerfRiskAuto)/2.9
           CostRisk=(CostRiskDHMAT+CostRiskIED+CostRiskICR+CostRiskPod+CostRiskSPY+&
                     CostRiskAuto)/1.27

SchedRisk=(SchedRiskDHMAT+SchedRiskIED+SchedRiskICR+SchedRiskPod+SchedRiskSPY+&
                     SchedRiskAuto)/1.51
           OMOR=.5*PerfRisk+.3*CostRisk+.2*SchedRisk
!
```

Figure 23 – Risk Module Code

For the design, if there is no new level of technology added to the design then CMan=1 and the cost and schedule risk will equal 0. As the use of automation increases, so does the risk. The risk equation is based on regression analysis and expert opinion.

3.4 Ship Synthesis Model Execution with Manning Model RSM

Once the old manning equation is replaced with the new RSM, the entire NSSM can be run as part of a Multi-Objective Genetic Optimization (MOGO) to identify non-dominated designs that properly estimate and integrate the effects of system selection, automation, and maintenance strategies on manning and total ship design.

CHAPTER 4 SURFACE COMBATANT CASE STUDY

A case study to demonstrate the use of the manning model in a ship design is presented in this chapter. The ship design that is being used is the Virginia Tech undergraduate ship design project for the 2005-2006 Academic Year [15]. The project is to design a replacement for the current Cruiser CG47. The new design will have to meet all of the current capabilities of CG-47 Class while reducing crew size and support cost. CGX must also be able to accomplish air superiority by sensing, tracking, and engaging airborne threats including out of atmosphere ballistic missiles.

4.1 Mission Need and Description of Design Problem

The requirements for CGX are set forth in the CGX Mission Needs Statement and the Virginia Tech CGX Acquisition Decision Memorandum. These documents can be found in Appendix E and F. From these documents, the design team created the following mission scenario for the ship.

Table 4 - Mission Scenario for CGX [15]

DAY	MISSION DESCRIPTION
1-21	Large CBG leaves port (CONUS); transit to Persian Gulf
22 - 59	ISR
	UNREP every 4-6 days
33	Engage missile threat against carrier
40	Launch cruise missiles at land target
57	Conduct ASW with LAMPS helo vs. diesel submarine threat
59 - 60	Port call for repairs and replenishment
61	Engage in response to in-port attack by several small boats and land-based missiles.
62 - 75	Rejoin CBG
65 - 89	ISR
70-72	Engage high speed boats using guns and harpoon missiles
75	SAR of crew from damaged destroyer
76 - 80	Conduct missile defense against continued aggression
80 - 90	Return transit to home port
90 +	Port call / Restricted availability

Based on this mission scenario, a one week scenario was created to test the crew and estimate required manning. A 90+ day scenario would have been too cumbersome to calculate and create. The crew utilization and in ISMAT is based on the amount of work for a standard navy work week which is currently 67 hours. Table 5 lists the required operational capabilities of the CGX design.

Table 5 - Required Operational Capabilities (ROCs) [15]

ROCs	Description
AAW 1	Provide anti-air defense
AAW 1.1	Provide area anti-air defense
AAW 1.2	Support area anti-air defense
AAW 1.3	Provide unit anti-air self defense
AAW 2	Provide anti-air defense in cooperation with other forces
AAW 3	Support Theater Ballistic Missile Defense (TBMD)
AAW 5	Provide passive and soft kill anti-air defense
AAW 6	Detect, identify and track air targets
AAW 9	Engage airborne threats using surface-to-air armament
AMW 6	Conduct day and night helicopter, Short/Vertical Take-off and Landing and airborne autonomous vehicle (AAV) operations
AMW 6.3	Conduct all-weather helo ops
AMW 6.4	Serve as a helo hangar
AMW 6.5	Serve as a helo haven
AMW 6.6	Conduct helo air refueling
AMW 12	Provide air control and coordination of air operations
ASU 1	Engage surface threats with anti-surface armaments
ASU 1.1	Engage surface ships at long range
ASU 1.2	Engage surface ships at medium range
ASU 1.3	Engage surface ships at close range (gun)
ASU 1.5	Engage surface ships with medium caliber gunfire
ASU 1.6	Engage surface ships with minor caliber gunfire
ASU 1.9	Engage surface ships with small arms gunfire
ASU 2	Engage surface ships in cooperation with other forces
ASU 4	Detect and track a surface target
ASU 4.1	Detect and track a surface target with radar
ASU 6	Disengage, evade and avoid surface attack
ASW 1	Engage submarines
ASW 1.1	Engage submarines at long range
ASW 1.2	Engage submarines at medium range
ASW 1.3	Engage submarines at close range
ASW 4	Conduct airborne ASW/recon
ASW 5	Support airborne ASW/recon
ASW 7	Attack submarines with antisubmarine armament
ASW 7.6	Engage submarines with torpedoes
ASW 8	Disengage, evade, avoid and deceive submarines
CCC 1	Provide command and control facilities
CCC 1.6	Provide a Helicopter Direction Center (HDC)
CCC 2	Coordinate and control the operations of the task organization or functional force to carry out assigned missions
CCC 3	Provide own unit Command and Control

ROCs	Description
CCC 4	Maintain data link capability
CCC 6	Provide communications for own unit
CCC 9	Relay communications
CCC 21	Perform cooperative engagement
FSO 5	Conduct towing/search/salvage rescue operations
FSO 6	Conduct SAR operations
FSO 8	Conduct port control functions
FSO 9	Provide routine health care
FSO 10	Provide first aid assistance
FSO 11	Provide triage of casualties/patients
INT 1	Support/conduct intelligence collection
INT 2	Provide intelligence
INT 3	Conduct surveillance and reconnaissance
INT 8	Process surveillance and reconnaissance information
INT 9	Disseminate surveillance and reconnaissance information
INT 15	Provide intelligence support for non-combatant evacuation operation (NEO)
MIW 4	Conduct mine avoidance
MIW 6	Conduct magnetic silencing (degaussing, deperming)
MIW 6.7	Maintain magnetic signature limits
MOB 1	Steam to design capacity in most fuel efficient manner
MOB 2	Support/provide aircraft for all-weather operations
MOB 3	Prevent and control damage
MOB 3.2	Counter and control NBC contaminants and agents
MOB 5	Maneuver in formation
MOB 7	Perform seamanship, airmanship and navigation tasks (navigate, anchor, mooring, scuttle, life boat/raft capacity, tow/be-towed)
MOB 10	Replenish at sea
MOB 12	Maintain health and well being of crew
MOB 13	Operate and sustain self as a forward deployed unit for an extended period of time during peace and war without shore-based support
MOB 16	Operate in day and night environments
MOB 17	Operate in heavy weather
MOB 18	Operate in full compliance of existing US and international pollution control laws and regulations
NCO 3	Provide upkeep and maintenance of own unit
NCO 19	Conduct maritime law enforcement operations
SEW 2	Conduct sensor and ECM operations
SEW 3	Conduct sensor and ECCM operations
SEW 5	Conduct coordinated SEW operations with other units
STW 3	Support/conduct multiple cruise missile strikes

The ROCs drive the systems that are needed on the ship, and are used to calculate an overall measure of effectiveness for the different design options.

4.2 Design Space

The design variables for CGX are listed in Table 6.

Table 6 - Design Variables (DVs) [15]

DV #	DV Name	Description	Design Space
***1**	**LWL**	**Waterline Length**	**550 – 700 ft. (150-200m)**
2	LtoB	Length to Beam ratio	7.9-9.9
3	LtoD	Length to Depth ratio	10.75-17.8
4	BtoT	Beam to Draft ratio	2.9-3.2
5	Cp	Prismatic coefficient	0.56 – 0.64
6	Cx	Maximum section coefficient	0.75 – 0.84
7	Crd	Raised deck coefficient	0.7 – 1.0
8	VD	Deckhouse volume	100,000-150,000 ft^3 ($2800-4250m^3$)
9	Cdhmat	Deckhouse material	1 = Steel, 2 = Aluminum, 3 = Advanced Composite
10	HULLtype	Hull: Flare or Tumblehome	1: flare= 10 deg; 2: flare = -10 deg
11	BALtype	Ballast/fuel system type	0 = clean ballast, 1 = compensated fuel tanks
***12**	**PSYS**	**Propulsion system alternative**	**Option 1) 2 shaft, mechanical, CPP, 4xLM2500+ Option 2) 2 shaft, mechanical, CPP, 4xMT30 Option 3) 2 shaft, mechanical, CPP, 2xLM2500+, 2x ICR WR29 Option 4) 2 shaft, mechanical, CPP, 2xMT30, 2x ICR WR29 Option 5) 2 shaft. IPS, FPP, 3xLM2500+, 2 x Allison 501K34 Option 6) 2 shaft. IPS, FPP, 3xMT30, 2 x Allison 501K34 Option 7) 2 shaft. IPS, FPP, 4xMT30, 2 x Allison 501K34 Option 8) 2 shaft. IPS, FPP, 2xLM2500+, 2x ICR WR29, 2 x Allison 501K34 Option 9) 2 shaft. IPS, FPP - 2xMT30, 2x ICR WR29, 2 x Allison 501K34 Option 10) 2 shaft. IPS, FPP, 3xMT30, 3x ICR WR29, 2 x Allison 501K34 Option 11) 2 pods, IPS, 3xLM2500+, 2 x Allison 501K34 Option 12) 2 pods, IPS, 3xMT30, 2 x Allison 501K34 Option 13) 2 pods. IPS, 4xMT30 + 2 x Allison 501K34 Option 14) 2 pods, IPS, 2xLM2500+, 2x ICR WR29 + 2 x Allison 501K34 Option 15) 2 pods, IPS, 2xMT30, 2x ICR WR29, 2 x Allison 501K34 Option 16) 2 pods, IPS, 3xMT30, 2x ICR WR29, 2 x Allison 501K34**
13	GSYS	Ship Service Generator system alternatives	Option 1) 5 x Allison 501K34 (@3,500 kW) Option 2) 4 x Allison 501K34 (@3,500 KW) Option 3) 2 x Allison 501K34 (@3,500 KW) For PSYS=5-16: no additional SSGTGs
14	Ts	Provisions duration	45-60 days
15	Ncps	Collective Protection System	0 = none, 1 = partial, 2 = full
16	Ndegaus	Degaussing system	0 = none, 1 = degaussing system
17	Cman	Manning reduction and automation factor	0.5 – 0.1
***18**	**AAW**	**Anti-Air Warfare alternatives**	**Option 1) SPY-3 (4 panel), VSR, AEGIS MK 99 FCS Option 2) SPY-3 (2 panel), VSR, AEGIS MK 99 FCS Option 3) SPY-1B (4 panel), SPS-49, 4xSPG-62, AEGIS MK 99 FCS**
***19**	**ASUW**	**Anti-Surface Warfare alternatives**	**Option 1) SPS-73(V)12, MK 160/34 GFCS, Small Arms Locker Option 2) SPS-73(V)12, SPQ-9, MK 86 GFCS, Small Arms Locker**
***20**	**ASW**	**Anti-Submarine Warfare alternatives**	**Option 1) SQS-53D, SQQ 89, MK 116 UWFCS, ASROC, 2xMK 32 Triple Tubes, NIXIE, SQR-19 TACTAS Option 2) SQS-56, SQQ 89, MK 116 UWFCS, ASROC, 2xMK 32 Triple Tubes, NIXIE, SQR-19 TACTAS**
***21**	**NSFS**	**Naval Surface Fire Support alternatives**	**Option 1) MK 45 5" – 64 mod 4 gun Option 2) 2 MK 110 57 mm gun**
***22**	**CCC**	**Command Control Communication alternatives**	**Option 1) Enhanced CCC Option 2) Basic CCC (CG 47)**
23	LAMPS	LAMPS alternatives	Option 1) Embarked 2 LAMPS w/Hangars Option 2) Embarked single LAMPS w/Hangar Option 3) LAMPS haven (flight deck)
***24**	**SDS**	**Self Defense System alternatives**	**Option 1) 2xCIWS Option 2) 1xCIWS Option 3) none**
***25**	**GMLS**	**Guided Missile Launching System alternatives**	**Option 1) 224 cells, MK 41 and/or MK57 PVLS Option 2) 192 cells, MK 41 and/or MK57 PVLS Option 3) 160 cells, MK 41 and/or MK57 PVLS Option 4) 128 cells, MK 41 and/or MK57 PVLS**

The design variables that directly influence the manning calculations are highlighted in Table 6. Design options are combined when the difference in design options would not significantly affect the maintenance tasks. As an example, propulsion system options 1-4 are combined into one option in ISMAT because there is very limited ICR turbine maintenance information and these options had similar machinery and maintenance requirements. Two additional design variables are added to the synthesis program for the manning module. These variables are LevAuto, for the level of automation and Maint for the level of maintenance. The level of automation for the manning module is level 1(lowest) to level 4(highest). These are reflected in 4 different scenarios. The maintenance strategy is determined by the design variable Maint. The maintenance strategy is based on the maintenance levels described in Section 3.2.3. These levels are reflected in three different equipment files and compartment files. Table 7 lists the CGX design variables and the corresponding variables that are used by ISMAT in the manning model.

