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Resource constrained scheduling problem at U.S. Naval Shipyards

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Resource Constrained Scheduling Problem at U.S. Naval Shipyards

by

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Submitted to the Department of Mechanical Engineering and Engineering Systems
Division in Partial Fulfillment of the Requirements for the Degrees of

Master of Science in Naval Architecture and Marine Engineering
and
Master of Science in Engineering and Management
at the
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ABSTRACT

Submarine repair schedules are some of the most complex schedules seen in project management. Repairs of a nuclear U.S. submarine are resource constrained since resources are divided among approximately thirty shops (e.g. electricians, welders, and pipefitters). The system complexity, the tight spaces, the operational nuclear reactor, the challenges inherent in repair, and resource competition all contribute to a dense integrated schedule. Minimizing the overall length of each project, the "makespan," is the primary objective function of this thesis. This thesis uses a commercially available simulation package, @Risk, to analyze a realistic submarine repair schedule. Simulation is used to analyze uncertainty in the task durations and identify crucial tasks that highly impact the makespan. Finally, a genetic algorithm is tested to assign resources to minimize the makespan. The submarine repair data was based on a schedule with 4038 tasks and 7723 constraints or ties. A simulation assigned all 4038 tasks a triangle probability distribution with the duration set at plus or minus 10 percent of the original duration estimate. Sensitivity analysis of the simulation identified key task nodes having significant impact on the overall duration. These top ten crucial tasks were then given similar probability distributions and another simulation was run keeping the remaining 4028 tasks as deterministic durations. Minimizing the makespan could only be executed on a small subset of data, 25 tasks, due to limiting assumptions on reducing task durations by assigning more resources. An overall improvement of 5.5-15.6 % was achieved; this gives an indication of the approximate makespan optimization potential in current U.S. submarine repair, maintenance and overhaul operations.

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TABLE OF CONTENTS

LIST OF FIGURES

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LIST OF TABLES

LIST OF ACRONYMS AND ABBREVIATIONS

A_o – Operational Availability

AIM – Advanced Industrial Management

AIM-NG – Advanced Industrial Management, Next Generation

AQWP – Actual Quantity of Work Performed

AQWS – Actual Quantity of Work Scheduled

AWP – Availability Work Package

BQWP – Budgeted Quantity of Work Performed

BQWS – Budgeted Quantity of Work Scheduled

CLT – Central Limit Theorem

CNO – Chief of Naval Operations

CUI – Component Unit Identifier

CVN – Carrier, Nuclear

DSRA – Docking Selected Restricted Availability

EDSRA – Engineered Docking Selected Restricted Availability

EOH – Engineered Overhaul

GA – Genetic Algorithm

GOTS – Government Off The Shelf

LOE – Level of Effort

NAVSEA – Naval Sea Systems Command

NAVSEA-04 – Naval Sea Systems Command, Logistics, Maintenance and Industrial Operations directorate

NNSY – Norfolk Naval Shipyard

NSSG – Navy Systems Support Group

PHNSY – Pearl Harbor Naval Shipyard

PIE – Production in the Innovation Economy

PNSY – Portsmouth Naval Shipyard

PSNSY – Puget Sound Naval Shipyard

PSS – Project Sequencing and Scheduling

RCSP – Resource Constrained Scheduling Problem

SRA – Selected Restricted Availability

SSBN – Submarine, Nuclear, Ballistic Missile

SSN – Submarine, Nuclear

SUBMEPP – Submarine Maintenance Engineering Planning and Procurement activity

SWLIN – Ships Work List Item Number

TOC – Theory of Constraints

TSD – Trade Skill Designator

USN – United States Navy

BIOGRAPHICAL NOTE

Commander Terry Nawara, USN, was commissioned in 1996 from the U.S. Naval Academy where he earned a Bachelor of Science in Mathematics. He later earned a Master of Science in Operations Analysis from the Naval Postgraduate School and a Master of Arts in National Security and Strategic Studies from the Naval War College in 2003.

Upon completion of Navy nuclear propulsion training, Commander Nawara reported to USS Billfish (SSN 676) where he served as Electrical Assistant and Reactor Controls Assistant during an Ice-Exercise. The boat completed a decommissioning and nuclear defueling at Puget Sound Naval Shipyard. He then served aboard USS Alaska (SSBN 732) as Damage Control Assistant during a D-5 missile conversion overhaul. Aboard USS L. Mendel Rivers (SSN 686) he served as Assistant Engineer during an Ice-Exercise and then as Operations and Combat Systems Officer during the decommissioning and nuclear defueling. From 2001 to 2003 he attended the Naval Postgraduate School. He next served as Combat Systems Officer aboard USS Springfield (SSN 761), completing a depot modernization period at Electric Boat and pre-deployment training. From 2006 to 2008 he worked at Seventh Fleet as the Submarine Operations Officer, Surveillance Towed Array Sensor System Operations Officer, Fleet Navigator, Senior Watch Officer, and Battle Watch Captain in Yokosuka, Japan.

In 2008 he became an Engineering Duty Officer and reported to Pearl Harbor Naval Shipyard. He served as Deputy Project Superintendent for the USS Chicago (SSN 721) Engineered Overhaul and as Project Superintendent for the USS North Carolina (SSN 777) 2011 emergent docking.

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ACKNOWLEDGMENTS

I would like to thank my advisors, Professor de Weck and CAPT Thomas, and MIT Research Associate Eric Rebentisch, for all of their time and assistance. Also, Dave Brodeur the head scheduler at Puget Sound Naval Shipyard gave me invaluable insight and greatly assisted by offering the data set used as a basis for this research. Mike Boisseau at Norfolk Naval Shipyard was a valuable mentor and gave me great background information. Other participants of the Production in the Innovation Economy study were able to provide useful data for follow-on research. Thanks to Joe Mendonsa and all the others at Pearl Harbor Naval Shipyard who taught me so much.

Finally, I would like to thank my wife, Flor, and children, Liam and Alexis, for all of their continued support.

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I. PROBLEM BACKGROUND

The field of project management has many foundations in the military shipbuilding industry. Henry L. Gantt developed his namesake Gantt charts to manage ship construction during World War I. In the 1950s, the U.S. Navy developed the Program Evaluation and Review Technique (PERT) for the Polaris missile program for nuclear submarines.[1] Furthermore, the U.S. Department of Defense developed Earned Value Management to measure project progress.[2] Ship construction and ship repair remain as significant practitioners of project management. In particular, this research focuses on project management of U.S. shipyards with particular focus on nuclear submarine repair, maintenance and overhaul in the U.S. Navy.

Lifecycle maintenance of U.S. nuclear submarines includes dry-docking repair periods of approximately 6-month or 18-month nominal durations. The U.S. has four remaining public naval shipyards that conduct this nuclear maintenance: Pearl Harbor Naval Shipyard, Puget Sound Naval Shipyard, Portsmouth Naval Shipyard, and Norfolk Naval Shipyard. At any given time each of these shipyards typically has three to four submarines at different stages of repair or overhaul. The schedules for the short minor maintenance availabilities have approximately 2,000 repair tasks while the longer major availabilities have approximately 8,000 repair tasks. The schedules of the repairs are (human) resource constrained since resources are divided among approximately 30 shops (e.g., electricians, welders, and pipefitters).[3]

Minimizing the overall length of each project, the "makespan," is the primary objective function. Other objectives include minimizing cost and minimizing overtime. There are important precedence constraints (i.e., some tasks have to be completed before others can start) as well as co-location constraints (i.e., only a few workers can fit in a

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[1] Richard Chase, et al., *Operations Management for Competitive Advantage* (Boston, MA: McGraw-Hill, 200) 72.

[2] Wayne Abba, "How Earned Value Got to Prime Time: A Short Look Back and a Glance Ahead," 31 Oct. 2006 <http://www.evmlibrary.org/library/EVLook%20Back-Glance%20Ahead.abba.pdf>.

[3] Mike Boisseau, "Lean Release," Project Management Fundamentals (Pearl Harbor, HI: 9 July 2009).

small work area). These types of project management scheduling problems, Resource Constrained Scheduling Problems (RCSP) are classified as NP-hard problems.[4]

NP-hard is a category of problems in computational complexity theory. A problem is NP-hard and considered inherently difficult when there does not exist an efficient algorithm with a "number of operations that is polynomial in the size of the input data."[5] Minimizing the makespan in a project schedule can be considered a subset of the constrained shortest path problem, an identified NP-hard problem.

A. PRODUCTION IN THE INNOVATION ECONOMY (PIE) STUDY

The Massachusetts Institute of Technology (MIT) started the Production in the Innovation Economy (PIE) study in 2011. The goal is to "develop recommendations for transforming America's production capabilities in an era of increased global competition."[6] In November 2012 the study began a two-year contract with the U.S. Navy to review U.S. shipbuilding and defense industries since they represent an important fraction of U.S. industrial activities.

The MIT PIE study for the U.S. Navy has five tasks: 1) Innovation in bidding and contracting, 2) Project management, 3) Benchmarking shipyard performance, 4) Supply chain management, and 5) Prospects for U.S. commercial shipbuilding.[7] This thesis work supports the second task for MIT's PIE study for the U.S. Navy. The key question is how project management practices in U.S. shipyards could be further improved to achieve productivity gains as measured against past results and also compared to foreign shipyards. Comparisons against foreign shipyards are outside the scope of this thesis, but a comparison of an optimized submarine repair schedule relative to an initial baseline is included in the thesis.

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[4] Gabriel Burnett, "Multiple Objective Assembly Scheduling with Spatial Resources and Recurring Tasks," (Pennsylvania State University, 2011), 35.

[5] Ravindra Ahuja, et al., *Network Flows: Theory, Algorithms, and Applications* (Englewood Cliffs, NJ: Prentice Hall, 1993), 788.

[6] "Production in the Innovation Economy," (Massachusetts Institute of Technology, 12 Feb. 2013), <http://mit.edu/pie/about/index.html>.

[7] Oliver de Weck and Eric Rebentisch, "Production in the Innovation Economy: How to Create Excellence Through Competition and Benchmarking in the U.S. Shipbuilding and Defense Industry," (MIT, Boston, MA, 2013), 3.

B. U.S. NAVAL SHIPYARDS

1. Submarine Lifecycle Maintenance

Lifecycle maintenance includes both depot maintenance, intermediate maintenance, and organizational-level maintenance. Depot maintenance, or D-level, includes "major overhaul or a complete rebuilding of parts, assemblies, subassemblies, and end items, including the manufacture of parts."[8] This complex level of repair work is done at a depot level facility, such as a shipyard. Any work that requires the ship out of the water (i.e., in a drydock) is typically D-level maintenance. Intermediate maintenance, or I-level, includes smaller repair work typically done pier side. Organizational-level maintenance is done by the ship's crew onboard and consists of preventative maintenance and day-to-day servicing.[9]

In the U.S. Navy all submarines and aircraft carriers are nuclear powered. Built between 1976 and 1996, the Los Angeles, or 688-class, submarines make up the majority of the fast attack submarine inventory of the U.S. Navy. Therefore, most submarine repair in the U.S. Navy is on Los Angeles class submarines.

The notional total lifecycle maintenance plan of Los Angeles class submarines has changed over the years. In 1974, two years before the first one was commissioned, the plan included a total of 1,024,000 man-days (or resource days) in 80 months of depot maintenance for the life of each submarine. Currently the maintenance plan is drastically lower with only 546,400 man-days in 48.3 months of depot maintenance for each submarine. This count of D-level activities excludes the yellow boxed PSA (Post Shakedown Availability) in Figure 1 since this maintenance is only done by the construction shipyard immediately following the initial build.[10]

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[8] Scott Williams, et al., "Visualizing Attack Submarine Maintenance Life Cycles," Intelligent Ships Symposium IX (American Society of Naval Engineers, 9 June 2011), 14 Sept. 2012, <https://www.navalengineers.org/SiteCollectionDocuments/2011%20Proceedings%20Documents/ISSIX/Papers/Donlan_9_ISS2011Final.pdf>.

[9] Ibid.

[10] Mike Palczynski, "SUBMEPP: Mission Capable. Service Proven" (MIT Mechanical Engineering Conference Room, Boston, MA: 17 Oct. 2012).

