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Manning and Automation Model for Naval Ship Analysis and Optimization

ABSTRACT

The manning of a ship is a major driver of 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]. This cost is largely determined by decisions made during concept design, which may include significant new support costs ashore. Consequently, reliable manpower estimates and related design decisions should be made 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 paper describes a method of implementing a manning task network analysis tool (ISMAT, Integrated Simulation Manning Analysis Tool) 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. 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. A concept exploration case study using this model is performed for an Air Superiority Cruiser, CG(X). The performance of the manning model in this case study is assessed and recommendations are made for future work.

MOTIVATION & INTRODUCTION

In a report to Congress on the effects of performing manpower estimates early in the design process, the GAO stated, "when applied to ships early in their development and throughout their design, human systems (analysis) has the potential to substantially reduce requirements for personnel, leading to significant cost savings" [1]. There are a number of options available to ship designers to reduce ship manning requirements. These options include automation, changing maintenance philosophies, improving system reliabilities, revising crew training and others. All of these options have the possibility to reduce crew size but cost (including shore-based cost), reliability, work-life issues, and effectiveness cannot be sacrificed or ignored. 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 early in the design process that can calculate manning levels for different levels of automation, maintenance strategies and ship system configurations.

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. Multi-objective optimization methods provide a solution to this problem [2-4].

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, discipline-specific 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. 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.

In this paper, a multi-objective genetic design optimization approach developed by Brown [3,4] 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) 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. 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.

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 presented in this paper is 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 generates data to construct a simple response surface model (RSM) to estimate baseline manning. This baseline manning estimate is then be used by the overall ship design program.

MANNING ANALYSIS AND MODEL

Traditionally, manpower analyses are conducted late in the ship design process. The guiding documentation for shipboard manning is the Ship Manpower Document (SMD). The Navy outlines the process 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.)
- 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.
- Conduct a fleet review of the documents

This process is manpower intensive, slow, and reliant on system experts. Another method for manpower estimation is to conduct a Top-Down Requirements Analysis (TDRA) earlier in the design process. The TDRA process as described by Thomas Malone [5] is shown in Figure 1.

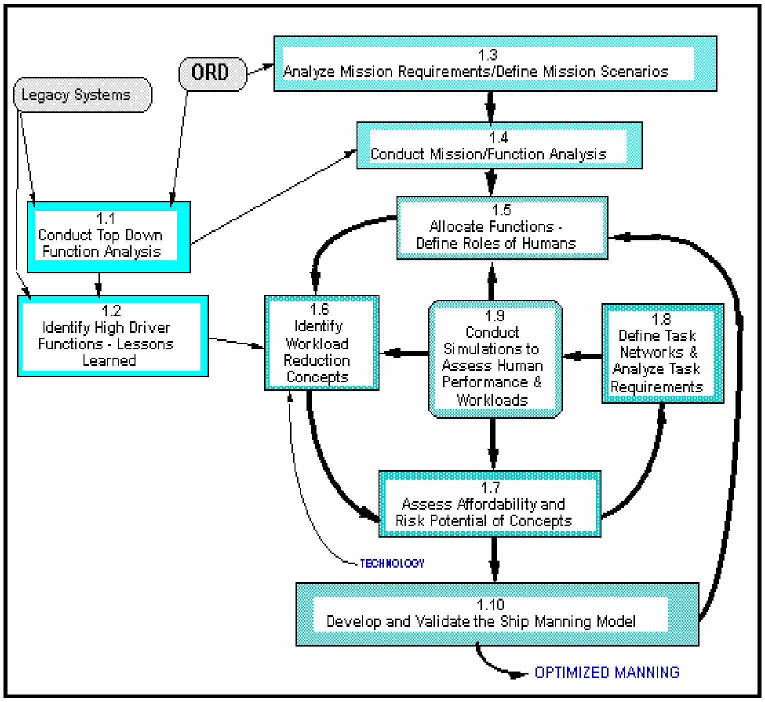


Figure 1 - Top Down Requirements Analysis [5]

The first step of a TDRA is to analyze the mission requirements of the new ship. Various mission scenarios are developed. Once the mission scenarios are developed, the missions are decomposed into the functions required to execute the mission. Functions may be both import and underway. 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 using a simulation to determine the effectiveness of the manning system. This process is similar to the method that is described in this paper, but the manning analysis described here is conducted much earlier in the design.

A number of computer 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 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) behavior of a system" [6]. 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, although complete and accurate task data may also be difficult to obtain, particularly with new technologies and systems. Tasks are connected using logic statements and probabilities. 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 2.

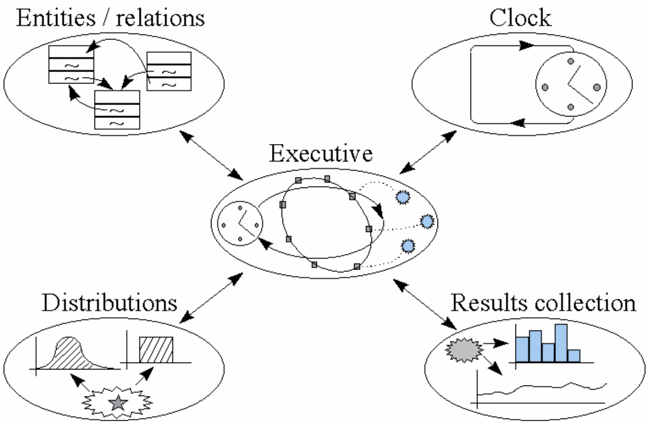


Figure 2 - Discrete Event Simulation Component Interactions [6]

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" [6]. 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" [7].

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" [7]. Micro Saint has been used by Microanalysis and Design (MAAD, now Alion) on DD21 and other projects. Micro Saint or Micro Saint Sharp are the base programs for most of the more-refined manpower estimation tools that were explored in this research.

MAAD also 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 [18]. 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 cost. SMART contains a database with the annual shipboard cost of each rank, rate and rating in the Navy. This simple cost is used in our study. Total ownership cost should be used including shore-based costs such as new facilities, family moves and training. This is particularly important with new technologies. The optimizer tries 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. Skill sets associated with each rating should also be considered for new technology. 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 also allows 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. This assumes that necessary skills exist within the rates and ratings of the division. 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 sub-functions 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 the manpower calculations done in this research.

The TDRA method used in conjunction with ISMAT was chosen to provide the 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 Scenarios
- Compartments
- Ship systems and equipment
- Level of automation
- Maintenance tasks to be performed by the crew
- Crew document of personnel to be considered in the automation

The mission scenarios come from the mission analysis that is conducted at the outset of concept exploration. A library of scenarios was 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 is used to estimate a preliminary amount of facilities maintenance that will be required by the ship. The ship systems information is input from the machinery module and the combat systems module of the ship synthesis model. Changing the systems that are used on the ship changes the amount of maintenance that must be performed by the crew. The systems onboard the ship effect 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 is 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).

Ship Design Application

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 space of 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 responsible department. 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 evaluating each design. The ship will either pass or fail the scenario and this determines whether the design manning is 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 in the allotted time. Personnel are selected for tasks based on their department 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, rates and ratings. The design options are defined so that Model Center can vary the designs using a multi-objective optimization. A Visual Basic program was developed so that design options can be created and tested in ISMAT based on the inputs from MC.

Model Center is used initially to create a response surface model (RSM) for the manning estimate to be used in the ship synthesis model. A RSM is an equation that is fit to the data created by the manning model. The RSM is then used in the ship synthesis program in place of ISMAT. This is done to reduce the time it takes to complete an optimization. The goal during concept design is to determine the personnel required for the crew and the total ship impact of this crew. The number 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.

The manning model inputs are ship systems, ship length, level of automation, and maintenance level. The model uses these inputs in a scenario to determine the personnel necessary to complete all mission and maintenance requirements. The output of the model is the number of enlisted and officers required in the crew. Figure 3 shows a simple block diagram of the manning module.