Table 7 – CGX and ISMAT Design Variables

DV #	DV Name	Description	Design Space	ISMAT Variable
1	**LWL**	**Waterline Length**	**550 – 700 ft. (150-200m)**	LWLComp Discrete 1-3
12	**PSYS**	**Propulsion system alternative**	**Option 1) 2 shaft, mechanical, CPP, 4xLM2500+** **Option 2) 2 shaft, mechanical, CPP, 4xMT30** **Option 3) 2 shaft, mechanical, CPP, 2xLM2500+, 2x ICR WR29** **Option 4) 2 shaft, mechanical, CPP, 2xMT30, 2x ICR WR29**	PSYS1
			Option 5) 2 shaft. IPS, FPP, 3xLM2500+, 2 x Allison 501K34 **Option 6) 2 shaft. IPS, FPP, 3xMT30, 2 x Allison 501K34** **Option 7) 2 shaft. IPS, FPP, 4xMT30, 2 x Allison 501K34** **Option 8) 2 shaft. IPS, FPP, 2xLM2500+, 2x ICR WR29, 2 x Allison 501K34** **Option 9) 2 shaft. IPS, FPP - 2xMT30, 2x ICR WR29, 2 x Allison 501K34** **Option 10) 2 shaft. IPS, FPP, 3xMT30, 3x ICR WR29, 2 x Allison 501K34**	PSYS2
			Option 11) 2 pods, IPS, 3xLM2500+, 2 x Allison 501K34 **Option 12) 2 pods, IPS, 3xMT30, 2 x Allison 501K34** **Option 13) 2 pods. IPS, 4xMT30 + 2 x Allison 501K34** **Option 14) 2 pods, IPS, 2xLM2500+, 2x ICR WR29 + 2 x Allison 501K34** **Option 15) 2 pods, IPS, 2xMT30, 2x ICR WR29, 2 x Allison 501K34** **Option 16) 2 pods, IPS, 3xMT30, 2x ICR WR29, 2 x Allison 501K34**	PSYS3
17	Cman	Manning reduction and automation factor	0.5 – 0.1	LevAuto Discrete 1-4
18	**AAW**	**Anti-Air Warfare alternatives**	**Option 1) SPY-3 (4 panel), VSR, AEGIS MK 99 FCS** **Option 2) SPY-3 (2 panel), VSR, AEGIS MK 99 FCS** **Option 3) SPY-1B (4 panel), SPS-49, 4xSPG-62, AEGIS MK 99 FCS**	AAW
19	**ASUW**	**Anti-Surface Warfare alternatives**	**Option 1) SPS-73(V)12, MK 160/34 GFCS, Small Arms Locker**	ASuW1
			Option 2) SPS-73(V)12, SPQ-9, MK 86 GFCS, Small Arms Locker	ASuW2
20	**ASW**	**Anti-Submarine Warfare alternatives**	**Option 1) SQS-53D, SQQ 89, MK 116 UWFCS, ASROC, 2xMK 32 Triple Tubes, NIXIE, SQR-19 TACTAS**	ASW1
			Option 2) SQS-56, SQQ 89, MK 116 UWFCS, ASROC, 2xMK 32 Triple Tubes, NIXIE, SQR-19 TACTAS	ASW2
21	**NSFS**	**Naval Surface Fire Support alternatives**	**Option 1) MK 45 5" – 64 mod 4 gun** **Option 2) 2 MK 110 57 mm gun**	NSFS
22	**CCC**	**Command Control Communication alternatives**	**Option 1) Enhanced CCC**	CCC1
			Option 2) Basic CCC (CG 47)	CCC2
24	**SDS**	**Self Defense System alternatives**	**Option 1) 2xCIWS** **Option 2) 1xCIWS** **Option 3) none**	SDS
25	**GMLS**	**Guided Missile Launching System alternatives**	**Option 1) 224 cells, MK 41 and/or MK57 PVLS** **Option 2) 192 cells, MK 41 and/or MK57 PVLS** **Option 3) 160 cells, MK 41 and/or MK57 PVLS** **Option 4) 128 cells, MK 41 and/or MK57 PVLS**	GMLS

4.3 Ship Synthesis Model

The ship synthesis model for CGX consists of multiple modules that are run together to design and balance a ship. The modules consist of FORTRAN code that is used to calculate ship characteristics using physics based equations and regression based equations. The model is run for multiple iterations and designs are optimized to minimize cost and risk while maximizing effectiveness. Model Center is used as the design environment for the program. The Darwin optimizer is used to conduct the optimization. The following is a brief description of each of the modules currently contained in the ship synthesis model.

- **Input module –** Receives input values from user or optimizer. Input values are written to an output file where they can be read by any subsequent modules.
- **Combat system module –** receives as input values for AAW, ASUW, ASW, CCC, NSFS, GMLS, LAMPS and SDS combat systems, and data with the weight, power, and volume characteristics of these systems. The module also receives length of the waterline and the length to depth ratio. From these inputs the module calculates the depth at station 10 and constructs a payload vector for each combat system listed above. These vectors are combined to form an overall payload vector. The values from this overall vector are used to input each component's weight and vertical center of gravity (VCG). The module also outputs electric power and deckhouse and hull area required based on component payload.
- **Propulsion module –** receives as input the propulsion system alternative and generator system alternative including the corresponding propulsion and generator system characteristics including the number systems, brake horsepower, weight of the system, specific fuel consumptions, power required, the machinery weights, and the machinery box dimensions. The module also receives LWL, Beam, average deck height, Depth at station 10, and the volume of the deckhouse. It outputs the selected propulsion system characteristics, the number of hull decks, the endurance and sustained speed specific fuel consumptions, the required machinery box dimensions and weight, the hull and deckhouse area lost to the propulsion system, transmission efficiency for the propulsion system, the total weight of the system, and the area impact of the inlets and exhaust.
- **Hull form module –** receives the length of the ship (LWL), beam to length ratio (B/L), depth at station 10 to length ratio (D/L), draft to beam ratio (T/B), prismatic coefficient (C_p), Maximum section coefficient (C_x), and sonar type as input. The module uses a Taylor series

method to calculate hull surface area and inputs sonar dome surface area and volume. The module calculates block coefficient (C_b), full load displaced volume with appendages, beam to draft ratio, volume coefficient (C_v), total hull surface area, the design waterplane coefficient (C_w), beam, draft, and hull flare which are all written to the output file.

- **Space available module –** receives as input ship characteristics such as load waterline, beam, draft, deckhouse volume, the required machinery box dimensions, and total hull volume. The module then determines the minimum depth at station 10 based on four factors including hull strength, heeled flooding prevention, machinery box accommodation, and the fact that this depth must be greater than or equal to the depth at station 20. This minimum depth is output with total hull volume, hull cubic number, total ship volume, height and volume of machinery box, and average depth. It calculates the available arrangeable space by subtracting the tankage and the machinery volumes from the hull volume.
- **Electric module –** receives as input various geometric ship characteristics, propulsion type, manning factor, electric margin factors, and payload weights and powers. The module calculates the total electric power required for the ship as the sum of individual electrical requirements with margins. The module also calculates and outputs manning requirements and auxiliary machinery room volume.
- **Resistance module –** receives as input overall ship characteristics, displacement volume, propulsion system characteristics, and total hull surface area and volume. The module uses the Holtrop-Mennon resistance calculation procedure to find the effective horsepower of the ship. This process includes calculations for viscous, wave-making, and bare hull resistance. These factors are then combined to find the total ship resistance and then to calculate horsepower. The module outputs the ship’s effective shaft horsepower, sustained speed, and propeller diameter.
- **Weight module –** receives as input ship characteristics such as length, beam, and draft, propulsion system characteristics, payload weights, output from the combat systems module, and manning requirements. It uses a series of parametric equations to calculate the SWBS weights. The total weight of the ship must equal displacement. Fuel weight is used as a slack variable to balance the displacement and weight. Parametric equations are also used to calculate VCGs for each weight. The module outputs the deckhouse weight, weights corresponding to each SWBS group, the interior communications system weight, weights of the ship fuel, lube oil, and freshwater, the total ship weight, and the ship’s KG.

- **Tankage module –** receives as input: ballast type, propulsion transmission efficiency, manning requirements, propulsion system characteristics, sustained and endurance speeds, required electric power, and specific fuel consumptions. The module then calculates annual fuel consumption assuming 2500 hours of endurance steaming per year, and fuel consumption for endurance range based on Navy DDS 200-1. The module calculates and outputs total tankage volume, fuel tankage volume, endurance range, brake propulsion power required at endurance speed, and gallons of fuel used per year.
- **Space required module** – receives as input: deckhouse volume, tankage volume, machinery room volume, required deckhouse area for payload, required hull area for payload, required area for engine inlets and exhausts, and manning requirements. The module calculates the total required and total available volume and arrangeable area. Required and available deckhouse area and total ship area are output by the module.
- **Feasibility module –** receives as input: available and required arrangeable areas, endurance range and required endurance range, sustained speed and required sustained speed, available and required generator power, GM/B ratio, minimum and maximum GM/B ratio, depth at Station 10 and minimum depth at Station 10, total manning, and maximum total manning. The module performs feasibility calculations using ratios of the difference of available and required properties to the required values. The resulting feasibility ratio value must be greater than or equal to zero within a 5% tolerance to be feasible. The module outputs feasibility ratios for total arrangeable area, deckhouse area, sustained speed, endurance speed, endurance range, electric power, hull depth, and maximum and minimum metacenter to beam ratio.
- **Cost module –** receives as input: propulsion system characteristics, endurance speed and range, fuel requirements, SWBS group weights, manning, base year profit margin, the number of ships to be built, inflation rates before and after the base year, and the shipbuilding rate per year after the lead ship. The module uses these values and modified weight-based parametrics with complexity factors to calculate lead and follow ship cost by SWBS group. Lead ship acquisition cost, follow ship acquisition cost, and follow ship ownership cost are returned as output.
- **Effectiveness and Risk modules –** These modules are discussed in more detail in Section 4.5

4.4 Integration of Manning and Automation Model

4.4.1 CGX Manning Model Setup

The first step to incorporate the manning and automation model in the CGX design is to build all of equipment files that correspond to the design options for the combat systems module and the propulsion module. These equipment files contain all of the equipment in each design option found in Table 4. Next a base equipment file is created. The base equipment file contains the equipment that is found on all CGX ship designs. These systems include refrigeration, electrical power distribution, air conditioning, etc. Next, the compartment files are built from the CG compartment file that is standard with ISMAT. The base compartment file in ISMAT is from CG-47. The number of compartments in this file is used as a baseline. The compartment difference between design options was assumed to be a function of length. The number of compartments for CG-47 contained in ISMAT is divided by the length of the waterline (LWL) for CG-47. This results in a compartment per foot of waterline relationship. This ratio is applied to three lengths within the design space of CGX to form three compartment options to choose from. Finally, each equipment and compartment option is modified to consider three levels of maintenance so there are three options to choose for each system and compartment. The maintenance levels used were 1-3 as discussed in Section 3.2.3.

Finally, the scenarios to test the crew are developed. The scenarios are one week long and consist of the following evolutions:

- Getting underway from homeport
- General Emergency fire
- General Quarters
- Major Conflagration
- Flight Operations
- At Sea Watch

Four scenarios options are developed to consider four levels of automation. Each scenario has a different level of automation for the entire scenario. The level of automation is based on the tasks that are automated for the specific scenario. The CGX manning module levels of automation are based on Table 2.

4.4.2 CGX Design of Experiments and Response Surface Model

Once all of the components were developed, the wrapper is loaded into Model Center. The wrapper in MC runs the program Manning.exe in the simulation. A DOE was conducted to obtain data for the design space of CGX. The results of the DOE are contained in Appendix B. Once this data was generated, a full quadratic RSM was created to fit the data. The equation for the RSM is:

$$\begin{aligned} NT = {} & 374.49 + 82.06*LevAuto - 6.09*MAINT + 11.29*LWLComp - 59.85*LevAuto^2 \\ & + 2.08*PSYS*LWLComp - .147*PSYS^3 + 8.52*LevAuto^3 - .294*ASuW*PSYS* \\ & LevAuto + .341*ASuw*MAINT^2 - .684*PSYS^2*LWLComp + .413*PSYS*LevAuto* \\ & CCC - .485*MAINT*CCC*LWLComp + .210*CCC*LWLComp^2 \end{aligned} \quad (1)$$

4.4.3 Integrating the Manning RSM into Naval Ship Synthesis Model (NSSM)

In the manning model, three distinct compartment lists are used because the compartment options need to be handled in a discretely by ISMAT. The LWL variable in the ship synthesis program is normalized to “LWLComp” which is equivalent to $\frac{LWL}{161.24m}$. The length of CG-47 is 161.24 meters. This equation is programmed into the Electrical Module in place of the previous manning equation. The synthesis model uses the variable “CMan” to specify automation. “LevAuto” is used with the scenario that is run by ISMAT and needs to be discrete. LevAuto equals -6*CMan +7. The values of LevAuto and LWLComp are programmed into FORTRAN in terms of CMan and LevAuto so that none of the other modules need to be changed to accommodate the manning model.

The manning model calculates the total crew number required for the ship. This number contains both the officers and enlisted crewmembers. This is equivalent to the variable “NT” found in the NSSM. The number of officers is important because the US Navy has different space requirements for officers and enlisted personnel onboard ship. To determine what percentage of the crew is officers, current Navy platforms were examined. Table 8 was created using Ship Manning Documents to determine crew size, number of officers, and percentage of crew being composed by officers.

Table 8 - US Navy Ship Crew sizes

Ship Class	Total Crew	Number Officers	% Officers
CG-47	398	29	7.29%
LPD-17	396	32	8.08%
DDG-51 flt IIA	298	24	8.05%
FFG-7	215	17	7.91%

Based on the table above, the number of officers, NO, is determined to be approximately 8% of the total number of personnel. The smallest number of officers for any CGX design is constrained to 23.