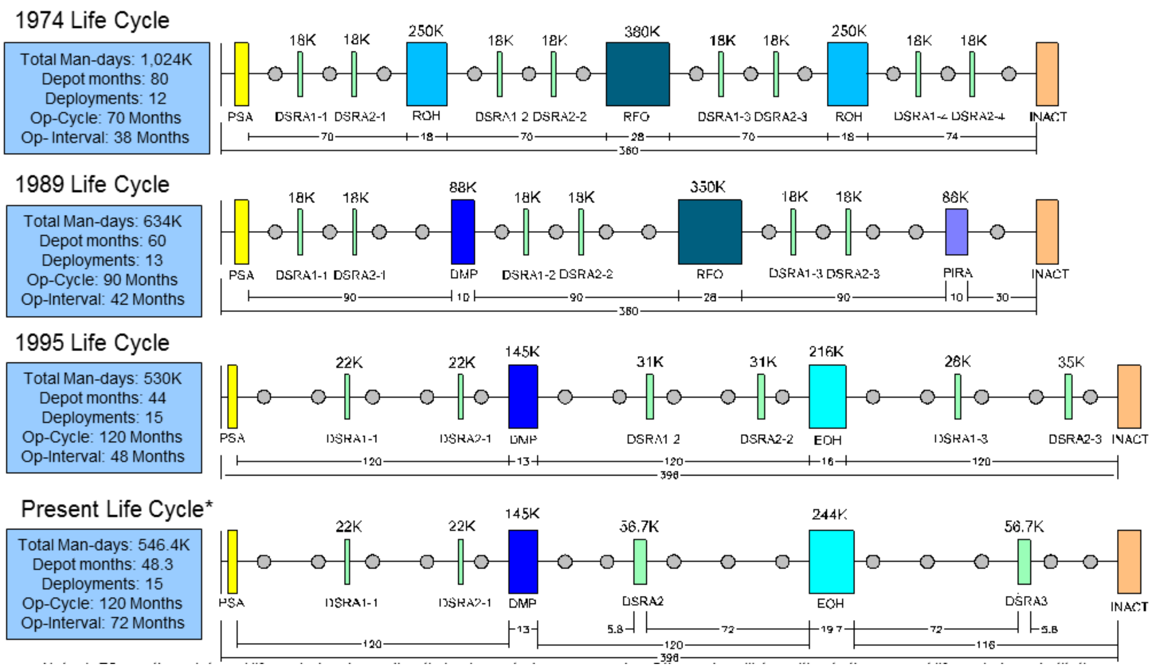

Figure 1. Evolution of Los Angeles Class Submarine Notional Maintenance Life Cycle[11]

The depot level maintenance system includes the green boxed "DSRA's" (Docking Selected Restricted Availability), the blue boxed "DMP" (Depot Maintenance Period), the cyan boxed "EOH" (Engineered Overhaul), and the tan boxed "Inact" (inactivation or decommissioning). Note that the term "availability" is used among the Naval shipyards to refer to any of these maintenance types: DSRA, DMP, or EOH. The DSRAs are generally less than six months and are considered minor availabilities. The DMPs and EOHs take one to two years and are considered major availabilities. During these periods the submarine is not available for service and occupies a drydock. The grey circles represent fifteen nominal deployments of the submarine when it operates for six to eight months overseas.

As the originally planned maintenance time was lowered, the number of deployments went from 12 in 1972 to 15 today. Although the maintenance time was considerably lowered, this was done with a careful analysis of technical and operational

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[11] Mike Palczynski, "SUBMEPP: Mission Capable. Service Proven" (MIT Mechanical Engineering Conference Room, Boston, MA: 17 Oct. 2012).

risk. The Submarine Maintenance Engineering Planning and Procurement (SUBMEPP) activity is tasked with analyzing the maintenance risk of the entire submarine system for all classes of submarine. The improvements were made by improving maintenance planning, reanalyzing data and adjusting reliability centered maintenance schedules, better subsystem performance, and other advancements. With all of these changes, the operational availability, A_o, of the Los Angeles class submarines has improved considerably over time.[12]

2. Shipyard Organization

The U.S. Naval Sea Systems Command (NAVSEA) provides lifecycle engineering support to all of the vessels in the U.S. Navy. One of NAVSEA's directorates, NAVSEA-04, is in charge of logistics, maintenance and industrial operations. This includes supervision of the public shipyards operated directly by the U.S. Navy. Since 1972, the public shipyards have only conducted repair while new construction has been left to private shipyards.[13]

During the 20th century, the Navy shut down nine of these public shipyards. Because of this drawdown the Navy contracts with private shipyards to perform maintenance on most of the conventionally powered ships. The four remaining public shipyards primarily focus on the more complex repair of nuclear powered ships in the Navy: submarines and aircraft carriers. Work involving nuclear reactors also requires extra security and safety precautions that are more easily enforced in U.S. government controlled shipyards. The presence of an operating nuclear reactor also imposes significant schedule constraints. The four public shipyards and their primary focus are shown in Figure 2. There are approximately 22,000 personnel at these four shipyards compared to nearly 70,000 personnel at the eight shipyards the Navy had in 1996.[14]

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[12] Mike Palczynski, "SUBMEPP: Mission Capable. Service Proven" (MIT Mechanical Engineering Conference Room, Boston, MA: 17 Oct. 2012).

[13] "Naval Ship Yards," U.S. Shipbuilding History, Shipbuilding Statistics, Tim Colton, 5 Dec. 2012, <http://shipbuildinghistory.com/history/shipyards/3public.htm>.

[14] Mike Boisseau, "Lean Release," Project Management Fundamentals (Pearl Harbor, HI: 9 July 2009).

While the size of the shipyards has gone down, the number of major (greater than six month duration) maintenance availabilities has gone up. In 1990, there were 11 EROs (Engineered Refueling Overhauls) or DMPs (Depot Maintenance Periods). In 2007, there were over 35 major availabilities.[15] This has driven the need for increased efficiency and productivity. Schedule accuracy is a crucial component of executing this new workload efficiently.

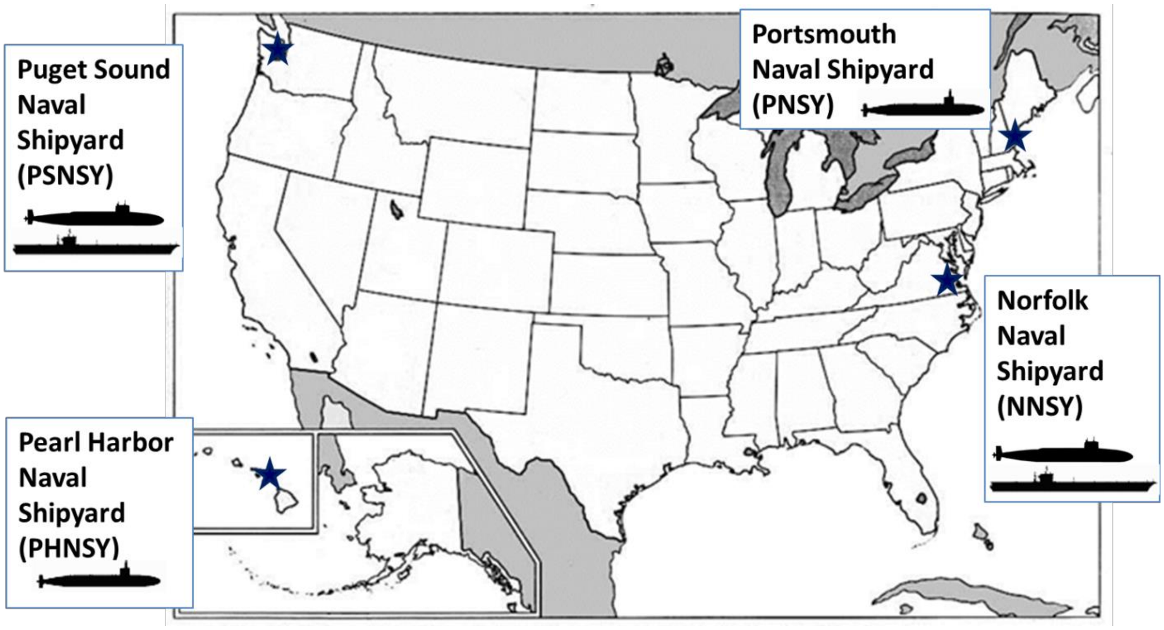

Figure 2. Four Active Public Naval Shipyards

3. Advanced Industrial Management

In the 1990s, the Navy created the Advanced Industrial Management (AIM) program to transition each of the public shipyards from a shop-managed maintenance plan to integrated project management. One crucial aspect of this transition was the publication of the Baseline AIM Process Manual: a 10 chapter instruction describing "the processes and products necessary to implement"[16] AIM concepts in the naval shipyards.

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[15] Mike Boisseau, "Lean Release," Project Management Fundamentals (Pearl Harbor, HI: 9 July 2009).

[16] Baseline AIM Process Manual, Rev C, September 10, 1997, page ii.

As seen in Table 1, between 2004 and 2006, the public shipyards had been performing poorly, particularly in submarines: averaging 24-months late (delay) total across the four shipyards. The total delays began to impact the Navy's concept of force structuring (how many total ships were needed in the inventory).[17] With between 50 to 60 fast attack submarines in service during that period, two were effectively out of service due to maintenance delays. Since the construction times take years, the Navy did not buy new submarines to replace this gap; however, the impact was felt in increased operational use of the remaining submarines. Over the long term, with new submarines costing over $2 billion each, accepting the pattern of longer submarine maintenance periods has a cost much higher than just the immediate project management cost delays.

Fiscal Year	Average Days Late
2004	50.0
2005	49.9
2006	41.7
2007	69.4
2008	25.1

Table 1. Average Days Late for Public Shipyard Maintenance Availabilities on Aircraft Carriers and Submarines[18]

4. Advanced Industrial Management - Next Generation

In 2006, NAVSEA headquarters began implementation of another new management program at the four naval shipyards: PHNS, PSNS, PNSY, and NNSY. NAVSEA created Advanced Industrial Management – Next Generation (AIM-NG). Headquarters' goal is to complete all maintenance on time or early, perform at 25 percent

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[17] Mike Boisseau, "Monthly Project Management Lean Release 2.0/3.0 Implementation Results," (NAVSEA, 4 October 2011), 5.

[18] Ibid.

less cost, and lower overtime usage to 5 to 10 percent. An emphasis is made in AIM-NG on program management versus project management. With the previous style of project management, individual ships would vie for attention at the shipyard and compete for resources. At a critical point in the schedule, such as undocking the ship, the project might overcompensate for resources and have workers on standby to “push through” the schedule hurdle. When doing this, other projects in the shipyard might suffer significantly, through less visible, schedule impacts. Pulling off labor resources for contingency on the submarine scheduled to undock next week might delay a critical path or near critical path job on an adjacent project. With AIM-NG, NAVSEA’s focus now is to balance resource allocation appropriately between all parallel projects in a shipyard, creating a more even-loading of resources so all projects are completed on time or early.[19]

NAVSEA-04, the logistics, maintenance and industrial operations branch, created a field activity, the Navy Systems Support Group (NSSG), to develop program management and resource management guidelines for the shipyards. The team consisted of subject matter experts throughout the four shipyards: schedulers, project superintendents, assistant project superintendents, resource managers, and others. With NSSG’s efforts, NAVSEA implemented the Theory of Constraints (TOC) as developed by Eliyahu M. Goldratt (also known as “critical chain”). The shipyards identified their system constraints as the critical chain for the availability. For minor availabilities (less than 6 months in duration), the critical chain is typically 15 to 18 percent of the total workload. For major availabilities (greater than 6 months in duration), the critical chain is typically 8 to 10 percent.[20] The shipyards other five steps following the theory of constraints[21] are:

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[19] Mike Boisseau, “Lean Release,” Project Management Fundamentals (Pearl Harbor, HI: 9 July 2009).

[20] Mike Boisseau, Phone interview, 24 Jan. 2013.

[21] Mike Boisseau, “Lean Release,” Project Management Fundamentals (Pearl Harbor, HI: 9 July 2009), 12.

1. Identify the System Constraint
    - The Critical Chain for the Availability
2. Exploit the System Constraint
    - Aggressive durations with buffers for uncertainty and variability. Distinction between feeder buffers and overall project buffer.
3. Subordinate Everything Else to Above Decisions
    - The Focus: Non-Stop Execution of the Critical Chain in Support of the Mechanic on the Jobsite
    - Never let the Critical Chain slow down or stop
    - Low Work in Process, No Multi-Tasking
    - Whole Team/Shipyard Focus (People, Paper, Parts, Tools, etc.)
4. Elevate the System Constraint
    - Increase Capacity & Focus Applied to the Critical Chain
5. Go Back to Step 1
    - Monitor Daily for New Constraints to the Critical Chain

A fundamental aspect of implementing the Theory of Constraints was proper prioritization "dependent upon an accurate and up-to-date network."[22] To conduct this improved resource allocation, a new scheduling tool was released in December 2006. The tool had a unique prioritization method meant to balance the priority among all projects at the shipyard. With the new IT tool, WebAIM, each task at the yard is prioritized numerically (one being the top priority). With supervisors updating the schedule performance daily, the software conducts a nightly critical path calculation among all the projects. The priority rule set, in order of highest priority, is:

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[22] Mike Boisseau, "Lean Release," Project Management Fundamentals (Pearl Harbor, HI: 9 July 2009), 10.

a. Minimum float (or slack)

b. Tie breaker: Earliest Start

c. Tie breaker: Earliest Planned Finish

d. Tie breaker: Priority project[23]

Shipyard Priority	**Project**	**Task**	**Float / Slack**	**Planned Start**	**Planned Finish**
1	Buffalo	Fix pump	-15	1JUL	1AUG
2	Key West	Inspect Sail	-14	1MAY	1DEC
3	Chicago	Install staging	-14	1JUN	1DEC
4	Chicago	Flush pipe	-14	1JUN	15DEC
5	Key West	Paint Tank	-14	1JUN	15DEC

Table 2. Example Prioritization among Projects

Using this rule set on Table 2, the number one priority of the shipyard would be to fix the pump on Buffalo since it has the worst float. Float or slack, is the amount of time the task could be delayed without impacting the overall schedule. By definition, anything with negative or zero float is thereby on the critical path. The Buffalo's task of fixing the pump with a -15 float indicates that the overall project will be 15 days late unless this task is accelerated.