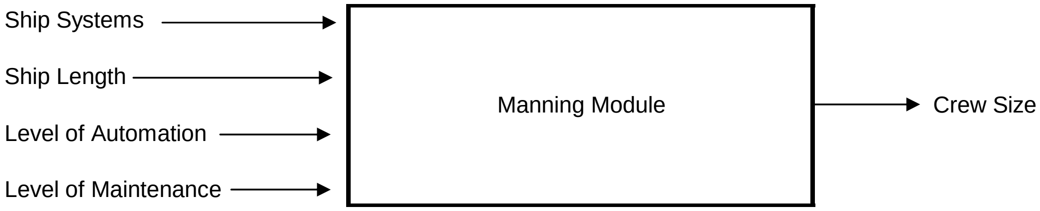
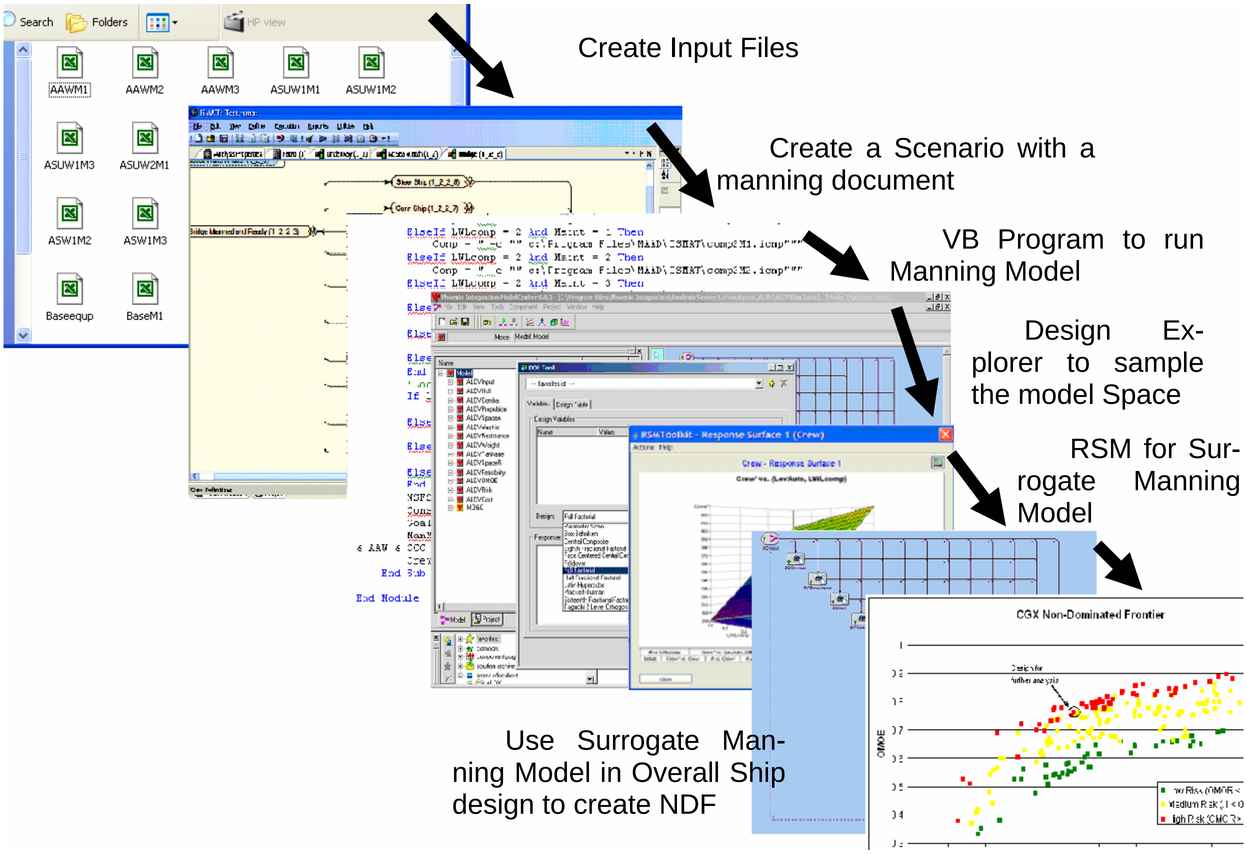


Figure 3 - Manning Module Block Diagram

The system selection affects the manning levels by altering the number of personnel that are required for maintaining and operating the equipment. If there are fewer or simpler systems, the manning level will be smaller than it would be for multiple complex systems. A simple combat system may be more advantageous than a more complex system because of the overall savings on the cost of the ship despite a lower Overall Measure of Effectiveness (OMOE) for the ship. Automation also may increase the risk and cost of a new ship design. Developing a maintenance concept early in the ship design process may help to reduce the number personnel 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. This can also have implications for personnel ashore.

Figure 4 shows the sequence of events for conducting the manning analysis and optimization. The manning analysis starts by creating input files for compartments and equipment. These input files define the alternative equipment and compartments in the design space and the maintenance 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 was 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 executes 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 the various 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 in the Ship Synthesis Model (SSM). The SSM and MOGO are used to explore the design space for feasible ship designs and to create a non-dominated frontier (NDF) of optimized design options. From the NDF, the designer can choose a ship design for further exploration and optimization.



Create Input Files

Create a Scenario with a manning document

VB Program to run Manning Model

Design Explorer to sample the model Space

RSM for Surrogate Manning Model

Use Surrogate Manning Model in Overall Ship design to create NDF

Figure 4 – Manning and Automation Analysis and Optimization Process

Scenarios

The scenarios are developed from the Mission Needs Statement or the Initial Capabilities Document at the beginning of concept exploration. The scenarios include 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 are performed while the ship is underway.
- Flight Quarters - if the ship is going to be equipped with a flight deck then it needs 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.
- Battle - the primary purpose of a U.S. Navy warship is to engage an enemy. Weapons and sensors must be ready to be employed. Sufficient crew must be available to operate them, and the crew must also be ready to control 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 whether the crew will be able to control extensive damage with a loss of personnel and damage to auto-

mated systems. In this scenario, the crew is faced with damage similar to that inflicted on the USS STARK. A portion of the ship's crew is treated as casualties and is unusable for the scenario.

- Other - Depending on the specific mission of a ship, there are other functions and tasks that 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 bottoms-up approach. The individual tasks are linked together to create functions. The functions are then related to form a scenario. The use of a bottoms-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, but it is essential that all tasks be captured. Although the construction of the scenario is bottoms-up, the overall process of determining the crew size is a top down process that begins with requirements.

The design of a scenario starts by examining a Watch Quarter and Station Bill (WQSB) from an existing ship. The WQSB lists the billets that must be filled during a shipboard evolution. 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 tasks that each crew member must perform 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. This is a redundant safety measure in the system. A separate task is not included in the simulation for each person. Instead, both personnel are accounted for in the task "steer the ship". Once the tasks are 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 5 shows the tasks that must be performed by the bridge watch when a ship is getting underway from port.

The duration of each task is estimated and a deviation may 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.

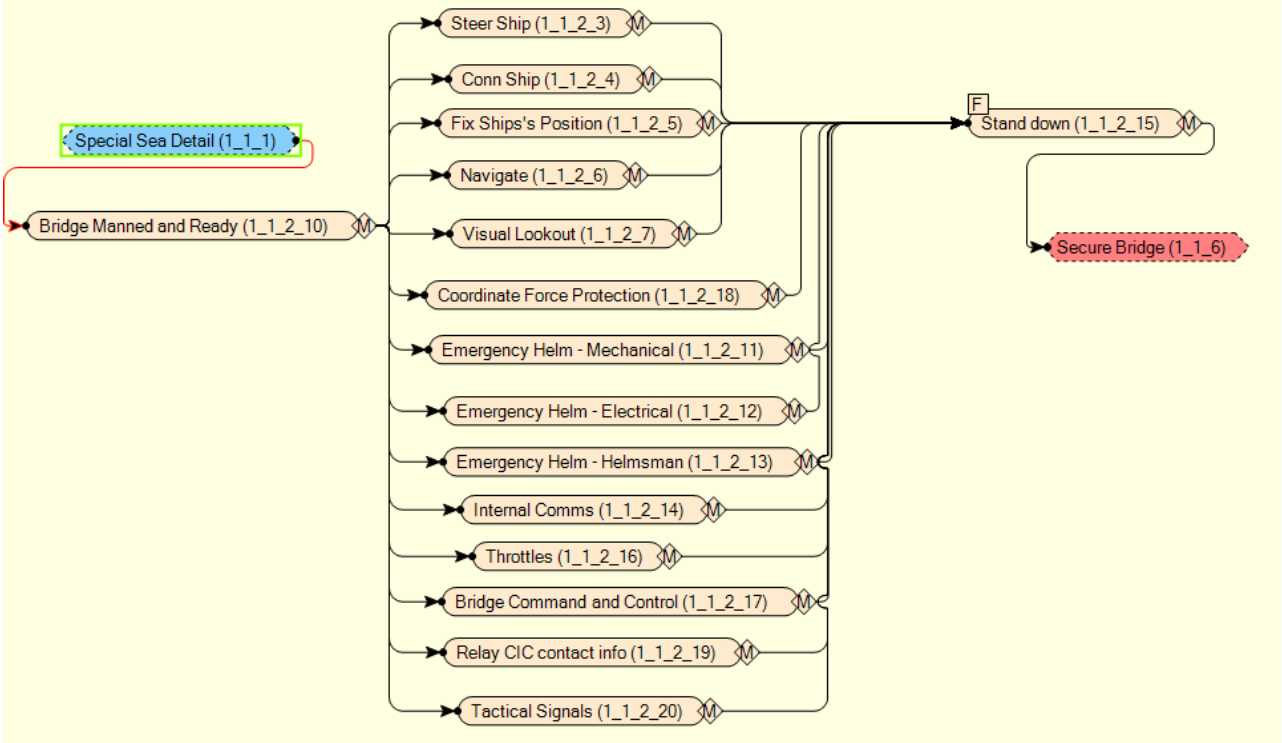


Figure 5 - ISMAT Bridge Watch Function

The tasks can be linked together in many ways to form a function. Figure 5 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.

