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# THESIS

**A SIMULATION ANALYSIS OF WORK BASED NAVY MANPOWER REQUIREMENTS**

by

Edward A. Carlton

September 2012


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**A SIMULATION ANALYSIS OF WORK BASED NAVY MANPOWER REQUIREMENTS**

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Submitted in partial fulfillment of the
requirements for the degree of

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# ABSTRACT

This thesis examines an alternative to current processes in use for developing enlisted manpower requirements aboard Navy surface ships. This research proposes a proof of concept for utilizing simulation in manpower requirements generation by examining data obtained from simulation models of the underway workload of two divisions aboard an Arleigh Burke-class destroyer. Given current manpower levels in CF and EA divisions, a mean work backlog of 1.449 tasks and 0.21 tasks, respectively, is observed when simulating a week of underway activity. The resulting data is then used to create a regression model with the amount of work backlog as a response variable. The predicted values of work backlog are then plotted against increasing division sizes to provide insight to manpower planners on possible effects of changing manpower requirement levels. The models generated indicate division personnel size and maintenance arrival rates are statistically significant in CF division and maintenance arrival rates and work times are significant in a model of EA division. This process supports the further use of simulation modeling when constructing ship manning documents for future ship classes.

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## LIST OF ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| AICc | Akaike Information Criteria (Corrected) |
| AMR | Auxiliary Machine Room |
| BA | Billets Authorized |
| CM | Corrective Maintenance |
| CNA | Center for Naval Analyses |
| COB | Current Onboard |
| CSOOW | Combat Systems Officer of the Watch |
| CUSFFC | Commander United States Fleet Forces Command |
| DDG | Guided Missile Destroyer |
| EDVR | Enlisted Data Verification Report |
| EOOW | Engineering Officer of the Watch |
| FM | Facilities Maintenance |
| FMRD | Fleet Manpower Requirements Determination |
| GAO | Government Accountability Office |
| MRPA | Make Ready/Put Away Allowance |
| MSS | Missile System Supervisor |
| NAVMAC | Navy Manpower Analysis Center |
| NEC | Navy Enlisted Classification |
| NMP | Navy Manning Plan |
| NMRS | Navy Manpower Requirements System |
| NOLH | Nearly Orthogonal Latin Hypercubes |
| NPS | Naval Postgraduate School |
| OARS | Open Architecture Retrieval System |

| | |
|---|---|
| OPNAV | Office of the Chief of Naval Operations |
| OUS | Own Unit Support |
| PA | Productivity Allowance |
| PM | Preventative Maintenance |
| PMS | Planned Maintenance System |
| POE | Projected Operational Environment |
| ROC | Required Operational Capability |
| RSC | Radar Systems Controller |
| SEED | Simulation Experiments and Efficient Design |
| SMD | Ship Manning Document |
| TAD | Temporary Assigned Duty |

# EXECUTIVE SUMMARY

Managing personnel costs is increasingly important for the military services. The Navy's agent for determining enlisted manpower requirements across the service is the Navy Manpower Analysis Center (NAVMAC), which conducts rigorous analysis of work requirements with the resulting total of man hours of workload being used to determine the total number of personnel requirements. Recent studies in the field of manpower requirements determination suggest some parts of the NAVMAC Fleet Manpower Requirements Determination process may be in need of revision. As a potential alternative, this thesis proposes the use of simulation to model the work requirements of a division aboard ship with the output data being used to formulate regression models that describe the behavior of a division in terms of work backlog. Specific models of CF and EA divisions aboard an Arleigh Burke-class destroyer are generated to illustrate the potential of this methodology.

The thesis employs the commercial simulation package Arena to develop the models in use. The models are composed of NAVMAC's standard areas of functional work, to include preventative maintenance, corrective maintenance, facilities maintenance, and own unit support. A number of system resources are available to the model, representing the different paygrades and Navy enlisted classification codes of sailors in each division. As work tasks arrive in the system following an underlying distribution (exponential in the case of CF division, Weibull in EA division), they seize resources, a process which represents sailors engaging in work. A sailor's work time follows a triangular distribution with variable minimum, mode, and maximum values.

In order to effectively study the output from the simulation models, a nearly orthogonal Latin hypercube (NOLH) experimental design approach is employed. The experimental design contains a number of factors for each division, including the arrival rate of corrective maintenance; as well as the minimum, mode, and maximum work times for corrective maintenance. Additionally, the amount of each type of sailor (represented by paygrade and NEC as stated above) is variable and are key input factors for this study. The response variables of interest in this simulation model include the amount of work

backlog in each type of work defined by NAVMAC, the scheduled utilization rate of sailors in the division, the total number of hours of preventative, and the total number of hours of corrective maintenance.

The simulation output analysis serves as a means of validating the underlying models; to ensure the models operate in a way that reasonably mimics reality. These data also provide information on the system and are presented from that perspective as well. The validation component of the results examines the output from three major areas: work backlog, sailor scheduled utilization rate, and the ratio of preventative maintenance to corrective maintenance. These areas are of interest to manpower planners and also inform the final piece of the analysis, the development of a metamodel that describes divisional work backlog as a function of the simulation input. The data show CF division with a mean work backlog of 1.449 tasks and EA division with a mean work backlog of 0.21 tasks. The model developed for CF division indicates the size of the division, the arrival rate of corrective maintenance, and the minimum corrective maintenance work time are statistically significant. This model has an adjusted $R^2$ value of 0.534. In the case of EA division, the parameters of the distribution used in modeling the arrival rate of corrective maintenance (the Weibull shape and scale parameters) and the maximum corrective maintenance work time are significant. The resulting model has an adjusted $R^2$ value of 0.841.

The models support the continued use of simulation in manpower requirements studies. Additionally, with further refinement, simulation and the resulting models may be used to develop manpower requirements documents for ship classes that are currently in construction or in the development phase. Also, manpower experts may wish to expand the simulation to also model the in-port workload of a ship, a subject where there is comparatively little data. Further research in this area is recommended and may be of significant value to the Navy manpower process.

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# I. INTRODUCTION

This thesis examines the problem of developing effective methods for determining manpower requirements aboard surface warships based on underway workloads. Broadly stated, the objective of this work is to examine currently employed assumptions used in determining enlisted manpower requirements. An additional objective is to investigate the possibility of using simulation output data to develop regression models to explain the amount of backlogged tasks in a ship's division's weekly work requirements. The development of such model is seen as important as it offers the possibility of lending insight into general behavior of divisions. This insight and the resulting models are then available to be used in the development of manpower documents for future ship classes or future flights of ship classes.

Effective documentation of manpower requirements is of significant importance to the Department of the Navy. As of the fiscal year 2012 budget request, personnel costs account for $46.6 billion of the Navy’s overall $161.4 billion request, roughly 29% of the total budget and the second largest expenditure behind Operations and Maintenance (Navy, 2011). It is thus of critical importance that the Navy have in place an effective and comprehensive methodology for determining which manpower requirements are valid for ensuring the safe and effective operation of the department’s ships, submarines, aircraft and shore facilities.

The Navy Manpower Analysis Center (NAVMAC) is designated as “the primary agent for determining Fleet manpower requirements… [working] in cooperation with cognizant Type Commanders and Warfighting Enterprises” (Navy, 2007). NAVMAC is also responsible for designing and executing appropriate studies that validate work requirements used to support overall Navy manpower requirements.

Current NAVMAC processes for determining manpower requirements rely on a process known as the Fleet Manpower Requirements Determination (FMRD). This process includes an explicit statement of the ratio of the amount of time spent on preventative, or planned, maintenance and corrective, or unplanned, maintenance. This thesis examines, via simulation, the effectiveness of NAVMAC's current FMRD process using the manning of CF and EA divisions aboard a Flight I Arleigh Burke Guided Missile Destroyer. The goal is to provide insight into the validity of NAVMAC's assumptions on the relationship between preventative and corrective maintenance. The thesis also explores the potential uses of simulation as a tool in the manpower determination process; in this case, by measuring work backlog as a result of varying manpower configurations in both CF and EA divisions.

## A. BACKGROUND

### 1. Manpower vs. Manning

Before proceeding further, it is necessary to highlight an important issue in any discussion of personnel issues: the distinction between manpower and manning. Manpower "equates to the personnel required to accomplish 100% of the work tasked to a unit, ship or staff in a wartime environment" (McGovern, 2003). By contrast, manning is best understood as a composition of billets authorized (BA), personnel assigned according to the Enlisted Data Verification Report (EDVR) and a specific unit's current onboard (COB). Figure 1 displays the relationship between Manpower and Manning.

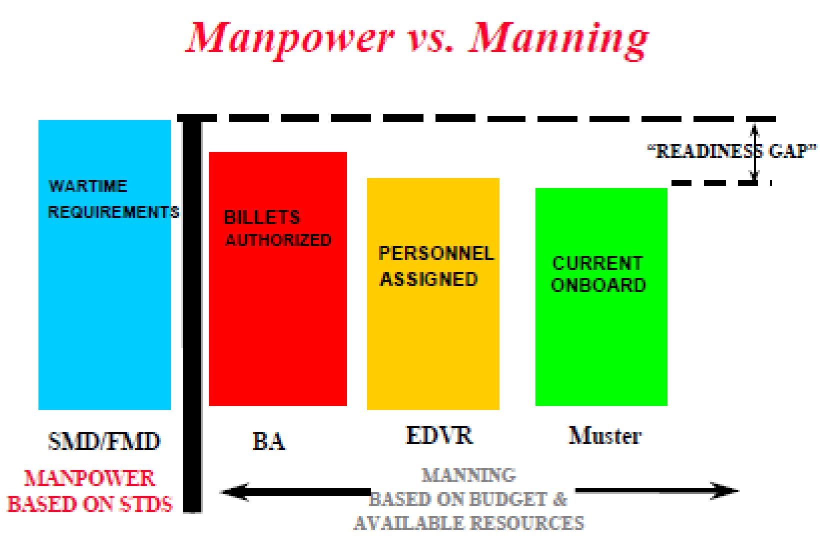


Figure 1. Relationship of manpower and manning levels in Navy units. From McGovern (2003)

Briefly stated, under the heading of manning, BA is best understood as the number of requirements the Navy has agreed to fund and remain within Congressionally mandated endstrength limits. The EDVR lists, by name, those personnel who have been assigned to a Navy unit. The number of personnel on the EDVR is a reflection of each unit's "fair share" of total Navy manning, referred to as Navy Manning Plan (NMP). Lastly, COB reflects the number of personnel that are actually present for work on a given day. This number may be less than NMP as a result of personnel who are assigned away from the command as a result of Temporary Assigned Duty (TAD) for example. In sum, the term "manning" is best understood to be a function of available fiscal resources and the amount of personnel who are actually in the Navy from year to year. The term "manpower is a function of workload" is determined through study and analysis of the needs of a Navy unit (McGovern, 2003).

### 2. Determining Workload Requirements

Afloat manpower requirements are documented in the form of a ship manning document (SMD). The most critical element used in formulation of an SMD is known as the Required Operational Capability/Projected Operational Environment (ROC/POE) instruction. Each surface ship class has its own ROC/POE instruction which serves to "spell out, in great detail, the purpose and capability of that asset" (McGovern, 2003). The missions that a ship is expected to perform and the environments in which it is expected to function have the greatest impact on the amount of manpower requirements generated for that vessel.

Using the ROC/POE instruction as a starting point, workload determinations can be generated beginning with operational, or watch station, manning. This refers to a station aboard the ship whose operation is essential to the proper functioning of the ship. It may vary as a result of different conditions of readiness aboard the ship; for example, a station may not need to be manned during normal underway steaming, but is manned continuously during general quarters, or the highest readiness condition.

Behind operational manning, maintenance is the most significant driver of manpower requirements. The category of maintenance is divided into three different components—preventative, corrective, and facilities maintenance. Preventative maintenance is defined as work accomplished in response to periodically scheduled preventative maintenance normally mandated by the Planned Maintenance System (PMS). Corrective maintenance is composed of any work that is accomplished on an unscheduled basis because of malfunction, failure or deterioration. Next, work that is directed toward the maintenance of the material condition of the ship falls under the category of facilities maintenance (McGovern, 2003). The amount of time required for preventative maintenance is documented in the PMS for a piece of equipment.

Predicting corrective maintenance times is an inherently difficult task, as it requires estimating the amount of time a task requires with very limited information available on the nature of the task. In order to handle this challenge, NAVMAC utilizes a fixed ratio between preventative maintenance and corrective maintenance, known as a PM:CM ratio. Current methodology is to use a 2:1 PM:CM ratio for hull/mechanical equipment and a 1:1 PM:CM ratio for electronics/electrical equipment (McGovern, 2003).

In the formulation of preventative maintenance and corrective maintenance, different factors are also included to represent how conducive the work environment is for task accomplishment, and the time necessary to prepare for accomplishment of preventative maintenance tasks. These factors are referred to as the Productivity Allowance (PA) and the Make Ready/Put Away Allowance (MRPA). MRPA is calculated as a flat 15% allowance of the PM task time and PA is a floating percentage from 2%–8% of the CM, FM and Own Unit Support (defined in the following paragraph) task times (McGovern, 2003). In this way, MRPA accounts for some variability in accomplishing preventative maintenance and PA is used to account for some of the variability inherent in corrective maintenance.

The last major work requirement used in determining total manpower requirements is defined as Own Unit Support (OUS). OUS work represents work done in support of the ship's mission, such as administrative tasks, food service, utility tasks and special evolutions. As this category covers such a broad range of work, it is necessarily the most complex category and significant attention is paid to properly documenting work in this category (McGovern, 2003). Figure 2 illustrates how all forms of work requirements combine to form a total workload that drives a unit's total workload, measured in man-hours.

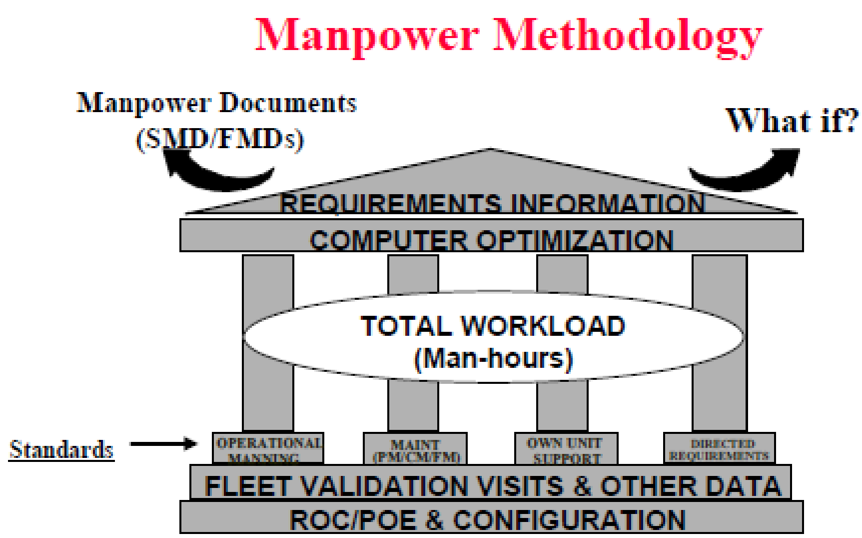


Figure 2. NAVMAC manpower methodology. From McGovern (2003)

Once all forms of work have been documented and the total workload derived, the Navy Standard Workweek Afloat is applied in a series of calculations that result in manpower requirements. The standard workweek is not an absolute figure and can be changed following analysis and decision by the Office of the Chief of Naval Operations (OPNAV) (GAO, 2010). The current workweek allots 70 hours a week of productive work to a sailor aboard an underway vessel. Of those 70 hours, 56 are set aside for watchstanding, or operational manning. This results in 14 hours a week available for other work, such as preventative and corrective maintenance. Figure 3 shows the current Navy Standard Workweek as defined by OPNAVINST 1000.16K, Navy Total Force Manpower Policies and Procedures.

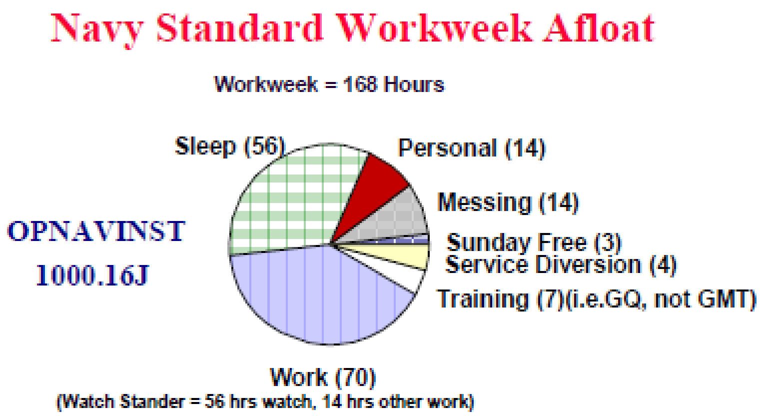


Figure 3. Breakdown of Navy Standard Workweek. From McGovern (2003)

## B. CURRENT ISSUES IN MANPOWER REQUIREMENTS DETERMINATION

### 1. Optimal Manning

The issue of manpower determination has the potential to become quite contentious, as shown most recently in the Navy's optimal manning initiative of 2001. The optimal manning initiative sought to reduce workload by "changing watchstanding requirements and more effectively using technology" aboard ships (GAO 2010). This process resulted in a 20% average decrease in the number of enlisted personnel required aboard all flights of DDGs from 2001 to 2009 (GAO 2010). Table 1 details the decreases in enlisted manning aboard cruisers and destroyers.

**Table 1: Changes in the Average Requirements, Authorized Positions, and Current Onboard Personnel for Guided-Missile Cruisers and Guided-Missile Destroyers from Fiscal Years 2001 to 2009**

| | Cruiser | | | | Destroyer | | | |
|---|---|---|---|---|---|---|---|---|
| | 2001 | 2009 | Average decrease | Percentage decrease | 2001 | 2009 | Average decrease | Percentage decrease |
| Average enlisted requirements | 383 | 301 | **82** | 21 | 324 | 259 | **65** | 20 |
| Average enlisted authorized positions | 345 | 295 | **50** | 14 | 292 | 251 | **41** | 14 |
| Average enlisted current onboard personnel[a] | 342 | 291 | **51** | 15 | 290 | 240 | **50** | 17 |

Source: GAO analysis of Navy data.