The number two priority is Key West "Inspect Sail" since it is tied with a float of -14, but has the earliest planned start. The tie breaker for number three and four is decided in favor of "Install Staging" since it has the earlier planned finish. Finally, priorities four and five have the same float, start date, and finish date, so the tie-breaker implies that Chicago has an overall priority higher than Key West. The ship priority comes from the customer, the submarine force command, telling the shipyard which boats are more important for operational reasons. With this WebAIM tool, the Navy plans to better distribute resources evenly and improve schedule performance.

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[23] AIM-NG Process Manual, Chapter 6A, Execution Priorities (Washington, DC: Naval Sea Systems Command, 2009).

The WebAIM system applies color coding based on the float values: red is for 10 shifts or less float, yellow is for 11 to 30 shifts of float, green is for more than 30 shifts of float, and blue is for level of effort (LOE) tasks. A LOE task would include management resources or other overhead required throughout the project's duration.[24]

Program managers then use this prioritization to allocate resources between projects at each shipyard. On the first pass of resource allocation, 100% of red and blue tasks are allocated. The second pass allocates 100% resources to yellow tasks. The final pass allocates remaining resources to green tasks. Overall, the project manning is resourced to 80% of the total Budgeted Quantity of Work Scheduled (BQWS). This helps control costs and work in process to finish the overall schedule faster. NSSG studied previous shipyard availabilities and determined that historically, 20% of tasks were delayed due to work stoppages (e.g., procedural errors, unavailability of tools…). Therefore, NSSG proposed the 80% limit for overall manning. The intent of this multi-pass resource allocation process is to minimize resource and schedule churn.[25]

The new mantra is non-stop execution of the critical chain in support of the mechanic on the jobsite. NAVSEA makes the analogy that the worker performing maintenance is like a surgeon: they are the one that truly matters in the maintenance outcome; everyone else is in a supporting role. One Lean initiative directed at this goal copied Toyota's Andon system. If a worker found a problem, he would no longer be required to stop, leave the ship, go to the engineering office, find the appropriate engineer, and get a procedure updated. This stop-and-go cycle led to many delays. Instead, temporary phones are now placed throughout the ship so that a worker encountering a problem can stop, call a hotline, and a responder gets the appropriate engineering and management support to the worksite. The "surgeon" no longer has to walk away from the operating room.[26]

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[24] AIM-NG Process Manual, Chapter 6A, Execution Priorities (Washington, DC: Naval Sea Systems Command, 2009), 8.

[25] Mike Boisseau, "Lean Release," Project Management Fundamentals (Pearl Harbor, HI: 9 July 2009), 10.

[26] Ibid.

Again, all of this effort in implementing the Theory of Constraints depends on an accurate schedule. The Navy collected data to show the effect of AIM-NG implementation on the shipyard's performance. The AIM-NG system is ranked weekly by an implementation score measuring nine areas. The total score ranges from 0 to 45. In Figure 3 the aircraft carriers and submarines repaired at the naval shipyards are ordered from highest to lowest average score. The x-axis records cost performance for the project while the red or green dot indicates schedule performance (as shown in the key). In Earned Value Management, performing the work for exactly the expected cost gives a cost performance index (CPI) of 1.0. A CPI below 1.0 indicates that the task is over budget, and a CPI above 1.0 indicates that the work is being performed below budget. In the Naval Shipyards, they use the shortened, Cost Performance (CP), instead of CPI. Each project lists the ship name, hull type, hull number, fiscal year of the availability start, and the type of availability. In general, the projects following AIM-NG processes (with a higher implementation score) were on time or early. Conversely, only 2 of 20 availabilities with scores below 25 finished on time or early. In addition, the average days late of nearly 50 from Table 1 had fallen by 2010 to an average of only 19.6 days.[27] A significant factor in the new AIM-NG performance score relies on scheduling.

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[27] Mike Boisseau, "Monthly Project Management Lean Release 2.0/3.0 Implementation Results," (NAVSEA, 4 October 2011), 5.

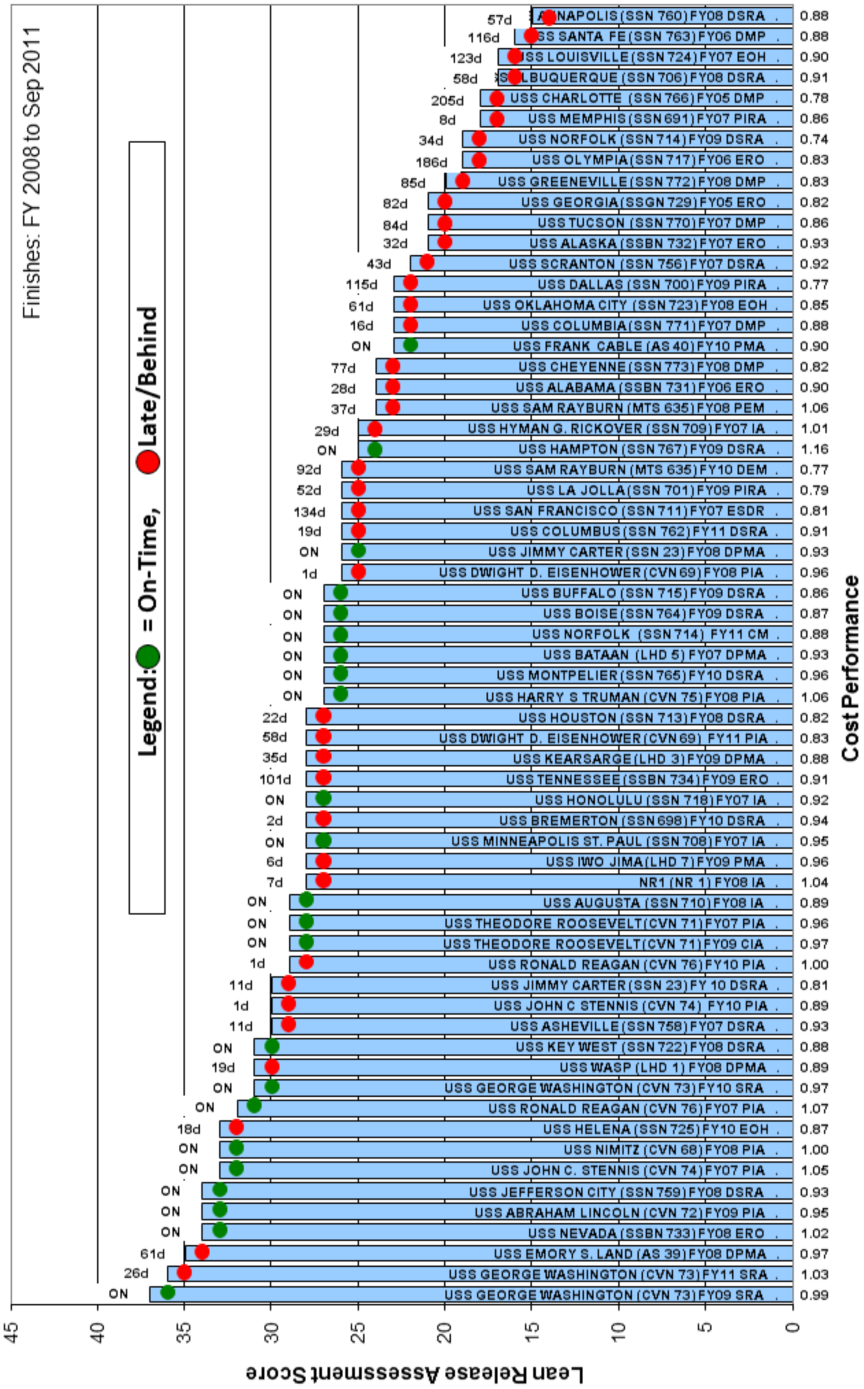

Figure 3. Lean Release Score (scaled 0 to 45) for All Aircraft Carrier and Submarine Repairs from 2008 to 2011[28] Sorted From Best (Left) to Worst (Right). Green Dots Indicate On-Time Float.

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[28] Mike Boisseau, "Monthly Project Management Lean Release 2.0/3.0 Implementation Results," (NAVSEA, 4 October 2011), 9.

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II. LITERATURE REVIEW

A. RESOURCE CONSTRAINED SCHEDULING PROBLEM (RCSP)

1. Scheduling Problems

A scheduling problem can be considered one of two types: deterministic or non-deterministic. In a deterministic problem, the durations of each task are fixed. A non-deterministic approach acknowledges the general uncertainty that most project managers face when predicting task durations. Through the 1970s and 1980s, deterministic scheduling problems were solved using linear programming, dynamic programming, or branch and bound techniques.

As Tarek Hegazy points out "Resource allocation and leveling are among the top challenges in project management." His 1999 paper used genetic algorithms for deterministic RCSP.[31] As noted by Hartmann and Briskorn in a 2010 survey, the RCSP "has become a standard problem for project scheduling in the literature."[32] The previous linear programming and dynamic programming techniques had solved general scheduling problems that were not constrained with resource limits. With the additional constraint of resources considered in the scheduling problem, researchers turned to genetic algorithms as the heuristic of choice to achieve near-optimal solutions in a timely computational manner.

One of the first solutions to the resource constrained scheduling problem (RCSP) under uncertainty, or non-deterministic, was in 2001 by Leu and Hung using genetic algorithms.[33] In 2007, Lu, Lam, and Dai analyzed a RCSP with discrete event simulation and particle swarm optimization, a newer type of genetic algorithm.[34] Particle Swarm

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[31] Tarek Hegazy, "Optimization of Resource Allocation and Leveling Using Genetic Algorithms," (*Journal of Construction Engineering and Management,* 125.1: 1999), 167.

[32] Sonke Hartmann and Dirk Briskorn, "A Survey of Variants and Extensions of the Resource-Constrained Project Scheduling Problem," (European Journal of Operational Research, 207.1: 2009), 1.

[33] Sou-Sent Leu and Tzung-Heng Hung, "A Genetic Algorithm-Based Optimal Resource-Constrained Scheduling Simulation Model," (Construction Management and Economics, 20.1: 2002), 132.

[34] Ming Lu, et al., "Resource-Constrained Critical Path Analysis Based on Discrete Event Simulation and Particle Swarm Optimization," (Automation in Construction, 17.1: 2008), 670.

Optimization Particle (PSO), another heuristic technique, was originally developed in 1995 by Kennedy and Eberhart to solve single unconstrained objective optimization problems. Convergence criteria were not added until 2006. With the addition of the convergence criteria, PSO could then be applied to the multi-objective optimization in a RCSP.

In 2011, Gabriel Burnett's dissertation used genetic algorithms to solve a RCSP for new construction of Virginia class submarines. He summarized how the gap between theory and practice often impacts academia and real-world practitioners of project management. Assumptions in literature often are restrictive and oversimplify the problem.[35] For instance, assumptions are made about the number of constraints that can be considered, or resources are unlimited. Other times, the relationship between work hours and percent task complete is considered linear. These simplifications transform the problems solved by academia into potentially oversimplified versions of problems faced by Project Managers.

Burnett's analysis of new construction data, versus repair, did "implicitly assume that processing time estimates are fairly accurate."[36] As he states, his use of real-world data and resource constraints on a low-volume problem addressed "an important real world problem that has not been adequately addressed in the literature."[37] This thesis takes another approach to that work by focusing on repair maintenance projects where the time estimates are no longer considered "fairly accurate." The reason that submarine repair schedules are more uncertain than new build schedules is that the repair work is conditional upon the actual state (e.g., corrosion, wear and tear, etc….) of equipment that has already been in use. Discovery of the extent of repair work can often only be made in detail once the equipment in question has been exposed and inspected. Furthermore, repair is often done of submarines whose nuclear reactor is operational and this imposes additional constraints that are not present during most phases of new construction

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[35] Gabriel Burnett, "*Multiple Objective Assembly Scheduling with Spatial Resources and Recurring Tasks,"* (Pennsylvania State University, 2011), 3.

[36] Ibid., 7.

[37] Ibid., 10.

projects. The only exception is new construction nuclear powered ships who have the nuclear reactor operating soon before ship construction is complete.

2. NP-Hard Problems

As discussed in the introduction, NP-hard is a category of problems in computational complexity theory. Computational complexity theory was developed in the 1970s for categorizing the algorithms that were increasingly executed on computers. Even with increased computer speed, some problems that seemed straightforward could still take years for a computer to solve. A problem is NP-hard and considered inherently difficult when there does not exist an efficient algorithm with a "number of operations that is polynomial in the size of the input data"[38]

Calculating the minimal makespan of a project is a variation of the shortest path problem. Often, network analysis models would solve the dual, or find the maximum series of task durations before a project could be completed. Effectively, solving this critical chain problem answers the shortest makespan.[39] Minimizing the makespan in a project schedule can be considered a subset of the constrained shortest path problem, an identified NP-hard problem.