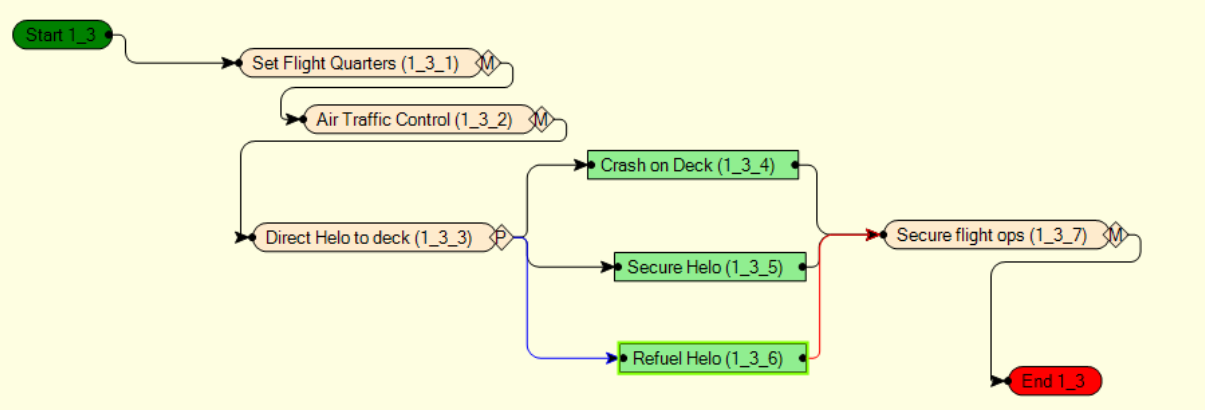


Figure 6 - ISMAT Flight Operations Function

Figure 6 is an example of the probabilistic decision that is used for the landing of a helicopter. A probabilistic decision is based on the probability of the task going to either option. The total of the probabilities must equal 1. In this scenario, the helicopter can either land and secure, fuel, or crash and catch on fire.

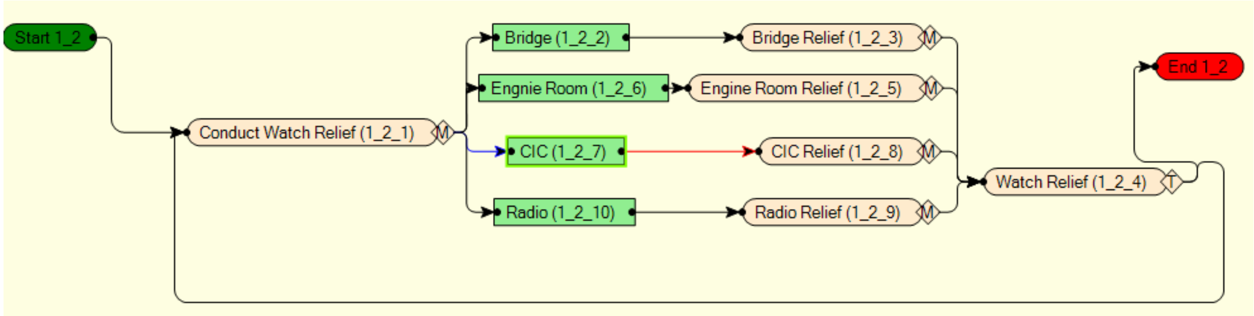
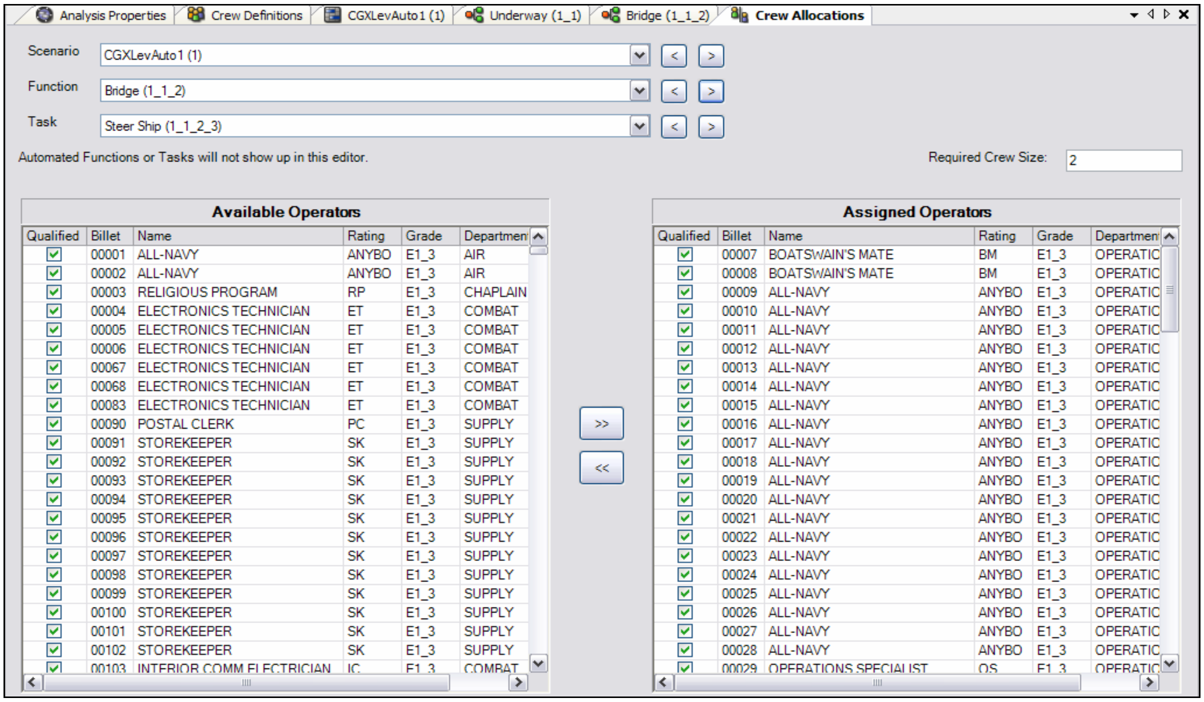


Figure 7 – At-Sea Watch Function

Figure 7 shows the at-sea watch function and demonstrates how a tactical decision is used in ISMAT. 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. 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.



Scenario: CGXLevAuto1 (1)
Function: Bridge (1_1_2)
Task: Steer Ship (1_1_2_3)

Automated Functions or Tasks will not show up in this editor.

Required Crew Size: 2

Available Operators

Qualified	Billet	Name	Rating	Grade	Departmen
☑	00001	ALL-NAVY	ANYBO	E1_3	AIR
☑	00002	ALL-NAVY	ANYBO	E1_3	AIR
☑	00003	RELIGIOUS PROGRAM	RP	E1_3	CHAPLAIN
☑	00004	ELECTRONICS TECHNICIAN	ET	E1_3	COMBAT
☑	00005	ELECTRONICS TECHNICIAN	ET	E1_3	COMBAT
☑	00006	ELECTRONICS TECHNICIAN	ET	E1_3	COMBAT
☑	00067	ELECTRONICS TECHNICIAN	ET	E1_3	COMBAT
☑	00068	ELECTRONICS TECHNICIAN	ET	E1_3	COMBAT
☑	00083	ELECTRONICS TECHNICIAN	ET	E1_3	COMBAT
☑	00090	POSTAL CLERK	PC	E1_3	SUPPLY
☑	00091	STOREKEEPER	SK	E1_3	SUPPLY
☑	00092	STOREKEEPER	SK	E1_3	SUPPLY
☑	00093	STOREKEEPER	SK	E1_3	SUPPLY
☑	00094	STOREKEEPER	SK	E1_3	SUPPLY
☑	00095	STOREKEEPER	SK	E1_3	SUPPLY
☑	00096	STOREKEEPER	SK	E1_3	SUPPLY
☑	00097	STOREKEEPER	SK	E1_3	SUPPLY
☑	00098	STOREKEEPER	SK	E1_3	SUPPLY
☑	00099	STOREKEEPER	SK	E1_3	SUPPLY
☑	00100	STOREKEEPER	SK	E1_3	SUPPLY
☑	00101	STOREKEEPER	SK	E1_3	SUPPLY
☑	00102	STOREKEEPER	SK	E1_3	SUPPLY
☑	00103	INTERIOR COMM ELECTRICIAN	IC	E1_3	COMBAT