Table 1. Changes in Navy Manpower Requirements Aboard Cruisers and Destroyers from FY01 to FY09. From GAO (2010)

Then-Vice Chief of Naval Operations Admiral Jonathan Greenert announced in January 2011 that the optimal manning initiative was ending and manpower requirements would be increased aboard surface combatants. In making his announcement, the admiral noted "we've just taken too much risk in things like optimal manning and others and that's pretty well documented" (Fellman, *Navy Times*, January 11, 2011).

### 2. Recent Studies

In recent years, government and private consulting firms have conducted several studies with the specific intention of examining the validity of the Navy manpower requirements process. Both the Center for Naval Analyses (CNA) and the Government Accountability Office (GAO) have produced relevant documents on the subject, the highlights of which are reviewed briefly. Also, in 2009, a significant review of surface force readiness was conducted at the order of Commander, US Fleet Forces Command (CUSFFC). The results of this review, if adopted by the Navy, may have significant impacts on future manpower requirement generation procedures. Lastly, the issue of the validity maintenance ratios was the subject of a March 2011 thesis at NPS.

A 2002 CNA study entitled *Inside the Black Box: Assessing the Navy's Manpower Requirements Process* was produced to evaluate the methods by which the Navy determines enlisted shipboard manpower requirements. CNA concludes that the current process employed by NAVMAC, NMRS, "accomplishes the stated goals of establishing a credible basis for ship manning, assisting in the management of readiness and personnel, and validating workload". However, while the CNA study finds the assumptions that are used in producing the NMRS generated solution are valid; they may be in need of review and update, with particular attention being paid to the Navy Standard Workweek and workload allowances (PA and MRPA) which may not reflect current technological processes or the ability of currently serving personnel (Moore, 2002).

The CNA study is important also because it focuses on the current assumptions behind the manpower requirements process, particularly the productivity allowance and the Navy Standard Workweek. Regarding the productivity allowance, CNA notes that it is a generally accepted allowance in manpower studies and is normally composed of three allowances: personal, fatigue and delay. Further, the CNA report highlights that "experts say that delay allowances should be reviewed and changed periodically…to reflect organizational learning and technical change" (Moore, 2002). The Navy's productivity allowance was last revised in 2002. Changes in the PA have the potential to have significant effects in personnel costs—CNA notes, at the time of its study, that a 50% reduction in PA over three ship classes (DDG-51, LHD-1, and CVN-68 class vessels) could save $42 million in billets over the course of a year (Moore, 2002).

The Navy Standard Workweek is also the subject of greater discussion in the 2002 CNA study. At the time, the Navy Standard Workweek was 67 hours of productive work, with 56 of those hours being taken up by operational manning, or watchstanding. CNA analysis reveals that increasing the amount of productive work time to 71 hours would reduce required billets on the same three ship classes noted earlier by 766 for a yearly savings of $61 million (Moore, 2002). CNA also notes that "informative documentation" regarding the reasons behind changes to the Navy Standard Workweek prior to 2002 no longer exists.

A June 2010 GAO report entitled "Navy Needs to Reassess Its Metrics and Assumptions for Ship Crewing Requirements and Training" examines the effects of some of the changes to Navy manpower assumptions as a result of the optimal manning experiment mentioned earlier. While much of the report is not directly related to maintenance related requirements, the GAO notes that they "found no evidence that [recent changes] to the Navy's Manpower Requirements System model were based on the type of analysis required in the Navy's [instructions]" (GAO, 2010). Further analysis of the inputs used in personnel models as they relate to maintenance aboard Navy ships would doubtlessly be of value to future Navy manpower studies.

In the same timeframe as the GAO report, CUSFFC ordered a review of Navy-wide manning, training, equipping, and maintenance decisions in the past decade and their impact on the surface fleet. While not publicly released, the final report includes several conclusions regarding programmed manpower requirements, manning levels and their impact on maintenance accomplishment throughout the fleet. The *Navy Times* reports specific concerns in the report regarding readiness of the Aegis weapon system, to include the statement "the advanced radar systems aboard cruisers and destroyers are in their worst shape ever" (Ewing, *Navy Times*, July 5, 2010).

Additionally, *Navy Times* reporter Phil Ewing notes the CUSFFC ordered review is "a comprehensive indictment of Navy decision-making since the late 1990s" (Ewing, *Navy Times*, July 5, 2010). The report cites several procedural changes to the development of continuous maintenance availability (CMAV) work packages as contributing factors to degradations in material readiness. Further, shore based maintenance facilities have also undergone similar personnel cuts as described earlier, which may also be a factor in the challenges to material readiness in the surface fleet.

Lastly, the topic of modeling maintenance requirements using ratios was recently examined as part of an NPS thesis conducted by Lieutenants Martin Fajardo and Luz Ortiz. The authors examine changes to the Ship Manning Document for a DDG-51 class vessel as a result of data documenting actual corrective maintenance times. Specifically, they examine the PM:CM ratio across all flights of DDG-class ships in the same divisions as this thesis (CF and EA). Their analysis reveals an actual ratio of 1:10.9 for electrical systems and 1:1.64 for mechanical systems. This had the effect of increasing the required number of billets in EA division by as much as four sailors, or 50% of the division's authorized manning. In CF division, their analysis results in an increase in the required number of billets by as much as five sailors or 26% of the division's manning (Fajardo and Ruiz, 2011).

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# II. SIMULATION MODEL DEVELOPMENT

Having established the importance of employing effective manpower requirement determination processes, this thesis now turns to addressing the issue of developing a simulation model that serves as an effective alternative to current manpower processes. This chapter discusses the formulation of a simulation model that represents the functioning of a division's at-sea work.

## A. ARENA

The commercial software package Arena (version 13.9), developed by Rockwell Automation, is used to develop the models for this thesis. The software is built on the SIMAN simulation language and is based on object oriented design that allows the user to create a graphical model of the simulated system. After a user creates a model, Arena generates the appropriate SIMAN model used to conduct the simulations (Takus, 1997).

### 1. Terms in Arena

A brief discussion of the terms used in Arena as components of a simulation model is necessary before discussing the specific model development.

#### *a. Entities*

An entity in Arena may be thought of as the key "players" in a simulation. These items are dynamic and generally move through the system in some fashion, beginning with their creation and ending with their disposal when they leave the system (Kelton, 2007). Common examples of entities include parts in a manufacturing process that enter a system, have some work performed on them by a machine, and then leave the system when they are ready for another stage in the process or have been added to a larger item being created.

#### *b. Attributes*

Arena allows for attributes to be attached to each entity so as to individualize the entities. An attribute is similar to a tag on each entity that contains some information of importance as the entity moves through the system. They are also equivalent to local variables in traditional computer programming (Kelton, 2007). An example may be information on an object's priority or type of work required. This information can be accessed as the entity moves through the system allowing it to be routed to the correct machine or process.

***c. Variables***

In Arena, variables may more specifically be described as "global variables" and reflect some characteristic of the system. The information contained in this variable is independent from the number of entities or many characteristics of the system. Variables may be designed to be static throughout the simulation or dynamically updated as entities move through the system or the state of the system changes (Kelton, 2007). Some examples of variables include the amount of time a certain process takes or the number of people waiting in a queue for service.

***d. Resources***

Entities in an Arena simulation require some sort of service to be performed and this service almost universally requires the use of some sort of resource. In the model, an arriving entity competes for some use of available resources. Arena uses the terms "seize and release" to describe an entity using a quantity of resources. Dr. Kelton's book on simulations with Arena notes one is better advised to consider resources being "given" to an entity as an entity may require service from several different types of resources (Kelton, 2007). Examples of resources include manufacturing equipment or personnel to work such equipment.

***e. Events***

Kelton defines an event as "something that happens at an instant of (simulated) time that might change attributes, variables or statistical accumulators". Arena stores a history of scheduled events on an event calendar that is kept sorted by the next soonest event. As the simulation proceeds, the top record of the event calendar is removed and the programming logic is executed; part of which may require the addition of a new event somewhere on the event calendar (Kelton, 2007).

## B. MODEL DEVELOPMENT

The basic framework of the categories of work used by NAVMAC in its manpower analyses form the core of each model: operational manning (watchstanding), maintenance (corrective, preventative, and facilities), and own-unit support. This allows for a type of modular construction when building the model; each type of work lends itself to independent development while still fitting into the overall goal of modeling the work performed by a division aboard an Arleigh Burke-class DDG. Additionally, by building the simulation around each type of work, the simulation is more easily adaptable to other divisions. The basic framework of the model remains largely unchanged when shifting from modeling CF division to EA division.

Prior to discussing the interactions within the model, the definitions described earlier are used to highlight some of the basic characteristics of the model.

### 1. Entities

The main entities in this model are the basic types of work performed by sailors in a division. Arena does this to allow the system to model the generation of a task, its entry into the system, a sailor working the task and eventually completing the task. This also facilitates the collection of statistics on work created and accomplished. Table 2 lists the entities in the simulation along with a brief description of the entity.

| Entity Type | Description |
|---|---|
| CM Job | A corrective maintenance job. Work that represents unscheduled maintenance. |
| PM Job | A preventative maintenance job. Work that represents scheduled maintenance. |
| Watch | Operational Manning. A task (watch) that requires a sailor's undivided attention. |
| OUS Task | An own-unit support task. Work that is required to perform administrative and special tasks in support of the ship's mission. |
| FM Task | A facilities maintenance task. Work that is required to maintain the material condition of the ship. |

Table 2. Entities Used In Simulation Model. Descriptions from McGovern (2003)

### 2. Attributes

The model requires a relatively small number of attributes in order to track certain characteristics of the entities entering the system. The most important attribute in the design of the model is a "job type" attribute to allow for the system to differentiate between corrective maintenance and preventative maintenance. This allows for the system to properly route these types of maintenance through the division's manning and work structure.

### 3. Resources

The resources simulated in this model consist of the sailors assigned CF and EA divisions. Resources were identified by paygrade and Navy Enlisted Classification (NEC). Table 3 shows the resources (sailors) for CF and EA divisions.

| CF Division | EA Division |
|---|---|
| FCCS 1104 | ENC 4206 |
| FCC 1112 | EN1 4291 |
| FC1 1344 | EN2 4398 |
| FC1 1114 | EN2 4340 |
| FC1 1113 | EN3 4398 |
| FC1 1111 | EN3 4291 |
| FC2 1322 | ENFN 0000 |
| FC2 1114 | |
| FC2 1113 | |
| FC2 1111 | |
| FC3 1322 | |
| FC3 1144 | |
| FC3 1143 | |

Table 3. Resources (Sailors) available for CF and EA Division

### 4. Sets

One of the most useful features in Arena when designing a system with multiple processes was the set feature. Sets enable resources to be distributed into several functional areas that represent their needed functions in the system. For example, the FC3 1143 resource may be placed into one set for his/her workcenter, another set for his/her watchstation, and another for all members of the division in the paygrade of E-6 and below. This allows for the design of the model to be based around functional tasks. The alternative would require the model to be built with such detail that every process was tied to a specific resource. By contrast, the set feature allows for a general process to be modeled (e.g. preventative maintenance in one work center) and Arena seizes the resource from the set of all sailors capable of performing that type of maintenance according to one of a number of selection rules the user may choose to implement. Table 4 illustrates the sets used in the development of both models.

| Set Name | Description |
|---|---|
| CF01 | (CF Div only) All sailors in CF01 Workcenter |
| CF02 | (CF Div only) All sailors in CF02 Workcenter |
| CF03 | (CF Div only) All sailors in CF03 Workcenter |
| EA01 | (EA Div only) All sailors in EA01 Workcenter |
| Senior Leader | Personnel in paygrade E7 and above |
| E6 and Below | Personnel in paygrade E6 and below |
| CSOOW Watchstanders | (CF Div only) All sailors assigned to stand CSOOW watch |
| MSS Watchstanders | (CF Div only) All sailors assigned to stand MSS watch |
| RSC Watchstanders | (CF Div only) All sailors assigned to stand RSC watch |
| Display Repair Watchstanders | (CF Div only) All sailors assigned to stand Display Repair watch |
| Computer Operator Watchstanders | (CF Div only) All sailors assigned to stand Computer Operator watch |
| SPY Repair Watchstanders | (CF Div only) All sailors assigned to stand SPY Repair watch |
| EOOW Watchstanders | (EA Div only) All sailors assigned to stand EOOW |
| AMR Supervisor Watch | (EA Div only) All sailors assigned to stand AMR Supervisor |

Table 4. List of sets used in models of CF and EA Divisions

## C. MODEL ASSUMPTIONS

In constructing the model for this thesis, an important first step was the identification of assumptions used in the design of the simulation. Leaders in the field of simulation analysis acknowledge the importance of documenting assumptions during model creations. As a general rule, subject matter experts and decision makers should have the opportunity to review model assumptions and how the assumptions fit into the entire model at the outset of any study (Law, 2000). In that spirit, this section examines the major assumptions used in the formulation of this model.

The first series of assumptions relates to the relative importance of each type of work. A sailor's watchstanding duties are considered to be the most important work he/she is assigned. If a sailor is scheduled for a watch, he/she must stand that watch ahead of any other work requirements to include interrupting a currently assigned task. Amongst the other types of work (PM, CM, FM, and OUS), there is no precedence assigned.

The next set of major assumptions concerned the nature of sailors performing maintenance work. For purposes of this model, it was assumed that facilities maintenance work is performed by sailors in the pay grades E-6 and below. It seemed reasonable to assume that maintenance focused on preserving the material condition of the ship and a division's work spaces would not commonly be performed by senior enlisted personnel. Further, it was assumed that preventative maintenance was also only performed by sailors in the pay grade of E-6 and below. As preventative maintenance is executed in accordance with the Navy's Preventative Maintenance System, it occurs with a known periodicity and is conducted in accordance with a division's unique maintenance plan. Thus, the assumption was made that due to the predictable nature of preventative maintenance, the amount of time that a senior enlisted sailor would be called upon to perform this work would not be significant enough to change the model's outcome.

Turning to the case of corrective maintenance, the underlying assumption in the model is that all members of the division are able to perform this work and expected to do so if needed. Specifically, the normal technician on a piece of failed equipment is the ideal candidate to troubleshoot and repair the equipment. However, this may not be possible for a variety of reasons, at which point another technician in the division is sought out, to include turning to a senior leader in the division if needed.

The last assumption concerning specific types of work relates to OUS work. As mentioned earlier, OUS is a nebulous category of work and can often encompass a wide variety of work. In the case of both CF and EA divisions, OUS work is assumed to be split between senior leaders and E-6 and below sailors at a rate of approximately 70:30 percent. That is, an OUS task that arrives requires it be performed by a senior leader nearly 70% of the time.

Several assumptions were also made as to the nature of the arrival rates of corrective maintenance. As noted earlier, current NAVMAC methodology involves the use of ratios between preventative maintenance and corrective maintenance. For the purposes of this simulation and from the perspective of programming the simulation, corrective maintenance would need to be modeled as occurring as a result of an underlying probability distribution.

In the case of CF division, which performs work on the ship's AEGIS weapon system, virtually all of the division's assigned equipment is electric/electronic in nature. As such, the failure of CF division equipment is modeled using an exponential distribution. This distribution is especially appropriate given its suitability in modeling components of a system whose failure is not effected by the effect of wear (Devore, 2009).

In contrast to CF division, EA division performs work on many auxiliary mechanical systems aboard the ship, such as air conditioning plants, equipment for operating the ship's boats and many hotel service systems. As a result, in this simulation, the Weibull distribution is used to model the failure rate of equipment for EA division. This distribution is better suited to describing failure in mechanical systems that have components which may be more subject to the effects of wear and tear (Devore, 2009).

## D. MODEL CONSTRUCTION

### 1. Resource Scheduling

Prior to building the actual model, certain conventions in the model needed to be adopted to account for the fact that most sailors are responsible for 8 hours of operational manning, or watchstanding, in the course of a day at sea. Additionally, the Navy's governing instruction on manpower policies, states that the Navy Standard Workweek includes 8 hours of sleep a day (Navy, 2007).

To properly model this while also treating watchstanding time as inviolable in a sailor's schedule, each sailor (resource) is scheduled to be "unavailable" for either 8 or 16 hours a day, depending on whether or not the ship's manning document called for the sailor to be assigned a Condition III watchstation. If the sailor stands a normal underway watch, he/she is unavailable for 16 hours a day and unavailable for 8 hours if he/she does not have a Condition III watch. The remaining time in a day (either 16 or 8 hours) is considered time available for work. In the model, this has the effect of only making the sailor available to the system during these non-scheduled hours. Figure 4 shows an example of a sailor's schedule as built into Arena. The graph's x-axis represents the hours in a day and the y-axis represents the capacity available. In the case of a specific sailor, he/she has a capacity of one when available for work and zero otherwise, this is represented by the dark bars on the graph.