Currently, the Naval Shipyards do not use any optimization techniques in minimizing the makespan, but rely on rules of thumb that have been established from prior experience. The scheduling methods of AIM-NG are not optimization heuristics but short-term scheduling aids classified in the literature as "priority rules."[40] These methods avoid the complexity of the NP-hard problem but also suffer in not providing the level of result of an NP-hard heuristic.

The size of the typical shipyard scheduling problem (4000 or more tasks and 7000 or more constraints) cannot generally be solved explicitly in linear time. Instead, using genetic algorithms as the heuristic to develop a near-optimal solution is a reasonable

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[38] Ravindra Ahuja, et al., *Network Flows: Theory, Algorithms, and Applications* (Englewood Cliffs, NJ: Prentice Hall, 1993), 788.

[39] Ibid., 733.

[40] Tyson R. Browning and Ali A. Yassine, "Resource-Constrained Multi-Project Scheduling: Priority Rule Performance Revisited," (International Journal of Production Economics 1.126, 2010): 212.

choice. The results of the optimization will not give an absolute guarantee of global optimality but represent a significant improvement over current practice.

3. Submarine Repair Difficulty

Submarine repair schedules are some of the most complex schedules seen in project management. The system complexity, the tight spaces, the nuclear reactor, the challenges inherent in repair, and resource competition all contribute to a dense integrated schedule. Making progress in improving scheduling in submarines will aid project management study of other scheduling problems.

a. System Complexity

One obvious aspect of a submarine is the tremendous hardware and software complexity. General Dynamic's, Electric Boat division, is one of two shipyards in the United States building the new Virginia class fast attack submarine. A case study on its construction practices highlighted the differences in project size with Table 3 by comparing a submarine to an M-1 tank and a Boeing 777 airplane.

	M-1 Battle Tank	**Boeing 777 Airliner**	**Virginia Class Submarine**
Weight (tons)	65	250	7800
Length (foot)	25	200	377
Number of Systems	25	40	200
Crew Size	4	10 (2 pilots)	113
Patrol Duration (hour)	24	8-14	2,000
Number of Parts to Assemble	14,000	100,000	1,000,000
Assembly (man-hours/unit)	5,500	50,000	>10,000,000
Production Time (months)	7.5	14	55
Production Rate (units/year)	600	72	0.5-3

Table 3. Comparing Complex Systems[41]

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[41] The Virginia Class Submarine Program: A Case Study, (Groton, CT: General Dynamics Electric Boat, 2002), 6.

Given the complexity of the system, a 20-month maintenance availability on a submarine can have nearly 8,000 repair tasks in the schedule. Each task can range from taking one shift up to 99 shifts in duration. Each shift is eight hours. Not only are there lots of tasks, but the low rate of production in shipbuilding limits the implementation of many Lean and other business initiatives more easily implemented on assembly line construction with many repeat builds. Nevertheless, improvements and a learning curve are also possible in shipyards as exemplified by the AIM-NG results discussed above for the 2008-2011 period.

b. Physical Constraints – Size of Submarine

As shown in Figure 4, a submarine has tight quarters and can be very confining for maintenance work. Inherent in its design, many of the subsystems must be co-located. For example, the aft end of the engine room, known as shaft alley, has the main propulsion shaft components and the hydraulic rams for the stern planes and rudder. Maintenance on these systems must be sequenced carefully so that workers on different systems are not competing for space and interfering with each other's actions. These additional co-location constraints add another layer of difficulty in submarine repair. In general, surface ships can be designed to allow for easier maintenance access to system components compared to submarines.[42]

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[42] Roy Burcher and Louis Rydill, *Concepts in Submarine Design* (Cambridge, UK: Cambridge University Press, 1998), 131.

Figure 4. Troubleshooting Aboard a Los Angeles Class Fast Attack Submarine[43]

c. Operating Nuclear Reactor

All U.S. fast attack submarines since USS Providence in 1985 have nuclear reactors onboard that last the lifetime of the ship.[44] Since the nuclear reactor remains operational throughout its depot maintenance, numerous subsystems must remain operational or have equivalent off-hull temporary systems. Hydraulic, electrical, and air systems must be operational to keep the nuclear reactor safe. Necessary maintenance must be conducted on one system while a backup system (permanently installed or temporary off-hull) provides support for the reactor. All of the steps needed to maintain reactor safety add yet another layer of difficulty in conducting submarine depot

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[43] U.S. Navy photo by Mass Communication Specialist 2nd Class Steven Khor, <http://www.navy.mil/view_single.asp?id=135041>

[44] *The United States Naval Nuclear Propulsion Program*, (Department of Energy, March 2009), 51.

maintenance. In contrast, a conventionally powered ship would de-energize and depressurize systems making maintenance simpler to plan and execute because of the presence of only inert components and systems.

d. Repair vice Construction

Scheduling maintenance on a submarine is also inherently more challenging than new construction because of the many unknowns. A common source of uncertainty independent of the actions of project manager is whether the maintenance task being performed requires more hours than originally scheduled. For example, when opening and inspecting tanks onboard the submarine, it is expected that the tanks may require some minimal amount of abrasive blasting and painting to refurbish due to corrosion. However, sometimes the existing corrosive protection system may have failed in the years since the tank was last opened and the work to restore the tank may grow from 40 hours of work to 320 hours.[45]

e. Program Management vice Project Management

Finally, the last challenge to submarine scheduling is due to a constraint at the shipyards. The four public naval shipyards each have approximately three to four drydocks to perform maintenance. At any one time, a shipyard might have a submarine nearing completion of its maintenance availability, a drydocked submarine a few weeks into a six-month availability, another submarine in drydock with 12 months remaining, and a final submarine in the middle of a six-month availability. The balancing of these competing projects requires careful coordination between the shipyard's operations officer and resource managers.

B. SCHEDULING TOOLS

In 2006, the public shipyards conducted their first critical chain project management schedule on the Engineered Overhaul of the USS Montpelier in Portsmouth

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[45] Dave Brodeur, Personal interview, 1 June 2012.

Naval Shipyard. For scheduling, the shipyard used Microsoft Project. The overhaul schedule was broken up between seventeen individual Microsoft Project files.[46]

Soon after, the four public shipyards shifted to the scheduling tool Concerto, which had an embedded critical chain algorithm. However, when Concerto leveled workload across projects, it proved inefficient. At the start of a schedule, nearly all activities were green (excessive float or slack) and over time most activities shifted to red priority (critical path). This was clearly unacceptable.[47]

The scheduling tool currently used by all four U.S. public naval shipyards is the Project Scheduling System (PSS). The core of PSS is a program named CAT written by Robbins-Gioia, LLC (a project management consulting group in Alexandria, VA). The PSS tool is a Government Off the Shelf (GOTS) program top-loaded onto CAT giving the shipyard extra abilities (e.g., naming key events and milestones, ties for testing ...). Each naval shipyard has a programmer on staff who maintains customized updates to the program. Currently, Robbins-Gioia is developing Jaguar, a web-based client server scheduling tool similar to PSS. The U.S. Navy has not made a commitment to shift tools considering the existing overhead and commitment to PSS.[48]

In the PSS software the only automatic scheduling is a "resource" button which automatically schedules tasks and aligns them with the resource plan. The AIM-NG manual prohibits using this function as the shipyards have assessed that the tool does not properly match schedule constraints. Generally, when executing this function, too many tasks are pushed to the left and the proposed schedule is unfeasible. Instead, PSS is used to track the current schedule; it uses no heuristics or optimization methods.[49]

While the resource leveling tool in PSS is the right approach, there are a number of reasons the current system can fail. The projected workload does not include new work, even if it is expected. Also, it assumes a 1.0 Cost Performance, where a CP of less

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[46] Dave Brodeur, Personal interview, 1 June 2012.

[47] Ibid.

[48] Ibid.

[49] Ibid.

than 1.0 would require additional resources not accounted for. It also shows resource needs and availability (i.e., resource pools) for inside shop work and not just the particular project. Every night at the shipyards, PSS interacts with the WebAIM tool by taking a forward pass and backward pass through all project schedules and determining the critical path of each project. The forward pass determines early start and early finish dates. The backward pass determines late start and late finish dates. Then, the WebAIM tool can prioritize each task by calculating float or slack as discussed in Chapter I, section A.4.[50]

Meanwhile, Electric Boat, a new construction submarine shipyard, uses Artemis. Artemis is a larger enterprise software solution that includes investment, asset manager, and other company operations besides project management. Electric Boat has not dedicated IT resources to develop and maintain a customized scheduling tool such as PSS.[51]

In 2011, the U.S. Navy began preliminary planning to shift their scheduling tool to Primavera. This tool, owned by Oracle, is one of the premier commercial scheduling tools. Projects that used Primavera include Boston's Big Dig and Kuala Lumpur's Petronas towers. However, current U.S. Navy testing with Primavera has shown significant issues when attempting to process a submarine Engineered Overhaul schedule. Many of these issues have been the difficulty with the enterprise solution of shifting from PSS to a new system that requires changing interfaces with other programs. Any method that builds upon PSS would eliminate these transition issues.[52]

C. OPTIMIZATION IN RESOURCE ALLOCATION

To minimize the makespan, the project manager can either accelerate the individual task durations, or change the ties in the network to reduce the length. Task durations can often be reduced by adding additional personnel. However, some tasks do not have a linear relationship between the number of workers assigned and the resulting

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[50] Mike Boisseau, "Lean Release," Project Management Fundamentals (Pearl Harbor, HI: 9 July 2009).

[51] Dave Brodeur, Personal interview, 1 June 2012.

[52] Ibid.

task duration. For instance, in a small space, an additional worker may not be able to help paint. The work duration cannot be reduced any further. Sometimes, physical processes such as paint curing or welding require a set amount of time. Additional workers cannot reduce these durations either. A full optimization of a schedule to reduce the makespan would need such details for each individual task.

In practice, shipyard managers re-allocate resources to each project on a periodic basis. At the U.S. public naval shipyards there is a weekly resource allocation meeting. Each program manager uses their updated schedule to petition for different resources. The shipyard operations officer and resource manager make the final decision on allocating resources for the next week.[53] Often, additional resources are requested to reduce the duration of ongoing tasks. Optimizing the resource allocation to reduce the overall makespan is a NP-hard problem.

D. FLAW OF AVERAGES

In 2000, Sam Savage, from Stanford University, coined the term "flaw of averages" to emphasize the common misunderstanding of risk under uncertainty. Managers often make decisions under uncertainty with the flawed assumption that averaging a large amount of inputs will result in an average outcome. As de Neufville and Scholtes state, "it is not correct to calculate the average value of a project based on its performance under average conditions."[54] This is exactly the temptation that project managers face when dealing with point estimates in the traditional critical path method.

Currently, at U.S. Naval shipyards, each trade supervisor (e.g., electrician or welder supervisor) conducts a job summary review for all tasks under their purview. This takes place up to six months before the availability start. Depending on the task complexity, a team reviewing a task could include engineers, supervisors, shop foreman and other process owners. The team reviews past projects, recent improvements or problems related to the task, and then develop an estimate for the task duration.

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[53] *Requirement for Management of Workforce Resources in Naval Shipyards*. NAVSEAINST 4850.11 (Washington, D.C.: Naval Sea Systems Command, 15 January 2010), 5.

[54] Richard de Neufville and Stefan Scholtes, *Flexibility in Engineering Design*, (Cambridge, MA: 2011), 17.

Although a range of durations is discussed, the only option that the supervisor has is to provide a point estimate of the duration to build the schedule.

The flaw of averages is evidenced when the project managers then build a schedule from thousands of point estimates and must ignore the underlying uncertainty in each task. It is assumed that the variability will "average out" and buffers are inserted to account for the risk of uncertainty. The tasks within the schedule are not independent when considering the overall makespan. Each of the tasks can come from many nonlinear, often discontinuous functions. This is the subject of Sam Savage's flaw of averages. Using simulation can account for the nonlinear nature of the project's duration impacted by the uncertain task durations that compose the project network.

E. IMPACT OF SCHEDULING

Overall, the literature in project management is clear that scheduling is crucial. For naval shipyard projects, it is estimated that over 70 percent of project costs are labor related. Much of this labor expense is tied to scheduling. Therefore, poor scheduling of resources can waste the primary resource and expense of the project.[55] Meanwhile, First Marine International, a British shipbuilding consultant firm, concluded in a 2005 study that "planning and scheduling are weak points in the U.S. shipbuilding industry."[56]

Giving project managers direct access to the scheduling tools to conduct what-if analysis and an increased level of understanding is a common point of discussion in the project management literature.[57] However, a 2004 survey of 735 project management personnel showed that over 60% did not use software for simulation or scenario analysis.[58] Given the large scope of work for shipyards however, the option should not be overlooked.

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[55] Mike Boisseau, "Lean Release," Project Management Fundamentals (Pearl Harbor, HI: 9 July 2009).

[56] First Marine International Findings for the Global Benchmarking Industrial Base Benchmarking Study, Part 1: Major Shipyards, (London: First Marine International, August 2005), 20.

[57] Gabriel Burnett, "*Multiple Objective Assembly Scheduling with Spatial Resources and Recurring Tasks,"* (Pennsylvania State University, 2011), 31.

[58] Claude Besner and Brian Hobbs, "An Empirical Investigation of Project Management Practice: In Reality, Which Tools do Practitioners Use?" (University of Quebec, 2004), 4.