Assigned Operators

Qualified	Billet	Name	Rating	Grade	Departmen
☑	00007	BOATSWAIN'S MATE	BM	E1_3	OPERATIC
☑	00008	BOATSWAIN'S MATE	BM	E1_3	OPERATIC
☑	00009	ALL-NAVY	ANYBO	E1_3	OPERATIC
☑	00010	ALL-NAVY	ANYBO	E1_3	OPERATIC
☑	00011	ALL-NAVY	ANYBO	E1_3	OPERATIC
☑	00012	ALL-NAVY	ANYBO	E1_3	OPERATIC
☑	00013	ALL-NAVY	ANYBO	E1_3	OPERATIC
☑	00014	ALL-NAVY	ANYBO	E1_3	OPERATIC
☑	00015	ALL-NAVY	ANYBO	E1_3	OPERATIC
☑	00016	ALL-NAVY	ANYBO	E1_3	OPERATIC
☑	00017	ALL-NAVY	ANYBO	E1_3	OPERATIC
☑	00018	ALL-NAVY	ANYBO	E1_3	OPERATIC
☑	00019	ALL-NAVY	ANYBO	E1_3	OPERATIC
☑	00020	ALL-NAVY	ANYBO	E1_3	OPERATIC
☑	00021	ALL-NAVY	ANYBO	E1_3	OPERATIC
☑	00022	ALL-NAVY	ANYBO	E1_3	OPERATIC
☑	00023	ALL-NAVY	ANYBO	E1_3	OPERATIC
☑	00024	ALL-NAVY	ANYBO	E1_3	OPERATIC
☑	00025	ALL-NAVY	ANYBO	E1_3	OPERATIC
☑	00026	ALL-NAVY	ANYBO	E1_3	OPERATIC
☑	00027	ALL-NAVY	ANYBO	E1_3	OPERATIC
☑	00028	ALL-NAVY	ANYBO	E1_3	OPERATIC
☑	00029	OPERATIONS SPECIALIST	OS	E1_3	OPERATIC

Figure 8 - Crew Allocation Screen for "Steer Ship"

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 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 study, the skills required to perform tasks are not explicitly considered. This would be an excellent area for further research, and is particularly important with new technologies and systems. As was stated earlier, the personnel that may be considered for each task are based on the department in the ship to which they are assigned. Tasks are assigned to departments based on the current Navy operating procedures. Figure 8 shows the crew allocation menu that is used to assign personnel considered for the task “Steer Ship”.

The “available operator” list includes the members of the crew who are qualified to perform the task. The “assigned operators” list contains 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. The personnel in the “assigned operators category are members of the Operations Department which is responsible for maneuvering the ship.

ISMAT contains a library of Ship Manning Documents (SMDs) for most of the ships in the Navy. Each manning document in ISMAT identifies the enlisted crewmembers assigned to the ships. Each crewmember in the SMD has a list of skills that they possess, and a measure of how well they can perform these skills. The cost of each crewmember is also listed in the SMDs. Since officers are not listed in the ISMAT SMDs, they must be added or calculated separately. Adding officers is a simple process covered in the ISMAT User Manual [9]. For this study, officer categories were limited to “division officers” and “department heads”. A Commanding Officer and Executive Officer are included in all crews.

Compartment and System Input Files with Variable Maintenance and Automation

The ship synthesis model combat systems and propulsion system modules are used to select different systems during the concept exploration of the ship. These modules also help define the manning requirements for the ship. Ship equipment data is contained in XML files with an .ieqd extension. The equipment files contain equipment information and maintenance information for all systems on the ship. There are equipment files for most of the ships currently in the U.S. Navy, although combat systems data is somewhat limited. Equipment files for existing Navy systems are created from NAVSEA PMS data CDs. The easiest way to add existing equipment is to obtain copies of the PMS CDs and follow the instructions of the ISMAT User’s Manual [9]. The best method for new equipment is to write estimated characteristics directly into the file. This process was used to create the equipment input files used in this study. The base equipment file is created using the installed CG-47 equipment file. The systems that are contained in the design option input files (propulsion, combat systems, communications, etc) are removed from the base equipment file and then selectively added back during Ship Synthesis. 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 the information for the 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 the equipment information using existing equipment information as a template. 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 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 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.

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 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 designer can modify the XML code for the compartment files using notepad or other text writer.

To create a baseline compartment file, the maintenance tasks with a “PerUnit” of one year or more are removed. All maintenance items with a “PerformEvery” value of greater than 12 months are 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 by adding compartments according to the ship length ratios. Compartments were 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. The final manning RSM allows continuous length and compartment variation.

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, and a major shift to condition-based maintenance is in the works. The navy currently schedules maintenance on 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 following maintenance levels 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.

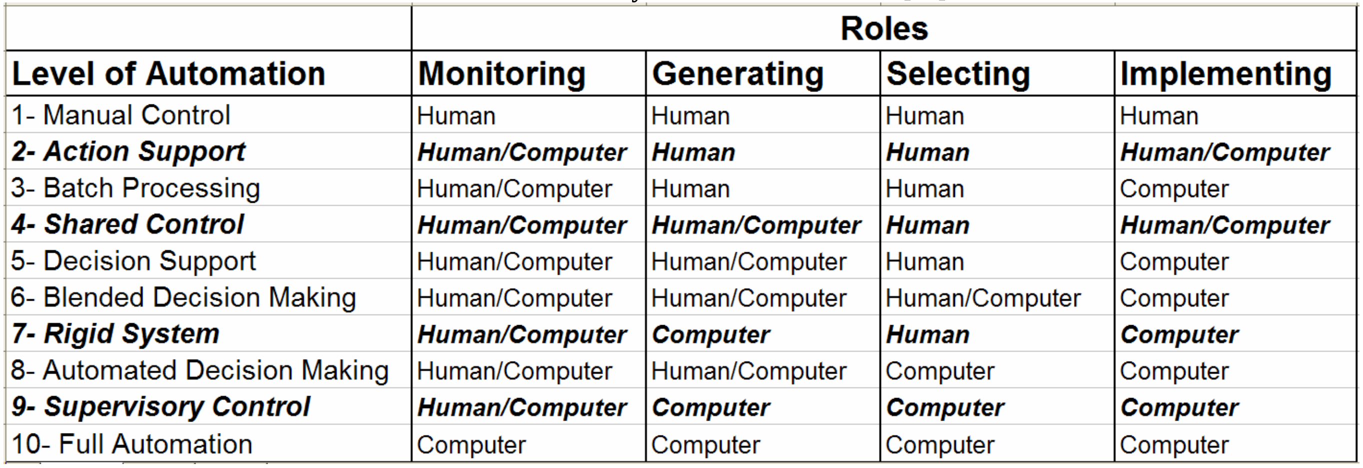
These maintenance levels enable reductions in the ship’s crew. A separate equipment file is needed for each level of maintenance. The levels of maintenance are created by deleting the maintenance tasks that are not performed by the crew for the level being considered. The program determines which operator to use based on the optimizer goal.

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. Compartment and equipment files are saved with an “M#” at the end of the file. This “M#” indicates which maintenance level is used.

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 [10]. 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 [10]. This allocation method is known as a “Fitts List”. These lists became the basis of function allocation between humans and machines. 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 [11]. 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 awareness and risk is valuable to the designer as levels of automation are chosen. Table 2 contains the 10-level taxonomy created by Endsley. Levels used in our manning model are indicted in ***bold italics***.

Table 2 - Taxonomy of Automation Levels [11]



	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. These functions can be assigned to either humans, machines, or both. Four of these levels are used in the scenarios of our manning model.

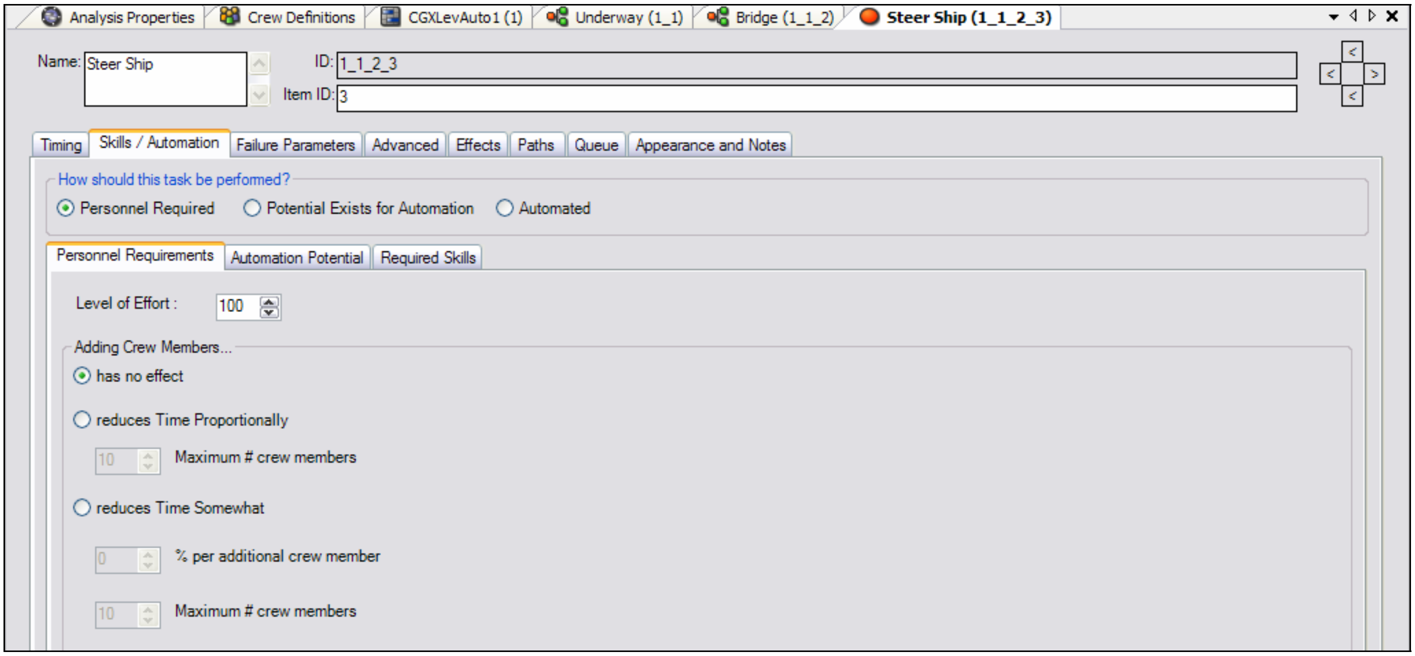
The following is a description of the four selected levels of automation (bold italics):

- 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 that the middle two options had the lowest 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 nozzle man 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 automation is used and where humans are used for the manning model. Figure 9 shows the menu in ISMAT for designating automation in a task.