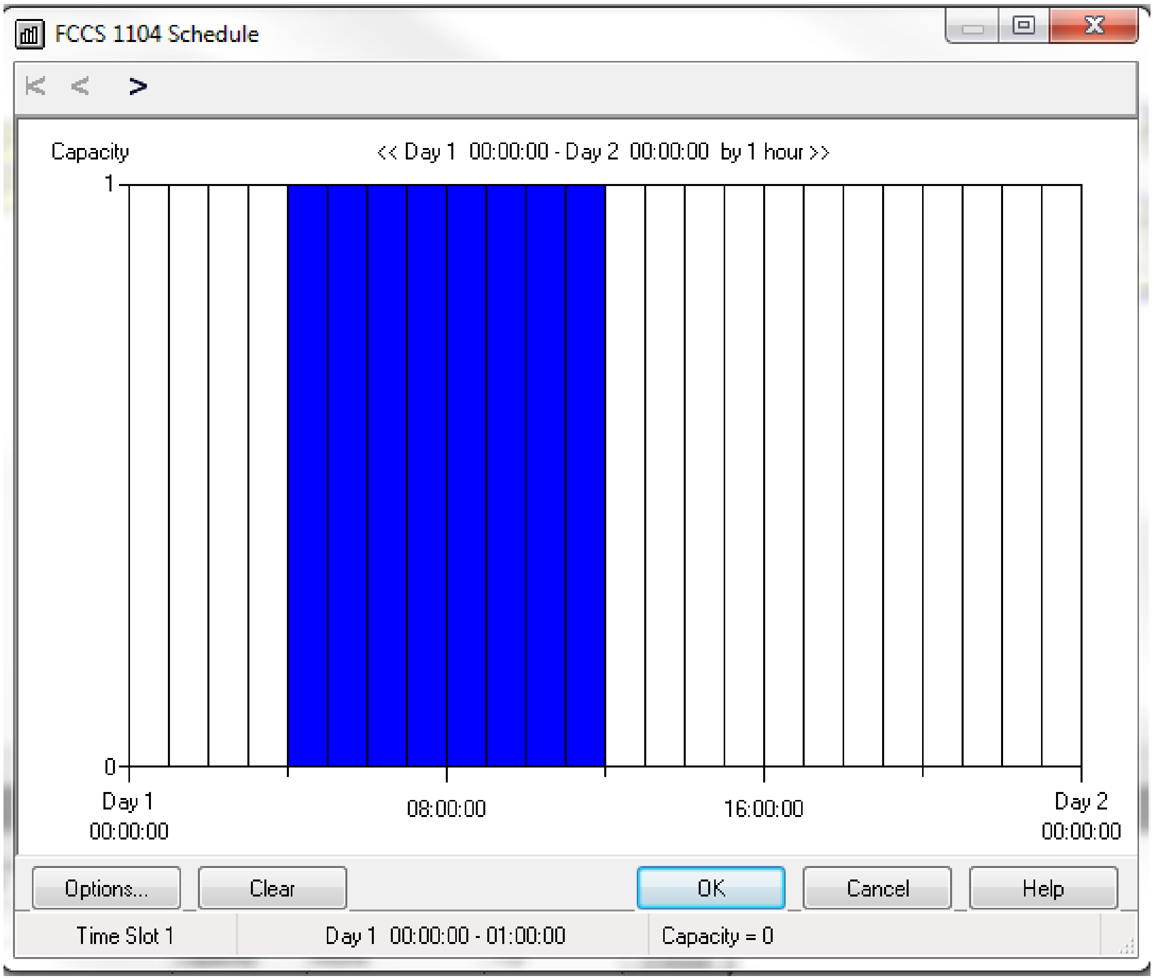


Figure 4. Example resource schedule as used in Arena's Schedule module

### 2. Preventative and Corrective Maintenance

The major system in the model relates to the execution of preventative and corrective maintenance requirements. The PM/CM section of the model is best viewed as being composed of four subsections. Each subsection is discussed in turn. Figure 5 shows the diagram of the entire PM/CM maintenance system and the breakdown of the subsection.

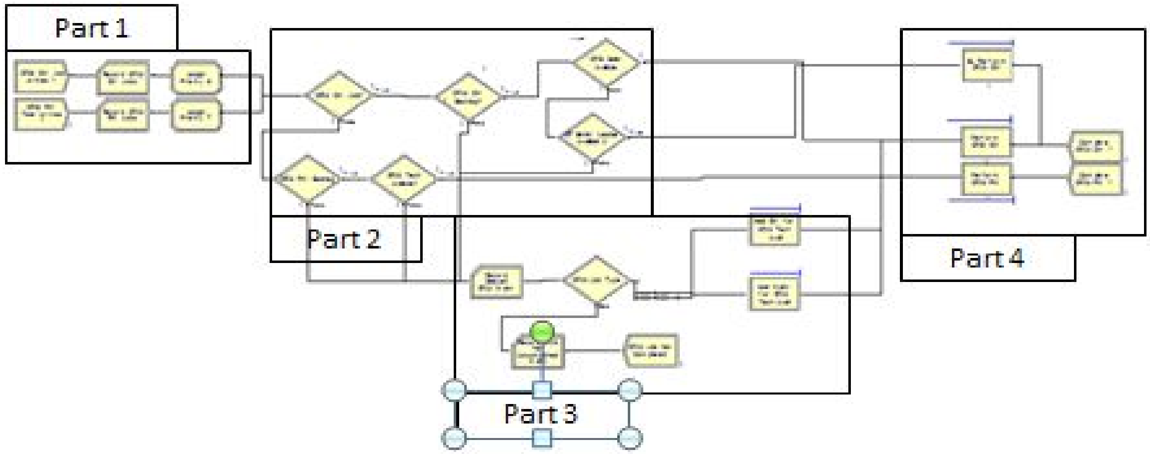


Figure 5. Model diagram of PM/CM system for one workcenter

In Part one, both preventative maintenance and corrective maintenance arrive into the system. Corrective maintenance arrives following an exponential distribution, in the case of CF division, with a variable arrival rate. In EA division, corrective maintenance arrives following a Weibull distribution, with variable shape and scale parameters. Preventative maintenance arrives at a constant rate based on the current PMS requirements for the division's equipment. Once each task arrives in the system, it is recorded by a module and then assigned an attribute that characterizes it as PM or CM. This attribute is used to ensure the maintenance task is properly routed through the system.

Part two of the PM/CM system begins the process of seeking out the correct sailor to perform the work. This is represented by the task moving through several decision nodes. These decision nodes are shown in greater detail in Figure 6. The maintenance task first is checked to see if it is CM work. If it is, the system then checks to see if there is are any CM tasks currently waiting to be accomplished. If not, the system then searches for a sailor to perform the maintenance, first checking for a technician then a senior leader level individual. If there is a CM backlog, the task is then sent to a holding queue where it is stored while the system checks for an available sailor. Once a sailor is available, the task is released from its holding queue and assigned for work.

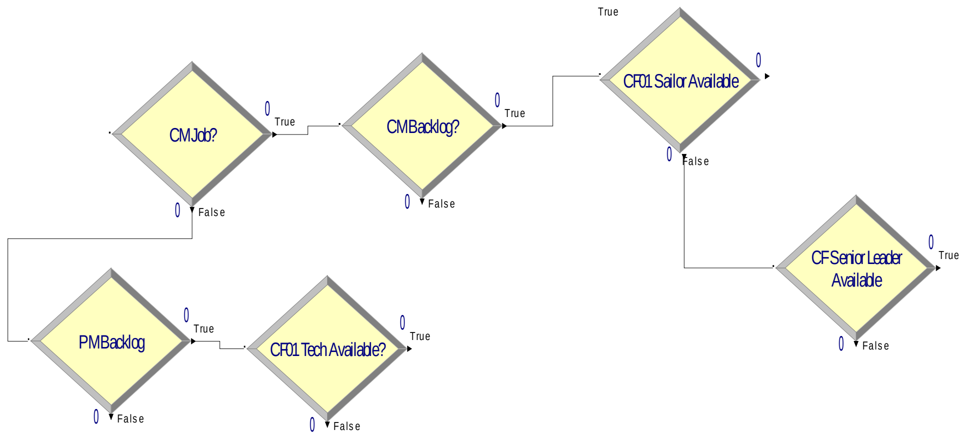


Figure 6. Wiring diagram of Phase 2 of PM/CM system

If the task is PM in nature, it is routed to a decision node that checks to see if there is a backlog of PM work. If not, the system then checks for a technician to perform the PM. As mentioned earlier, the system does not consider assigning a senior leader to a PM task. If there is a PM backlog, the task is routed to a similar holding queue as in the case of CM.

Phase three of the system consists of a module that records delayed maintenance in a counter and then stores it in a hold module. As mentioned previously, the hold module monitors the system regularly for an available sailor to whom the task can be assigned.

Phase four of the system contains the actual working of the maintenance, manifested in Arena's process modules. There are three different process modules through which a task may be completed. In the case of preventative maintenance, the task is sent through a "Perform PM" module in which a sailor is assigned to the task, the task is completed, the sailor is released for further assignment, and the task is disposed of by the Arena system. PM work time is accomplished following a triangular distribution which comes from the PMS system work times. In the case of CM, a task is routed to one of two modules depending on which type of sailor (technician or senior leader) is assigned to complete the maintenance.  CM work time is also randomly determined following a triangular distribution of varying minimum, mode, and maximum times. Work times are derived from the Open Architectural Retrieval System (OARS) which serves as a repository of fleet reported corrective maintenance actions.

### 3. Facilities Maintenance and Own-Unit Support

The implementation of the FM and OUS work systems is much more straight-forward than the PM/CM system.  Both of these systems are based on the idea that a task arrives randomly following an exponential distribution.  Also, in both cases, the task is then recorded as entering the system through an Arena record module.  Figure 7 displays the wiring diagram of the FM and OUS systems in the model.

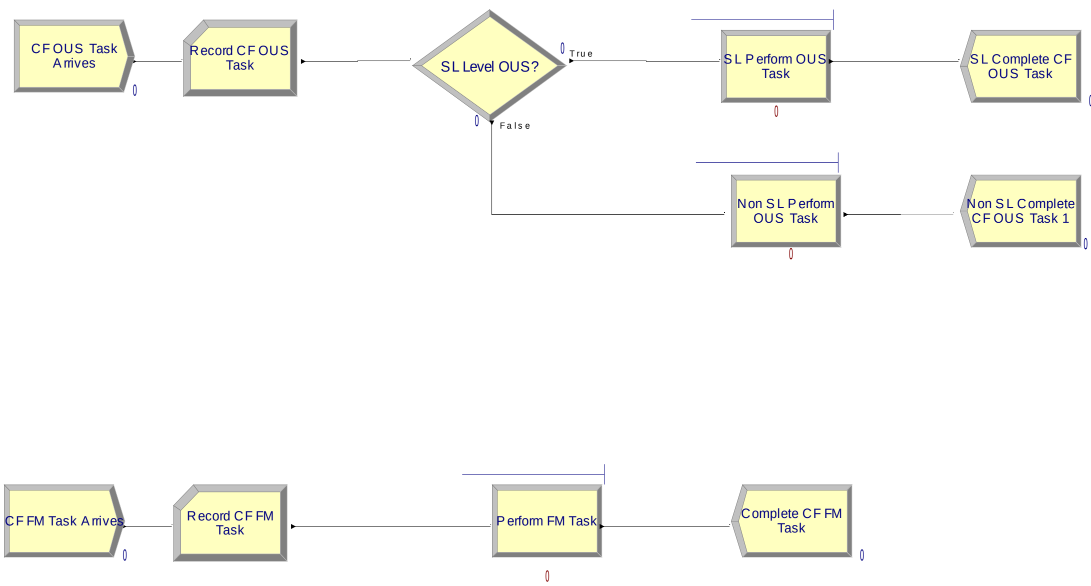


Figure 7. Model diagram of OUS and FM work

In the implementation of the FM work system, once the task has been recorded, it attempts to seize the necessary resource to complete the task.  As mentioned in the assumptions section, the task only attempts to seize a member of the E-6 and below set. When a resource is assigned to the task, the task is then completed with a work time following a triangular distribution with varying minimum, mode, and maximum values.

Once the task is complete, the seized resource is released for new tasking and the task leaves the system and its exit is recorded as a completed FM task by Arena.

In the case of the OUS system, after arriving, the OUS task then reaches a decision node which determines whether the needed resource comes from the Senior Leader set or the E-6 and below set. The decision is made as a result of chance with approximately 70% of entities entering the decision node resulting in the system returning a value of true. In this model, the value true is taken to mean that a member of the Senior Leader is required to complete the task. The value false thus represents that the task requires a member of the E-6 and below set to complete. Depending on the result of the decision node, the system attempts to seize the appropriate resource. After seizing a resource, the task is completed with a work time following a triangular distribution with varying minimum, mode, and maximum values. Once the task is complete, the seized resource is released for new tasking and the task leaves the system and its exit is recorded as a completed OUS task by Arena.

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# III. EXPERIMENTAL DESIGN

With the simulation model fully constructed, the next issue this thesis explores is the effective employment of the thesis model. Many theories exist on the best manner to use a simulation model, but virtually all agree that a systematic approach is preferred. To that end, this project follows a predetermined experimental design approach, which this chapter more fully explains.

## A. BACKGROUND

The subject of experimental design in simulation analysis is a complex one and this thesis does not attempt to break new ground on the subject. Nevertheless, a brief discussion of some of the background material in the field of design of experiments is of benefit in providing the context for the analysis done for this thesis.

Any simulation model contains a number of factors; that is, the "input parameters and structural assumptions" underlying a model. These factors are then varied to produce responses or "output performance measures." When constructing the simulation, the designer may consider the inclusion of certain factors that are either controllable or uncontrollable. Controllable factors are ones that represent real world changes to managers of the system being modeled; whereas, uncontrollable factors may affect the performance outcome of the simulation, but are not necessarily options readily available to be changed in the real world system (Law, 2000).

One method of conducting a simulation study is to simply create a list of varying configurations of factors and run them through the model and observe the changes in responses. While this process is of some value, it runs the risk of being more of a "hit or miss" type of approach which may result in flawed conclusions or increased inefficiencies caused by unnecessary use of resources in the simulation. By contrast, a properly constructed experimental design offers greater reliability in interpreting results as well as improved efficiencies (Law, 2000).

### 1. Nearly Orthogonal Latin Hypercubes

The Naval Postgraduate School's Simulation Experiments and Efficient Design (SEED) Center for Data Farming is responsible for a significant amount of recent research into the topic of experimental design. With a focus on developing efficient designs, much of their research (as seen in greater detail at http://harvest.nps.edu) has allowed for greater exploration of the merits of changing system inputs or policies while minimizing the amount of resources needed to acquire this data. One of the results of the SEED Center's research that this thesis uses is the development of Nearly Orthogonal Latin Hypercubes (NOLH) as a basis for an experimental design.

One of the challenges of creating an effective experimental design is that the number of design points can become very large very quickly. One of the easiest types of designs to construct and explain is the factorial, or gridded design. This type of design explores all possible combinations of factor levels. Factorial designs are traditionally denoted as $m^k$, where $k$ equals the number of factors to be investigated and $m$ is the number of levels for each factor (Sanchez, 2008). While this type of design is readily explainable and has the advantage of exploring every possible combination of factors, it is often difficult to execute, in terms of the amount of computing resources needed. For example, an experiment with 20 different factors to be explored at two levels for each factor would require over one million design points in full factorial experimental design. When considering multiple replications of each design point and the amount of time necessary to run a single iteration of a model, this type of design quickly becomes impractical.

Additionally, the factorial design examines design points at the corners of a hypercube by only exploring the low and high settings of factors. While this information is worthwhile, it fails to fully account for interaction between terms and may not give the level of detailed insight that is beneficial when factors can take on more than just two settings (Sanchez, 2008). To create a true space filling design (one that examines more than just the corners of the hypercube) frequently requires the large number of design points described earlier.

The challenge for the simulator is then to select an appropriate experimental design that offers reasonable space filling properties while also requiring a minimum amount of resources to execute. The NOLH design offers significant advantages in this respect. While the design does not fill the space the same way a full factorial design does, an NOLH offers the ability to explore a large number of factors with a much smaller number of design points (Sanchez, 2008). In the example listed previously where over one million design points were needed to examine 20 different factors at 2 levels, an NOLH design requires 129 design points—a task that is much more reasonable in terms of computational resources. Tables 5 and 6 display the data requirements for full factorial designs and NOLH designs, respectively.

| No. of factors | $10^k$ factorial | $5^k$ factorial | $2^k$ factorial |
|---|---|---|---|
| 1 | 10 | 5 | 2 |
| 2 | $10^2 = 100$ | $5^2 = 25$ | $2^2 = 4$ |
| 3 | $10^3 = 1,000$ | $5^3 = 125$ | $2^3 = 8$ |
| 5 | 100,000 | 3,125 | 32 |
| 10 | 10 billion | 9,765,625 | 1,024 |
| 20 | *don't even* | $9.5 \times 10^9$ | 1,048,576 |
| 40 | *think of it!* | $9.1 \times 10^{21}$ | $1.0 \times 10^9$ |

Table 5. Data requirements for full factorial designs (From Sanchez 2008).

| No. of Factors | No. of Design Points |
|---|---|
| 2–7 | 17 |
| 8–11 | 33 |
| 12–16 | 65 |
| 17–22 | 129 |
| 23–29 | 257 |

Table 6. Data requirements for NOLH designs (From Sanchez 2008).

The factors and responses listed in the following sections were used in developing an NOLH experimental design for this thesis.  NPS' SEED Center provides tools on its website that construct NOLH designs and those tools were used to create the design for both models (CF and EA division) in this thesis.

## B. FACTORS

In the two models created for this thesis, the factors consisted of each type of sailor in the division along with the parameters used in modeling the distribution of corrective maintenance times and the minimum, mode, and maximum CM work times. For the personnel factors, a quantity of 1 is the current number of each factor that appears in the ship manning document.  The experimental design was constructed assuming the Navy would have the option to either increase that quantity by one (double it) or remove it entirely, resulting in low and high levels of 0 and 2, respectively.  The low and high levels for the factors relating to CM arrival times and CM accomplishment rates came from the OARS data discussed earlier.  Table 7 lists the factors used in simulating CF division, along with their respective low and high levels.  Table 8 displays the same information for EA division.

| FACTOR NAME | LOW LEVEL | HIGH LEVEL |
|---|---|---|
| CM ARRIVAL RATE | 1.02 | 3.56 |
| MIN CM WORK TIME | 1 | 2 |
| MODE CM WORK TIME | 2 | 79 |
| MAX CM WORK TIME | 115 | 2000 |
| FCCS 1104 QTY | 0 | 2 |
| FCC 1112 QTY | 0 | 2 |
| FC1 1111 QTY | 0 | 2 |
| FC1 1114 QTY | 0 | 2 |
| FC1 1113 QTY | 0 | 2 |
| FC1 1344 QTY | 0 | 2 |
| FC2 1322 QTY | 0 | 2 |
| FC2 1114 QTY | 0 | 2 |
| FC2 1113 QTY | 0 | 2 |
| FC2 1111 QTY | 0 | 2 |
| FC3 1322 QTY | 0 | 2 |
| FC3 1144 QTY | 0 | 2 |
| FC3 1143 QTY | 0 | 2 |
| FC3 1119 QTY | 0 | 2 |
| FC2 1114 2 QTY | 0 | 2 |
| FC2 1113 2 QTY | 0 | 2 |
| FC3 1322 2 QTY | 0 | 2 |
| FC2 1111 2 QTY | 0 | 2 |
| FC3 1119 3 QTY | 0 | 2 |
| FC3 11192 2 QTY | 0 | 2 |
| FC3 1143 2 QTY | 0 | 2 |

Table 7. CF Division factors with low and high values

| FACTOR NAME | LOW LEVEL | HIGH LEVEL |
|---|---|---|
| CM MAINT ARRIVAL RATE SHAPE | 1.26 | 3.94 |
| CM MAINT ARRIVAL RATE SCALE | 0.703 | 1.04 |
| MIN CM WORK TIME | 1 | 2 |
| MODE CM WORK TIME | 2 | 40 |
| MAX CM WORK TIME | 51 | 1021 |
| ENC 4206 QTY | 0 | 2 |
| EN1 4291 QTY | 0 | 2 |
| EN2 4398 QTY | 0 | 2 |
| EN 4340 QTY | 0 | 2 |
| EN3 4398 QTY | 0 | 2 |
| EN3 4398 2 QTY | 0 | 2 |
| EN3 4291 QTY | 0 | 2 |
| ENFN 0000 QTY | 0 | 2 |
| ENFN 0000 2 QTY | 0 | 2 |

Table 8. EA Division factors with low and high levels.