4.5 Objective Attributes

4.5.1 Overall Measure of Effectiveness (OMOE)

The Overall Measure of Effectiveness (OMOE) is a single overall figure of merit ranging from 0-1.0 and is based on Measures of Performance (MOP), Values of Performance (VOP), and weighting factor (w_i). The equation for this OMOE is shown in Equation (2).

$$OMOE = g\left[VOP_i\left(MOP_i\right)\right] = \sum_i w_i VOP_i\left(MOP_i\right) \tag{2}$$

To build the OMOE function, the first step is to identify the MOPs that are critical to the ship mission with goal values (VOP) of 1.0 and threshold values (VOP) of 0 (Table 10). These MOPs are then organized into an OMOE hierarchy, Figure 26 which organizes the MOPs into groups such as mission, mobility, susceptibility, vulnerability, etc. Each of these groups receives its own weight and is incorporated into the OMOE under specific Mission Types such as SAG or CBG. Expert Choice is used to conduct pairwise comparison to calculate the weights for the MOPs based on their relative importance to a specific mission type, where the sum of these weights equals 1. The CGX MOP weights are illustrated in Figure 26. A VOP with goal value of 1.0 and threshold value of 0 is assigned to a specific MOP to a specific mission area for a specific mission type.

Table 9 - ROC/MOP/DV Summary [15]

ROCs	Description	MOP	Related DV	Goal	Threshold
AAW 1	Provide anti-air defense	AAW	AAW, GMLS	AAW=1 GMLS=1	AAW=3 GMLS=4
AAW 1.1	Provide area anti-air defense	AAW	AAW GMLS	AAW=1 GMLS=1	AAW=3 GMLS=4
AAW 1.2	Support area anti-air defense	AAW	AAW GMLS	AAW=1 GMLS=1	AAW=3 GMLS=4
AAW 1.3	Provide unit anti-air self defense	AAW, RCS, IR	SDS, VD, PSYS	SDS=1 1500m3	SDS=2 2000m3
AAW 2	Provide anti-air defense in cooperation with other forces	AAW	CCC	CCC=1	CCC=2
AAW 3	Support Theater Ballistic Missile Defense (TBMD)	AAW	CCC	CCC=1	CCC=2
AAW 5	Provide passive and soft kill anti-air defense	AAW, IR, RCS	VD, PSYS	1500m3	2000m3
AAW 6	Detect, identify and track air targets	AAW, IR, RCS	VD PSYS	1500m3	2000m3
AAW 9	Engage airborne threats using surface-to-air armament	AAW, IR, RCS	VD PSYS	1500m3	2000m3
AMW 6	Conduct day and night helicopter, Short/Vertical Take-off and Landing and airborne autonomous vehicle (AAV) operations	ASW, ASUW, FSO (NCO)	LAMPS	LAMPS=1	LAMPS=3
AMW 6.3	Conduct all-weather helo ops	ASW, ASUW, FSO (NCO)	LAMPS	LAMPS=1	LAMPS=3
AMW 6.4	Serve as a helo hangar	ASW, ASUW, FSO (NCO)	LAMPS	LAMPS=1	LAMPS=3
AMW 6.5	Serve as a helo haven	ASW, ASUW, FSO (NCO)	LAMPS	LAMPS=1	LAMPS=3
AMW 6.6	Conduct helo air refueling	ASW, ASUW, FSO (NCO)	LAMPS	LAMPS=1	LAMPS=3
AMW 12	Provide air control and coordination of air operations	ASW, ASUW, FSO (NCO)	LAMPS	LAMPS=1	LAMPS=3
AMW 14	Support/conduct Naval Surface Fire Support (NSFS) against designated targets in support of an amphibious operation	NSFS	NSFS	NSFS=1	NSFS=2
ASU 1	Engage surface threats with anti-surface armaments	ASUW	ASUW LAMPS	ASUW=1 LAMPS=1	ASUW=2 LAMPS=3
ASU 1.1	Engage surface ships at long range	ASUW	ASUW LAMPS	ASUW=1 LAMPS=1	ASUW=2 LAMPS=3
ASU 1.2	Engage surface ships at medium range	ASUW	ASUW LAMPS	ASUW=1 LAMPS=1	ASUW=2 LAMPS=3
ASU 1.3	Engage surface ships at close range (gun)	ASUW	NSFS	NSFS=1	NSFS=2
ASU 1.5	Engage surface ships with medium caliber gunfire	ASUW	NSFS	NSFS=1	NSFS=2
ASU 1.6	Engage surface ships with minor caliber gunfire	ASUW	NSFS	NSFS=1	NSFS=2
ASU 1.9	Engage surface ships with small arms gunfire	ASUW	NSFS	NSFS=1	NSFS=2
ASU 2	Engage surface ships in cooperation with other forces	ASUW, FSO	CCC	CCC=1	CCC=2
ASU 4	Detect and track a surface target	ASUW	ASUW LAMPS	ASUW=1 LAMPS=1	ASUW=2 LAMPS=3
ASU 4.1	Detect and track a surface target with radar	ASUW	ASUW LAMPS	ASUW=1 LAMPS=1	ASUW=2 LAMPS=3
ASU 6	Disengage, evade and avoid surface attack	ASUW	ASUW	ASUW=1	ASUW=2
ASW 1	Engage submarines	ASW	ASW	ASW=1	ASW=2
ASW 1.1	Engage submarines at long range	ASW	ASW	ASW=1	ASW=2
ASW 1.2	Engage submarines at medium range	ASW	ASW	ASW=1	ASW=2
ASW 1.3	Engage submarines at close range	ASW	ASW, PSYS	ASW=1 PSYS=5-16	ASW=2
ASW 4	Conduct airborne ASW/recon	ASW	LAMPS	LAMPS=1	LAMPS=3

ROCs	Description	MOP	Related DV	Goal	Threshold
ASW 5	Support airborne ASW/recon	ASW	LAMPS CCC	LAMPS=1, CCC=1	LAMPS=3 CCC=2
ASW 7	Attack submarines with antisubmarine armament	ASW	ASW LAMPS CCC	ASW=1 LAMPS=1 CCC=1	ASW=2 LAMPS=3 CCC=2
ASW 7.6	Engage submarines with torpedoes	ASW	ASW LAMPS CCC	ASW=1 LAMPS=1 CCC=1	ASW=2 LAMPS=3 CCC=2
ASW 8	Disengage, evade, avoid and deceive submarines	ASW	ASW	ASW=1	ASW=2
CCC 1	Provide command and control facilities	CCC	CCC	CCC=1	CCC=2
CCC 1.6	Provide a Helicopter Direction Center (HDC)	CCC, ASW, ASUW	CCC	CCC=1	CCC=2
CCC 2	Coordinate and control the operations of the task organization or functional force to carry out assigned missions	CCC, FSO	CCC	CCC=1	CCC=2
CCC 3	Provide own unit Command and Control	CCC	CCC	CCC=1	CCC=2
CCC 4	Maintain data link capability	ASW, ASUW, AAW	CCC	CCC=1	CCC=2
CCC 6	Provide communications for own unit	CCC	CCC	CCC=1	CCC=2
CCC 9	Relay communications	CCC	CCC	CCC=1	CCC=2
CCC 21	Perform cooperative engagement	CCC, FSO	CCC	CCC=1	CCC=2
FSO 5	Conduct towing/search/salvage rescue operations	FSO	LAMPS	LAMPS=1	LAMPS=3
FSO 6	Conduct SAR operations	FSO	LAMPS	LAMPS=1	LAMPS=3
FSO 8	Conduct port control functions	FSO	CCC, ASUW, LAMPS	CCC=1 ASUW=1 LAMPS=1	CCC=2 ASUW=2 LAMPS=3
FSO 9	Provide routine health care	All designs			
FSO 10	Provide first aid assistance	All designs			
FSO 11	Provide triage of casualties/patients	All designs			
INT 1	Support/conduct intelligence collection	INT	CCC	CCC=1	CCC=2
INT 2	Provide intelligence	INT	CCC	CCC=1	CCC=2
INT 3	Conduct surveillance and reconnaissance	INT	LAMPS	LAMPS=1	LAMPS=3
INT 8	Process surveillance and reconnaissance information	INT, CCC	CCC	CCC=1	CCC=2
INT 9	Disseminate surveillance and reconnaissance information	INT, CCC	CCC	CCC=1	CCC=2
INT 15	Provide intelligence support for non-combatant evacuation operation (NEO)	INT, CCC	CCC	CCC=1	CCC=2
MIW 4	Conduct mine avoidance	MIW	Degaus	Yes	Yes
MIW 6	Conduct magnetic silencing (degaussing, deperming)	Magnetic Signature	Degaus	Yes	Yes
MIW 6.7	Maintain magnetic signature limits	Magnetic Signature	Degaus	Yes	Yes
MOB 1	Steam to design capacity in most fuel efficient manner	Sustained Speed, Endurance Range	Hullform PSYS	Vs = 35 knts E=4000	Vs = 29 knt E = 5000 nm
MOB 2	Support/provide aircraft for all-weather operations	ASW, ASUW, FSO (NCO)	LAMPS	LAMPS=1	LAMPS=3
MOB 3	Prevent and control damage	VUL	Cdhmat	Cdmat =1 Composite	Cdmat = 3 steel
MOB 3.2	Counter and control NBC contaminants and agents	NBC	CPS	CPS=2 (full)	CPS=0 (none)
MOB 5	Maneuver in formation	All designs			
MOB 7	Perform seamanship, airmanship and navigation tasks (navigate, anchor, mooring, scuttle, life boat/raft capacity, tow/be-towed)	All designs			
MOB 10	Replenish at sea	All designs			
MOB 12	Maintain health and well being of crew	All designs			

ROCs	Description	MOP	Related DV	Goal	Threshold
MOB 13	Operate and sustain self as a forward deployed unit for an extended period of time during peace and war without shore-based support	provisions	Ts	60 days	45 days
MOB 16	Operate in day and night environments	All designs			
MOB 17	Operate in heavy weather	Seakeeping index	hullform	MCR=15	MCR=4
MOB 18	Operate in full compliance of existing US and international pollution control laws and regulations	Compensated Fuel System/ Clean Ballast	BalType	BalType=0	BalType=1
NCO 3	Provide upkeep and maintenance of own unit	All designs			
NCO 19	Conduct maritime law enforcement operations	NCO	ASUW NSFS	ASUW =1 NSFS=1	ASUW = 2 NSFS = 2
SEW 2	Conduct sensor and ECM operations	AAW	CCC	CCC=1	CCC=2
SEW 3	Conduct sensor and ECCM operations	AAW	CCC	CCC=1	CCC=2
SEW 5	Conduct coordinated SEW operations with other units	AAW	CCC	CCC=1	CCC=2
STW 3	Support/conduct multiple cruise missile strikes	STK	GMLS CCC	GMLS=1 CCC=1	GMLS=4 CCC=2

Table 10 - MOP Table [15]

MOP #	MOP	Metric	Goal	Threshold
1	AAW	AAW Option GMLS Option SDS Option CCC Option	AAW =1 GMLS=1 SSD=1 CCC =1	AAW =3 GMLS=4 SSD=3 CCC =2
2	ASW	ASW Option LAMPS Option CCC Option	ASW =1 LAMPS=1 CCC =1	ASW =2 LAMPS=3 CCC =2