Name: Steer Ship
ID: 1_1_2_3
Item ID: 3

How should this task be performed?
● Personnel Required ○ Potential Exists for Automation ○ Automated

Level of Effort : 100

Adding Crew Members...
● has no effect
○ reduces Time Proportionally
10 Maximum # crew members
○ reduces Time Somewhat
0 % per additional crew member
10 Maximum # crew members

Figure 9 - 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 10 shows bridge watch for a ship getting underway with a level of automation of 1. Figure 11 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.

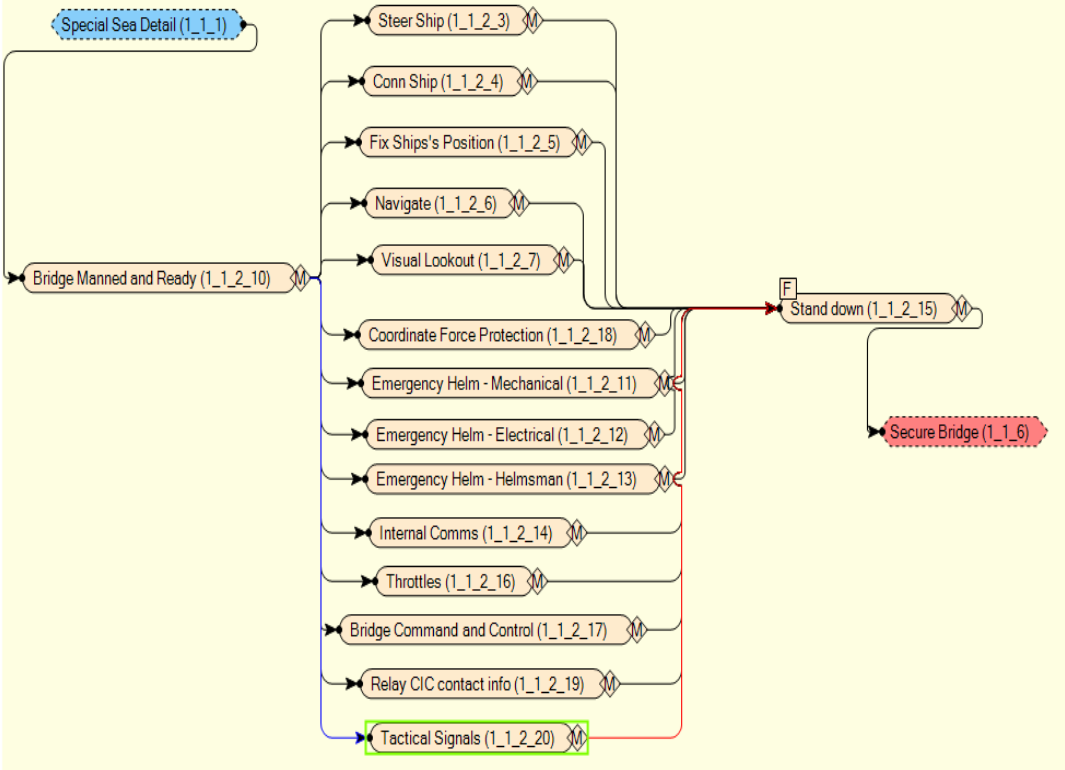


Figure 10 - Underway Bridge - LevAuto 1

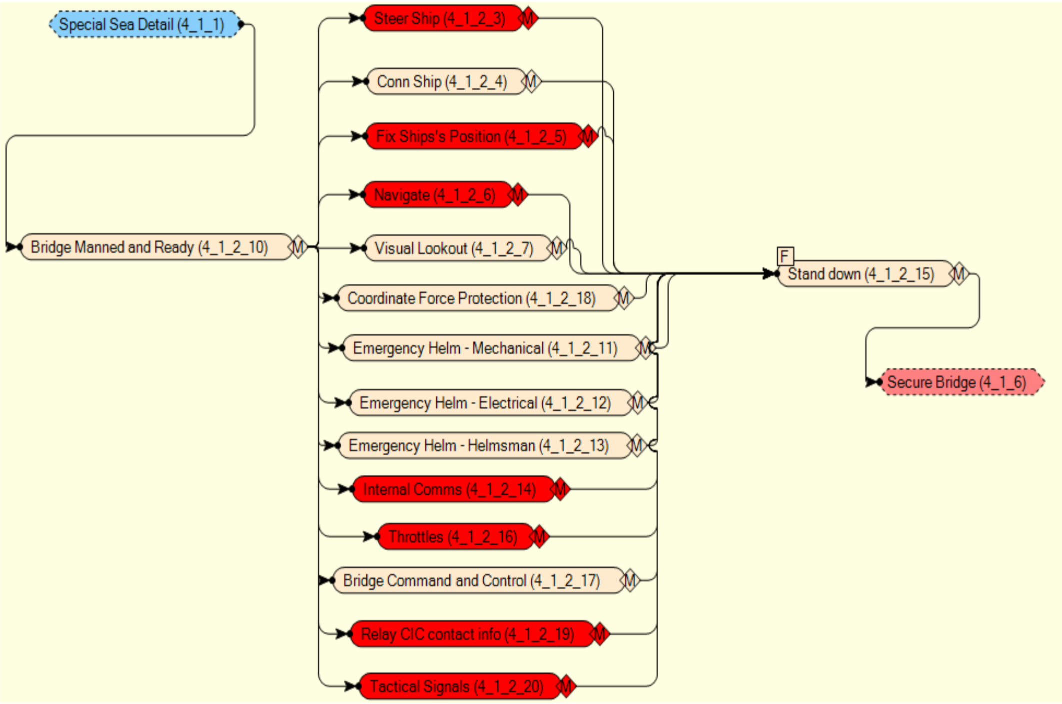
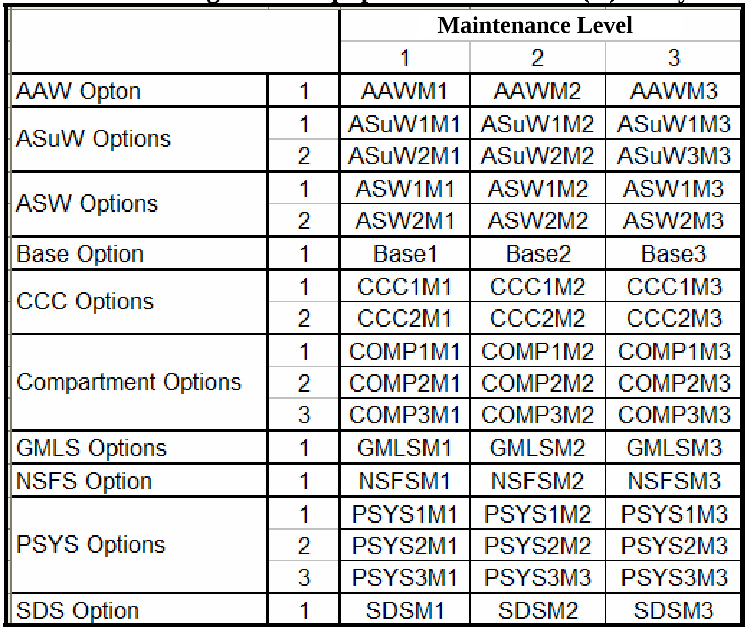


Figure 11 - Underway Bridge - LevAuto 4

Table 3 lists the equipment and equipment files and the levels of maintenance that were created for the manning model for the case study presented in this paper for CG(X).

Table 3 – Manning Model Equipment Files for CG(X) Study



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

Model Execution, Initial Calculations and Manning Response Surface Model

Once the components of the ISMAT simulation are created, the 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 was 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 size 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.

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 generate the necessary equipment files and compartment files using a text editor. 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. 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.

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 required during a simulation. These operators may be used for maintenance, operations, or a combination of the two. This number is written to the output file.

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 to the crew of the actual CG-47. The configuration and results from this validation are listed in Table 4.