## C. RESPONSES

The primary goals of this thesis are to examine the possible work backlog caused by changes in the number of sailors available for work in a division and to gain insight into the relationship between corrective maintenance and preventative maintenance times. As such, the response variables in this study all relate to measures of backlog of different types of work or the amount of hours spent engaged in a type of work. Table 9 contains the major response variables examined.

| |
|---|
| CM BACKLOG |
| PM BACKLOG |
| FM BACKLOG |
| OUS BACKLOG |
| TOTAL CM HOURS |
| TOTAL PM HOURS |
| CM WAIT TIME |
| FM WAIT TIME |
| OUS WAIT TIME |
| PM WAIT TIME |
| AVERAGE SAILOR SCHEDULED UTILIZATION |

Table 9. Major response variables for both CF and EA division simulations

## D. FINAL DESIGN

When all factors were entered into the SEED Center NOLH design generator, the resulting experiment contains 257 design points for CF division and 65 design points for EA division. The experimental design is run with 100 replications of each design point using Arena's built-in Process Analyzer, where each simulation run represents one week (seven days) of a division operating under at sea conditions. While 100 replications of each design point are relatively small for a simulation study, it is a great enough number to provide initial insight into the system. The Process Analyzer averages results over all replications of each design point and displays the results of specified responses. Figure 8 shows the basic set up of Arena's Process Analyzer.

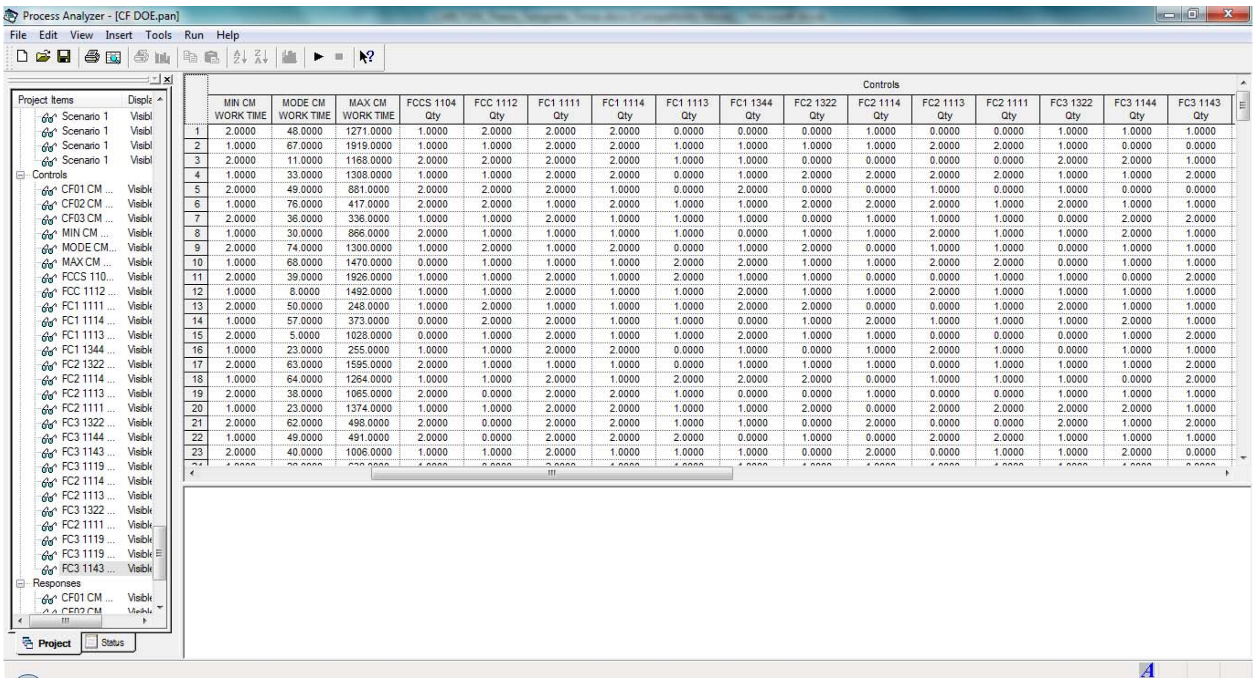



Figure 8. The Arena Process Analyzer as set up to run part of the designed experiment for CF division

# IV. RESULTS

The two simulation models are run separately and the results analyzed using the commercial software package JMP (version 9 Pro). The results for each division are discussed separately and includes discussion on observations regarding work backlog, sailor utilization rates, the PM:CM ratio observed, and lastly a discussion on attempts to fit a regression model to division behavior using work backlog as a response variable. While the information gained from a discussion of work backlog, sailor utilization rates, and PM:CM ratio is valuable, they are presented in this section for informational purposes but also to serve as a form of model validation. That is to say, the results displayed in those sections match what is expected from the real world system, indicating the model performs in an adequate manner at replicating reality.

The reader should note with particular attention the sections devoted to modeling divisional behavior. Development of effective models that explain a response variable of interest (in this case, number of backlogged tasks) offers a potentially invaluable tool for manpower planners. The process described in this thesis can thus be used as the basis to create models for use by manpower planners in constructing initial manning documents for ship classes yet to be built.

## A. CF DIVISION

The summary data for the response variables is listed in Table 10 and provides a starting point for a more detailed analysis. Backlog response variables represent quantity of tasks and wait times represent the average amount of time a type of task spent in backlog during the simulation run. Lastly, the average utilization is the average scheduled utilization rate of all the sailors in the division (defined to be the time average number of units of resources that are busy divided by the time average number of units of resources schedule) (Kelton, 2007).

| | Min | 1st Quarter | Median | Mean | 3rd Quarter | Max |
|---|---|---|---|---|---|---|
| PM BACKLOG | 0.002 | 0.131 | 0.376 | 0.9470505837 | 0.9425 | 8.966 |
| FM BACKLOG | 0 | 0.002 | 0.008 | 0.0263540856 | 0.0265 | 0.819 |
| OUS BACKLOG | 0.144 | 0.1955 | 0.366 | 0.5681206226 | 0.586 | 3.069 |
| TOTAL CM BACKLOG | 0 | 0.004 | 0.011 | 0.0443579767 | 0.032 | 0.627 |
| TOTAL CM HOURS | 12.702 | 41.5195 | 62.245 | 85.459023346 | 103.5905 | 420.481 |
| TOTAL PM HOURS | 79.406 | 170.052 | 180.724 | 175.08259144 | 189.0885 | 195.79 |
| CM WAIT TIME | 0 | 0 | 13.975 | 11.81170428 | 20.3705 | 37.83 |
| FM WAIT TIME | 0.143 | 0.743 | 0.949 | 1.0992023346 | 1.246 | 6.929 |
| OUS WAIT TIME | 1.092 | 3.0735 | 3.796 | 4.0380544747 | 4.976 | 9.331 |
| PM WAIT TIME | 2.067 | 2.875 | 3.556 | 3.8018715953 | 4.602 | 10.738 |
| AVERAGE UTILIZATION | 0.27248 | 0.4257431818 | 0.4932083333 | 0.5007265219 | 0.5625681818 | 0.8419166667 |
| TOTAL WORK BACKLOG | 0.153 | 0.4725 | 0.862 | 1.5858832685 | 1.6745 | 10.97 |

Table 10. Summary data of CF Division response variable results

### 1. Work Backlog

In examining the results further, the first point of discussion is the quantity of work backlog. JMP is used to present information regarding the distribution of data in the backlog of each type of work along with information on the distribution of the total number of tasks in backlog. Figure 9 shows the JMP output from this analysis.

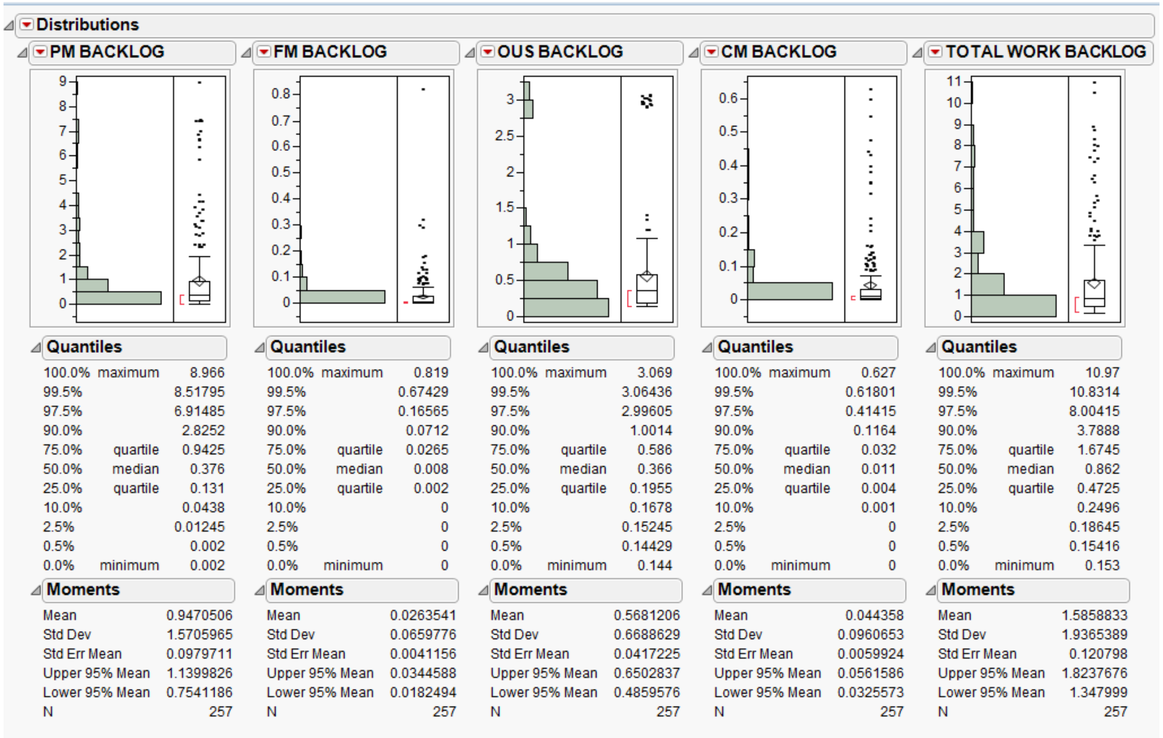



Figure 9. JMP output showing distribution of backlogged tasks in CF division

The first thing that is apparent from viewing the distribution of data is that over all simulation runs, the mean number of tasks in backlog status is approximately 1.6 with no single type of work having a mean backlog greater than 1. Additionally, with the exception of PM, the range of backlogged work is relatively narrow. Nonetheless, in the PM case, 90% of all observations contained no more than 2.8 tasks entering backlog. With only 10% of the observations resulting in backlogs ranging from 2.8–8.9 PM tasks in backlog, it is possible that result is an artifact of a unique simulation configuration and not necessarily indicative of a risk of a high number of PM tasks in backlog.

Taking the analysis one step further, the data are presented to examine the backlog as a result of division size. The graph in Figure 10 shows the amount of backlog for each type of work as a result of different division sizes. Division sizes are a result of the experimental design discussed previously. Further, the graph in Figure 11 shows the amount of total backlog at each division size along with box plots to lend greater insight to the data.

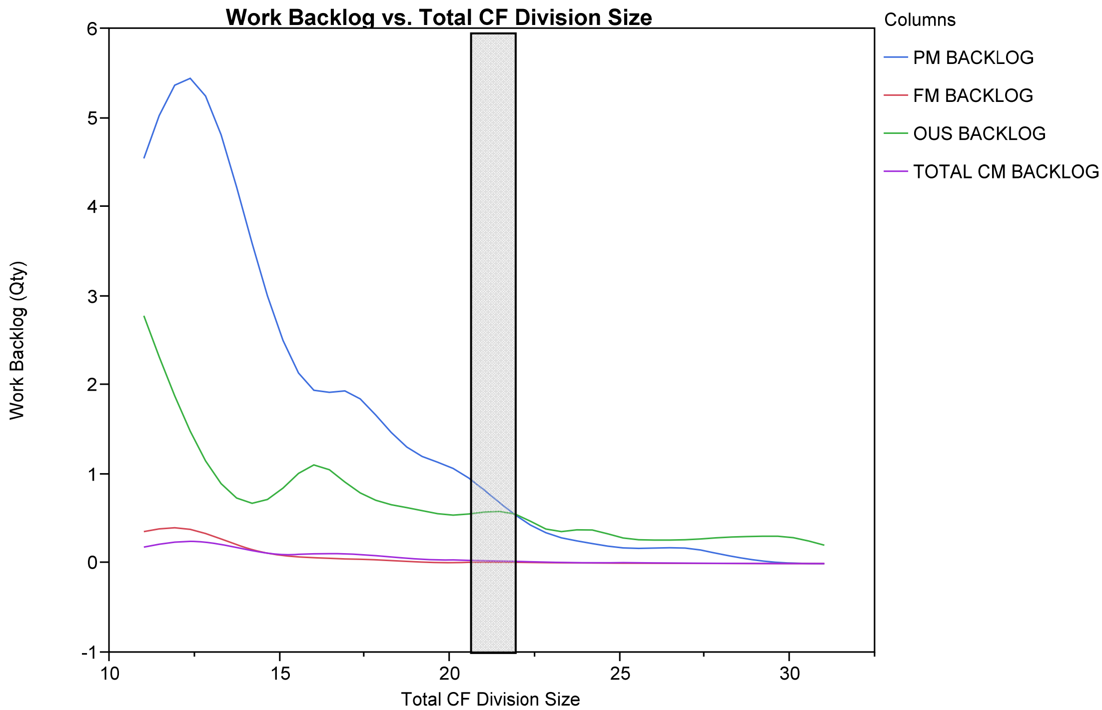



Figure 10. Work Backlog (of each type) vs. Total CF division Size (SMD authorized division size shaded above)

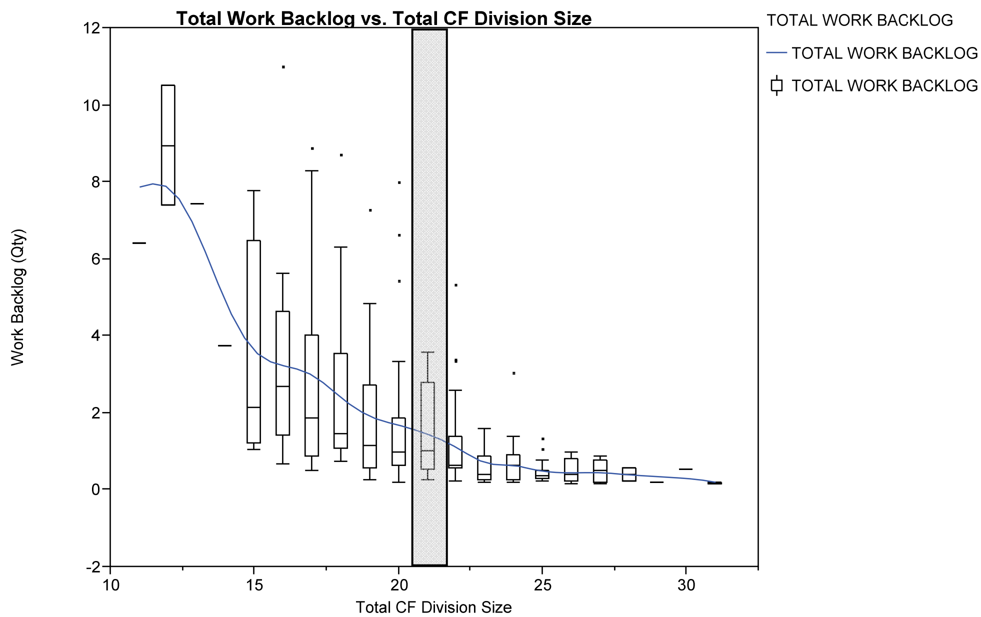



Figure 11. Total Work Backlog vs. Total CF division size (SMD authorized division size shaded above)

Current CF manpower requirements consist of 21 sailors, as stated in the DDG 51 Flight I Class Ship Manning Document (Navy, 2011). As a result, using a 95% confidence interval, at current manpower requirement levels, the confidence interval about the mean work backlog of 1.449 tasks is given by [1.01, 1.89]. This result appears to be a reasonable amount of work backlog accumulation in a week's time.