3	ASUW/NSFS	ASUW Option LAMPS Option NSFS Option CCC Option SDS Option	ASUW=1 LAMPS=1 NSFS=1 CCC =1 SDS=1	ASUW=2 LAMPS=3 NSFS=2 CCC=2 SDS=3
4	C4I	CCC Option	CCC=1	CCC=2
5	STK	GMLS Option C4I Option	GMLS=1 CCC=1	GMLS=4 CCC=2
6	BMD	AAW Option GMLS Option CCC Option	AAW=2 GMLS=1 CCC=1	AAW=3 GMLS=4 CCC=2
7	Sustained Speed	Knts	Vs=35knt	Vs=29knt
8	Endurance Range	Nm	E=6000nm	E=4000nm
9	Provisions Duration	Days	Ts=60days	Ts=45days
10	Seakeeping	McCreight Index HULLtype	McC=16 Flare	McC=6 tumblehome
11	Environmental	Ballast Option	Clean	Compensated fuel
12	Vulnerability	Cdhmat PSYS	Steel No pods	Composite Pods
13	NBC	CPS Option	Full	Part
14	RCS	ft3 HULLtype SDS	VD=100000ft3 Tumblehome None	VD=150000ft3 Flare 2xCIWS
15	Acoustic Signature	PSYStype	PSYStype=5	PSYStype=2,13
16	IR Signature	PENGtype	PENGtype=1	PENGtype=1
17	Magnetic Signature	Ndegaus PSYS	Degaussing No pods	None Pods
18	Maintenance	Maint	Maint=4	Maint=1

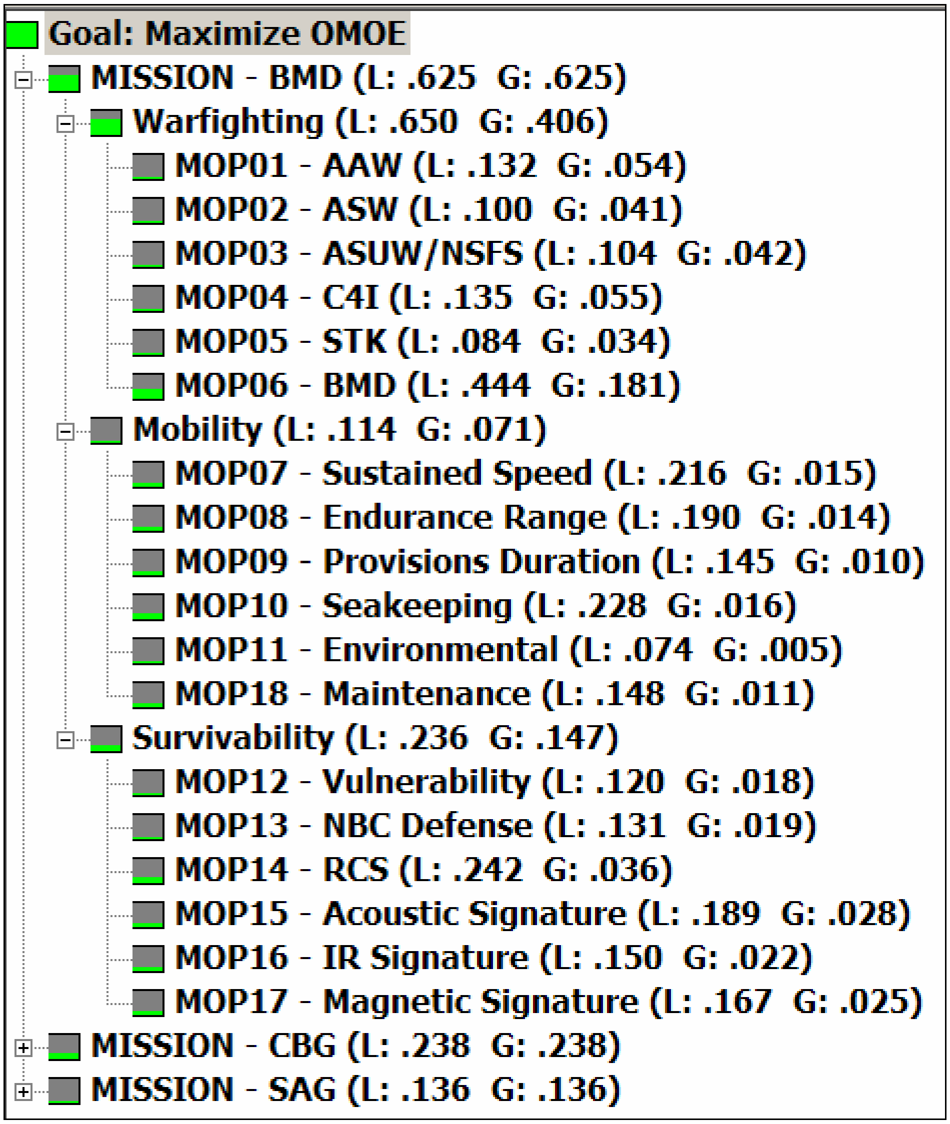

Figure 24 – OMOE Hierarchy

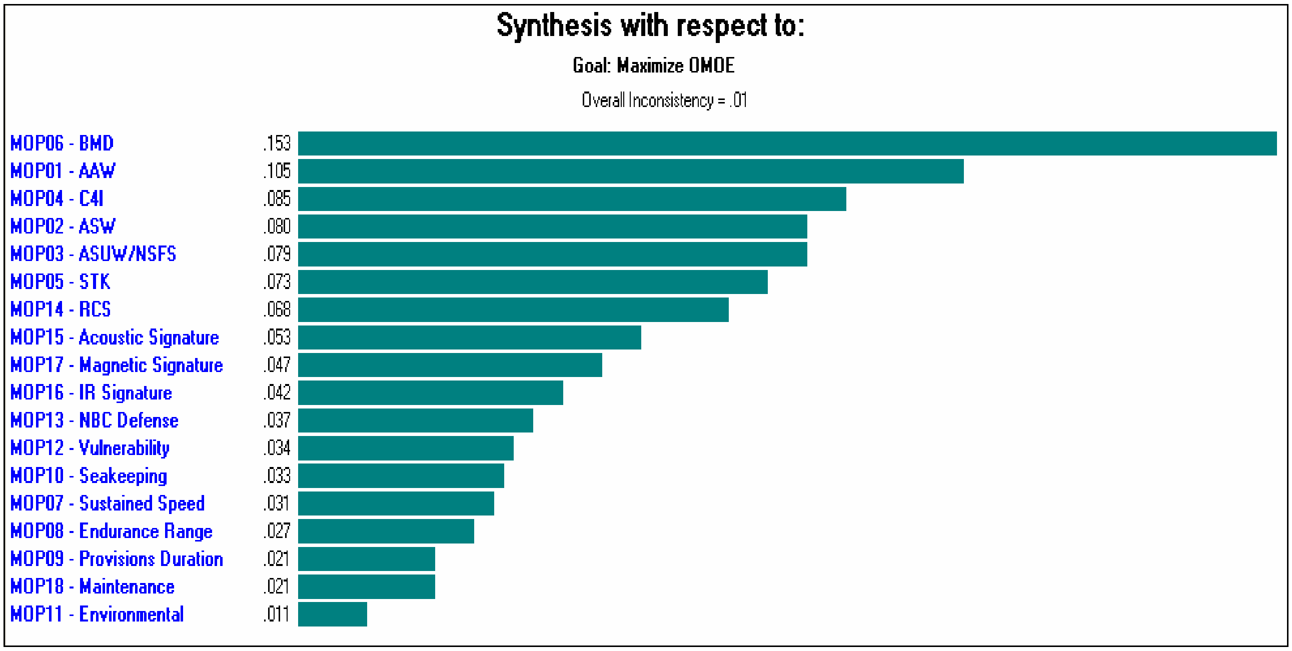

Figure 25 MOP Weights

4.5.2 Overall Measure of Risk (OMOR)

In the process to design a new naval vessel there are often new and untested technologies that are necessary so that specific performance or cost criteria can be attained. These new technologies often come with inherent risk of failure.

The OMOR is a numerical representation of the total technology risk associated with a ship. It is based on three risk events including performance, cost, and schedule. The risk for each event for a selected technology is a product of probability of occurrence (P_i) and consequence of the occurrence (C_i) (Equation 3):

$$R_i = P_i C_i \tag{3}$$

Table 11 and Table 12 provide an estimate of the probability of the risk event, P_i, and for corresponding consequence, respectively. Table 13 is the Risk Register, in which the risk events for performance, cost, and schedule for each DV are identified. Equation (4) below is then used to calculate the OMOR, where W_{perf}, W_{cost}, and W_{sched} are the weights for each type of risk and w_i, w_j, and w_k are the risk for each event.

$$OMOR = W_{perf} \sum_i \frac{w_i}{\sum_i w_i} P_i C_i + W_{cost} \sum_j w_j P_j C_j + W_{sched} \sum_k w_k P_k C_k \quad \textbf{(4)}$$

Table 11 - Event Probability Estimate

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

Table 12 - Event Consequence Estimate

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

Table 13 - Risk Register [15]

SWBS	Risk Type	Related DV #	DV Options	DV Description	Risk Event Ei	Risk Description	Event #	Pi	Ci	Ri
1	Performance	DV9	3	Deckhouse Material	Composite material producibilitty problems	USN lack of experience with material	1	0.5	0.6	0.3
1	Performance	DV9	3	Deckhouse Material	Composite material RCS, and fire performance does not meet performance predictions	In development and test	2	0.4	0.5	0.2
1	Cost	DV9	3	Deckhouse Material	Composite material cost overuns impact program	In development and test	3	0.5	0.3	0.15
1	Schedule	DV9	3	Deckhouse Material	Composite material schedule delays impact program	In development and test	4	0.5	0.2	0.1
1	Performance	DV10	2	Hull Type	Tumblehome Seakeeping Performance	Seakeeping not satisfactory	5	0.7	0.8	0.56
2	Performance	DV12	5-16	Propulsion Systems	IPS Development and Implementation	Reduced reliability and performance (un-proven)	6	0.3	0.6	0.18
2	Cost	DV12	5-16	Propulsion Systems	IPS Development, acquisition and integration cost overruns	Reasearch and Development cost overruns	7	0.4	0.4	0.16
2	Schedule	DV12	5-16	Propulsion Systems	IPS Schedule delays impact program	In development and test	8	0.3	0.4	0.12
2	Performance	DV12	3,4,8,9,10, 14,15,16	Propulsion Systems	ICR Development and Implementation	Unproven, recuperator problems	9	0.6	0.5	0.3
2	Cost	DV12	3,4,8,9,10, 14,15,16	Propulsion Systems	ICR Development, acquisition and integration cost overruns	Unproven, recuperator problems	10	0.6	0.4	0.24
2	Schedule	DV12	3,4,8,9,10, 14,15,16	Propulsion Systems	ICR Schedule delays impact program	Unproven, recuperator problems	11	0.6	0.5	0.3
2	Performance	DV12	11-16	Propulsion Systems	Development and Implementation of podded propulsion	Reduced Reliability (un-proven)	12	0.7	0.4	0.28
2	Performance	DV12	11-16	Propulsion Systems	Development and Implementation of podded propulsion	Shock and vibration of full scale system unproven	13	0.7	0.6	0.42
2	Cost	DV12	11-16	Propulsion Systems	Podded Propulsion Implimentation Problems	Unproven for USN, large size	14	0.6	0.45	0.27
2	Schedule	DV12	11-16	Propulsion Systems	Podded Propulsion Schedule delays impact program	Unproven for USN, large size	15	0.6	0.6	0.36
4	Performance	DV17	0.5	Automation	Automation systems development and implementation	Reduced Reliability and Performance (un-proven)	16	0.6	0.7	0.42
4	Cost	DV17	0.5	Automation	Automation systems development, acquisition and integration cost overruns	Reasearch and Development cost overruns	17	0.5	0.5	0.25
4	Schedule	DV17	0.5	Automation	Automation systems schedule delays impact program	Reasearch and Development schedule delays	18	0.5	0.7	0.35
4	Performance	DV18	1,2	AAW Systems	SPY-3 and VSR Development and implementation	Reduced Reliability and Performance (un-proven)	19	0.3	0.8	0.24
4	Cost	DV18	1,2	AAW Systems	SPY-3 and VSR Development, acquisition and integration cost overruns	Reasearch and Development cost overruns	20	0.4	0.5	0.2
4	Schedule	DV18	1,2	AAW Systems	SPY-3 and VSR Schedule delays impact program	Reasearch and Development schedule delays	21	0.4	0.7	0.28

4.5.3 Cost

Three types of CG(X) cost are considered: lead ship acquisition cost, follow ship acquisition cost, and modified Life-Cycle Cost. Figure 26 illustrates how the cost components are broken down. The lead ship acquisition cost is estimated using a weighted sum of all the SWBS weights, and the total being the Basic Cost of Construction (BCC) shown in Figure 26. The acquisition cost includes shipbuilder profit and any change orders that develop along the process of shipbuilding. Included in the model but held separate in Figure 26 are the government costs, which include a sum of the Government Furnished Material (GFM) and Program Managers

Growth. The total end cost of the ship is the sum of the Government Cost and the Shipbuilder Cost. CG(X) life cycle cost includes the Total End Cost and operating and support costs due to manning and fuel.

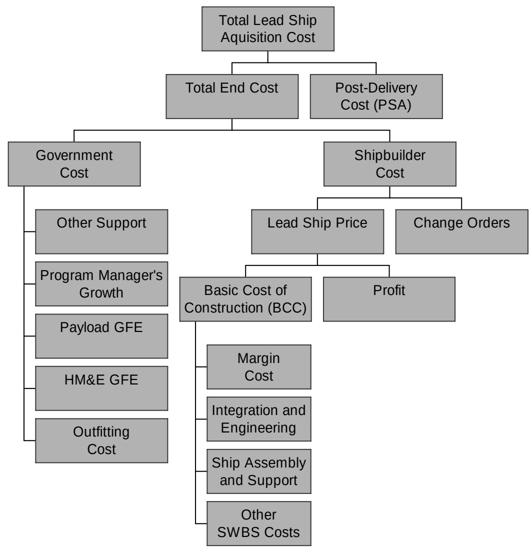

Figure 26 - Naval Ship Acquisition Cost Components [15]

4.6 Concept Exploration

Concept exploration runs the NSSM in the MOGO to find a non-dominated frontier (NDF). The NDF is analyzed and designs are chosen for further evaluation based on the customer's preference for cost, effectiveness, and risk. The designs that are chosen can be further optimized using a single objective function and constraints on the other objectives. Continuous variables are still used in the optimization, but discrete variables are held constant. This will finish the concept level design with an optimized ship that can be used in the next steps of the design process.

CHAPTER 5 RESULTS AND CONCLUSIONS

5. 1 Manning Model and Design Explorer

The manning model is run to test the scenario by comparing the results of an analysis with compartments, equipment, maintenance practices, and automation similar to the current CG-47 class ships to the crew of an actual CG-47 class ship. The configuration and results from the test run are contained in Table 14.

Table 14 – Model Test Configuration and Results

ASuW	ASW	PSYS	LevAuto	Maint	CCC	LWLComp	Crew
2	1	1	1	1	2	1	412

According to the Ship Manning Document for CG-47, the crew size is 398 personnel. The manning model found a crew size of 412. This is 3.5% more than the crew of CG-47. It demonstrates that the scenario used in the manning model is sufficient to calculate and optimize shipboard manning in concept level design. An area for future research is to refine the scenario to improve the correlation between model crew size and the actual crew size.