In 2010, Pearl Harbor Naval Shipyard executed an Engineered Overhaul (EOH) on the USS Chicago. This overhaul was executed with the new scheduling functionality of WebAIM and the AIM-NG process. As shown in Figure 5, the Chicago project's improvements in cost performance compared to previous overhauls of equivalent vessels was the equivalent of over 21,400 resource-days. This is nearly 10% of the overall project manning that had a baseline schedule of 240,000 resource-days.

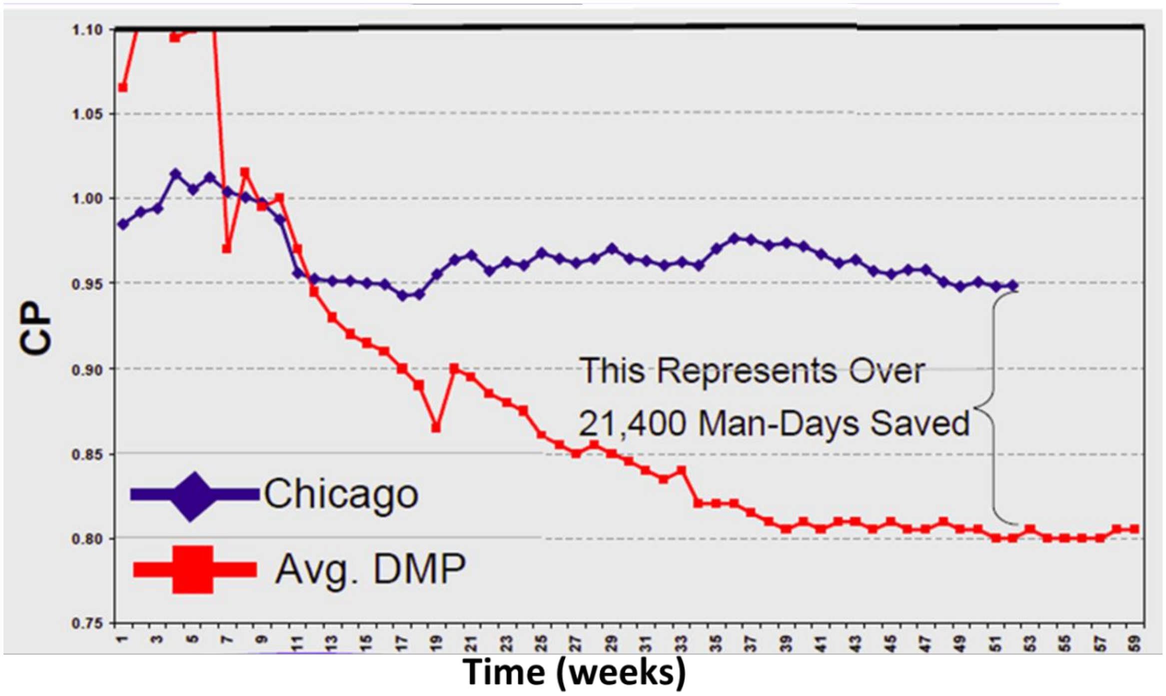

Figure 5. USS Chicago's Cost Performance (CP) Improvements by using AIM-NG Processes and Improved Scheduling[59]

F. SUMMARY

Overall, the literature review showed that RCSP is applicable to U.S. Naval shipyards. The shipyards are certainly resource constrained. Also, submarine repair offers multiple unique challenges making it a difficult case for project management scheduling. The current methods at the shipyards rely on process rule prioritization vice optimization techniques. Also, point estimates for duration are relied upon to build the

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[59] Mike Boisseau, "Monthly Project Management Lean Release 2.0/3.0 Implementation Results," (NAVSEA, 4 October 2011), 12.

project network and buffers are used to assume the risk of the uncertainty. Instead, this thesis proposes simulation and optimization techniques to account for the uncertainty and solve the RCSP using a heuristic genetic algorithm (GA) that can handle realistic precedence and resource availability constraints.

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III. DATA SET

A. DATA DESCRIPTION

The data set provided as a basis for this research is a notional submarine overhaul schedule. The data is notional since full submarine maintenance availability information would indicate expected lifetime of the equipment. The data was created by NAVSEA to give industry a sample data set to test future developments in scheduling software. Specifically, NAVSEA provided this data set to test Oracle's Primavera software.[60] The MIT PIE study continues to seek data for new construction naval shipyards. At the time of publishing, this data was unavailable for comparison.

The data set includes 4038 individual tasks and 7723 constraints or ties. The tasks durations are measured in units of shifts where a shift is equal to an eight-hour work day. The maximum number of shifts that the four public shipyards use is 99 since the current software limits entry to two-digits. The Work Breakdown Structure (WBS) of the notional data has longer task durations to adjust the overall project schedule duration to match a real data set. The notional data set does not include the nuclear-related tasks.[61]

The data's 7723 ties are either strategic or technical ties. A technical tie is made between jobs when task X must be completed prior to task Y starting. For example, inspection of a tank has a technical tie to the task of opening the tank. In contrast, a strategic tie is not required but has other strategic rationale: perhaps part of a strategy or to sequence work. For example, two systems co-located in the same small area on a submarine may have strategic constraints set to finish work on the first system before starting work on the second adjacent system.[62] For the 7723 constraints in the data, some are assumed to be strategic while others are technical. However, the data does not clearly differentiate the type. In a working schedule, this information would be available by questioning the supervisors.

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[60] Dave Brodeur, Personal interview, 1 June 2012.

[61] Ibid.

[62] AIM-NG Process Manual, Chapter 6A, Execution Priorities (Washington, DC: Naval Sea Systems Command, 2009), 13.

B. FORMATTING DATA

The date provided by the Navy is written as a "*.csv" or comma separated value file saved to Microsoft Excel. This is the format exported by the current Navy scheduling tool, Project Scheduling System (PSS). The data was successfully loaded into both the Microsoft Project 2010 and 2013 versions. Details of importing the data and properly formatting it with Microsoft Project are listed in Appendix A.

C. DATA ASSESSMENT

The data set was initially assessed using the @Risk audit tool. The three "error" types identified were: 1) No successor tasks, 2) No predecessor tasks, and 3) Tasks out of sequence. For the no successors or no predecessors, these "errors" are generally allowed in accordance with the shipyard's AIM-NG instruction. For no predecessors, AIM-NG requires that such tasks with "planned starts" be limited to no more than five percent of the total number of tasks.[63] However, the tasks out of sequence errors also violated the process rules in AIM-NG. These errors were corrected in two ways. First, if a task had multiple predecessors that were valid, the predecessor that was out of sequence was deleted. Second, if the only predecessors listed were out of sequence, then a new predecessor was identified that was in sequence and was consistent with the task description. The audit results are included in Appendix B.

D. NAMING STRUCTURE

The description of each task includes a job order code used by the four public shipyards as shown in Figure 6. In the notional data set, the project is designated as "BAT." The Job Order number comes from the work summary that is reviewed by a relevant supervisor during the planning phase when the initial duration is estimated. The "Key op" entry is the Key Operation done in the task for a specific "cuphase" or Component Unit phase. For instance, "H" would indicate off ship repair.

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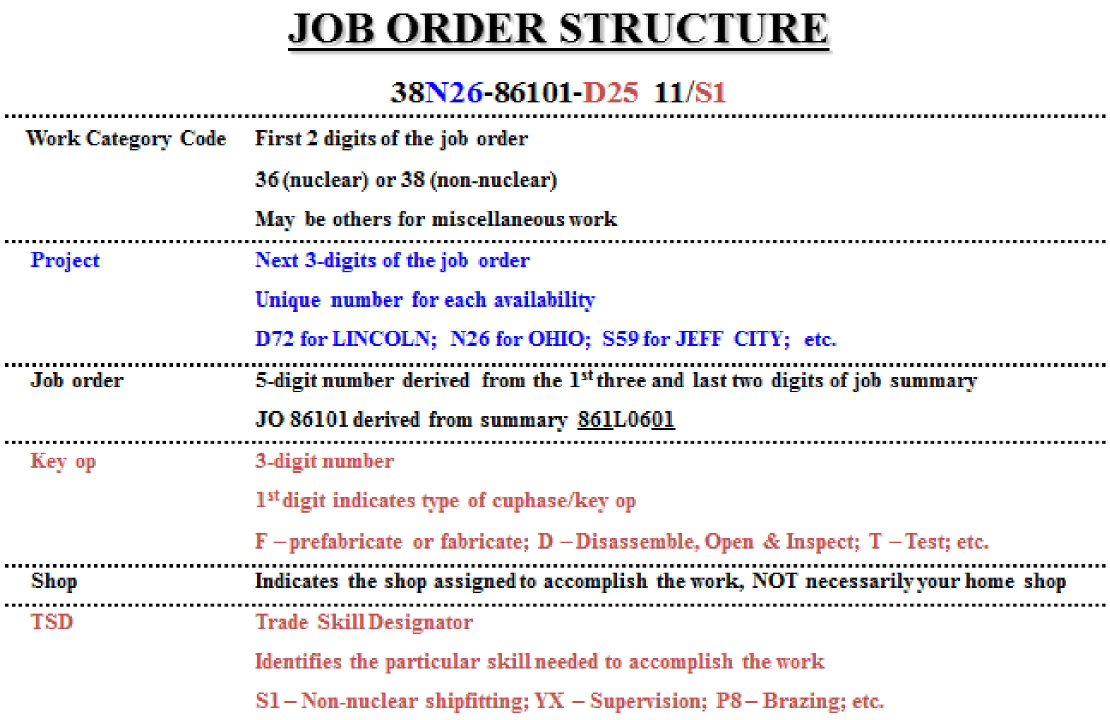
[63] AIM-NG Process Manual, Chapter 6A, Execution Priorities (Washington, DC: Naval Sea Systems Command, 2009), 23.



JOB ORDER STRUCTURE

38N26-86101-D25 11/S1

Work Category Code	First 2 digits of the job order 36 (nuclear) or 38 (non-nuclear) May be others for miscellaneous work
Project	Next 3-digits of the job order Unique number for each availability D72 for LINCOLN; N26 for OHIO; S59 for JEFF CITY; etc.
Job order	5-digit number derived from the 1st three and last two digits of job summary JO 86101 derived from summary 861L0601
Key op	3-digit number 1st digit indicates type of cuphase/key op F – prefabricate or fabricate; D – Disassemble, Open & Inspect; T – Test; etc.
Shop	Indicates the shop assigned to accomplish the work, NOT necessarily your home shop
TSD	Trade Skill Designator Identifies the particular skill needed to accomplish the work S1 – Non-nuclear shipfitting; YX – Supervision; P8 – Brazing; etc.

Figure 6. NAVSEA Job Order Structure[64] Provides Unique Task ID

The other code used in task descriptions is the Key Event or Milestone description. These are fully listed in the appendices of the NAVSEA Baseline Project Management Plan, instruction NAVSEAINST 4790.23. For instance SA00 is the "Start of the Availability" while CA00 is the "Completion of the Availability."[65]

For resources, the data includes two-digit shop descriptions. The public shipyards shop numbering evolved over time and have no clear logical pattern. A summary of the shop system for PHNSY is included in Table 4. Other naval shipyards may have slightly differing organizations. Of note, even though a welder may be identified in X26, there exist specific Trade Skill Designators (TSDs) that further differentiate the skill sets within each shop. For instance, a welder may be qualified for different types of welds

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[64] Mike Boisseau, "Lean Release," Project Management Fundamentals (Pearl Harbor, HI: 9 July 2009).

[65] Baseline AIM Process Manual, Version C (Washington, D.C.: Naval Sea Systems Command, 1997), E1-E9.

(e.g., TIG or MIG) and that TSD will be listed in the job summary description for the individual task.

Shop Code	Description
C920	Structural Shops (Shops 11, 17, 26)
X11	Shipfitter
X17	Sheet metal
X26	Welders
C930	Mechanical Shops (Shops 31, 38, 41)
X31	Inside Machine Shop
X38	Marine Machinery Mechanical
X38M6	Marine Machinery Mechanical - Hydraulics
X41	Boilermaker
C950	Electrical (Shops 51, 52, 67)
X51	Electrical
X52	Calibration Lab
X67	Electronics Shop
C960	Pipe and Temporary Ship Systems (Shops 06, 56, 99)
X06	Tool Room
X56	Pipefitting and Refrigeration
X99	Temporary Services
C970	Service Shops (64, 71, 72)
X64	Shipwrights
X71	Painters
X72	Non-Nuclear Cleaners
C700	Lifting and Handling Department (Shop 98)
X98	Riggers (crane support)
C760	Divers

Table 4. Code (C) and Shop (X) Descriptions

IV. ALGORITHM IMPLEMENTATION

A. ALGORITHM DESCRIPTION

To maximize the chance that results could be used at a shipyard, the analysis tool was chosen from a readily-available software package. A more academic tool, or computer code analysis package, would likely be relegated to obscurity for shipyard implementation. The tools chosen were "@Risk" and "Evolver," both included in a software package available from Palisade software. The software is an add-on to Microsoft Excel and can also interface directly with Microsoft Project. The current shipyard scheduling tool, PSS, already has export features (*.csv format discussed in Chapter III), that make it readily compatible with Microsoft Project, and hence @Risk.