### 2. Sailor Utilization

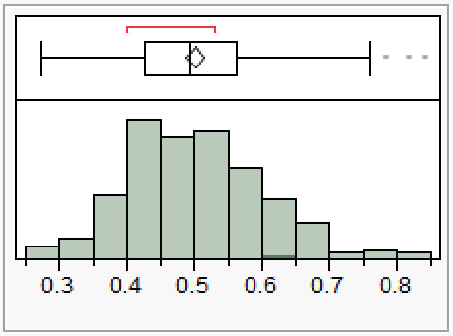
The next primary area to be discussed is the issue of sailor utilization. Much like work backlog, the scheduled utilization rate of resources (in this case, sailors) can be used to provide insight into the flexibility built into the system. A very low utilization rate may suggest an overmanned division -- there is not enough work to support the amount of requirements. Likewise, a high utilization rate gives rise to the possibility that the division is undermanned—there are not enough manpower requirements to support the amount of work that needs to be done.

By way of background, Kelton's Arena text makes note of two ways of measuring utilization: scheduled utilization and instantaneous utilization. Among other differences, instantaneous utilization considers time periods where a resource has a capacity of zero as having a utilization of zero (Kelton, 2007). Since the models in this thesis assume a sailor has certain hours that he or she is not available for work, scheduled utilization appears to be the more applicable measure of utilization than instantaneous utilization. Nevertheless, this section examines both types of utilization for insight.

Arena reports scheduled utilization rates for each entity in the simulation. In this model, every sailor was represented as a separate entity. In order to provide better insight to the system as a whole, the utilization rate was averaged over the number of sailors present in the division during each design point of the simulation. Figure 12 shows the distribution of the scheduled utilization rates and Figure 13 presents a box plot of the utilization rates for different total division sizes.

Distributions

AVERAGE SCHEDULED UTILIZATION




Quantiles

| | | |
|---|---|---|
| 100.0% | maximum | 0.84192 |
| 99.5% | | 0.83525 |
| 97.5% | | 0.72897 |
| 90.0% | | 0.63241 |
| 75.0% | quartile | 0.56257 |
| 50.0% | median | 0.49321 |
| 25.0% | quartile | 0.42574 |
| 10.0% | | 0.3782 |
| 2.5% | | 0.32642 |
| 0.5% | | 0.27601 |
| 0.0% | minimum | 0.27248 |

Moments

| | |
|---|---|
| Mean | 0.5007265 |
| Std Dev | 0.1005391 |
| Std Err Mean | 0.0062715 |
| Upper 95% Mean | 0.5130767 |
| Lower 95% Mean | 0.4883763 |
| N | 257 |

Figure 12. Distribution of average scheduled utilization results

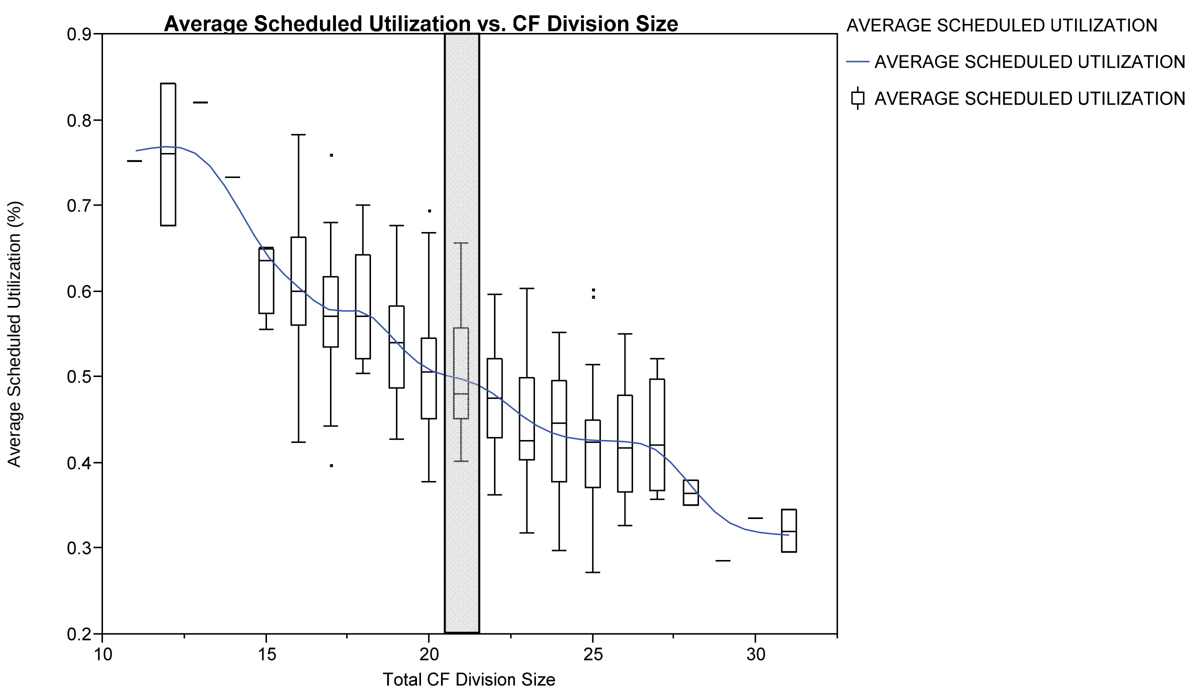



Figure 13. Scheduled Utlization Rate vs. CF division size (SMD authorized division size shaded above)

As expected, the sailor scheduled utilization rate appears to decrease as the division size increases. Also, the data are examined to see what insights can be offered regarding current manpower requirement levels. In the case of CF division's 21 sailors, the 95% confidence interval about the mean utilization rate of 0.499 (49.9%) is [0.47, 0.53]. Information regarding the worth of sailor utilization rates is difficult to quantify. Any answer depends on what level of utilization is considered "good" or "correct" by manpower planners. While the results observed in this case may appear somewhat low in that, at the current authorized division size, a sailor is only actively engaged in work approximately 50% of the time; this result may also indicate the division is sized at an appropriate level to allow flexibility for additional tasking or high levels of activity that may be encountered during an extended deployment.

Turning now to instantaneous utilization, JMP presents the data as the sum of total hours spent working on tasks (PM, CM, FM, or OUS) divided by the product of the number of sailors assigned to the division and the total number of hours a sailor is scheduled to work. Figure 14 presents the distribution of instantaneous utilization rates and Figure 15 illustrates this utilization rate at different division sizes.

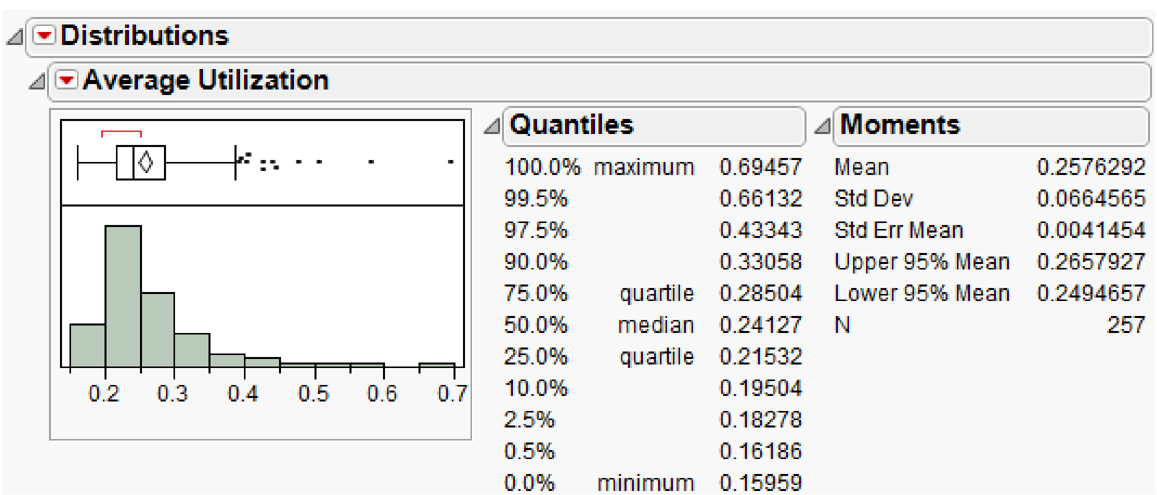



Figure 14. Distribution of CF division average utilization results and summary statistics

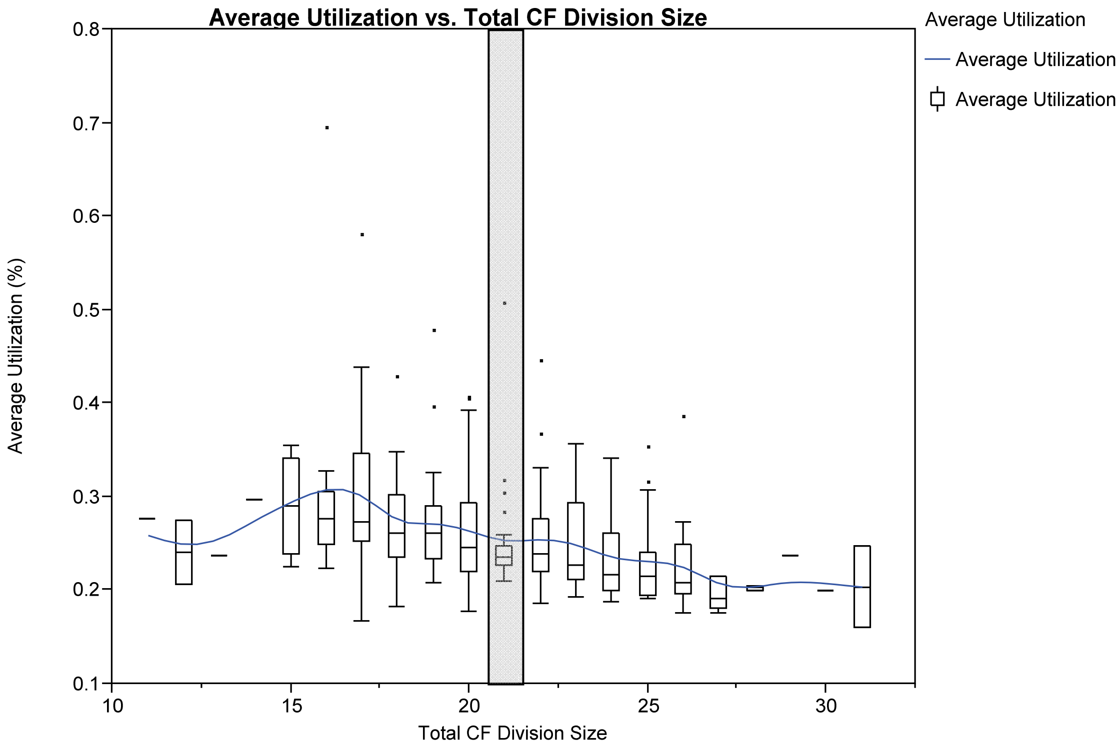



Figure 15. Average utilization vs. CF division size (SMD authorized division size shaded above)

The results as shown in Figures 14 and 15 yield a 95% confidence interval about the mean utilization rate (0.258 or 25.8%) of [0.249, 0.266]. This answer is notably different from the mean scheduled utilization rate of 0.5. This is likely a reflection of the fact that every member, except one, of CF division is responsible for standing a watch and thus has several hours of scheduled availability during which time they cannot accomplish any other work.

### 3. PM:CM Ratio

As stated previously, NAVMAC employs a fixed ratio to determine the number of CM hours in relation to the assigned hours of PM in a given division. This ratio is assumed to be 1:1 (PM:CM) for electronics/electrical equipment. CF Division works almost exclusively on such equipment, thus the data are examined in light of that ratio. Figure 16 shows the distribution of the CM and PM hours and other descriptive statistics generated from the data.

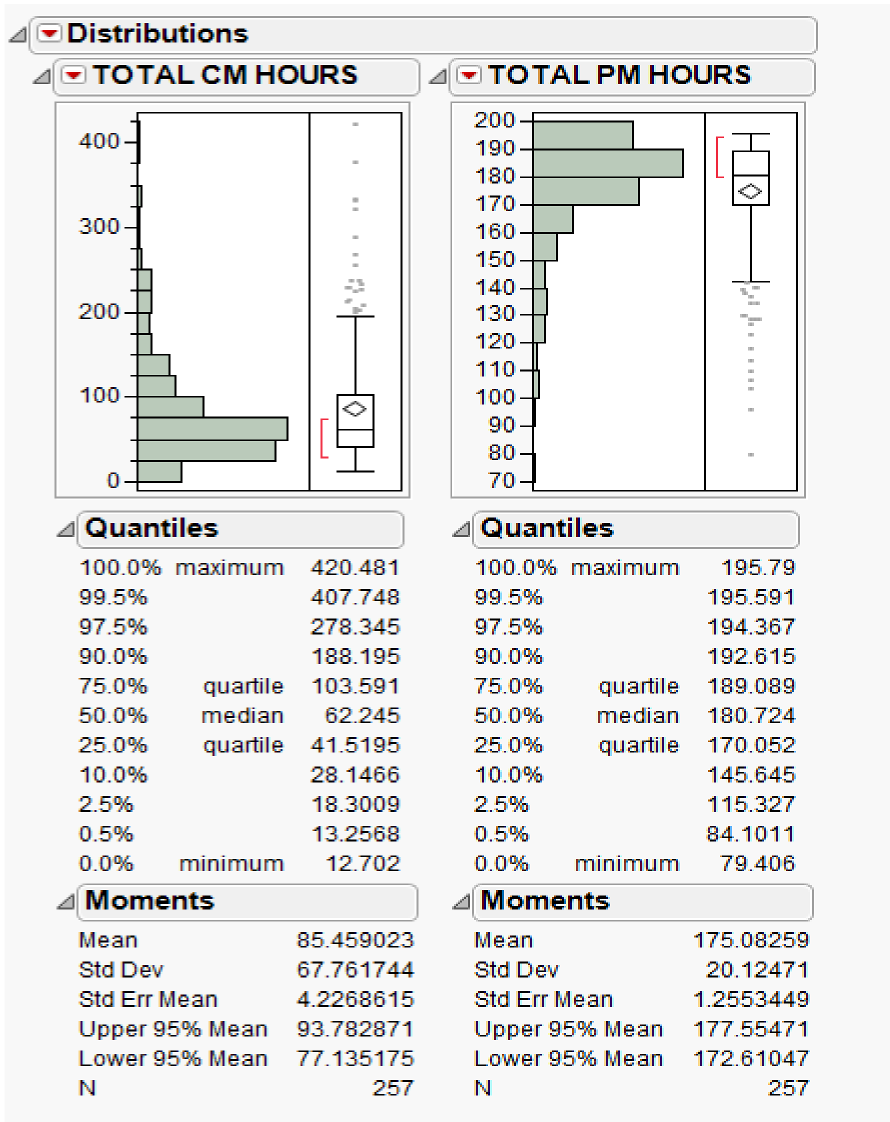
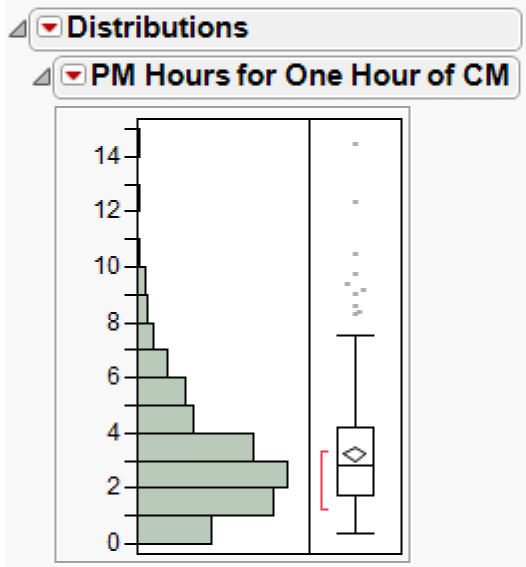



Figure 16. Distribution and summary statistics for CM and PM hours in CF division

In addition to presenting total hours of PM and CM in the simulation, JMP computes the number of hours of PM for every hour of CM. This variable represents the PM:CM ratio for each design point in the simulation. Figure 17 shows the distribution of this value and accompanying summary statistics.




**Quantiles**

| | | |
|---|---|---|
| 100.0% | maximum | 14.4358 |
| 99.5% | | 13.8212 |
| 97.5% | | 9.06277 |
| 90.0% | | 6.10412 |
| 75.0% | quartile | 4.19441 |
| 50.0% | median | 2.79911 |
| 25.0% | quartile | 1.71153 |
| 10.0% | | 0.94494 |
| 2.5% | | 0.59381 |
| 0.5% | | 0.41483 |
| 0.0% | minimum | 0.39151 |

**Moments**

| | |
|---|---|
| Mean | 3.2388309 |
| Std Dev | 2.1798524 |
| Std Err Mean | 0.1359755 |
| Upper 95% Mean | 3.5066038 |
| Lower 95% Mean | 2.9710579 |
| N | 257 |

Figure 17. Distribution and summary statistics of PM hours for one hour of CM in CF division

The results shown in Figure 17 indicate a mean ratio of 3.24 hours of PM for every hour of CM. Under the NAVMAC standard, one expects this value to be 1:1. Perhaps more importantly, the data show a range in values from 0.39 hours to 14.44

hours of PM for every hour of CM, with 90% of all cases having a value of less than 6.1 hours of PM for every hour of CM. This suggests the NAVMAC ratio of 1:1 may not be the most appropriate for electrical/electronic equipment or that the model may require further revision.

To further validate the model, the simulation output of the PM:CM ratio observed over all replications at the current manpower requirements level (21 sailors with each resource set to a value of one) is compared to PM:CM ratios available from OARS data. As an individual ship's maintenance record is the basis for OARS data, a PM:CM ratio from the simulation that is at or near the mean PM:CM ratio across the ship class suggests the model is performing adequately. Figure 18 displays the distribution of PM:CM ratios across the DDG FLT I class.