After the scenario was tested, a DOE is run to gather data for the full range of design options. The DOE used is the parameter scan method. This method scans all of the values in the manning model. The smallest and largest crews and their associated design options are listed in Table15.

Table 15 – Smallest and Largest CGX Crews

ASuW	ASW	PSYS	LevAuto	Maint	CCC	LWLComp	Crew
2	1	3	4	3	1	1	272
1	2	1	1	1	2	3	444

The smallest crew is 61% smaller than the largest crew. This reduction in crew size is smaller than was assumed by the previous method of manpower calculation used in the NSSM. This reduction in crew size is also smaller than what is being required by the Navy. A further analysis of crew reduction methods should be conducted to determine if desired crew reductions are possible on US Navy ships.

Design Explorer is used to investigate the effects of each of the design variables on the crew size. Figure 27 shows the effect that each design variable has on crew size.

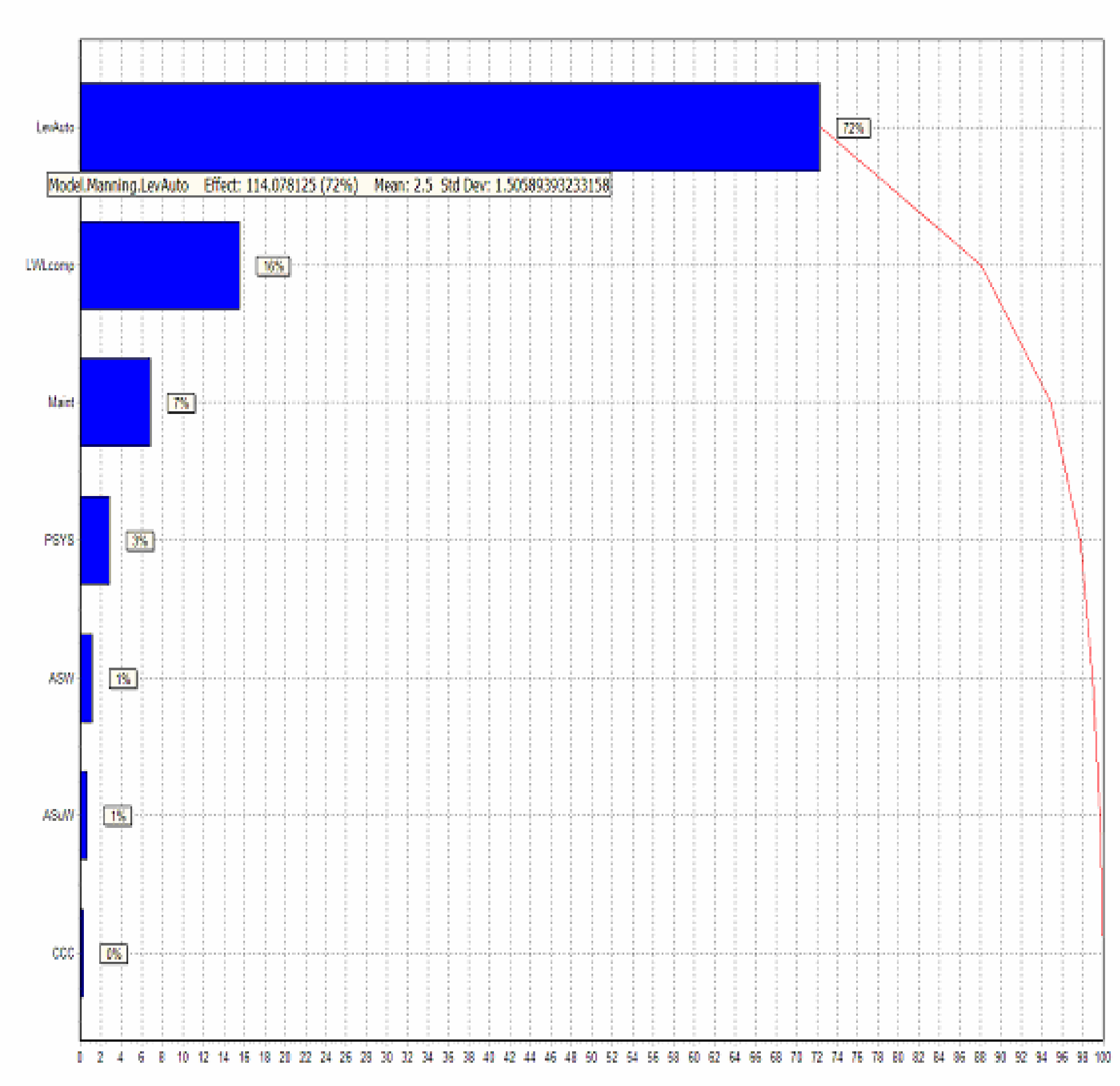

Figure 27 - Design Variable Effects

The level of automation has the largest impact on the size of the crew. This result is important because it quantitatively demonstrates that automation is the largest driver in crew reduction. These results indicate that the US Navy needs to continue moving forward with implementing automation onboard new ship designs to effectively reduce crew size. The significance of the reduction in crew size due to automation dictates that barriers to automation must be overcome to reduce the cost of new ship designs. Figure 27 also shows that ship systems have a relatively small impact on the crew size. Further research should be conducted to determine to what extent it is sufficient to consider only LevAuto, LWL, and maintenance. This analysis may yield an equation that can be applied to other ship designs once calibrate to a baseline manning since ship systems do not affect the crew as dramatically as LevAuto, LWL, and maintenance.

5.2 Response Surface Model

After the DOE was run and the data table was created, a Response Surface Model is derived to fit an equation to the data. A cubic stepwise regression is used. The RSM can then be used as a surrogate manning model in the NSSM. Table 16 contains the statistical data for the RSM.

Table 16 – RSM Curve Fit Data

S	CoV	R-Squared	Adjusted R-Asquared
5.211157	1.46%	98.76	98.74

The S value measures the standard error and should be as small as possible. Similarly, the Coefficient of Variation, CoV, should be as small as possible. The R-squared and the adjusted R-squared values should be as close to 100% as possible. They should also be as close to each other as possible. Based on Table 16, the RSM used in the NSSM to calculate crew size for the CGX design options is a good approximation. A 3-D plot of the RSM for Crew Size v. LevAuto and LWLComp is shown in Figure28.

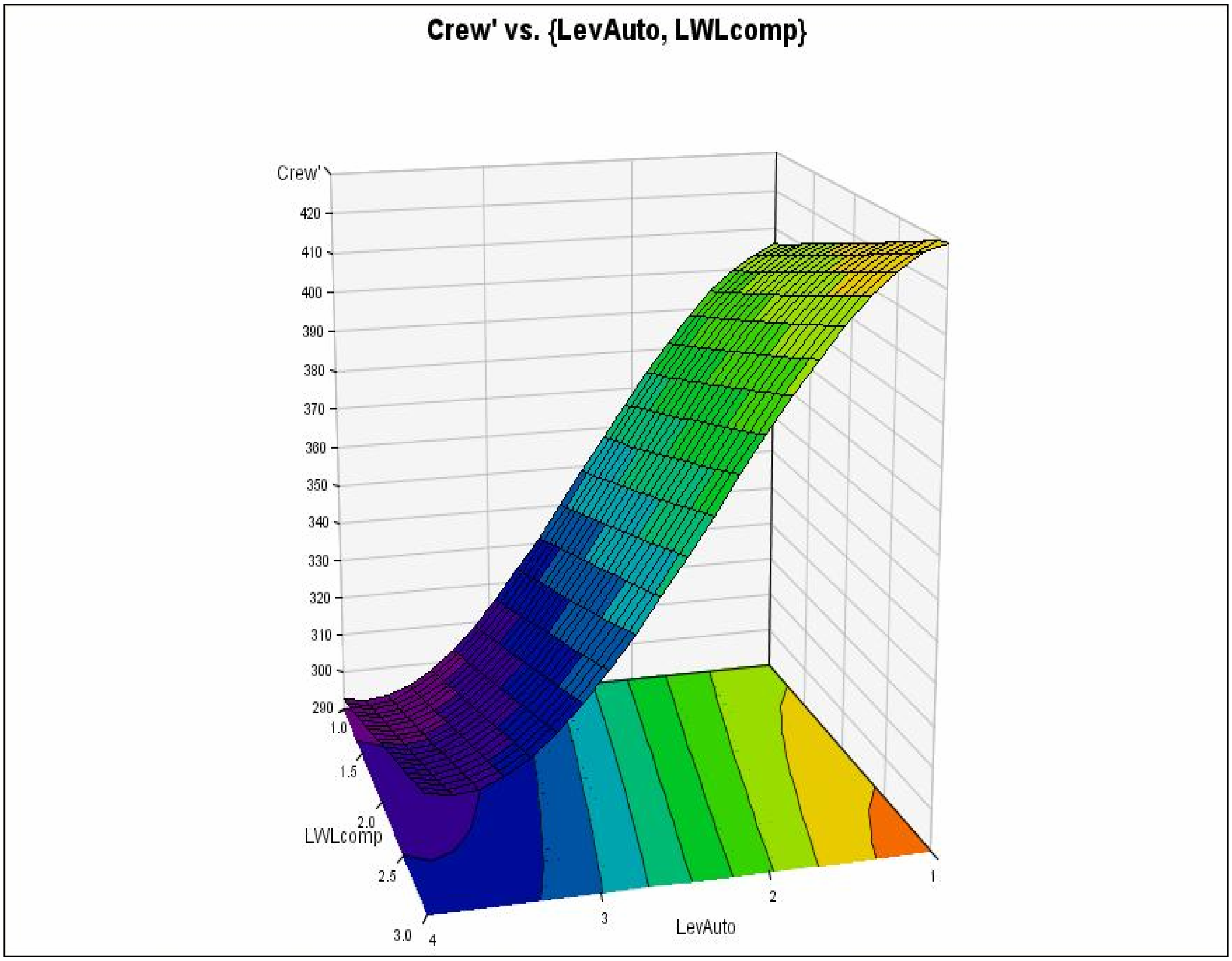

Figure 28 - RSM for Crew vs. LevAuto&LWLComp

The response of the surface to a change in the level of automation is very interesting. There is a substantial reduction in crew size between a LevAuto of 2 and 3. After a LevAuto of 3, the crew size begins to level out. Figure 28 shows that using more automation in the design after LevAuto 3 will yield smaller crew size reduction. Automation is an excellent method of reducing the crew size and reducing the cost of a ship but it must be used judiciously because more automation does not necessarily improve the design. Two dimensional plots are created to further analyze how variables used in the manning model effect crew size. Figure 29 displays the effect of propulsion (PSYS), level of automation (LevAuto), maintenance (MAINT), command, control, and communications (CCC), and length waterline (LWLComp) on crew size.

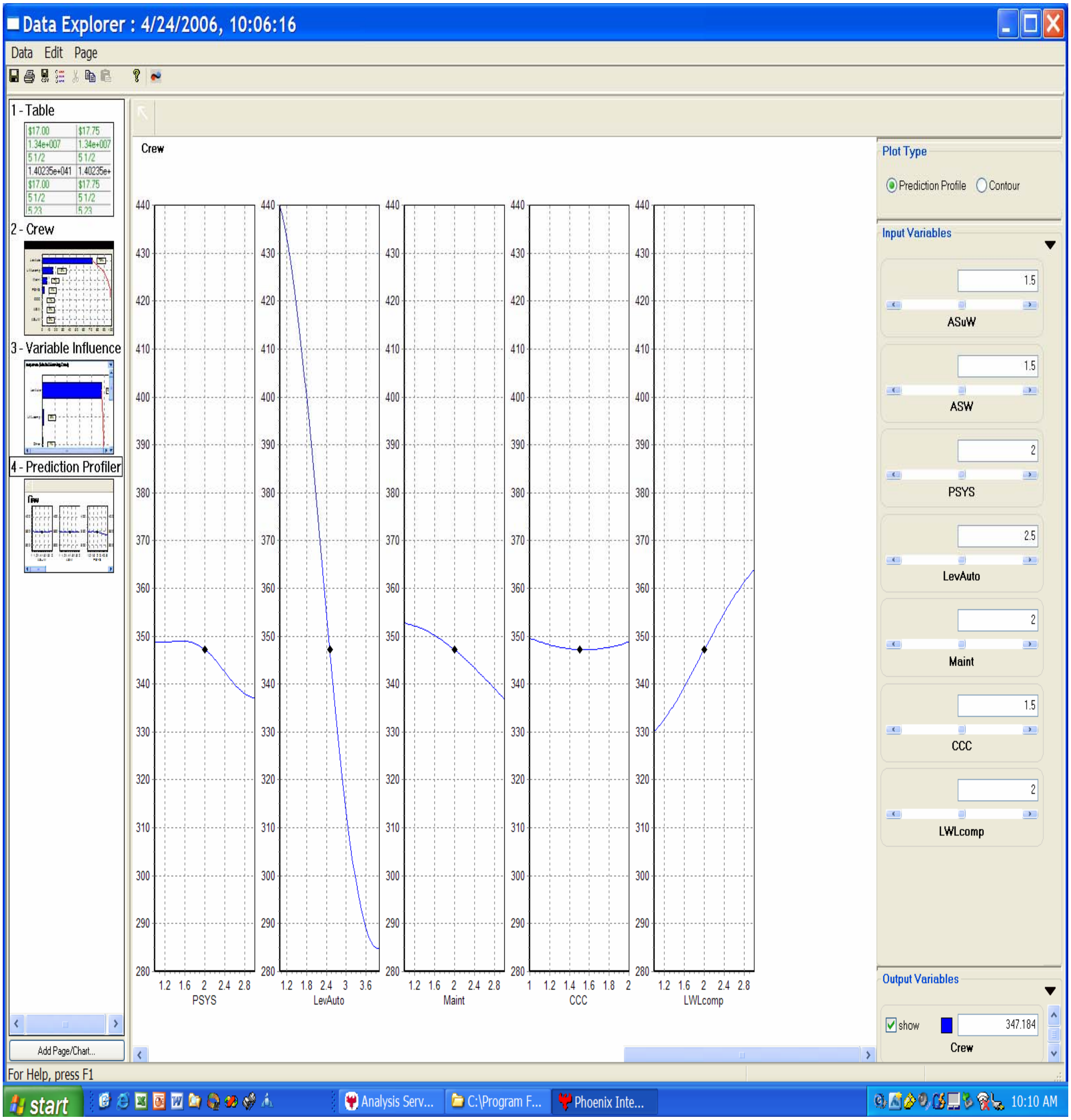

Figure 29 – Design Explorer Profile Predictor

The profile predictor creates graphs by taking slices of the RSM. It holds all variables constant except for one to determine how that variable influences the crew size. Figure 29 shows the dominant effects of the level of automation. Automation alone is able to change the crew size by approximately 155 people. The next largest factor in determining crew size is the length of the ship. The ship length changes the crew size by approximately 34 people over the range of LWL considered if all other variables are held constant. The small effect of maintenance is surprising. The number of personnel required for each task should be further explored to ensure the accuracy of the maintenance files contained in ISMAT. Further research should be conducted to ensure that the correct amount of maintenance is being specified and how much time is spent actually doing maintenance relative to other tasks.