Table 4 – CG-47 Validation Configuration and Results

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

The Ship Manning Document for CG-47 specifies a crew size of 398 personnel. The manning model found a crew size of 412. This is 3.5% more than the crew of CG-47. This is sufficient to calculate and optimize shipboard manning in concept 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 Design of Experiments (DOE) is run to gather data for the full range of design options. A DOE is an efficient sampling and analysis of the design space intended to minimize sample points and computation time. The initial DOE used 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 Table 5. The smallest crew is 61% smaller than the largest crew. This includes automation, system, maintenance and ship size effects. Next Design Explorer (Phoenix Integration, Model Center) was used to investigate the effects of each design variable on the crew size. Figure 12 shows the relative effect that each design variable has on crew size.

Table 5 – Smallest and Largest CG(X) Crews

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

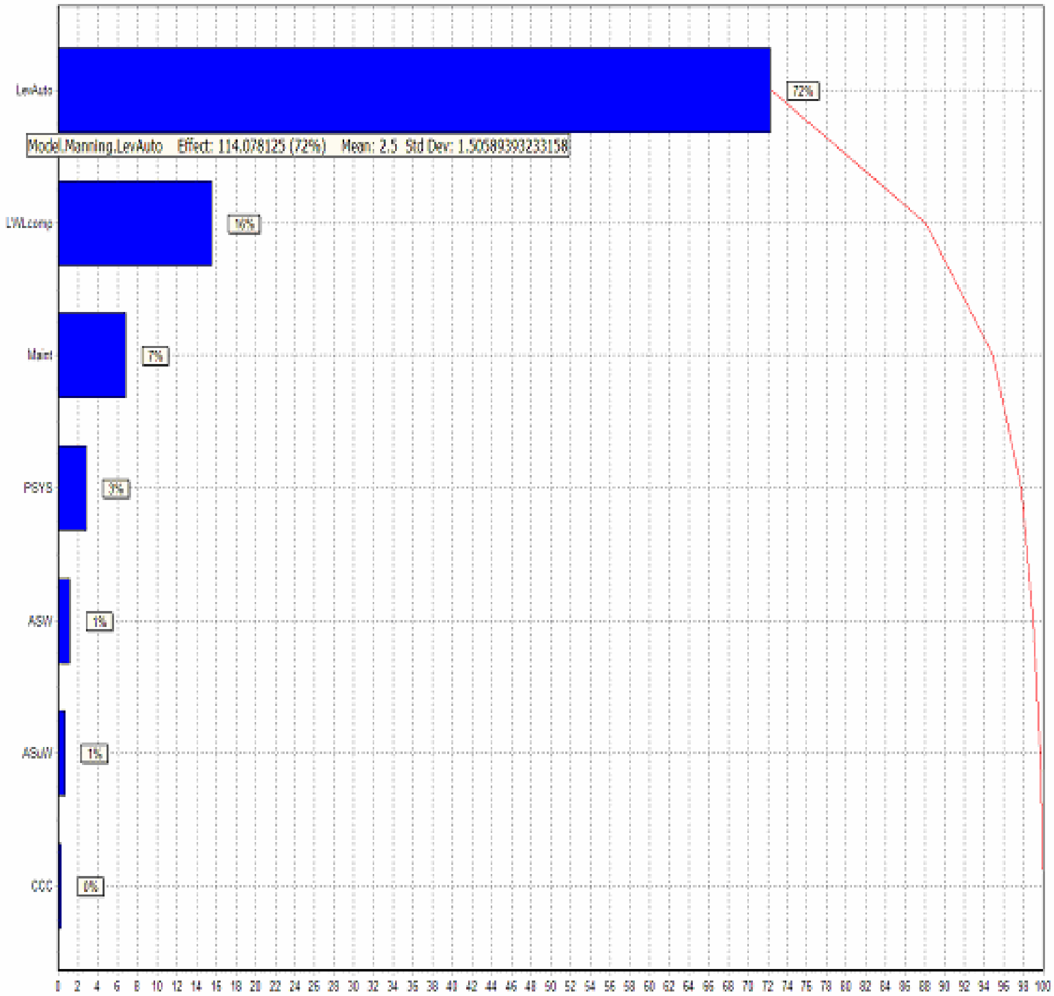


Figure 12 - Design Variable Effects

The level of automation has the largest impact on the size of the crew. This result is important because it quantitatively indicates that the level of automation is the largest driver in crew reduction.

A Design of Experiments (DOE) was also used in Model Center to create a data sample relating total crew size to the related input variables that are representative of the design space. This data is used to build a Response Surface Model (RSM) surrogate for the manning model. The full factorial method DOE in Model Center Design Explorer was used for this analysis. 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 Model Center. This equation is added to the ship synthesis model in Model Center to calculate manning for each design. A cubic stepwise regression is used. 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. Table 6 lists the statistical data for the RSM.

Table 6 – RSM Curve Fit Data

S	CoV	R-square	Adjusted R-square
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 SSM to calculate crew size for the CG(X) design options is a good approximation.

A 3-D plot of the RSM for Crew Size v. LevAuto and LWLComp is shown in Figure 13. 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.

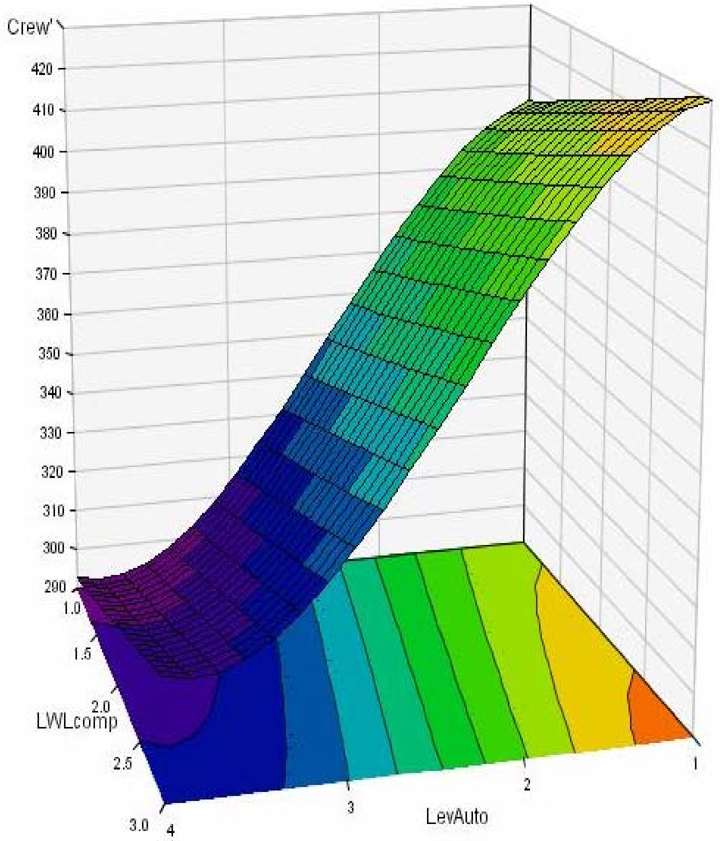
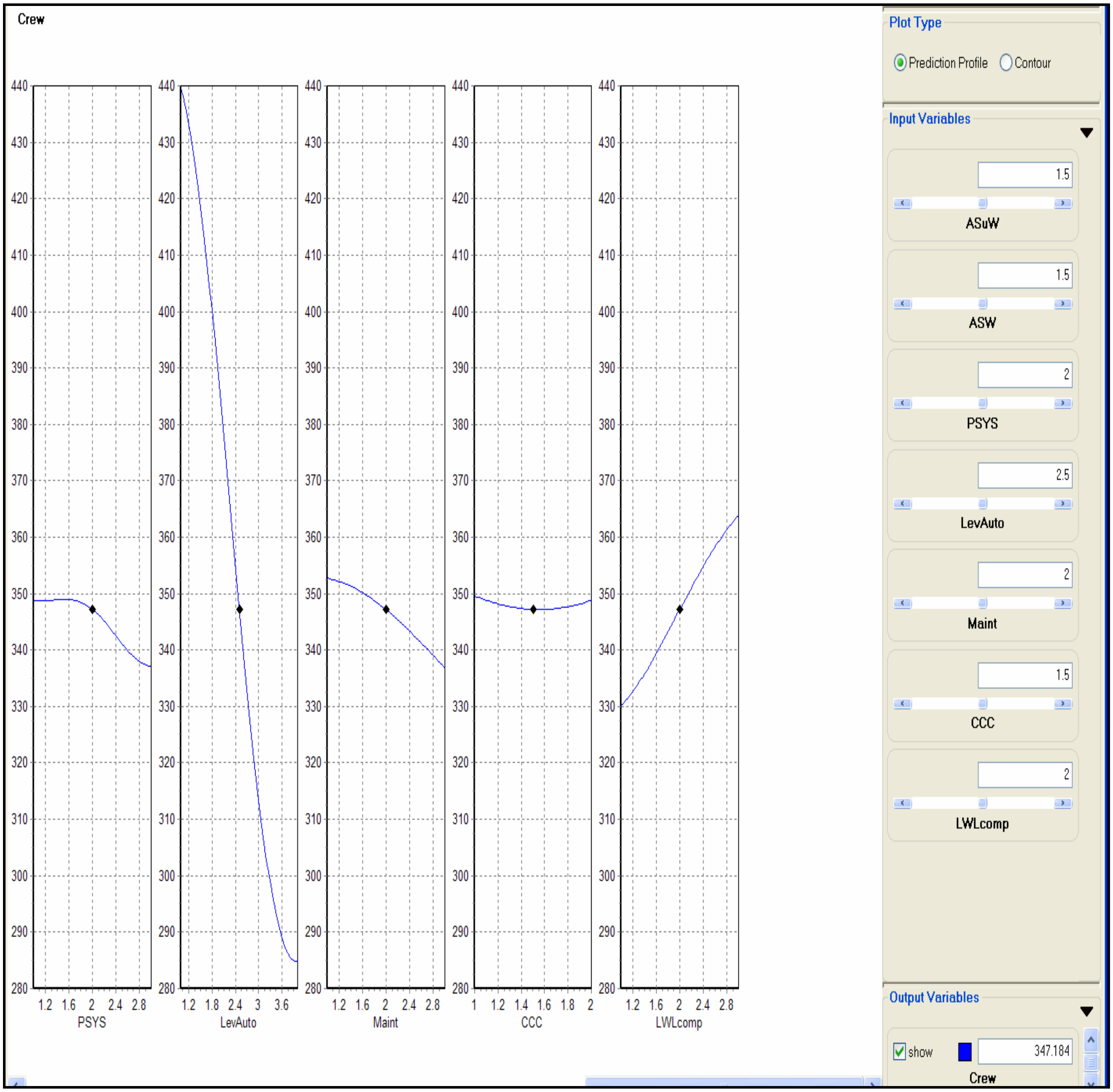