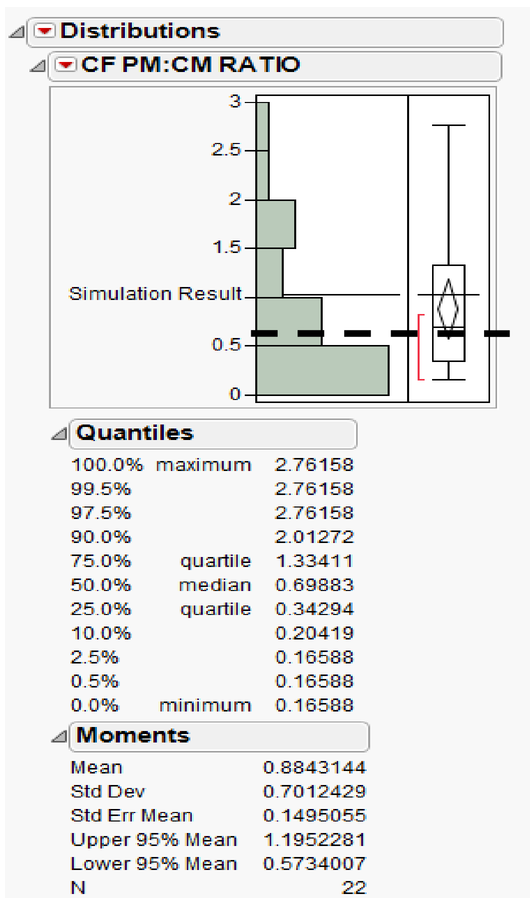



Figure 18. Distribution of CF division PM:CM ratio across all ships of the DDG FLT I class and accompanying summary statistics

With the manpower levels fixed at current authorized levels, the only remaining variable factors in the simulation are the CM arrival rate and the CM work minimum, mode, and maximum work times. With small changes to these values, the simulation yields an average PM:CM ratio at the current manpower level of 1.03:1 (as highlighted in Figure 18), very nearly 1:1. This value is also near the mean class average of 0.89:1. Thus, after making slight adjustments to the factors other than personnel levels, it is reasonable to conclude the model is performing adequately.

### 4. Modeling Divisional Behavior

The last major goal when examining the simulation results is an attempt to fit the data to a model using work backlog as a response variable. JMP's stepwise regression feature is used to select the best model according to a minimum Akaike information criteria (AIC) selection rule. Initial attempts at model construction reveals the model residuals do not appear to have a constant variance. To correct for this, the work backlog variable is logarithmically transformed, resulting in a regression of log(work backlog) against the resulting model parameters as shown in Figure 19. Model summary statistics are shown in Figure 20. Candidate models included all main effects, two way interactions, and quadratic terms.

**Parameter Estimates**

| Term | Estimate | Std Error | t Ratio | Prob>\|t\| |
|---|---|---|---|---|
| Intercept | 5.2404055 | 0.330579 | 15.85 | <.0001* |
| CM ARRIVAL RATE | -0.470079 | 0.057902 | -8.12 | <.0001* |
| MIN CM WORK TIME | -0.131087 | 0.08516 | -1.54 | 0.1250 |
| TOTAL DIVISION SIZE | -0.191387 | 0.012656 | -15.12 | <.0001* |
| (CM ARRIVAL RATE-2.29004)*(MIN CM WORK TIME-1.50195) | -0.180351 | 0.115995 | -1.55 | 0.1212 |
| (CM ARRIVAL RATE-2.29004)*(TOTAL DIVISION SIZE-21.0817) | 0.0042897 | 0.017539 | 0.24 | 0.8070 |

Figure 19. Regression model estimates of log(work backlog) in CF Division

**Summary of Fit**

| | |
|---|---|
| RSquare | 0.543213 |
| RSquare Adj | 0.534114 |
| Root Mean Square Error | 0.68219 |
| Mean of Response | -0.06623 |
| Observations (or Sum Wgts) | 257 |

Figure 20. CF division model summary

The model's residuals are examined to ensure they meet the requirements of constant variance and normality in the distribution of the residuals. Figure 21 shows the constant variance of the residuals and Figure 22 shows the distribution of the residuals and a normal quantile plot of the residuals.

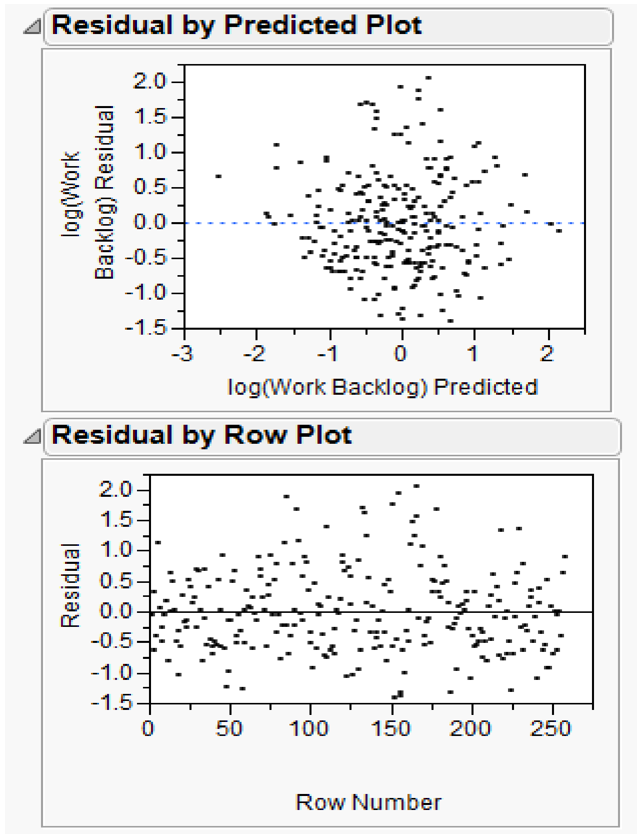



Figure 21. CF division model residual by predicted plot and residual by row plot

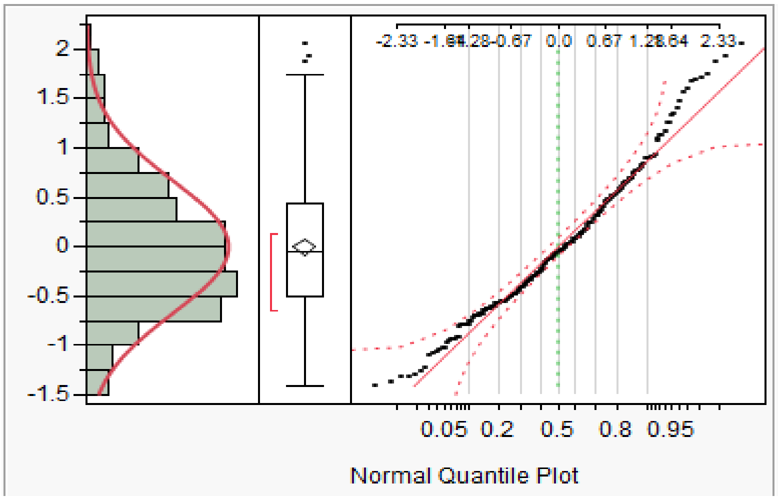



Figure 22. Distribution of CF division model residuals and normal quantile plot of residuals

The normal quantile plot in Figure 22 indicates the model residuals are approximately normally distributed. While the data in the tails seems to diverge slightly from a normal distribution, this is not significant enough to call into question the assumption of residuals being normally distributed.

With the model validity tests showing the key regression assumptions are met, the model estimates from Figure 19 are examined to determine what insights are offered. The first point to note is the model concluded that the significant factors for determining work backlog consist of the rate at which CM arrives, the minimum CM work time, and divisional size. Also included in the model are the interaction between CM arrival rate and minimum CM work time and the interaction between CM arrival rate and division size. This seems to make a certain amount of intuitive sense. The rate at which corrective maintenance arrives determines the number of instances of equipment breakdown that are observed. The minimum CM work time is important in determining the least amount of time a sailor is occupied with CM work. Also, division size is clearly connected to work backlog; a larger division has more available sailors for work and is less likely to experience tasks going into backlog. The signs of the parameter estimates are also in line with the expected outcome, most notably in the area of CM arrival rate and division size. Both of these parameters are negative, suggesting, as noted earlier, a higher division size will decrease the amount of backlogged tasks. A higher arrival rate also suggests less backlogged tasks, as the arrival rate is the parameter used in describing the exponential distribution underlying equipment breakdown. Thus, a higher arrival rate actually indicates a greater period of time between breakdowns and generation of a CM work requirement.

Finally, a plot of predicted work backlog values is created and presented in Figure 23.

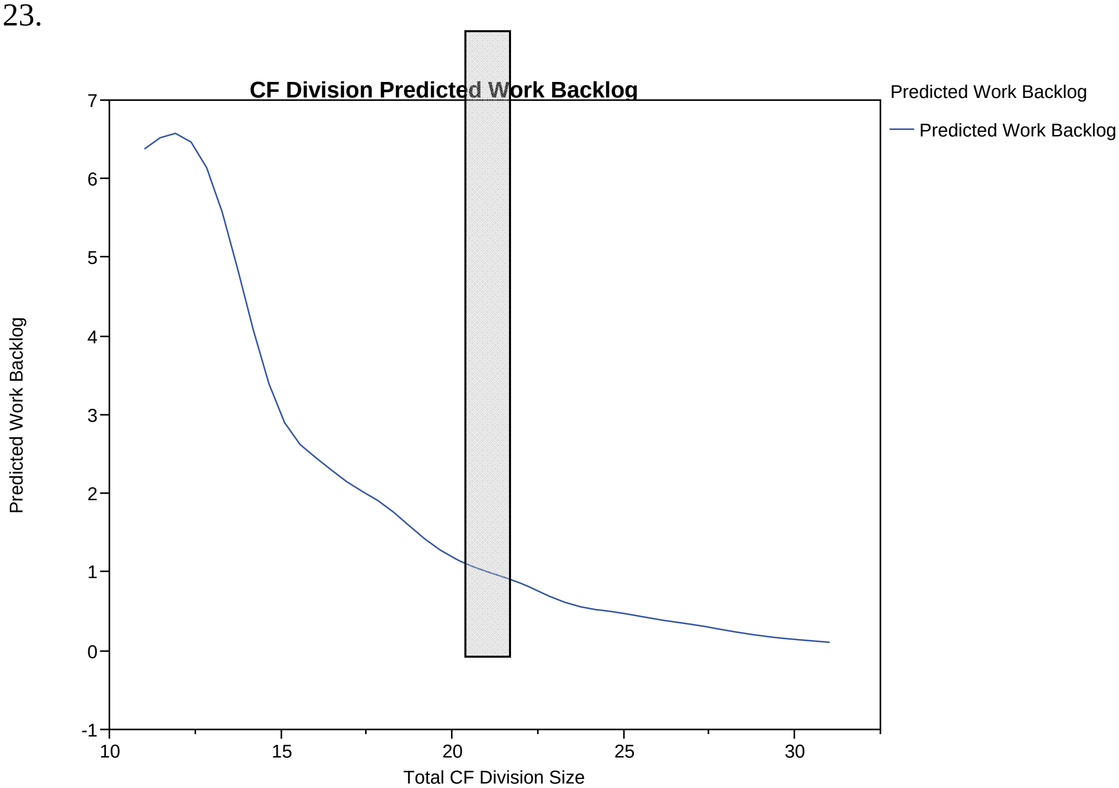



Figure 23. Predicted work backlog in CF division (SMD authorized division size shaded above)

The CF division model offers a fair amount of insight to the current behavior of the division. To begin with, the adjusted R2 of approximately 53% suggests that the model is of value in explaining the variability of work backlog, but there are other variables that have an impact and exploration of this topic would be of value in further modeling the division. Additionally, Figure 23 indicates a type of diminishing returns in adding more sailors to the division. While the amount of work backlog drops notably when going from 10 to 15 sailors (from 6 tasks in backlog to slightly more than 2 tasks in backlog, approximately 60%), moving from 15 to 20 sailors results in far less of a decrease in backlogged tasks. This also suggests the manning level in CF division is appropriate for the work assigned. Further increase in divisional size would no doubt decrease the amount of work backlog, but the gains achieved by assigning a new sailor to the division are less significant at current manning levels.

## B. EA DIVISION

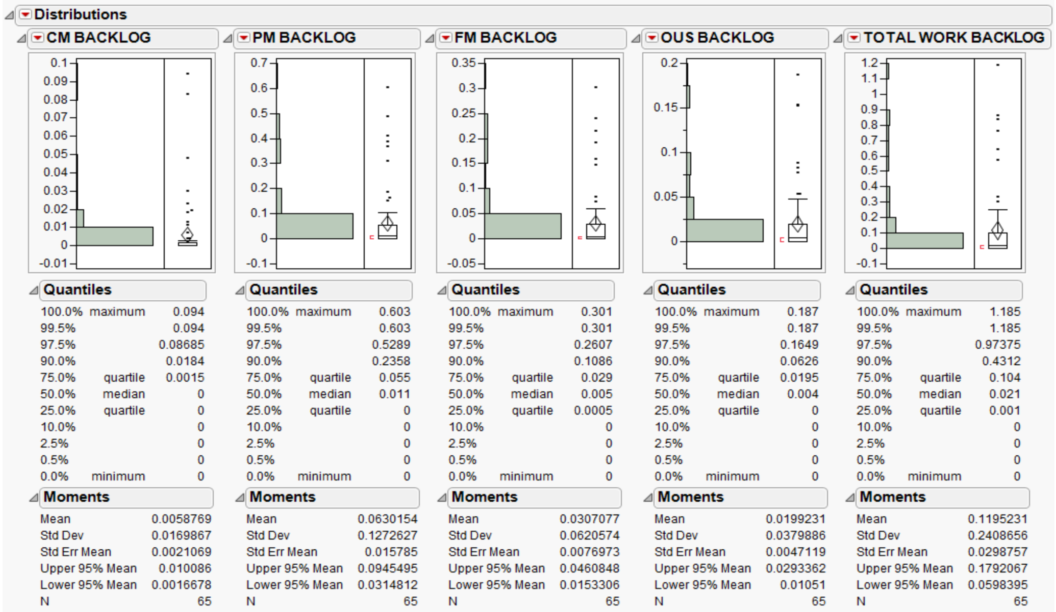
The summary data for the response variables is listed in Table 11 and provides a starting point for a more detailed analysis. As was the case with CF Division, backlog response variables represent quantity of tasks and wait times represent the average amount of time a type of task spent in backlog during the simulation run. Lastly, the average utilization is the average scheduled utilization rate of all the sailors in the division (defined to be the time average number of units of resources that are busy divided by the time average number of units of resources schedule) (Kelton, 2007).

| | Min | 1st Quarter | Median | Mean | 3rd Quarter | Max |
|---|---|---|---|---|---|---|
| PM BACKLOG | 0 | 0 | 0.011 | 0.0630153846 | 0.055 | 0.603 |
| FM BACKLOG | 0 | 0.0005 | 0.005 | 0.0307076923 | 0.029 | 0.301 |
| OUS BACKLOG | 0 | 0 | 0.004 | 0.0199230769 | 0.0195 | 0.187 |
| CM BACKLOG | 0 | 0 | 0 | 0.0058769231 | 0.0015 | 0.094 |
| TOTAL CM HOURS | 42.089 | 71.576 | 111.799 | 119.54896923 | 161.503 | 272.777 |
| TOTAL PM HOURS | 48.407 | 54.3435 | 55.355 | 54.783738462 | 55.7385 | 56.182 |
| CM WAIT TIME | 0 | 0 | 0 | 0.0313076923 | 0.011 | 0.4 |
| FM WAIT TIME | 0 | 0.001 | 0.052 | 0.3009846154 | 0.3005 | 2.188 |
| OUS WAIT TIME | 0 | 0.0005 | 0.027 | 0.1786615385 | 0.2445 | 1.285 |
| PM WAIT TIME | 0 | 0.001 | 0.051 | 0.2433538462 | 0.2085 | 1.95 |
| AVERAGE UTILIZATION | 0.119 | 0.2214545455 | 0.3142727273 | 0.335376031 | 0.4006428571 | 0.6475 |
| TOTAL WORK BACKLOG | 0 | 0.001 | 0.021 | 0.1195230769 | 0.104 | 1.185 |

Table 11. Summary data of EA division response variable results

### 1. Work Backlog

The analysis of the data from the EA division simulation also begins by examining work backlog. Figure 24 shows the distribution of work backlogs by type and the distribution of the total work backlog.




Quantiles

| Quantile | | CM BACKLOG | PM BACKLOG | FM BACKLOG | OUS BACKLOG | TOTAL WORK BACKLOG |
|---|---|---|---|---|---|---|
| 100.0% | maximum | 0.094 | 0.603 | 0.301 | 0.187 | 1.185 |
| 99.5% | | 0.094 | 0.603 | 0.301 | 0.187 | 1.185 |
| 97.5% | | 0.08685 | 0.5289 | 0.2607 | 0.1649 | 0.97375 |
| 90.0% | | 0.0184 | 0.2358 | 0.1086 | 0.0626 | 0.4312 |
| 75.0% | quartile | 0.0015 | 0.055 | 0.029 | 0.0195 | 0.104 |
| 50.0% | median | 0 | 0.011 | 0.005 | 0.004 | 0.021 |
| 25.0% | quartile | 0 | 0 | 0.0005 | 0 | 0.001 |
| 10.0% | | 0 | 0 | 0 | 0 | 0 |
| 2.5% | | 0 | 0 | 0 | 0 | 0 |
| 0.5% | | 0 | 0 | 0 | 0 | 0 |
| 0.0% | minimum | 0 | 0 | 0 | 0 | 0 |

Moments

| Moment | CM BACKLOG | PM BACKLOG | FM BACKLOG | OUS BACKLOG | TOTAL WORK BACKLOG |
|---|---|---|---|---|---|
| Mean | 0.0058769 | 0.0630154 | 0.0307077 | 0.0199231 | 0.1195231 |
| Std Dev | 0.0169867 | 0.1272627 | 0.0620574 | 0.0379886 | 0.2408656 |
| Std Err Mean | 0.0021069 | 0.015785 | 0.0076973 | 0.0047119 | 0.0298757 |
| Upper 95% Mean | 0.010086 | 0.0945495 | 0.0460848 | 0.0293362 | 0.1792067 |
| Lower 95% Mean | 0.0016678 | 0.0314812 | 0.0153306 | 0.01051 | 0.0598395 |
| N | 65 | 65 | 65 | 65 | 65 |

Figure 24. JMP output showing distribution of backlogged tasks in EA division

The data show that over all simulation runs, the mean number of tasks in backlog status is 0.12 with all types of work having a mean backlog that is approximately zero. The range of backlog in all types of work is also narrow; in all types of work, the range from the minimum to maximum backlog values is less than one. The data is then examined against the varying division sizes that were generated by each design point of the experiment. Figure 25 shows the work backlogs against division sizes and Figure 26 shows the amount of total backlog at each division size along with box plots to lend greater insight to the data.