1. @Risk

The @Risk software package is built around Monte Carlo simulations executed in Microsoft Excel. When executing simulations with project data, the program synchronizes data between Microsoft Project and Excel. The @Risk software includes a selection of probability distributions and sensitivity analysis options. A key aspect of selecting the @Risk software was to ensure implementation ease at the public naval shipyards. This software has been on the market since the 1980s and has been frequently updated. It includes expansive examples, instruction details, and online help. Another algorithm may not be easily executable by the public shipyards or have the established support of @Risk.

2. Evolver

Evolver is another add-on to Excel that uses genetic algorithms, Tabu search, neural networks, linear programming and integer programming to solve optimization problems. Developed in 1990, it was the first genetic algorithm software commercially available. It currently comes with the optional Decision Tools Suite for @Risk.[68]

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[68] http://www.palisade.com/evolver/

Genetic algorithms are a common heuristic chosen to solve NP-hard resource constrained scheduling problems.

B. ALGORITHM EXECUTION

1. Varying Each Task Duration

The first experiment executed was to vary the duration of each task by plus or minus 10 percent. Currently, the naval shipyards use point estimates for the duration of every task in the schedule. During the planning stage when supervisors conduct job summary reviews, the supervisors often have a range estimate for the task duration. This simulation was meant to simply model this level of individual task variation.

Using the "Parameter Entry Table" option within @Risk, the 4038 tasks were each assigned a triangle distribution. The triangle distribution was chosen for its simplicity and ease of defining parameters. This is anticipation of future implementation at the naval shipyards. Supervisors could likely assign the minimum, maximum, and most likely duration. More advanced probability distributions are beyond the training and background of most shipyards supervisors and managers. For this reason, it is often used as an initial distribution in project management simulations.

For the triangle distribution, the minimum was assigned as minus 10 percent of the point estimate duration and the maximum being plus 10 percent. Then the overall project was simulated with 100 iterations. The project finish date was assigned as the @Risk output. Results of this experiment are shown in Chapter V.

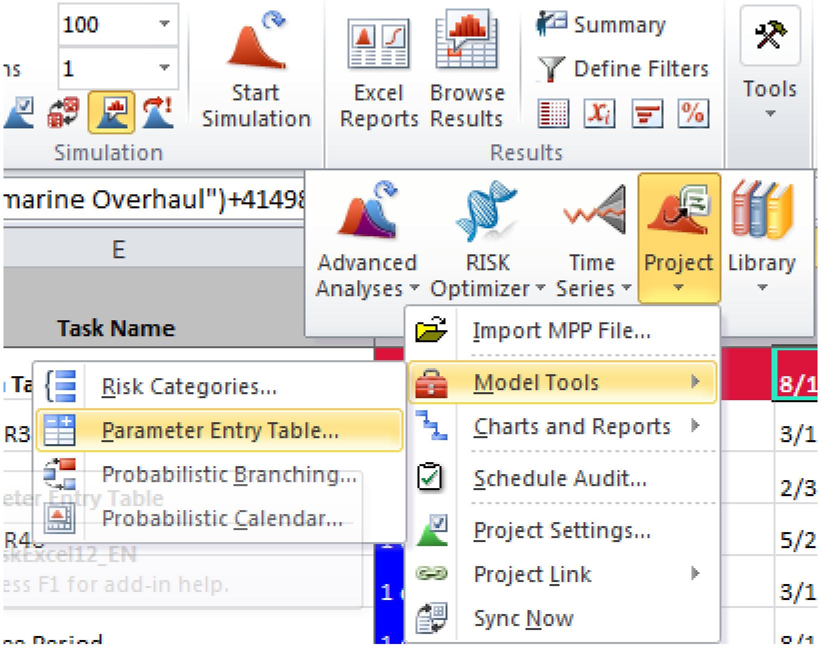
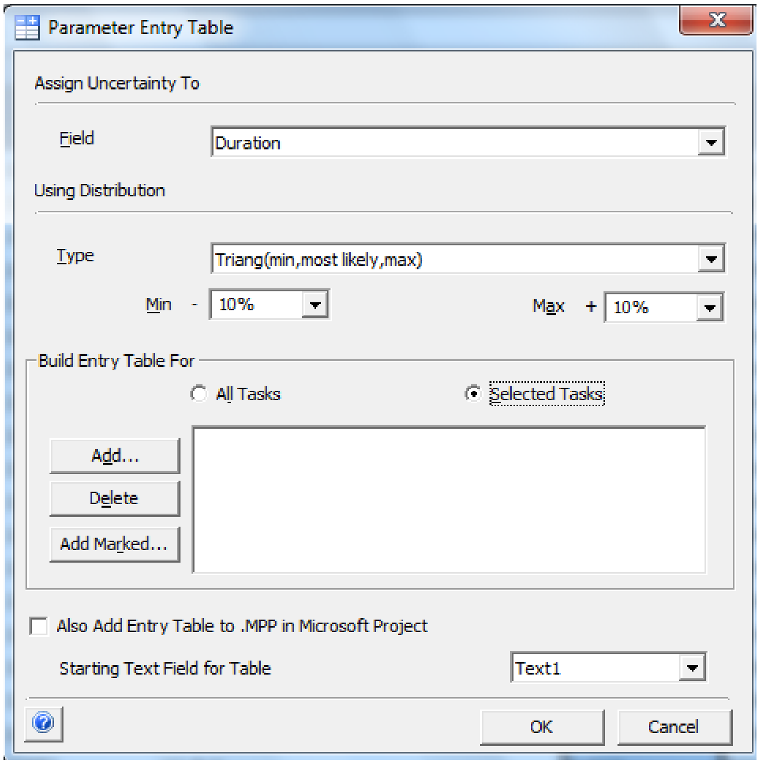


Figure 7. Accessing the Parameter Entry Table in @Risk



Assign Uncertainty To

Field: Duration

Using Distribution

Type: Triang(min,most likely,max)

Min - 10%   Max + 10%

Build Entry Table For

○ All Tasks   ● Selected Tasks

☐ Also Add Entry Table to .MPP in Microsoft Project

Starting Text Field for Table: Text1

Figure 8. Modifying Durations in the @Risk Parameter Entry Table

2. Variation on Critical Path

The next experiment executed was to vary the estimated duration of key tasks in the critical path. While the first analysis took a general 10% variability to all of the tasks estimated durations, the shipyard typically has more detailed data of specific critical tasks. For instance, repairing the main ballast tanks of a submarine is often on the critical path of a submarine repair plan. Simply, the drydock cannot be flooded until this work is complete. Therefore, the shipyards have detailed histories on the variability of the tasks related to inspecting, sand blasting, repairing, and painting of the main ballast tank system.

This analysis step shows how variability of key tasks (while holding other task durations as constant), still has a significant impact on the overall schedule. Often, this variability is unknown and cannot be forecasted. For instance, the physical condition of a main ballast tank can only be estimated until an inspector first enters the tank.

Specifically, in @Risk, the top 10 task durations that affected the finish date from the simulation in Section B.1 were then confirmed in the critical path. These durations were then adjusted to Triangle distributions with the minimum being minus 20 percent of the point estimate duration and the maximum being plus 20 percent. Then the overall project was simulated with 100 iterations. The remaining 4028 tasks had their durations fixed at the original point estimate.

This simulation demonstrates a more realistic project management problem where specific tasks may have detailed estimates of variation in task duration while only point estimates may be available for other tasks. For instance, a shipyard knows how long blasting and painting ballast tanks has taken on the last few projects since it commonly falls on the critical path. The project finish date was assigned as the @Risk output. Results are discussed in Chapter V.

3. Optimizing Resource Allocation to Minimize the Makespan

To simulate the shipyard's weekly resource allocation, a portion of the schedule was selected to represent one-week of data to test. The @Risk and Evolver software were used to optimize resource allocation to minimize the makespan. The baseline for this model was the "Scheduling Job Tasks on Machines with Uncertainty" example file provided with @Risk. The file provided a template for the simulation that the submarine data could be easily inserted into. Data output analyzed included the primary objective function to minimize the makespan (in 8-hour shifts). Other output analyzed included the total shop idle time (in 8-hour shifts), the number of workers, and the total task time (in man hours).

The assumptions made in this model include:

- Duration of each job task follows a normal distribution with standard deviation as a percentage of the mean. The mean was set as the estimated task duration (used in the fixed model). The standard deviation was taken as 20% of the mean.
- Task duration varies linearly with the number of workers assigned to the task. For instance if the task takes 40 hours, it would be completed in 20 hours if two workers are assigned.
- Work is blocked in 8-hour shifts so that hours are rounded to the number of shifts. For instance, a 6-hour job is considered 1-shift.

The decision rule implemented in the simulation was a simplified rule that matches a common management decision. Since most workers are scheduled for Monday-Friday, one shift a day, then a 5-shift, or 40-hour, job should take a worker one week. Therefore, additional workers are added to any job scheduled over 40-hours to keep the task completion time within one work week. If the job is between 120 and 160 hours, four total workers were assigned. If between 80 and 120 hours, three total workers were assigned. If the job was between 40 hours to 80 hours, two total workers were assigned. Only if the job was less than 40 hours was only one worker assigned.

There were a total of 25 tasks with five different worker types. The number of tasks was divided evenly so that each worker type needed to do five tasks. The five worker types included: Welder (shop 26), Electrician (shop 51), Mechanic (shop 38), Inside Machine Shop (shop 31), and Shipwright (shop 64). For the sample data, the mean task time estimate (in man hours) varied from 2 to 99. The task duration was rounded to eight-hour shifts as well for some data calculations.

Table 5 shows the 25 tasks mapped to the five worker types. The fourth column, “Mean task time estimate (man hours)” represented no additional management decision to allocate additional resources. This was considered the “fixed design.” In comparison, the fifth column, “Actual task time (man hours)” was used for additional resource allocation. This actual time was taken as a normal distribution centered on the estimate with a standard deviation of 20% of the mean. Allocating additional workers was considered the “flexible design.” The sixth column, “# Workers,” was set so that an additional worker was assigned for every 40 hours of work. This matches a short-cut planning approach that could be implemented where managers try to keep the task duration within one week of completion. For example, a 75-hour job could be completed by two workers in one week (each doing 8-hour days for five days).

Task ID	Job ID	Work Shop required	Mean task time Estimate (manhrs)	Actual Task time (manhrs)	# Workers	Total Task Time (manhrs)	Task Time (shifts)
1	1	1	64	64.00	2	32	4.00
2	1	2	32	32.00	1	32	4.00
3	1	3	29	29.00	1	29	4.00
4	1	4	32	32.00	1	32	4.00
5	1	5	48	48.00	2	24	3.00
6	2	1	6	6.00	1	6	1.00
7	2	2	72	72.00	2	36	5.00
8	2	3	24	24.00	1	24	3.00
9	2	4	7	7.00	1	7	1.00
10	2	5	11	11.00	1	11	2.00
11	3	1	14	14.00	1	14	2.00
12	3	2	10	10.00	1	10	2.00
13	3	3	18	18.00	1	18	3.00
14	3	4	2	2.00	1	2	1.00
15	3	5	88	88.00	3	29	4.00
16	4	1	36	36.00	1	36	5.00
17	4	2	22	22.00	1	22	3.00
18	4	3	99	99.00	3	33	5.00
19	4	4	74	74.00	2	37	5.00
20	4	5	12	12.00	1	12	2.00
21	5	1	77	77.00	2	39	5.00
22	5	2	44	44.00	2	22	3.00
23	5	3	15	15.00	1	15	2.00
24	5	4	10	10.00	1	10	2.00
25	5	5	70	70.00	2	35	5.00

Table 5. Task IDs Mapped to Five Worker Types for Smaller Experiment with 25 Tasks and Uncertain Task Durations

For the full data set of 4038 tasks, more detailed knowledge would be needed since many tasks durations cannot simply be compressed by adding more personnel. The simulation on the 25 tasks was run with 1000 iterations. This simulation uses the Evolver tool within @Risk. Results are presented in Chapter V.

C. SUMMARY

The algorithms chosen on the data can all be implemented relatively easily with little additional software than the naval shipyards currently use. The shipyard's PSS tool has the capability to export data into comma separated value (*.csv) format which can then be loaded into Microsoft Excel and then Microsoft Power Point. The @Risk software package from Palisade software is an add-on to Excel and with the latest release, version 6.1, it synchronizes directly with Project.

The first experiment chosen was to vary all 4038 tasks by plus or minus ten percent duration (with a triangle distribution). Almost every task in a submarine overhaul has some variability in the duration. Ten percent was chosen since it is a simple representation of an average expected variability across all tasks. However, a more detailed data set might reveal that some tasks have much wider variability, twenty percent or more.

The second experiment was run on ten crucial tasks that have high impact on the overall makespan. These tasks were simulated with variability (a triangle distribution) of plus or minus twenty percent. This larger variability was chosen to represent the more likely variability seen on some of the more challenging critical path tasks in a submarine overhaul. The complexity of some of these more crucial tasks typically have wider variability for some of the reasons listed in Chapter II, section 3.