Figure 13 - RSM for Crew vs. LevAuto and LWLComp

Two dimensional plots are created to further analyze how variables used in the manning model effect crew size. Figure 14 displays the effect of propulsion (PSYS), level of automation (LevAuto), maintenance (MAINT), command, control, and communications (CCC), and length waterline (LWLComp) on crew size. 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.



Plot Type: ● Prediction Profile ○ Contour

Input Variables:
ASuW 1.5
ASW 1.5
PSYS 2
LevAuto 2.5
Maint 2
CCC 1.5
LWLcomp 2

Output Variables:
☑ show Crew 347.184

Figure 14 – Design Explorer Profile Predictor for Manning RSM

Within Model Center, there are two ways to implement the RSM. The first method is to write the RSM equation into one of the existing ship synthesis FORTRAN modules. 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 with an estimate of crew reduction due to automation. The RSM equation from the manning model replaces the existing equation to calculate manning. 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 Model Center (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 reduction factor (0.5-1.0) 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 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 model. The CMan variable used in the manning model is also included in the cost and risk modules because cost and risk are affected by manning and automation.

Once the old manning equation is replaced with the new RSM, the entire ship synthesis model is 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 the total ship design.

CASE STUDY

A design case study, Concept Exploration for an Air Superiority Cruiser, CG(X), was performed to demonstrate the manning model. Mission requirements and process were based on a similar design completed by undergraduate students in a two-semester ship design course at Virginia Tech [2-4,12]. This process is illustrated in Figure 15.

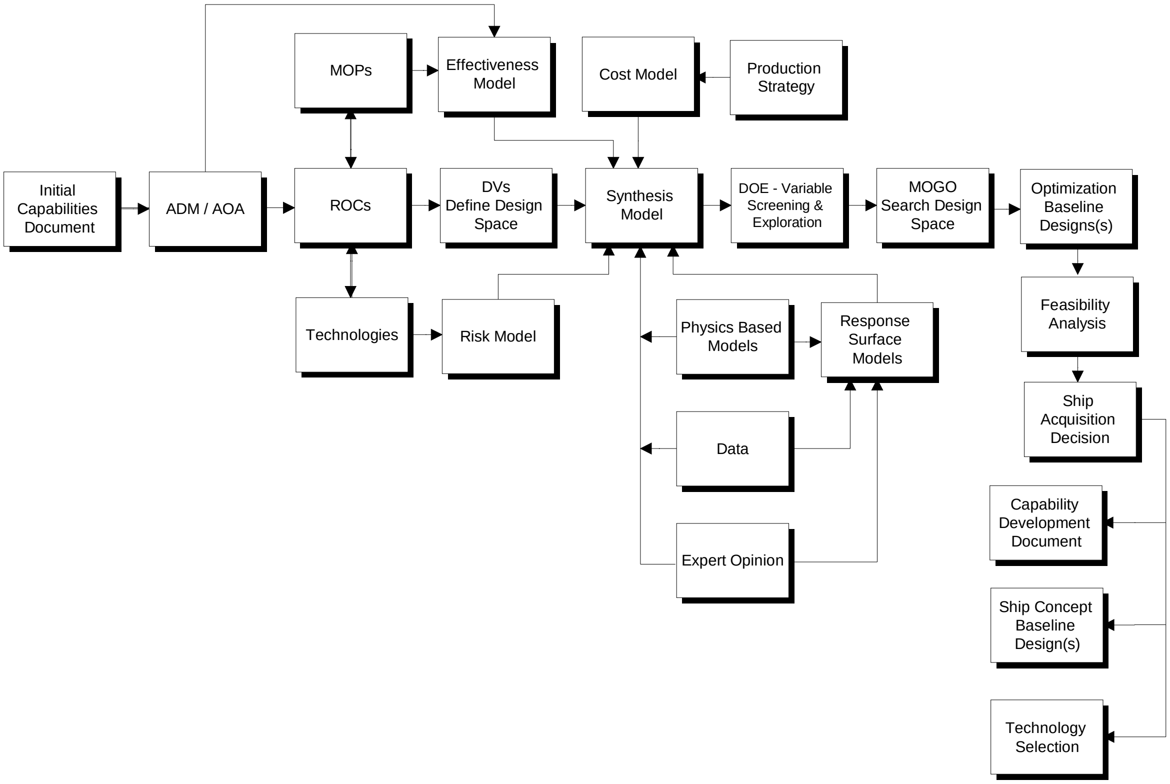


Figure 15 - Concept and Requirements Exploration [12]

This process does not begin by jumping into specific performance requirements or design characteristics. These should be products of concept exploration, not initiating constraints. Requirements and design characteristics cannot be rationally specified without a thorough understanding of their impact on total ship cost, risk and effectiveness.

The first step in this process is to develop a clear and precise mission definition and list of required operational and functional capabilities starting with a Initial Capabilities Document (ICD) and Acquisition Decision Memorandum (ADM). Refinement of the mission definition typically includes a Concept of Operations (CONOPs), Projected Operational Environment (POE) and threat, specific missions and mission scenarios, and Required Operational Capabilities (ROCs).

Next, the design space is defined using available or developing technology necessary to provide required capabilities. Concept Exploration need consider only those requirements and design parameters that have a significant impact on ship balance: military effectiveness, cost and risk. Cost, risk and effectiveness models must be developed consistent with mission requirements and the alternative technologies [13-17]. A ship synthesis model is used to balance the designs, assess feasibility and calculate cost, risk and effectiveness.

Finally, a multiple-objective genetic optimization (MOGO) is used to search the design space for non-dominated feasible designs using the synthesis and objective attribute models [2-4]. This optimization requires mathematically-defined objective functions for effectiveness, cost and risk. Mission effectiveness, cost and risk have different metrics and cannot logically be combined into a single objective attribute. Multiple objectives associated with a range of designs must be presented separately, but simultaneously, in a manageable format for trade-off and decision-making. There is no reason to pay or risk more for the same effectiveness or accept less effectiveness for the same cost or risk. Various combinations of ship features and dimensions yield designs of different effectiveness, cost and risk. Preferred designs must always be on the non-dominated frontier. The selection of a particular non-dominated design depends on the decision-maker's preference for cost, effectiveness and risk. This preference may be affected by the shape of the frontier and cannot be rationally determined a priori. Acquisition and life cycle cost are calculated using a modified weight-based cost model.

The CG(X) design space is shown in Table 7. Design variables that are used in the manning calculations are listed in ***bold italics***. A Design of Experiments (DOE) was conducted using only the manning model to obtain manning data for the design space of CG(X). Once this data was generated, a full quadratic Response Surface Model (RSM) was generated to fit this data. The equation for the RSM is:

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

The manning model calculates the total crew number required for the ship. This number contains both officers and enlisted crewmembers. This equation was added to the synthesis as described in the previous section. Variable effects in this equation are illustrated in Figure 14.

Finally the MOGO is run with the embedded surrogate manning model to find the non-dominated frontier (NDF) for CG(X). The NDF is analyzed and designs are chosen for further evaluation based on the customer's preference for cost, effectiveness, and risk. The non-dominated frontier is shown in Figure 16. The x-axis represents the follow-ship acquisition cost and the y-axis the Overall Measure of Effectiveness (OMOE). The color of the points corresponds to the level of risk for the design. Based on the NDF, a knee in the curve design is chosen for further evaluation. This design is highlighted in Figure 16. 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 and a significant increase below. The characteristics of this design are listed in Table 8.