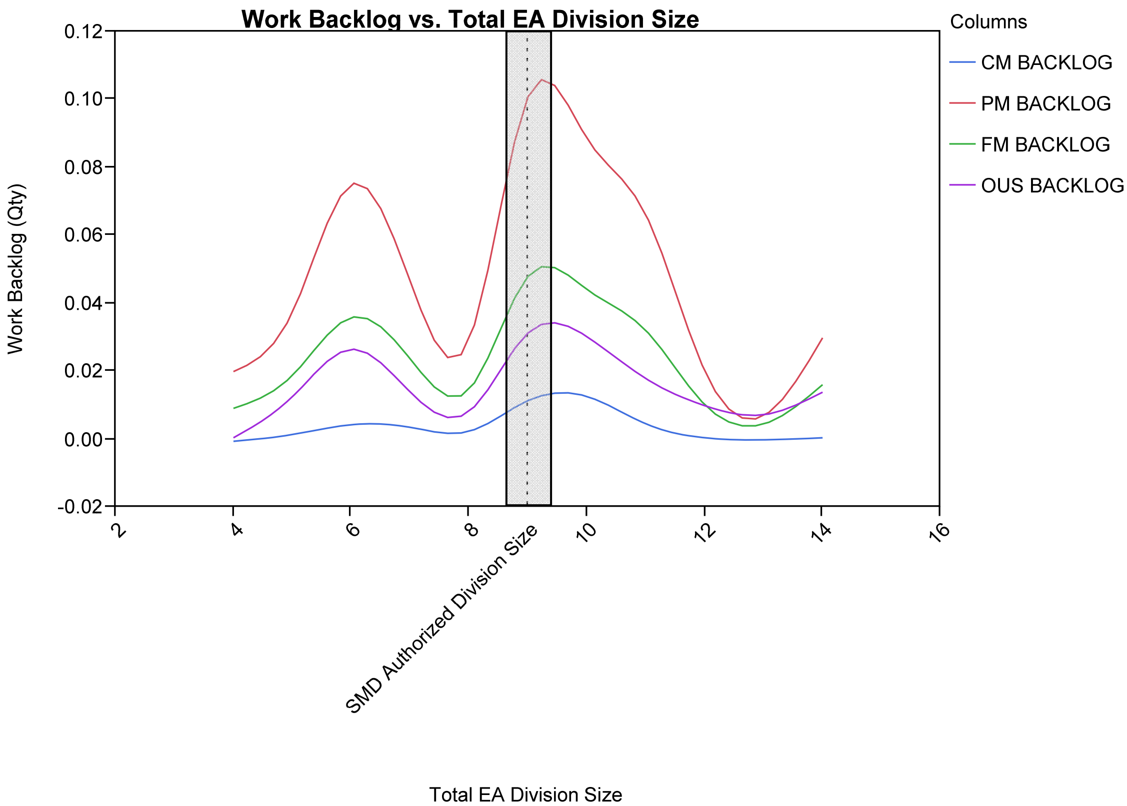



Figure 25. Work backlog (of each type) vs Total EA division size

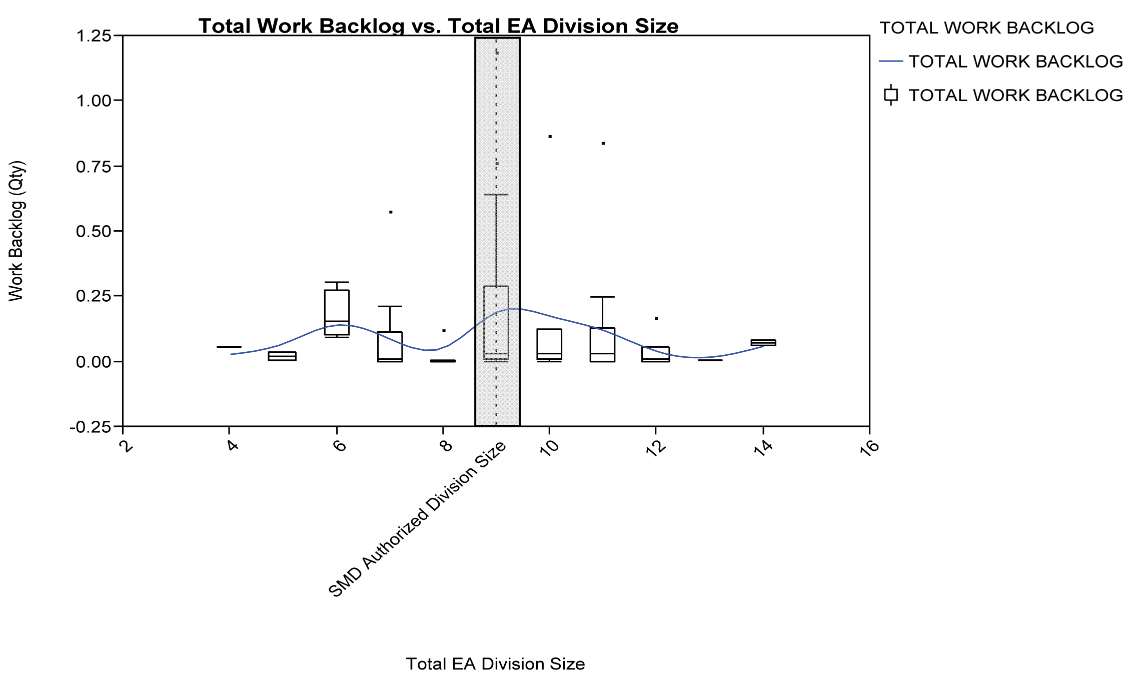



Figure 26. Total Work Backlog vs. Total EA division size

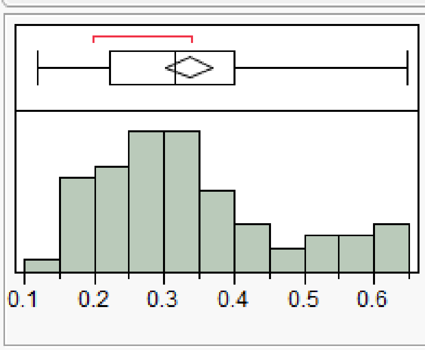
Current EA manpower requirements total nine sailors, as stated in the DDG 51 Flight I Class Ship Manning Document (Navy, 2011). As a result, using a 95% confidence interval, at current manpower requirement levels, the confidence interval about the mean work backlog of 0.21 tasks is given by [0.02, 0.39]. This result appears to be appropriate, if a little lower than expected. One also notes the bimodal shape of the graph in Figure 24. There is no ready explanation for this fact and further research is recommended to determine potential underlying causes.

### 2. Sailor Utilization

Next, the data from EA division is examined for information with regard to the scheduled utilization rates of sailors. As stated in the discussion of the CF division data, the EA data is a result of Arena reporting scheduled utilization on each entity in the simulation. The resulting scheduled utilization is averaged over the number of sailors present in the division in each design point to provide information on the total division scheduled utilization rate. Figure 27 shows the distribution of scheduled utilization rates and Figure 28 presents a box plot of the scheduled utilization rate for different total division sizes.

**Distributions**

**AVERAGE SCHEDULED UTILIZATION**




**Quantiles**

| | | |
|---|---|---|
| 100.0% | maximum | 0.6475 |
| 99.5% | | 0.6475 |
| 97.5% | | 0.63018 |
| 90.0% | | 0.57657 |
| 75.0% | quartile | 0.40064 |
| 50.0% | median | 0.31427 |
| 25.0% | quartile | 0.22145 |
| 10.0% | | 0.186 |
| 2.5% | | 0.14002 |
| 0.5% | | 0.119 |
| 0.0% | minimum | 0.119 |

**Moments**

| | |
|---|---|
| Mean | 0.335376 |
| Std Dev | 0.1326325 |
| Std Err Mean | 0.016451 |
| Upper 95% Mean | 0.3682408 |
| Lower 95% Mean | 0.3025113 |
| N | 65 |

Figure 27. Distribution of average schedule utilization results for EA division

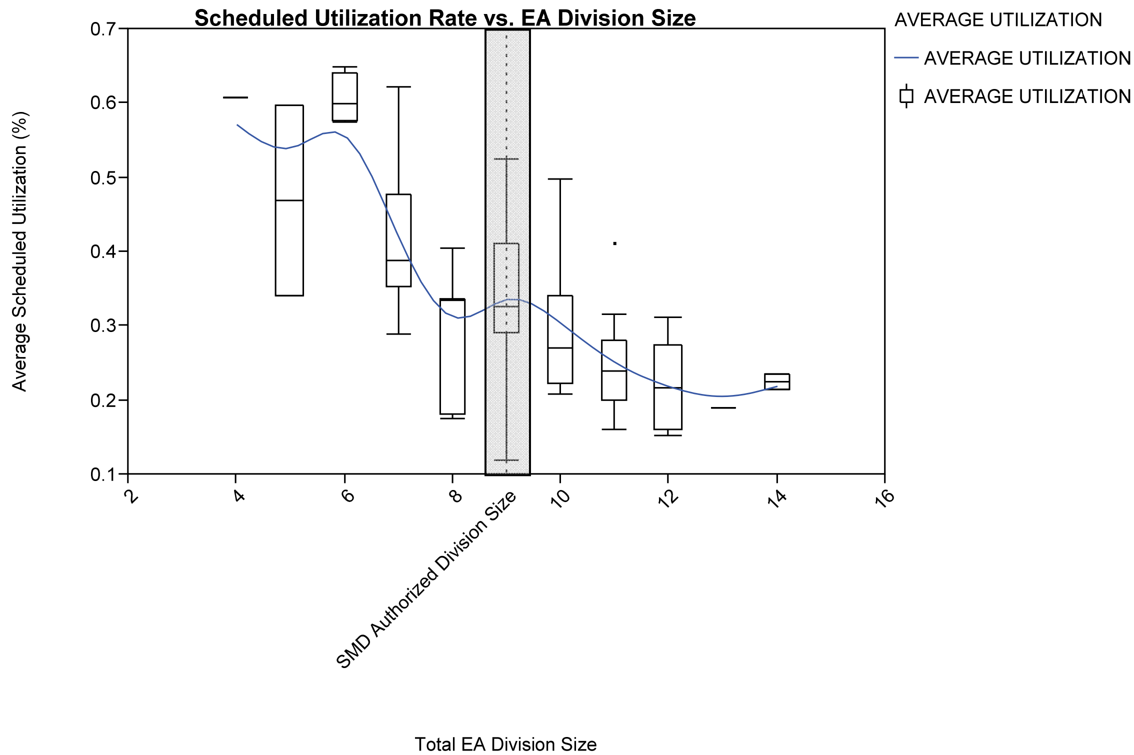



Figure 28. Scheduled Utilization Rate vs. EA division size

Figure 27 seems to support the idea that scheduled utilization rate decreases as more sailors are assigned to the division. As before, the data are examined to determine the confidence intervals about the mean at current manpower requirements levels. In the case of EA division's nine sailors, the 95% confidence interval about the mean scheduled utilization rate of 0.344 (34.4%) is [0.29, 0.40]. As in the case of CF division, there is no "correct" level of sailor utilization, yet a mean utilization rate of 34.4% appears somewhat low. Nevertheless, this result indicates a fully manned EA division is well positioned to respond quickly to increases in workload demand.

As in CF division, the analysis turns now to instantaneous utilization and JMP presents the data as the sum of total hours spent working on tasks (PM, CM, FM, or OUS) divided by the product of the number of sailors assigned to the division and the total number of hours a sailor is scheduled to work. Figure 29 presents the distribution of instantaneous utilization rates and Figure 30 illustrates this utilization rate at different division sizes.

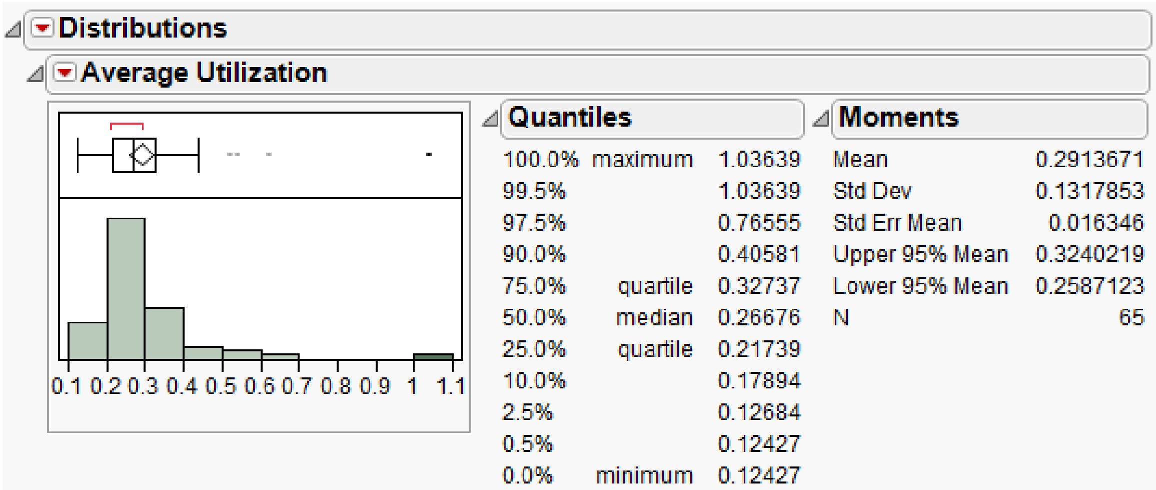



Figure 29. Distribution of EA division utilization results and summary statistics

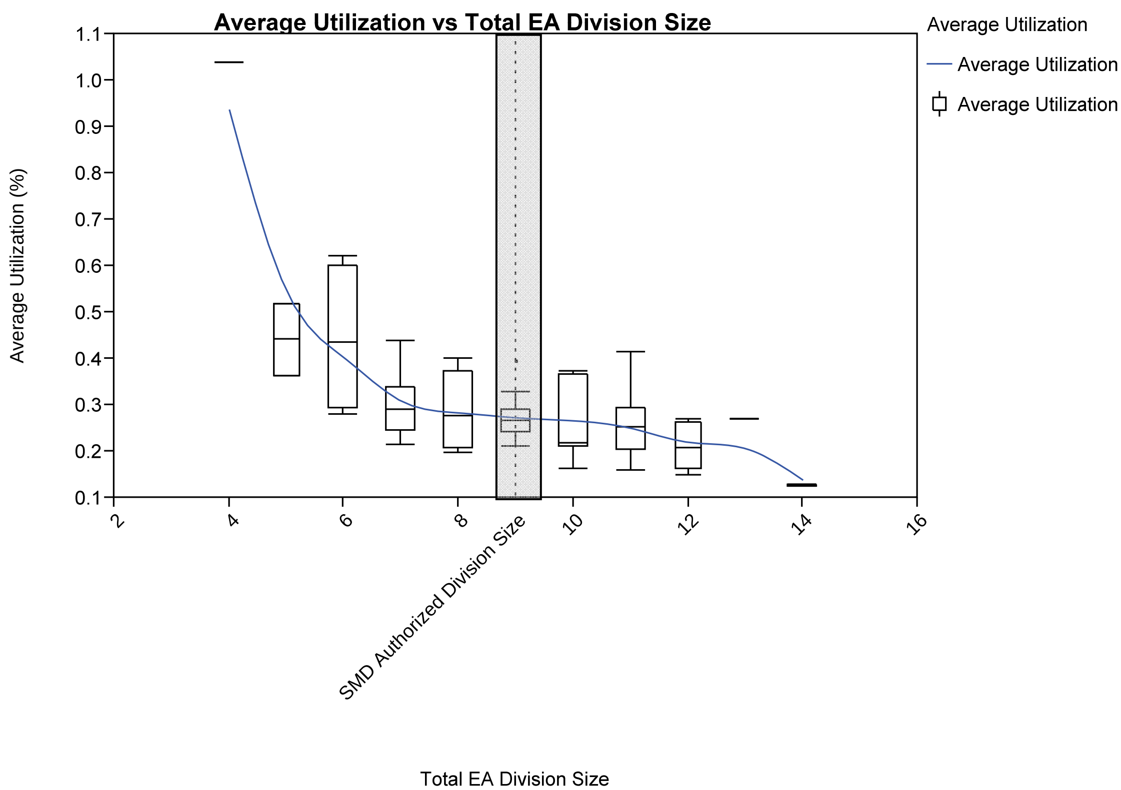
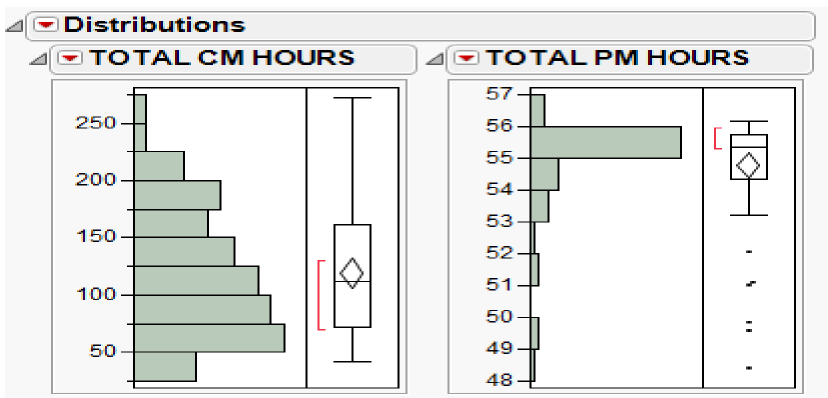



Figure 30. Average Utilization vs. EA division size

The first major observation that stands out from the preceding figures is the one instance of a utilization rate greater than one. This is a result of a small division size (only four sailors) and a large enough workload that the sailors were forced to continue working past a scheduled work time. The reader may consider this an outlier, but it is presented for the sake of completeness. Regarding the rest of the data, a 95% confidence interval about the mean utilization rate of 0.291 (29.1%) is [0.258, 0.324]. This is similar to the result observed in the area of scheduled utilization, suggesting a consistent level of activity across an entire sailor day and the amount of time sailors are specifically scheduled to work.