5.3 Non-Dominated Frontier and Design for Further Consideration

The results of the RSM are integrated into the overall ship synthesis model. A multi-objective optimization is used to find non-dominated designs. The objectives for the optimization are to minimize cost and risk (OMOR) and to maximize effectiveness (OMOE). The non dominated frontier that is found by the optimizer is displayed in Figure 30.

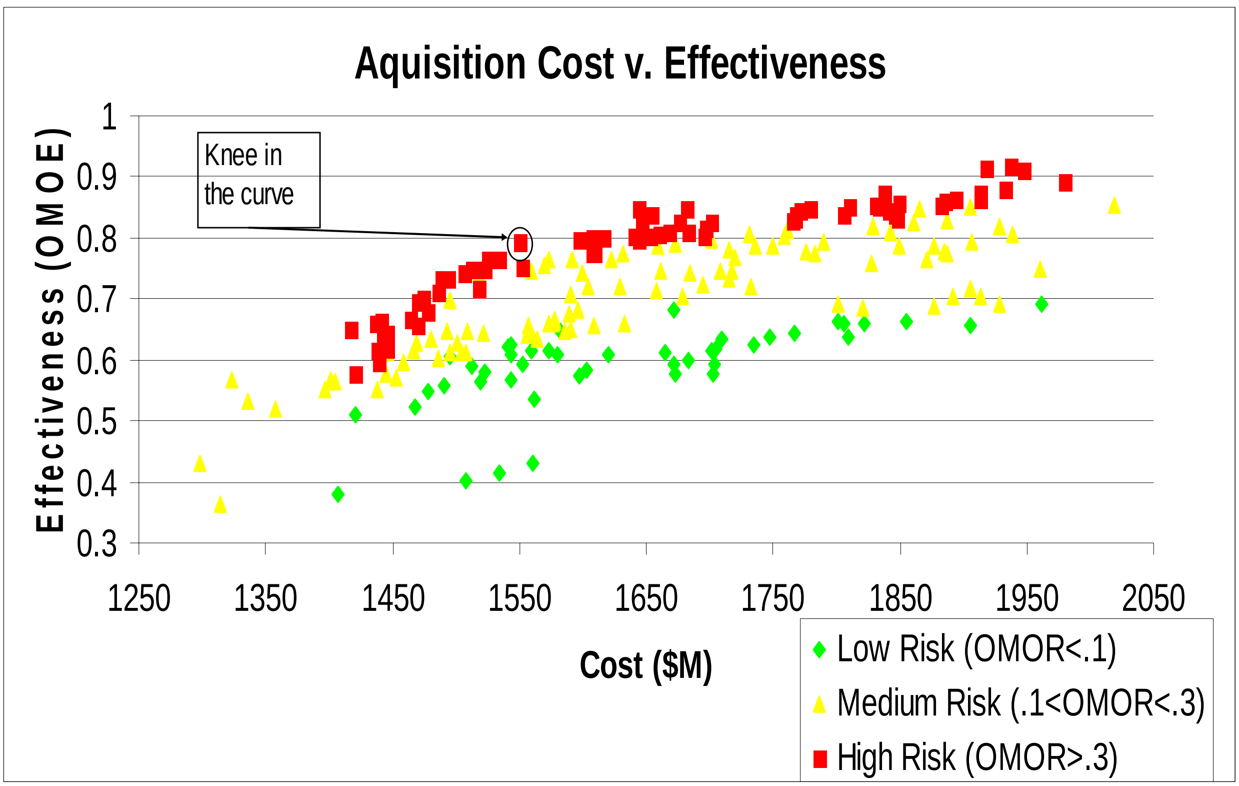

Figure 30 – Non-Dominated Frontier for CGX

The x-axis is the follow-on ship acquisition cost and the y-axis is the Overall Measure of Effectiveness (OMOE). The color of the points corresponds to the level of risk for the design. Figure 31 shows the 3-D design space in 2-D so that it is easier for the analyst to see the relationship between cost, risk and effectiveness for the designs. Based on the NDF, a knee in the curve design is chosen for further evaluation. This design is highlighted in Figure 30. This design is considered to be a “best buy” because there is only a small increase in effectiveness for large increases in cost above this knee. The specifications for this design are listed in Table 17.

Table 17 – Concept Exploration Baseline Design

Characteristic	Baseline Value
Hull form	flare = -10 deg
Δ (MT)	10697.99
LWL (m)	180.418178
Beam (m)	18.49354
Draft (m)	5.779301
D10 (m)	13.07095
Beam to Draft Ratio, C_{BT}	3.199962
W1 (MT)	3999.502
W2 (MT)	954.5943
W3 (MT)	322.1093
W4 (MT)	667.6382
W5 (MT)	53.77505
W6 (MT)	1371.598
W7 (MT)	804.3633
Lightship Δ (MT)	319.3263
KG (m)	7.481505
GM/B=	0.09032358
Propulsion system	2 Shafts, IPS, FPP, 3x LM2500+, 2x Allison 501K34
Engine inlet and exhaust	Vertical
AAW system	SPY-3 (4 panel), VSR, AEGIS MK 99 FCS
ASUW system	SPS-73(V)12, MK 160/34 GFCS Small Arms Locker
ASW system	SQS-53D, MK 116 UWFCS, ASROC, 2xMK 32 Triple Tubes, SQQ-89 NIXIE, SQR-19 TACTAS
NSFS	2 MK 110 57mm gun
CCC/STK/SEW	Enhanced CCC
GMLS	128 cells, MK 41 and/or MK57 PVLS
LAMPS	LAMPS haven (flight deck)
SDS	None
Cman	0.65
Total Officers	25
Total Enlisted	325
Total Manning	350
Follow Ship Acquisition Cost	1.51 Billion

This design is further optimized with the single objective to minimize the cost. The levels of effectiveness and risk from the knee-in-the-curve design are treated as constraints. All of the continuous variables are varied and all of the discrete variables are held constant. To study the effect of automation and manning on the cost of this ship design, a series of optimizations are run for a range of fixed levels of automation. Figure 31 shows the resulting relationship between cost and automation.

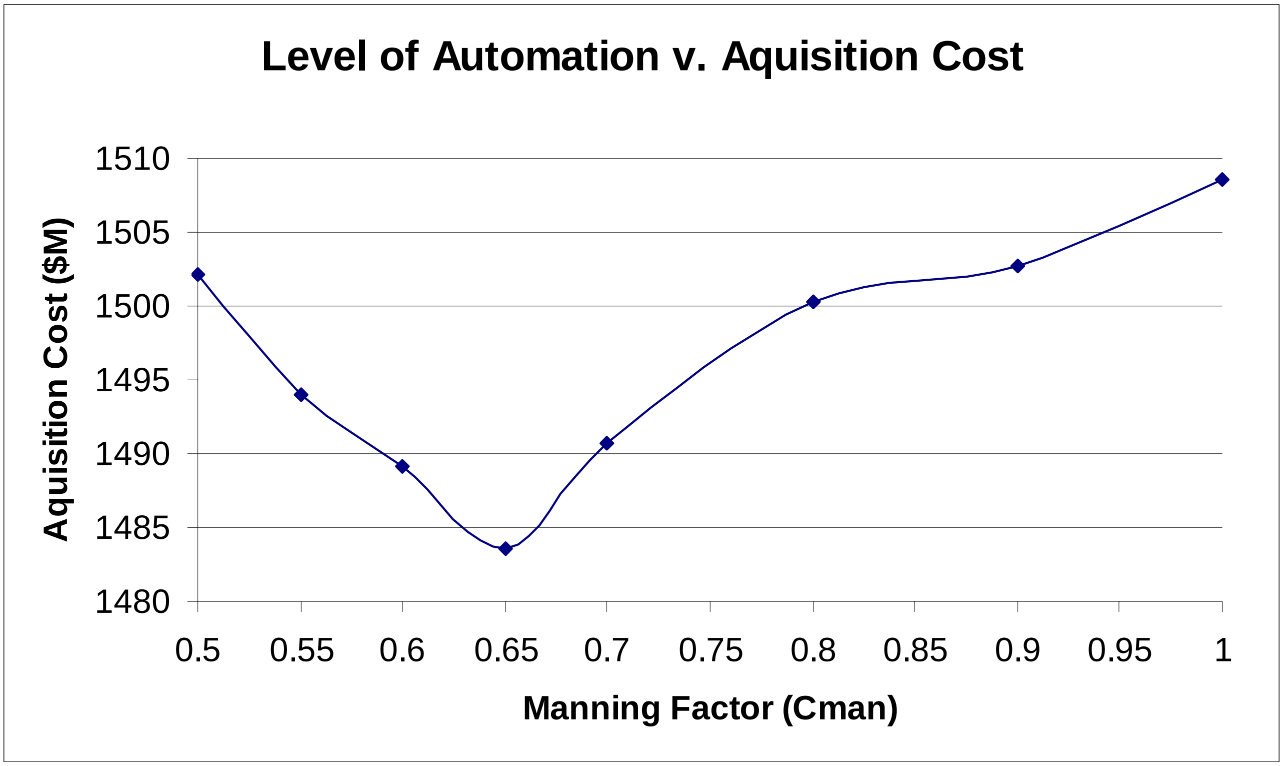

Figure 31 – Chart of Level of Automation v. Cost

The CMan factor of 1 corresponds to ship with the lowest amount of automation and the largest crew size. Initially, the cost of the total ship is reduced by replacing personnel with automation. Once the automation reaches a CMan value of .65, a minimum is reached. A CMan value of .65 is approximately equal to a level of automation (LevAuto) of 3. LevAuto 3 is the "Rigid System" from Table 2 that uses a mixture of humans and automation. In the Rigid System, the human is mostly responsible for selecting responses from a list of options provided by the computer system. After this point, the automation becomes more expensive than the resulting reduction in ship cost. The minimum cost of the ship due to manning is found by optimizing the level of automation that is used rather than simply reducing the amount of people onboard the ship. Although the crew size is a main driver of the acquisition cost of a ship, the design that was chosen (Table 17) did not reduce the crew size to the smallest possible level with the maximum level of automation. The size of the crew is 24% larger than the smallest possible crew. This research shows that there is difference between minimum manning and optimal manning on US Navy Ships. The ship found by the MOGO may have larger crews than other design options but for a given level of effectiveness and risk, they have the lowest cost, or for a given level of cost and risk, they have the highest effectiveness. This is achieved by (among other things) using “optimal manning” no minimum manning.