Table 7 - 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***

Table 8 – Concept Exploration Baseline Design

Characteristic	Baseline Value
Hull form	flare = -10 deg
Δ (MT)	10697
LWL (m)	180.4
Beam (m)	18.5
Draft (m)	5.8
D10 (m)	13.1
Beam to Draft Ratio, C_{BT}	3.2
W1 (MT)	3999
W2 (MT)	955
W3 (MT)	322
W4 (MT)	668
W5 (MT)	54
W6 (MT)	1372
W7 (MT)	804
Lightship Δ (MT)	319
KG (m)	7.48
GM/B=	0.09
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	2x MK 110 57mm gun
CCC/STK/SEW	Enhanced CCC
GMLS	128 cells MK 41 and/or MK57 PVLS
LAMPS	LAMPS haven (flight deck)
Total Officers	25
Total Enlisted	325
Total Manning	350
Cman	0.65
OMOE	0.739
OMOR	0.586
Follow Ship Acquisition Cost	1.51 Billion

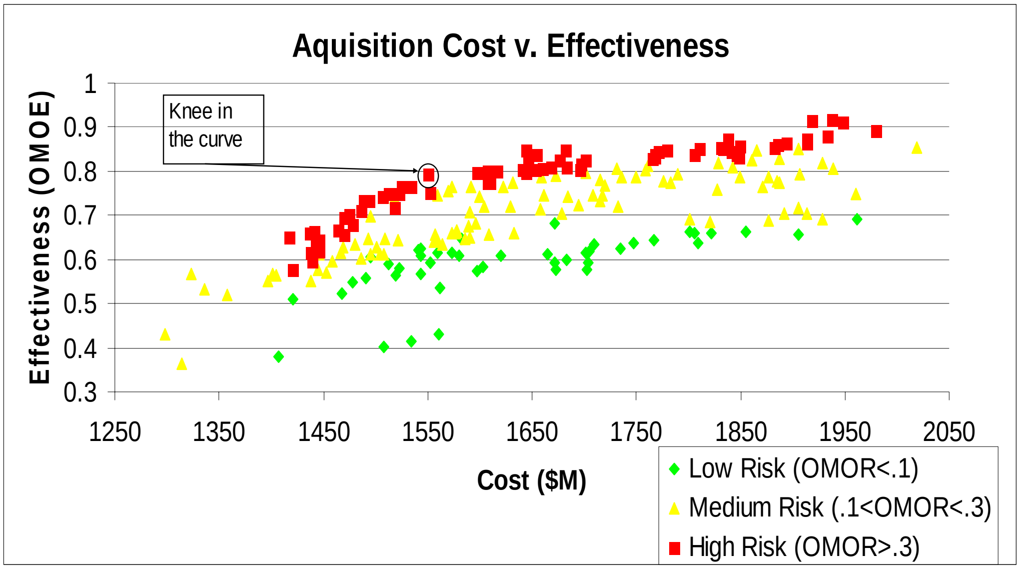


Figure 16 – Non-Dominated Frontier for CG(X)

Finally, the baseline design is further optimized with the single objective to minimize the cost by varying only continuous variables. 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 specified levels of automation. Figure 17 shows the resulting relationship between cost and automation.

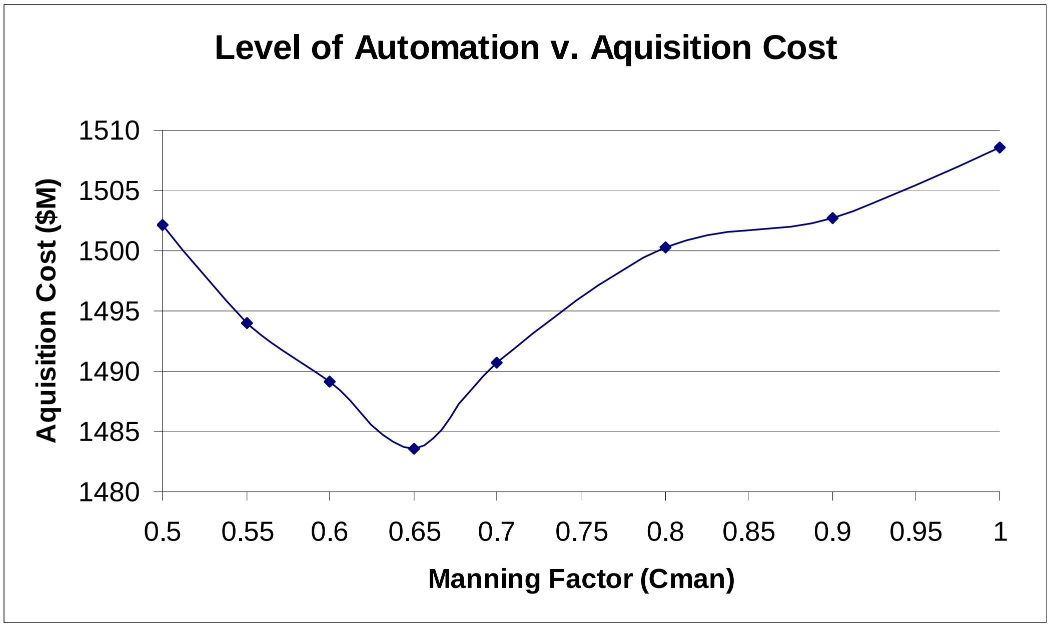


Figure 17 – Chart of Level of Automation v. Cost

The CMan factor of 1.0 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 8) 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.

CONCLUSIONS

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 13 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.

Figure 12 shows the dominant effects of the level of automation. Automation alone was able to change the crew size of a notional CG(x) by approximately 155 people. The next largest factor in determining crew size is the length of the ship (chosen metric for size). 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. The cost model and cost objective should be improved to consider total ownership cost including shore-based and infrastructure cost.

REFERENCES

1. *Military Personnel Navy - Action Needed to Optimize Ship Crew Size and Reduce Total Ownership Costs*, G.A. Office, Editor, GAO. p. 54, 2003.
2. Stepanchick, J. and Brown, A.J., *Revisiting DDGX / DDG-51 Concept Exploration, ASNE Day 2006.*
3. Brown, A.J. and J. Salcedo, *Multiple Objective Genetic Optimization in Naval Ship Design*, ASNE Day 2002.
4. Brown, A.J. and M. Thomas, *Reengineering the Naval Ship Concept Design Process*, in *From Research to Reality in Ship Systems Engineering Sympsium*, 1998.
5. Malone, T.B. *HSI Top-Down Requirements Analysis for Ship Manpower Reduction*, [Internet], cited 2004.
6. Ball, P., *Introduction to Discrete Event Simulation*, in *2nd DYCOMANS workshop on Management and Control: Tools in Action*, DYCOMANS: Algarve, Portugal, 1996.
7. Wetteland, C.R., et al, *The Human Simulation: Resolving Manning Issues Onboard DD21*, *2000 Winter Simuilation Conference*, 2000.
8. Bowen, S.A.M., C.R. Wetteland, and J. French, *The Total Crew Model (TCM): Using task network models to solve manning optimization issues,* Micro Analysis and Design, p. 1-12, 2005.
9. Wenger, T. and B. Plott, *Software User's Manual for the Integrated Simulation Mapower Analysis Tool (ISMAT),* Micro Analysis and Design, Inc. p. 1-237, 2005.
10. Salvendy, G., ed. *Handbook of Human Factors and Ergonomics,* 2 ed., A John Wiley & Sons, Inc: New York, 1997.

11. Endsley, M.R. and D.B. Kaber, *Level of automation effects on performance, situation awareness and workload in a dynamic control task*, Ergonomics, 42(3): p. 462-492, 1999.
12. CG(X) Design Report, Team 1 Undergraduate Ship Design Project, Virginia Tech Aerospace and Ocean Engineering, 2006.
13. Demko, Daniel, "Tools for Multi-Objective and Multi-Disciplinary Optimization in Naval Ship Design", MS Thesis, Department of Aerospace and Ocean Engineering, Virginia Tech, 2005.
14. Mierzwicki, T., "Risk Index for Multi-objective Design Optimization of Naval Ships", MS Thesis, Department of Aerospace and Ocean Engineering, Virginia Tech, 2003.
15. Mierzwicki, T., Brown, A.J., "Risk Metric for Multi-Objective Design of Naval Ships", *Naval Engineers Journal*, Vol. 116, No. 2, pp. 55-71, 2004.
16. Belton, V., "A comparison of the analytic hierarchy process and a simple multi-attribute value function", European Journal of Operational Research, 1986.
17. Saaty, T.L., *The Analytic Hierarchy Process*, RWS Publications, Pittsburgh, 1996.
18. Plott, B., Archer, S., White, D. "SMART Build 3 – A Simulation Tool for Assessing Job Skill Requirements" Micro Analysis and Design and NAVSEA Dahgren Division, p 1-6.

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