### 3. PM:CM Ratio

The NAVMAC PM:CM ratio for hull/mechanical equipment is 2:1. A significant amount of EA division's work is on such equipment, thus the next portion of the discussion examines the data in light of that ratio. Figure 31 shows the distribution of the CM and PM hours and other descriptive statistics generated from the data.




Quantiles (TOTAL CM HOURS)

| | | |
|---|---|---|
| 100.0% | maximum | 272.777 |
| 99.5% | | 272.777 |
| 97.5% | | 248.196 |
| 90.0% | | 200.058 |
| 75.0% | quartile | 161.503 |
| 50.0% | median | 111.799 |
| 25.0% | quartile | 71.576 |
| 10.0% | | 55.8438 |
| 2.5% | | 43.8882 |
| 0.5% | | 42.089 |
| 0.0% | minimum | 42.089 |

Moments (TOTAL CM HOURS)

| | |
|---|---|
| Mean | 119.54897 |
| Std Dev | 54.435414 |
| Std Err Mean | 6.7518821 |
| Upper 95% Mean | 133.0374 |
| Lower 95% Mean | 106.06053 |
| N | 65 |

Quantiles (TOTAL PM HOURS)

| | | |
|---|---|---|
| 100.0% | maximum | 56.182 |
| 99.5% | | 56.182 |
| 97.5% | | 56.1612 |
| 90.0% | | 55.9584 |
| 75.0% | quartile | 55.7385 |
| 50.0% | median | 55.355 |
| 25.0% | quartile | 54.3435 |
| 10.0% | | 52.7612 |
| 2.5% | | 49.1714 |
| 0.5% | | 48.407 |
| 0.0% | minimum | 48.407 |

Moments (TOTAL PM HOURS)

| | |
|---|---|
| Mean | 54.783738 |
| Std Dev | 1.6385295 |
| Std Err Mean | 0.2032346 |
| Upper 95% Mean | 55.189746 |
| Lower 95% Mean | 54.377731 |
| N | 65 |

Figure 31. Distribution and summary statistics for CM and PM hours in EA division

In addition to presenting total hours of PM and CM in the simulation, JMP computes the number of hours of PM for every hour of CM. This variable represents the PM:CM ratio for each design point in the simulation. Figure 32 shows the distribution of this value and accompanying summary statistics.

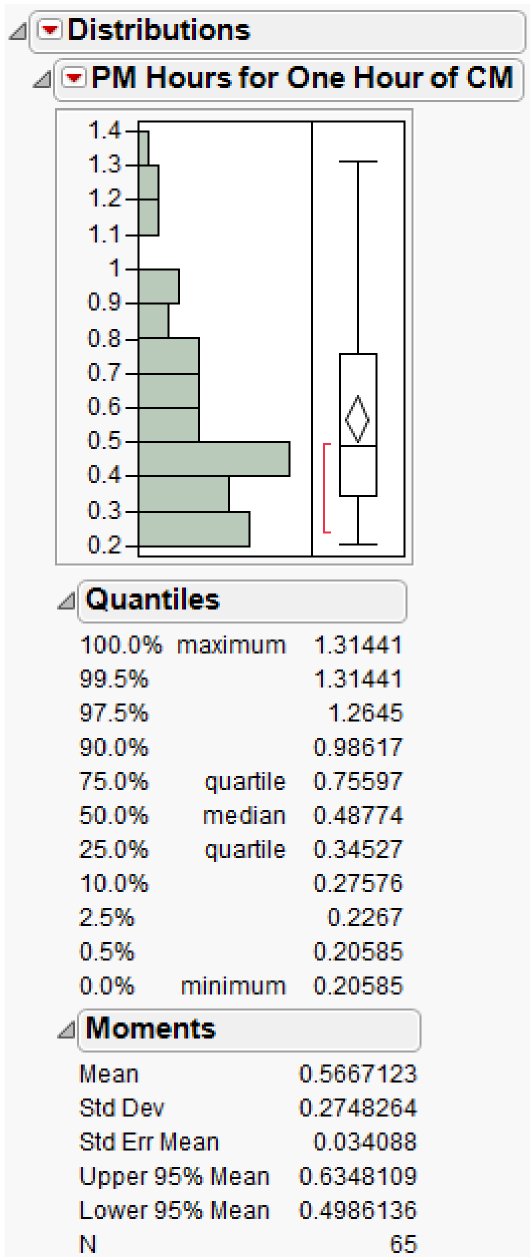
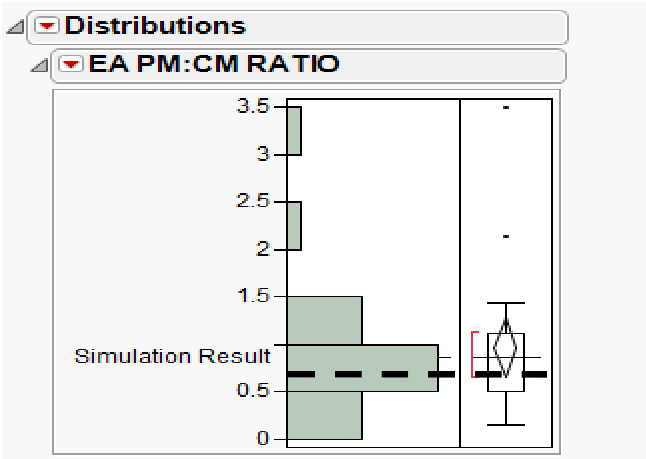



Figure 32. Distribution and summary statistics of CM hours for one hour of PM in EA division

The results shown in Figure 32 indicate a mean value of 0.57 hours of PM for every hour of CM in EA division. Under the NAVMAC standard, one would expect a value closer to 2 hours of PM for every hour of CM. The results also indicate a range of values from 0.21 to 1.31 hours of PM for every hour of CM. This indicates the current NAVMAC standard of a 2:1 PM:CM ratio may not be the most appropriate for hull/mechanical equipment.

As in the analysis of the CF division model, the average value of the PM:CM ratio observed over all simulation replications at the current manpower requirements level (nine sailors with each resource set to a value of one) is compared to PM:CM ratios available from OARS data. As an individual ship's maintenance record is the basis for OARS data, a PM:CM ratio from the simulation that is at or near the mean PM:CM ratio across the ship class suggests the model is performing adequately. Figure 33 displays the distribution of EA division PM:CM ratios across the DDG FLT I class.




**Quantiles**

| | | |
|---|---|---|
| 100.0% | maximum | 3.47545 |
| 99.5% | | 3.47545 |
| 97.5% | | 3.47545 |
| 90.0% | | 1.9192 |
| 75.0% | quartile | 1.11572 |
| 50.0% | median | 0.85647 |
| 25.0% | quartile | 0.5039 |
| 10.0% | | 0.2941 |
| 2.5% | | 0.14775 |
| 0.5% | | 0.14775 |
| 0.0% | minimum | 0.14775 |

**Moments**

| | |
|---|---|
| Mean | 0.9701419 |
| Std Dev | 0.707436 |
| Std Err Mean | 0.1508259 |
| Upper 95% Mean | 1.2838015 |
| Lower 95% Mean | 0.6564824 |
| N | 22 |

Figure 33. Distribution of EA division PM:CM ratios across all ships of the DDG FLT I class and accompanying summary statistics

The simulation yields an average PM:CM ratio at the current manpower level of 0.86:1 (as highlighted in Figure 29). This value is also near, though slightly below, the mean class average of 0.97:1 suggesting the model performs adequately.

### 4. Modeling Divisional Behavior

The EA division data is put into JMP for use with the software's stepwise regression feature to fit the data to a model using work backlog as a response variable. As in the case of CF division, JMP's stepwise regression selects the best model based on minimum Akaike information criteria (AICc) selection rule. Candidate models included all main effects, two way interactions, and quadratic terms. In the case of this model, a square root transformation was used on the response variable, resulting in a regression of the square root of work backlog against the resulting model parameters as shown in Figure 34. Figure 35 displays model summary statistics.

**Parameter Estimates**

| Term | Estimate | Std Error | t Ratio | Prob>\|t\| |
|---|---|---|---|---|
| Intercept | 0.9818623 | 0.12675 | 7.75 | <.0001* |
| CM MAINT ARRIVAL RATE SHAPE | -0.235871 | 0.016501 | -14.29 | <.0001* |
| CM MAINT ARRIVAL RATE SCALE | -0.437427 | 0.13134 | -3.33 | 0.0015* |
| MAX CM WORK TIME | 0.0003321 | 4.559e-5 | 7.28 | <.0001* |
| (CM MAINT ARRIVAL RATE SHAPE-2.60031)*(MAX CM WORK TIME-536.015) | -0.000299 | 0.000053 | -5.64 | <.0001* |
| (CM MAINT ARRIVAL RATE SHAPE-2.60031)*(CM MAINT ARRIVAL RATE SHAPE-2.60031) | 0.1494596 | 0.024521 | 6.10 | <.0001* |
| (MAX CM WORK TIME-536.015)*(MAX CM WORK TIME-536.015) | -3.712e-7 | 1.872e-7 | -1.98 | 0.0520 |

Figure 34. Regression model estimates of the square root of work backlog in EA division

**Summary of Fit**

| | |
|---|---|
| RSquare | 0.856017 |
| RSquare Adj | 0.841122 |
| Root Mean Square Error | 0.104525 |
| Mean of Response | 0.227629 |
| Observations (or Sum Wgts) | 65 |

Figure 35. EA division model summary

The model's validity is tested in the same manner as discussed in modeling the behavior of CF division and the model is found to be adequate both in terms of constant variance and the normal distribution of the residuals.

With the model validity tests showing the key regression assumptions are met, the model estimates from Figure 26 are examined to determine what insights are offered. The first point to note is the model concluded that the significant factors for determining work backlog consist of the rate at which CM arrives (in the form of the distribution's arrival rate shape and scale parameters) and the maximum CM work time. Also included in the model is the interaction between CM arrival rate shape parameter and maximum CM work time and the quadratic terms for CM arrival rate shape and maximum CM work time. As with CF division, the sign on the arrival rate parameters is negative which appears reasonable as a higher arrival rate actually reflects a longer period between incidents of CM work.  The sign on the maximum CM work time parameter is positive, indicating that a higher possible amount of work time will drive up the amount of backlogged tasks.  Again, this also seems reasonable.

Figure 36 shows the plot of predicted work backlog values in the division.

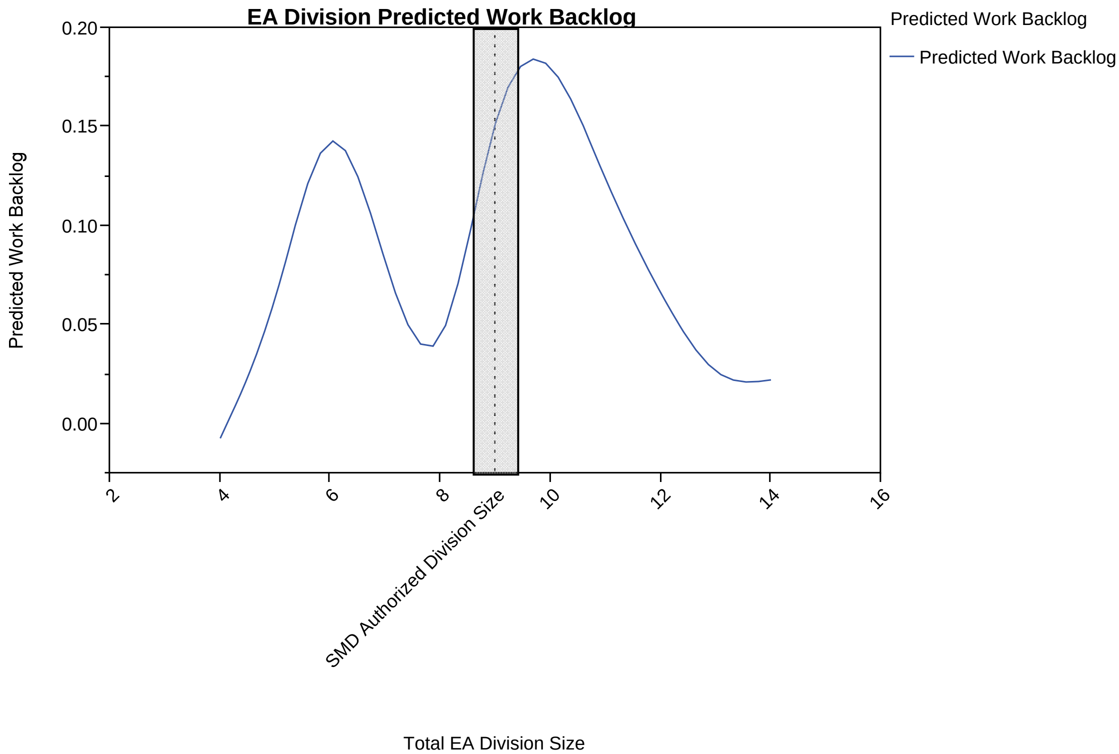



Figure 36.     Predicted work backlog in EA division

The model for EA division yields significantly different insight than that generated for CF division.  To begin with, the model is statistically valid as shown by p-value of the F statistic and the adjusted $R^2$ (shown in Figure 28); however, Figure 26, containing the results of JMP's stepwise regression, does not include the size of the division as a statistically significant term.  This fact is somewhat unexpected as the number of people available to perform work is assumed to be a key driver in the resulting backlog of work.  Further investigation of this result is clearly warranted.  One possible explanation is the fact that EA division works predominantly on mechanical equipment may suggest there is a fundamental difference in the work process between divisions that are responsible for mechanical equipment than those responsible for electronic/electrical systems.

# V. CONCLUSIONS

The preceding chapter on the results of the simulation model offers several insights into the manpower determination process. In order to tie all of these insights together to larger overarching themes, this chapter discusses overall conclusions that can be drawn in light of the original questions posed in the first chapter and the results obtained and detailed in the fourth chapter.

## A. WORK BACKLOG

The work backlog component of this thesis is best seen as a combination of the work backlog data and the sailor scheduled utilization rates. One consideration when determining manpower requirements is the need to balance both work backlog and scheduled utilization rates. Minimizing work backlog is a relatively trivial problem; a large enough number of sailors in a division can easily drive the backlog down to zero. Yet, this is not fiscally reasonable, nor is it an appropriate approach as it no doubt results in a significantly lowered scheduled utilization rates. This has the effect of creating a large number of idle sailors or sailors who spend a significant amount of their work day idle. This is clearly wasteful from the Navy's point of view, but there is also risk in accepting a high scheduled utilization rate. Such a system may suggest overworked sailors or, of more immediate concern, a system that does not have much flexibility built in to handle changing workload needs.

On the subject of work backlog, the data indicate some degree of backlog is present in both divisions. However, EA division shows a backlog of no more than a single task as a general rule. By contrast, CF division indicates a wider range of backlog. In the data presented earlier (Table 10), work backlog is as high as approximately 11 tasks. While these high values were observed in less than 10% of the data, CF division has consistently higher work backlogs than EA division in the results of this simulation.

The data generated in this thesis indicate a wide variety of scheduled utilization rates in both divisions. CF division rates took on values from 27.2% to 84.2% and EA division rates covered a range from 11.9% to 64.7%. This data is presented for informational purposes as there is no commonly accepted definition of a "correct" or "ideal" scheduled utilization rates. Further studies to quantify a best scheduled utilization rate would also be beneficial.

## B. MAINTENANCE RATIOS

The data gathered on maintenance ratios suggest the current PM:CM ratios are more accurate in the case of the 2:1 ratio used in hull/mechanical equipment than the 1:1 ratio used in electrical/electronic equipment. The data as presented earlier in Figure 15 (CF division) shows a range of values from 0.39 to 14.44 hours of PM for every hour of CM. Given this wide of a range, the 1:1 ratio does not seem to be a reasonable representation of the amount of CM hours required for electronics/electrical systems. Further study of the nature of electrical/electronic systems and the associated repair times is recommended.

By contrast, the data in Figure 28, which covers EA division, shows a range of PM values from 0.21 to 1.31 for every hour of CM. This seems to suggest that mechanical equipment does not follow a 2:1 PM:CM ratio. Nonetheless, given the relatively narrow range of values for a PM:CM ratio in EA division, the 2:1 ratio may be a reasonable approximation based on other manpower planning concerns.

## C. FURTHER RESEARCH

This thesis demonstrates the value of simulation analysis in manpower requirements and personnel related studies. Simulation gives the analyst the opportunity to examine the effects of any number of changes to the existing system without making changes to the real world system and collecting data on observed results. This approach offers the potential for significant cost savings to the Navy and further use of simulation study is recommended.

This thesis relies on existing data resident at NAVMAC or systems to which NAVMAC personnel had access. While there is no reason to question the validity of this data, a future study author may consider collecting data personally, either through survey, interviews, or observation of work routine aboard a ship underway. Additionally, subsequent studies may validate or challenge modeling assumptions made for the models in this thesis. In particular, while NAVMAC maintains significant data on FM and OUS work types, a detailed analysis of the distribution of arrival rates of these types of work would be of great value in refining the model. Further, the greatest distinction in the current model is made between sailors in the paygrade of E-6 and below and E-7 and above. Further analysis may examine the various utility of different paygrades (e.g. an E-6 is typically a more productive sailor than an E-4).

Also, this thesis only captures work that fits into current definitions of work. A further study, coupled with the suggestion of conducting research aboard ship, could examine whether or not there is a need for new categories of work or the extent to which observed workload fits into the current categories of work.

Finally, a significant amount of research exists on workloads for Navy vessels when underway. In relative terms, there is a limited amount of data documenting in port work requirements. Documenting in port work requirements represents a greater challenge as there is a much greater range of work demands and one must then consider off ship demands such as schools, training assist visits, and the personal needs of sailors (e.g. medical appointments, etc.). Further research in this area combined with the use of simulation modeling could be very useful and may result in significant insights into current manning levels. Such research may reveal a challenge to the long held notion that a ship's crew is busier underway than in port.

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