The final experiment was an optimization of the RCSP for a subset of the data, 25 tasks. Again, all 4038 tasks have individualized relationships between resources and duration. Often, more workers would not be able to necessarily speed up a task's duration. The data set would have to include much more robust information to properly model the RCSP for the entire project makespan. With the level of information currently in the data set, the amount of assumptions necessary to optimize the entire schedule would render the results irrelevant to a real submarine overhaul.

V. ANALYSIS AND RESULTS

A. ALGORITHM ANALYSIS

1. Varying Each Task Duration

After assigning a triangle distribution to each task's duration of plus or minus 10 percent, the @Risk simulation was run with 100 iterations. With the original point estimates for each task's duration, the overall project was scheduled for 640 days with a start date of 3/1/2011 and finish date of 8/12/2013. The output of the @Risk simulation is shown in Figure 9 and Table 6.

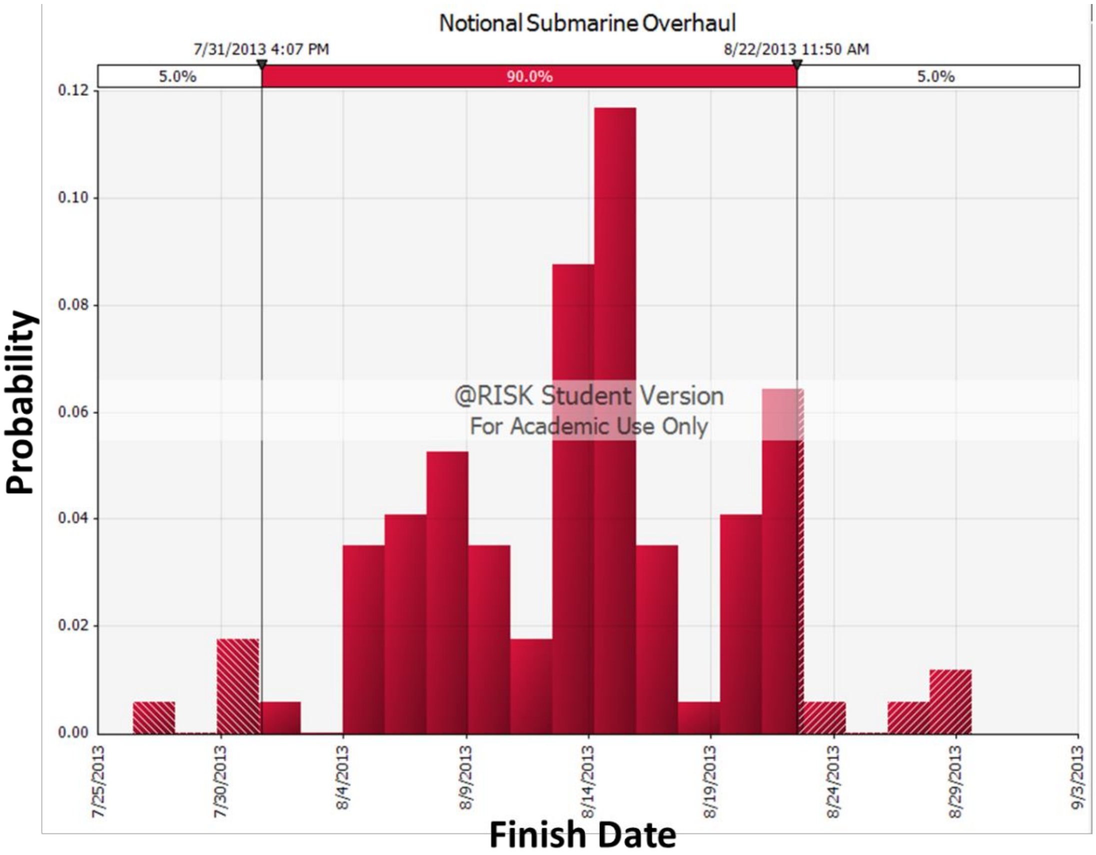


Figure 9. Probability Versus Finish Date When Varying Individual Task Duration by +/- 10%

	Date	**Duration (Start of 3/1/2011)**
Original Finish (without simulation)	8/12/2013	640
Minimum (with simulation)	7/26/2013	628
Mean (with simulation)	8/13/2013	641
Maximum (with simulation)	8/29/2013	653
Mode (with simulation)	8/9/2013	639
Median	8/13/2013	643
Standard Deviation	6.485 Days	

Table 6. Finish Date Statistics When Varying Individual Task Duration by +/- 10%

The data results for varying the task duration demonstrate the nonlinearity warned against in the flaw of averages discussed in Chapter II, section D. Even though the overall duration is 640 days, the finish date varies only 37 days, or +/- 2.9 percent, with a standard deviation of 6.5 days. While input durations varied by 10 percent, the overall duration varied by only 2.9 percent. At first glance, this seems somewhat surprising.

These results match predictions of the Central Limit Theorem (CLT). According to the CLT, the distribution of the sample mean approaches a normal distribution as the sample size increases. The original population, the baseline schedule, had a population mean, μ equal to 640 days. In accordance with the CLT, the mean of the sample (the 100 iterations of the simulation) would have a mean of μ (result was actually 641 days vice 640 days in the population).

Although the overall makespan was only +/- 2.9 percent while the inputs varied by 10 percent, the results do not contradict the CLT. The CLT assumes independent random variables and the network provides multiple dependencies for the tasks. For instance, if the network only consisted of ten sequential tasks, then the upper bound on the overall makespan would be plus 10 percent. However, as soon as multiple near critical paths exist, then the overall makespan upper bound is lowered.

An additional feature of @Risk is the sensitivity analysis using tornado graphs from the simulation's inputs. The @Risk simulation shows the top 10 tasks that affected the mean finish date as shown in Figure 10. In Figures 11 and 12, the input tasks effects on the finish date are ranked by regression coefficient and correlation coefficient. This analysis would assist a project team in examining durations and plans for these key tasks. The @Risk default lists tasks in Figures 10 through 12 in order (top to bottom) from most impact to least impact on the objective function (i.e., makespan). The three graphs effectively represent three models of how the tasks affect the impact: direct network ties (Figure 10), a regression model (Figure 11), or Spearman rank of correlation (Figure 12). The figures display three separate common statistical models for correlating the inputs (i.e., tasks) to the output makespan.

Essentially, these tasks are not only on the critical path, but they also have significant impact due to their ties in the broader network. They act as chokepoints where prolonged duration for their completion has large impacts throughout the schedule. This sensitivity analysis is a valuable tool in identifying these types of tasks. With this information identified in the planning stage, a project manager could task a further analysis to explore shortening the makespan. For instance, is one of the tasks identified overburdened with successors? Is there a way to re-tie the network to reduce the chokepoint effect of this task? Again, some of the constraints are technical (i.e., task A must be completed before task B), but some are strategic (i.e., best strategy is to work system A before system B). Strategic constraints could be more readily altered to reduce the impact of identified chokepoint tasks. Or, if additional resources (personnel or specialized equipment) could be applied to reduce the duration, then these tasks likely have the greatest return on investment.

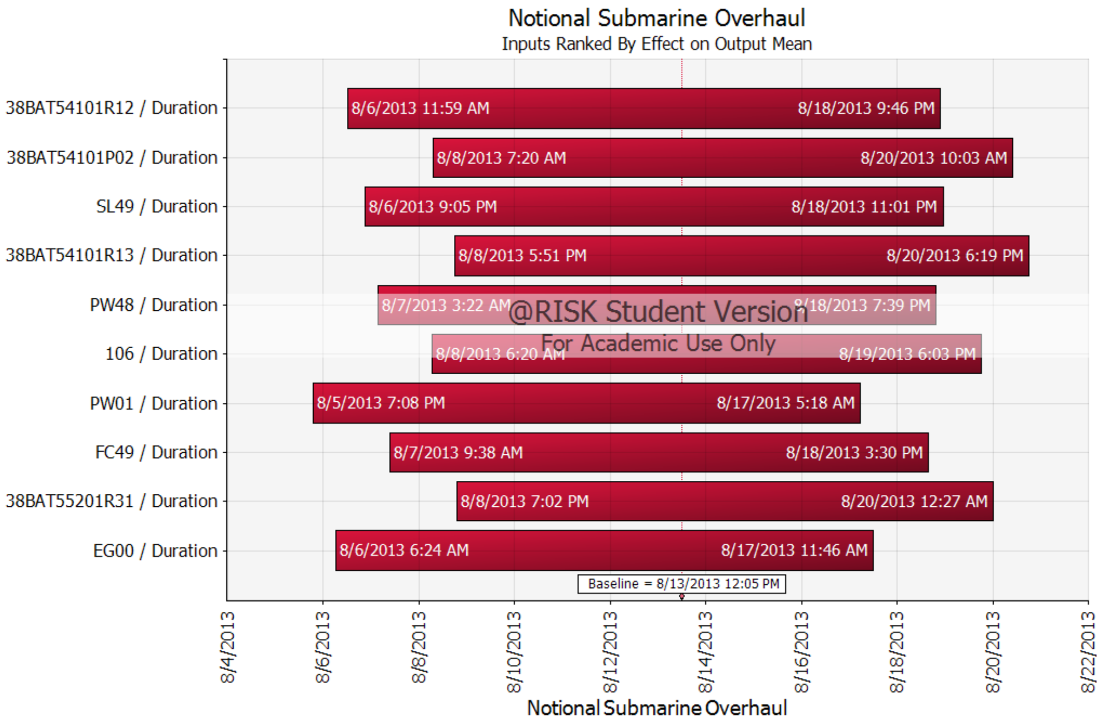


Figure 10. @Risk Tornado Diagram: Input Tasks with Greatest Effect on Output (Finish Date) Mean

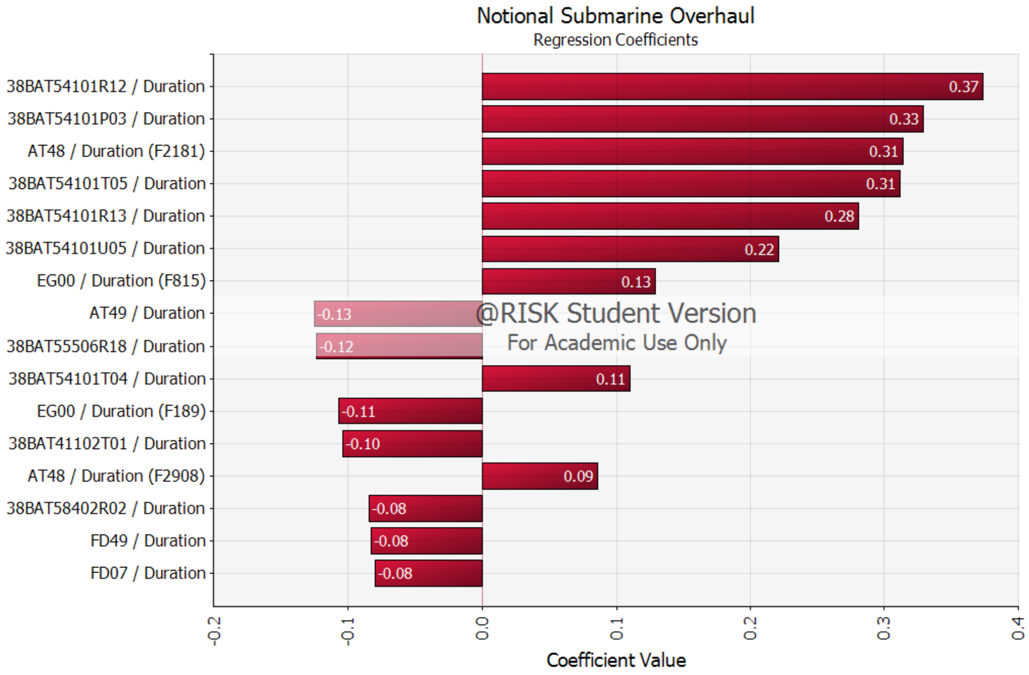


Figure 11. @Risk Tornado Diagram: Input Tasks with Largest Regression Coefficients Impacting the Output (Finish Date)

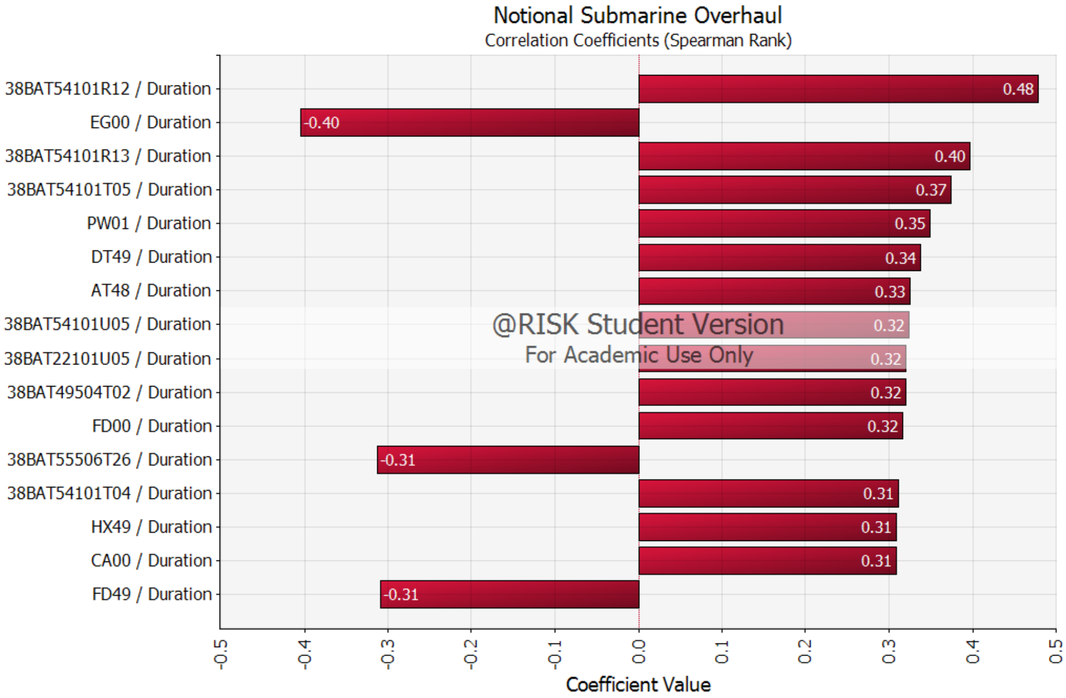


Figure 12. @Risk Tornado Diagram: Input Tasks with Largest Correlation Coefficients Impacting the Output (Finish Date)

2. Variation on Critical Path

Just as in the previous simulation, the overall project was scheduled for 640 days with a start date of 3/1/2011 and finish date of 8/12/2013. Now, instead of varying the duration estimates for all 4038 tasks, only 10 tasks on the critical path had their duration varied. These 10 tasks were identified in the previous simulation's sensitivity analysis from Figure 10. Again, each of these 10 tasks was assigned a triangle distribution to the duration of plus or minus 20 percent, twice the amount of uncertainty as compared to the prior analysis. The output of the @Risk simulation is shown in Figure 13 and Table 7.