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APPENDIX A – ISMAT OUTPUT CODE

```
int resultnumber=ISMATModel.GetNumOperatorsUtilized();
Console.WriteLine(resultnumber);
     try
     {
          FileInfo f = new FileInfo("CGcrewnum.out");
          StreamWriter w=f.CreateText();
          {
               w.WriteLine(resultnumber);
          }
          w.Close();
     }
     catch(Exception e)
     {
          Console.WriteLine("Exception: " + e.Message);
     }
     finally
     {
          Console.WriteLine("Executing finally block.");
     }
```

APPENDIX B – MODEL CENTER FILE WRAPPER

```
# Analysis Server FileWrapper component for Manning
# @author: Tyson
# @version: 1.0 Tyson
# @description: Fortran FileWrapper for Manning
RunCommands
{
  generate inputFile
  run "manning.exe"
  parse outputFile
  # run "del manning.out"
}
RowFieldInputFile inputFile
{
 templateFile:     manning.template
 fileToGenerate:   manning.in

 setDelimiters ", "
 #      name             type      row   field
 #---------------------------------------------------
 variable: ASuW        integer   1    1
 variable: ASW         integer   1    2
 variable: PSYS        integer   1    3
 variable: LevAuto               integer   1    4
 variable: Maint       integer   1    5
 variable: CCC         integer   1    6
 variable: LWLcomp     integer   1    7
}
RowFieldOutputFile outputFile
{
  fileToParse: manning.out
 #      name                     type    row   field
 #------------------------------------------------------------
  variable: Crew                 integer 1        1
}
```

APPENDIX C - MANNING.EXE CODE

```
Module Module1

    Sub Main()
        Dim ApptoRun As String      'string required to start the console
version of ISMAT
        Dim FiletoRun As String     'name of the ISMAT file to be executed
        Dim Baseequip As String     'may not actually need this since it will
be the same for all
        Dim ManModel As String      'puts all of the inputs together to
launch console ISMAT
        Dim Goal As String          'specifies the objective for the
optimizer.  may not need this
        Dim Consolekill As String   'used to shut down console ISMAT after
the simulation is complete
        Dim Crew As Integer         'used for the shell appplication
        Dim AAW As String           'Equipment info for the AAW system
        Dim ASuWopt As Integer       'Input from MC for the ASW option
        Dim ASuW As String           'Equipment info for the ASW system
        Dim ASW As String           'Equipment info for the ASuW system
        Dim ASWopt As Integer       'Input from MC for ASW option
        Dim Prop As String          'Equipment info for the Propulsion system
        Dim PSYS As Integer      'Input from MC for Propulsion Option
        Dim SDS As String           'Equipment info for the SDS system
        Dim GMLS As String          'Equipment info for the GMLS System
        Dim LevAuto As Integer      'Level of Automation of the ship
        Dim Scenario As String      'Sets the scenario to run based on the
LevAuto
        Dim Maint As Integer        'Maintenance Level for the ship
        Dim NSFS As String          'Equipment for the NSFS System
        Dim Comp As String          'The compartments in the ship
        Dim CCCopt As Integer       'Input from MC for CCC option
        Dim CCC As String           'Equipment for CCC system
        Dim LWLcomp As Integer      'Input from MC for ship size
        '
        '
        ApptoRun = """c:\Program Files\MAAD\ISMAT\MAAD.ISMAT.Console.exe"""
        FiletoRun = " -f "" c:\Program Files\MAAD\ISMAT\cgxmanmod.ismat"""
        'Read the inputs for the model from Model Center
        FileOpen(1, "c:\Program Files\Phoenix Integration\Analysis Server
4.1\analyses\Manning\manning.in", OpenMode.Input, OpenAccess.Read)
        Input(1, ASuWopt)
        Input(1, ASWopt)
        Input(1, PSYS)
        Input(1, LevAuto)
        Input(1, Maint)
        Input(1, CCCopt)
        Input(1, LWLcomp)
        FileClose(1)
        'Based on the input prepare strings to run Console ISMAT
        'Loop for Baseequip
        If Maint = 1 Then
            Baseequip = " -e "" c:\Program Files\MAAD\ISMAT\BaseM1.ieqd"""
        ElseIf Maint = 2 Then
            Baseequip = " -e "" c:\Program Files\MAAD\ISMAT\BaseM2.ieqd"""
        Else : Baseequip = " -e "" c:\Program Files\MAAD\ISMAT\BaseM3.ieqd"""
```

```
        End If
        'Loop for AAW, SDS, and GMLS
        If Maint = 1 Then
            AAW = " -e "" c:\Program Files\MAAD\ISMAT\AAWM1.ieqd""" : SDS = "
-e "" c:\Program Files\MAAD\ISMAT\SDSM1.ieqd""" : GMLS = " -e "" c:\Program
Files\MAAD\ISMAT\GMLSM1.ieqd"""
        ElseIf Maint = 2 Then
            AAW = " -e "" c:\Program Files\MAAD\ISMAT\AAWM2.ieqd""" : SDS = "
-e "" c:\Program Files\MAAD\ISMAT\SDSM2.ieqd""" : GMLS = " -e "" c:\Program
Files\MAAD\ISMAT\GMLSM2.ieqd"""
        Else : AAW = " -e "" c:\Program Files\MAAD\ISMAT\AAWM3.ieqd""" : SDS
= " -e "" c:\Program Files\MAAD\ISMAT\SDSM3.ieqd""" : GMLS = " -e ""
c:\Program Files\MAAD\ISMAT\GMLSM3.ieqd"""
        End If
        'Loop for ASuW
        If ASuWopt = 1 And Maint = 1 Then
            ASuW = " -e "" c:\Program Files\MAAD\ISMAT\ASUW1M1.ieqd"""
        ElseIf ASuWopt = 1 And Maint = 2 Then
            ASuW = " -e "" c:\Program Files\MAAD\ISMAT\ASUW1M2.ieqd"""
        ElseIf ASuWopt = 1 And Maint = 3 Then
            ASuW = " -e "" c:\Program Files\MAAD\ISMAT\ASUW1M3.ieqd"""
        ElseIf ASuWopt = 2 And Maint = 1 Then
            ASuW = " -e "" c:\Program Files\MAAD\ISMAT\ASUW2M1.ieqd"""
        ElseIf ASuWopt = 2 And Maint = 2 Then
            ASuW = " -e "" c:\Program Files\MAAD\ISMAT\ASUW2M2.ieqd"""
        Else : ASuW = " -e "" c:\Program Files\MAAD\ISMAT\ASUW2M3.ieqd"""
        End If
        'Loop for ASW
        If ASWopt = 1 And Maint = 1 Then
            ASW = " -e "" c:\Program Files\MAAD\ISMAT\ASW1M1.ieqd"""
        ElseIf ASWopt = 1 And Maint = 2 Then
            ASW = " -e "" c:\Program Files\MAAD\ISMAT\ASW1M2.ieqd"""
        ElseIf ASWopt = 1 And Maint = 3 Then
            ASW = " -e "" c:\Program Files\MAAD\ISMAT\ASW1M3.ieqd"""
        ElseIf ASWopt = 2 And Maint = 1 Then
            ASW = " -e "" c:\Program Files\MAAD\ISMAT\ASW2M1.ieqd"""
        ElseIf ASWopt = 2 And Maint = 2 Then
            ASW = " -e "" c:\Program Files\MAAD\ISMAT\ASW2M2.ieqd"""
        Else : ASW = " -e "" c:\Program Files\MAAD\ISMAT\ASW2M3.ieqd"""
        End If
        'Loop for PSYS
        If PSYS = 1 And Maint = 1 Then
            Prop = " -e "" c:\Program Files\MAAD\ISMAT\PSYS1M1.ieqd"""
        ElseIf PSYS = 1 And Maint = 2 Then
            Prop = " -e "" c:\Program Files\MAAD\ISMAT\PSYS1M2.ieqd"""
        ElseIf PSYS = 1 And Maint = 3 Then
            Prop = " -e "" c:\Program Files\MAAD\ISMAT\PSYS1M3.ieqd"""
        ElseIf PSYS = 2 And Maint = 1 Then
            Prop = " -e "" c:\Program Files\MAAD\ISMAT\PSYS2M1.ieqd"""
        ElseIf PSYS = 2 And Maint = 2 Then
            Prop = " -e "" c:\Program Files\MAAD\ISMAT\PSYS2M2.ieqd"""
        ElseIf PSYS = 2 And Maint = 3 Then
            Prop = " -e "" c:\Program Files\MAAD\ISMAT\PSYS2M3.ieqd"""
        ElseIf PSYS = 3 And Maint = 1 Then
            Prop = " -e "" c:\Program Files\MAAD\ISMAT\PSYS3M1.ieqd"""
        ElseIf PSYS = 3 And Maint = 2 Then
            Prop = " -e "" c:\Program Files\MAAD\ISMAT\PSYS3M2.ieqd"""
        Else : Prop = " -e "" c:\Program Files\MAAD\ISMAT\PSYS3M3.ieqd"""
```

```
        End If
        'Looop for CCC
        If CCCopt = 1 And Maint = 1 Then
            CCC = " -e "" c:\Program Files\MAAD\ISMAT\CCC1M1.ieqd"""
        ElseIf CCCopt = 1 And Maint = 2 Then
            CCC = " -e "" c:\Program Files\MAAD\ISMAT\CCC1M2.ieqd"""
        ElseIf CCCopt = 1 And Maint = 3 Then
            CCC = " -e "" c:\Program Files\MAAD\ISMAT\CCC1M3.ieqd"""
        ElseIf CCCopt = 2 And Maint = 1 Then
            CCC = " -e "" c:\Program Files\MAAD\ISMAT\CCC2M1.ieqd"""
        ElseIf CCCopt = 2 And Maint = 2 Then
            CCC = " -e "" c:\Program Files\MAAD\ISMAT\CCC2M2.ieqd"""
        Else : CCC = " -e "" c:\Program Files\MAAD\ISMAT\CCC2M3.ieqd"""
        End If
        'Loop for Compartments
        If LWLcomp = 1 And Maint = 1 Then
            Comp = " -c "" c:\Program Files\MAAD\ISMAT\comp1M1.icmp"""
        ElseIf LWLcomp = 1 And Maint = 2 Then
            Comp = " -c "" c:\Program Files\MAAD\ISMAT\comp1M2.icmp"""
        ElseIf LWLcomp = 1 And Maint = 3 Then
            Comp = " -c "" c:\Program Files\MAAD\ISMAT\comp1M3.icmp"""
        ElseIf LWLcomp = 2 And Maint = 1 Then
            Comp = " -c "" c:\Program Files\MAAD\ISMAT\comp2M1.icmp"""
        ElseIf LWLcomp = 2 And Maint = 2 Then
            Comp = " -c "" c:\Program Files\MAAD\ISMAT\comp2M2.icmp"""
        ElseIf LWLcomp = 2 And Maint = 3 Then
            Comp = " -c "" c:\Program Files\MAAD\ISMAT\comp2M3.icmp"""
        ElseIf LWLcomp = 3 And Maint = 1 Then
            Comp = " -c "" c:\Program Files\MAAD\ISMAT\comp3M1.icmp"""
        ElseIf LWLcomp = 3 And Maint = 2 Then
            Comp = " -c "" c:\Program Files\MAAD\ISMAT\comp3M2.icmp"""
        Else : Comp = " -c "" c:\Program Files\MAAD\ISMAT\comp3M3.icmp"""
        End If
        'Loop For LevAuot
        If LevAuto = 1 Then
            Scenario = " -s 1"
        ElseIf LevAuto = 2 Then
            Scenario = " -s 2"
        ElseIf LevAuto = 3 Then
            Scenario = " -s 3"
        Else : Scenario = " -s 4"
        End If
        NSFS = " -e "" c:\Program Files\MAAD\ISMAT\NSFS.ieqd"""
        Consolekill = " -k "" True"""
        Goal = " -g ""MinimizeCrewSize"""
        ManModel = ApptoRun & FiletoRun & Baseequip & ASuW & ASW & SDS & GMLS
& AAW & CCC & Prop & NSFS & Comp & Goal & Scenario & Consolekill
        Crew = Shell(ManModel, AppWinStyle.MinimizedNoFocus, True, -1)
    End Sub

End Module
```

APPENDIX D – ELECTRICAL MODULE CODE

```
      Program SCElectric
! This subroutine calculates electrical load and auxiliary machinery rooms
! total volume.All loads in [kW].
      real LWL,KWp,KWs,KWe,KWm,KWcps,KWb,KWf,KWhn,KWa,KWserv,KWnp,KWpay
            real KWmfl,KWh,KWv,KWac,KWmflm,KWgreq,KW24,KW24avg,KG,KWfins
            integer PSYStype,PSYS,PSYSM,CCC,ASW,ASUW
! Input
!           LWL=length at design waterline=LBP (m)
!           T=draft to design waterline (m)
!           Vt=total ship volume (m3)
!           Vfl=full load displaced hull volume (m3)
!           VD=deckhouse volume
!           Pbpengtot=total brake propulsion power (kW)
!           Vht=total hull volume (m3)
!           KWpay=payload required electric power (kW)
!           Vmb=propulsion machinery box volume required (m3)
!           Ncps=Collective Protection System alternative (0=none,1=partial,2=full)
!           Nfins=number of stabilizer fin pairs
!           Nssg=number of ship service generators
!           EFMF=electric power fuel margin factor
!           EDMF=electric power design margin factor
!           E24MF=electric power 24 hour average margin factor
!           PSYStype=propulsion system type (1=mechanical, 2=elctric drive
!           CMan=manning reduction and automation factor
!           Wp=total payload weight
!           Nprop=number of propulsors
!           Maint=maintenace level
!           PSYS=propulsion system option
!           PSYSM=propulsion system option for manning calculation
!           CCC=CCC option
!           ASW=ASW option
!           ASUW=ASUW option
!
      open(4,file='SCelectric.in',status='old')
            read(4,*) LWL,T,Vt,Vfl,VD,Pbpengtot,Vht,KWpay,Vmb,Ncps,Nfins,Nssg,EFMF,&
                  EDMF,E24MF,PSYStype,CMan,Wp,Nprop,Maint,PSYS,CCC,ASW,ASUW
            close(4)
            LWL=LWL*3.28084
            T=T*3.28084
            Vt=Vt*35.315
            Pbpengtot=Pbpengtot/.7457
            Vht=Vht*35.315
            Vmb=Vmb*35.315
            Vfl=Vfl*35.315
            VD=VD*35.315
      Wp=Wp/1.016047
!
!           Manning from manning model RMS
            If (PSYS .LT. 5) then
                  PSYSM=1
            Elseif (PSYS .GT. 4 .AND. PSYS .LT. 11) then
                  PSYSM=2
            Else
                  PSYSM=3
            END IF
```

```
        NT=INT(453.8569-ASW*8.328125-(-6.0232*CMan+7.0174)*39.85031-
Maint*7.703488+(LWL/161.24)*13.73633+ASW*Maint*3.203125-
Maint*CCC*1.676841*ASUW*CCC**2*.4738692-(LWL/161.26)*PSYSM**2*.2832031+(-
6.0232*CMan+7.0174)**2*CCC*.2432359)                    !=total crew
        NOS=INT(.07*NT)
       !=number fo officers
        If (NOS .GT. 23) then
              NO=NOS
        Else
         NO=23
        END IF
        NE=NT-NO
       !=number of enlisted
        NA=INT(.1*NT)
       !=additional accomodations
!
        KWp=0.00323*Pbpengtot                        !=propulsion auxiliary electric power reqd
        KWs=0.00826*LWL*T                            !=steering electric power reqd, SWBS 561
        KWe=0.000213*Vt                              !=SWBS 300 electric power reqd
        Wcps=Ncps*.00005*Vt                     !=Collective Protection System weight
        if(Wcps.gt.0.0) KWcps=0.000135*Vt     !=Collective Protection System electric power reqd
        KWm=101.4                                        !=miscelaneous electric power reqd
        KWb=0.235*NT                                     !=auxiliary boiler electric power
reqd
        KWf=0.000097*Vt                              !=firefighting electgric power reqd, SWBS
521
        KWhn=0.000177*Vht                            !=fuel handling electric power reqd, SWBS
540
        KWfins=Nfins*50.                             !=stabilizing fins electric power reqd
        KWa=0.65*NT+KWfins                      !=misc auxiliary electric power reqd
        KWserv=0.395*NT                              !=services electric power reqd, SWBS 600
        KWnp=KWp+KWs+KWe+KWm+KWb+KWf+KWhn+KWa+KWserv       !=total non-payload
electric power reqd
! Iterative loop for net electrical load and AMR volume.
        KWmfl=3000.0           ! First guess at maximum functional load
 1      Vaux=56900.0*KWmfl/3411.0    !auxiliary machinery room reqd volume
        KWh=0.00064*(Vt-Vmb-Vaux)               !=heating reqd electric power
        KWv=0.103*(KWh+KWpay)+KWcps             !=ventilation reqd electric power
        KWac=0.67*(0.1*NT+0.00067*(Vt-Vmb-Vaux)+0.1*KWpay)     !=air conditioning reqd electric
power
        KWhorac=max(KWh,KWac)                        !=maximum of heating or AC reqd electric
power
        f=KWnp+KWhorac+KWv+KWpay
        if(abs((KWmfl-f)/KWmfl).gt.0.01) then
              KWmfl=f
              goto 1
        endif
        KWmfl=f
        Vaux=56900.0*KWmfl/3411.0
        KWmflm=EDMF*EFMF*KWmfl                  ! maximum functional load with margins
        KWgreq=KWmflm/(Nssg-1)/0.9            ! electric power reqd per generator
        if(PSYStype.eq.2) KWgreq=1000.
        KW24=0.5*(KWmfl-KWp-KWs)+KWp+KWs        ! 24 hour average electrical load
        KW24avg=E24MF*KW24                           ! 24 hour average electrical load with
margins
! Output
        Vaux=Vaux/35.315
```

```
          open(5,file='SCelectric.out',status='old')
          write(5,*) KWmflm,KWgreq,KW24avg,Vaux,NO,NE,NT,NA
          close(5)
!
     stop
          end
```

APPENDIX E – MISSION NEED STATEMENT (MNS)

MISSION NEED STATEMENT

FOR

21st CENTURY SURFACE COMBAT PLATFORM(s)

1. DEFENSE PLANNING GUIDANCE ELEMENT.

The Department of the Navy's 1992 white paper, "From the Sea", outlines a significant change in priorities from a "Blue Water Navy fighting a traditional Super Power". The rapidly changing global political climate, and seven major theater operations conducted over the following 22 months, prompted the Department of the Navy to publish a revised white paper, "Forward from the Sea", in December 1994.

"Forward from the Sea" emphasizes the importance of action against aggression of regional powers at the farthest points on the globe. Such action requires a rapid, flexible response to emergent crises which projects decisive military power to protect vital U.S. interests (including economic interests), and defend friends and allies. It states, "...the most important mission of naval forces in situations short of war is to be *engaged* in forward areas, with the objectives of *preventing* conflicts and *controlling* crises". Naval forces have five fundamental and enduring roles in support of the National Security Strategy: projection of power from sea to land, sea control and maritime supremacy, strategic deterrence, strategic sealift, and forward naval presence.

Most recently, the Quadrennial Defense Review Report, the Department of the Navy's whitepaper, "Naval Transformational Roadmap", and CNO's "Sea Power 21" vision statement provide additional unclassified guidance and clarification on current DoD and USN defense policies and priorities.

The Quadrennial Defense Review Report identifies six critical US military operational goals. These are: 1) protecting critical bases of operations; 2) assuring information systems; 3) protecting and sustaining US forces while defeating denial threats; 4) denying enemy sanctuary by persistent surveillance, 5) tracking and rapid engagement; 6) enhancing space systems; and 7) leveraging information technology.

The "Naval Transformational Roadmap" and "Sea Power 21" provide the US Navy's plan to Support these goals including nine necessary war fighting capabilities in the areas of Sea Strike – strategic agility, maneuverability, ISR, time-sensitive strikes; Sea Shield – project defense around allies, exploit control of seas, littoral sea control, counter threats; and Sea Base – accelerated deployment & employment time, enhanced seaborne positioning of joint assets.

This Mission Need Statement specifically addresses critical components of Sea Strike and Sea Shield consistent with operational goals 1), 3) and 5) of the Quadrennial Defense Review. While addressing these capabilities, there is also a need to reduce cost and minimize personnel in harms way.

2. MISSION AND THREAT ANALYSIS.

a. Threat.

(1) The shift in emphasis from global Super Power conflict to numerous regional conflicts requires increased flexibility to counter a variety of threat scenarios which may rapidly develop. Two distinct classes of threats to U.S. national security interests exist:

(a) Threats from nations with either a superior military capability, or the demonstrated interest in acquiring such a capability. Specific weapons systems that could be encountered include ballistic missiles, land and surface launched cruise missiles, significant land based air assets and submarines.

(b) Threats from smaller nations who support, promote, and perpetrate activities which cause regional instabilities detrimental to international security and/or have the potential for development of nuclear weapons. Specific weapon systems include diesel/electric submarines, land-based air assets, and mines.

(2) Since many potentially unstable nations are located on or near geographically constrained bodies of water, the tactical picture will be on smaller scales relative to open ocean warfare. Threats in such an environment include: (1) technologically advanced weapons – cruise missiles like the Silkworm and Exocet, land-launched attack aircraft, fast gunboats armed with guns and smaller missiles, and diesel electric submarines; and (2) unsophisticated and inexpensive passive weapons - mines, chemical and biological weapons. Many encounters may occur in shallow water which increases the difficulty of detecting and successfully prosecuting targets. Platforms chosen to support and replace current assets must have the capability to dominate all aspects of the littoral environment.

b. Mission

(1) Forward deployed naval forces will be the first military forces on-scene having "staying and convincing" power to promote peace and prevent crisis escalation. The force must have the ability to provide a "like-kind, increasing lethality" response to influence decisions of regional political powers. It must also have the ability to remain invulnerable to enemy attack. The new platforms must complement and support this force.

(2) The new platforms must ultimately perform the missions of all ship classes to be replaced, including traditional "Blue Water" AAW, ASUW and ASW operations. This may be accomplished by a single multi-mission platform or a family of multiple mission platforms.

(3) Power Projection requires the execution and support of flexible strike missions and support of naval amphibious operations. This includes gunfire support, protection to friendly forces from enemy attack, unit self defense against littoral threats, area defense, and theater ballistic missile defense.

(4) The platforms must be able to maintain Battle Space Dominance, including: command/control/communications/connectivity and intelligence (C_4/I) operations beyond weapons range.

(5) The platforms must be able to support, maintain and conduct operations with the most technologically advanced unmanned/remotely controlled tactical and C_4/I reconnaissance

vehicles.

(6) The platform must possess sufficient mobility and endurance to perform all missions on extremely short notice, at locations far removed from home port.

(8) The platform must be able to support non-combatant or NEO operations in conjunction with national directives. It must be flexible enough to support a peacetime presence mission yet be able to provide instant wartime response should a crisis escalate.

c. Need:

With the decommissioning of the *Perry* class frigates, the number of surface combatants available
to carry out these requirements has been significantly reduced. The current inventory of exceptionally capable ships, the *Ticonderoga* and *Arleigh Burke* classes, will be retired before the
end of the third decade of the next century. **There is a need for multi and multiple mission ships to complement, and eventually replace the *Ticonderoga* and *Arleigh Burke* class surface combatants. Immediate deficiencies include strike, fire support, and Theater Ballistic Missile Defense (TBMD). These new ships must start delivery no later than 2003.**

3. NON-MATERIAL ALTERNATIVES.

a. Change the U.S. role in the world by reducing U.S. international involvement.

b. Increase reliance on foreign political and military activity to meet the interests of the U.S.

c. Increase reliance on non-military assets and options to enhance the U.S. performance of the missions identified above while requiring a smaller inventory of naval forces.

4. POTENTIAL MATERIAL ALTERNATIVES.

a. Retain and upgrade current fleet assets as necessary. Possibilities include a service life extension to the most capable current assets. Continue production of the *Arleigh Burke* class at a rate that maintains surface combatant force levels.

b. Design and build a new modified-repeat DDG. Select those changes that satisfy identified mission deficiencies, improve overall capabilities, or improve affordability.

c. Design and build a new class or classes of surface combatant ships satisfying current mission deficiencies in strike, fire support, and Theater Ballistic Missile Defense (TBMD). Upgrade or follow these ships with additional new ships to replace multi-mission capability of retiring ships.

d. Design and build a family of variants with a single hull design and common HM&E which is configured for adaptability to alternate mission or combat system capabilities.

5. CONSTRAINTS.

a. The cost of the platforms must be kept to the absolute minimum, acknowledging the rapidly decreasing U.S. defense department budget.

b. The platforms must be highly producible, minimizing the time from concept to delivery to the Fleet.
The design must be flexible enough to support variants if necessary.

c. The platforms must operate in current logistics support capabilities.

d. Inter-service and Allied C_4/I (inter-operability) must be considered in the development of any new
platform or the upgrade of existing assets.

e. The platform or system must be capable of operating in the following environments:
(1) A dense contact and threat environment;
(2) Conventional and nuclear weapons environments;
(3) Open ocean (sea states 0 through 9) and littoral regions;
(4) All-Weather, Battle Group Environments;
(5) Independent operations.

f. The platform must have absolute minimum manning.

APPENDIX F – ACQUISITION DECISION MEMORANDUM

Virginia Tech

Aerospace and Ocean Engineering

VIRGINIA POLYTECHNIC INSTITUTE
AND STATE UNIVERSITY

215 Randolph Hall
Mail Stop 0203, Blacksburg, Virginia 24061
Phone # 540-231-6611 Fax: 540-231-9632

August 24, 2005

From: Virginia Tech Naval Acquisition Executive
To: CG(X) Design Teams

Subject: ACQUISITION DECISION MEMORANDUM FOR an Air Superiority Cruiser

Ref: (a) Virginia Tech SC-21 Battle Force Combatant Mission Need Statement

1. This memorandum authorizes concept exploration of a single material alternative proposed in Reference (a) to the Virginia Tech Naval Acquisition Board on 24 August 2005. Additional material and non-material alternatives supporting this mission may be authorized in the future.

2. Concept exploration is authorized for a CG(X) Air Superiority Gruiser consistent with the mission requirements and constraints specified in Reference (a), with particular emphasis on providing outer umbrella air superiority for the entire battle force, and supporting national ballistic missile defense using long-range missiles (Kinetic Energy Interceptor, KEI) and air defense X-band radars currently under development. The radar system must be able to: counter low-radar cross section (RCS) threats at extended ranges; and detect, track and engage ballistic missiles outside of the atmosphere. Additional essential requirements include survival in a high-threat environment and operation in all warfare areas (multi-mission). The design must minimize personnel vulnerability in combat through automation, innovative concepts for minimum crew size, and signature reduction. CG(X) must have significant commonality with DD-21/DD(X) including: propulsion and power system and hull form. Likely differences include additional missile capacity, and removal of the Advanced Gun System (AGS). Concepts shall include moderate to high-risk alternatives. Average follow-ship acquisition cost shall not exceed $900M (FY2010) with a lead ship acquisition cost less than $1.5B. It is expected that 18 ships of this type will be built with IOC in 2015.

A.J. Brown
VT Acquisition Executive

VITAE

LT Tyson Scofield was born in Swampscott, MA. He graduated from the U. S. Coast Guard Academy and was commissioned as an ensign in the Coast Guard in 2000. LT Scofield's first assignment was as an Engineering Officer in Training onboard US Coast Guard Cutter ESCANABA (WMEC 907). Following this tour, LT Scofield was assigned as a Port Engineer at Naval Engineering Support Unit (NESU) Boston, MA. At NESU Boston, LT Scofield was responsible for assistaning with the maintenance of Coast Guard Cutters ranging in sizes from 87' to 175'. LT Scofield is a licensed Professional Engineer in the Commonwealth of Virginia and is a member of the American Society of Engineers.

LT Scofield is married to the former Michelle Duggan of Center Moriches NY and has one daughter Anna.