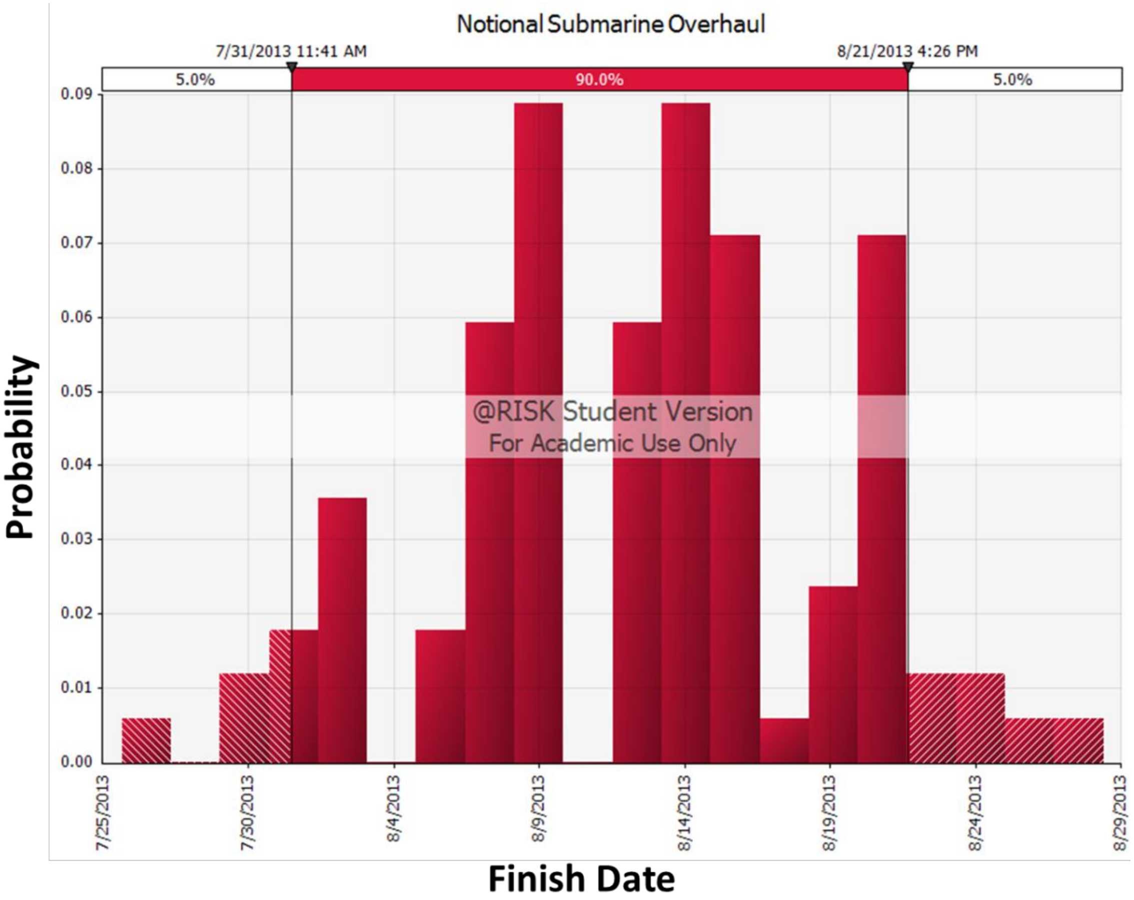
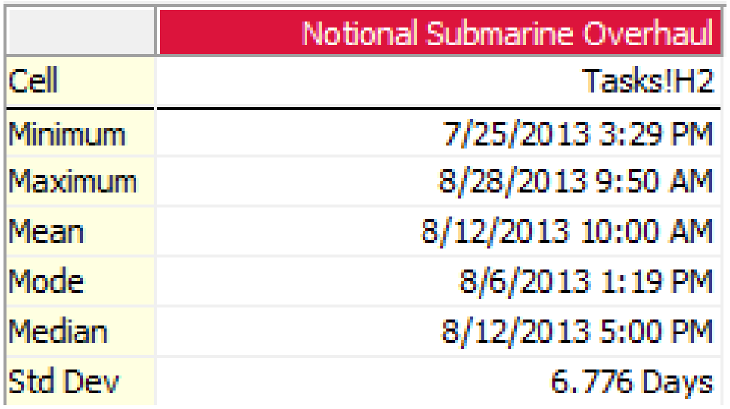


Figure 13. Probability Versus Finish Date When Varying Individual Task Duration by +/- 20% Only for the Top 10 Tasks



	Notional Submarine Overhaul
Cell	Tasks!H2
Minimum	7/25/2013 3:29 PM
Maximum	8/28/2013 9:50 AM
Mean	8/12/2013 10:00 AM
Mode	8/6/2013 1:19 PM
Median	8/12/2013 5:00 PM
Std Dev	6.776 Days

Table 7. Finish Date Statistics when Varying Duration of the Top 10 Critical Tasks by +/-20%

While varying the duration for all tasks by 10 percent resulted in a finish date range of 37 days, varying just 10 critical tasks by 20 percent resulted in a range of 35 days. Again, the other 4028 tasks were kept with fixed durations in this case. The standard deviation in the previous simulation was 6.5 days while it is now 6.8 days. This similar output with variation on only 10 critical tasks compared to 4038 tasks shows the importance of project management on the critical chain.

3. Optimizing Resource Allocation to Minimize the Makespan

In this experiment, the simulation is only done on a small portion of the much larger network seen in actual submarine maintenance. The analyzed simulation only covers 25 tasks. However, this simulation demonstrates analysis that could be carried out on individual portions of the schedule, such as weekly lists or critical path tasks.

The overall schedule could be similarly analyzed if there was data justifying reducing every task duration linearly with worker resources. However, many task's durations are fixed (e.g., 7 days for paint to cure…). Also, many tasks on a submarine suffer from physical constraints (discussed in Chapter II, section A.3.b.) where multiple workers just cannot fit in the confined workspace.

The simulation captures in simplified form the decision by shipyard management to more closely track the actual duration of tasks and to adjust workers accordingly. The savings in the makespan will be a measure of the input variables (the higher the variability in duration, the more likely the difference in duration between the fixed and flexible designs of resource allocation).

a. Evaluation of the Cumulative Distribution Function

The cumulative distribution function for shifts required to complete the sample of 25 tasks is shown in Figure 14 and Table 8. The result is discrete and looks like a staircase as opposed to a smooth curve since the unit of measure is number of shifts. As shown, the flexible resource allocation design (in red) is stochastically dominant since the objective function is to minimize the time required. In other words, the flexible resource allocation design has a shorter makespan in all cases. This is expected in the case of adding additional resources.

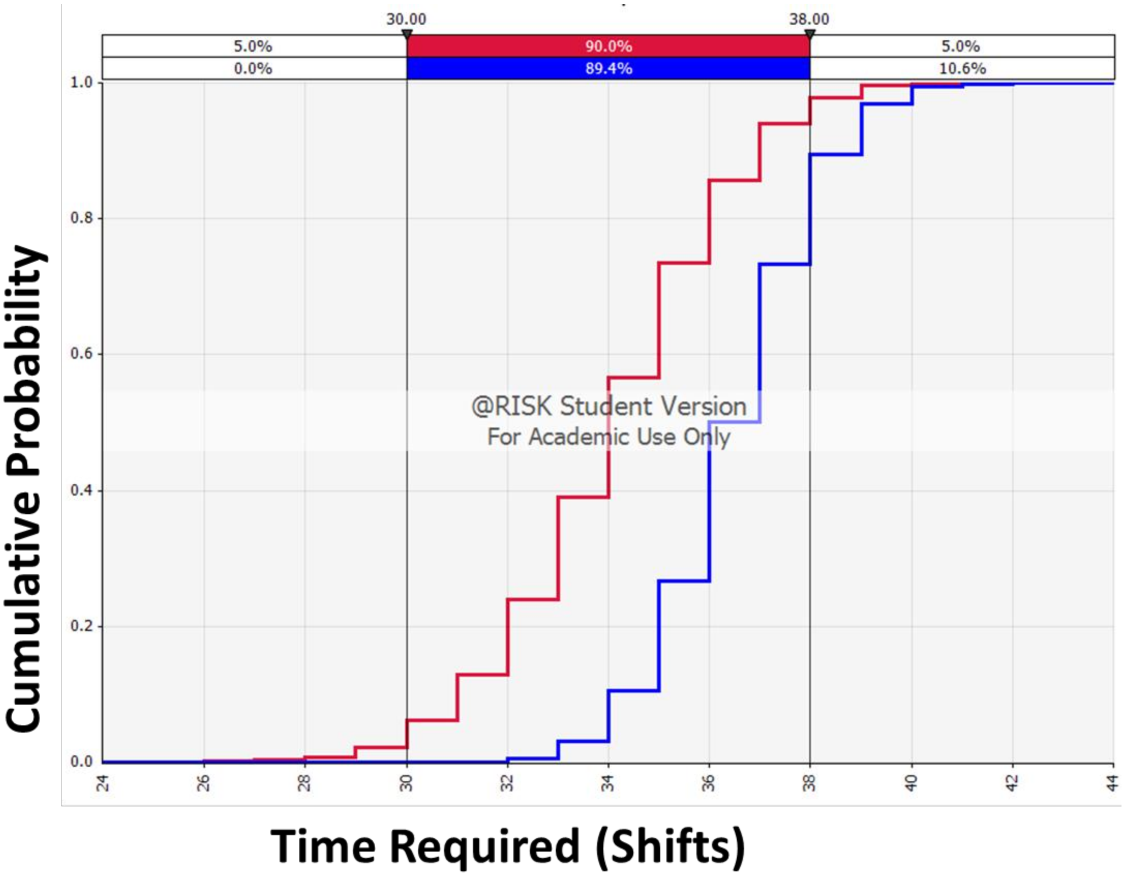
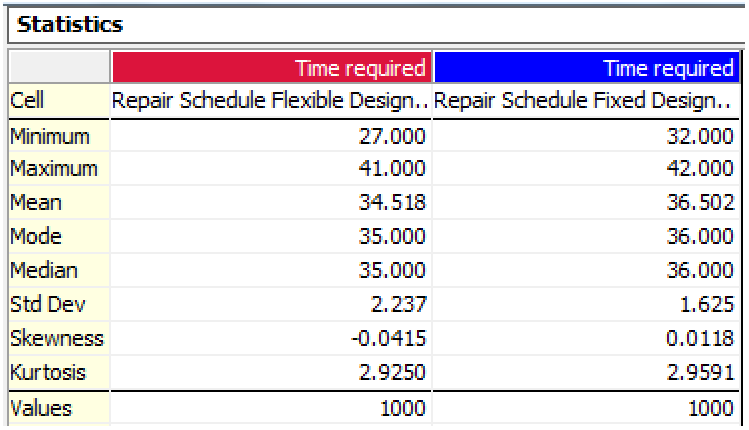


Figure 14. Cumulative Probability Distribution: Comparison of Time Required (Blue is Fixed Design, Red is Flexible Resource Allocation Design)



Statistics

	Time required	Time required
Cell	Repair Schedule Flexible Design..	Repair Schedule Fixed Design..
Minimum	27.000	32.000
Maximum	41.000	42.000
Mean	34.518	36.502
Mode	35.000	36.000
Median	35.000	36.000
Std Dev	2.237	1.625
Skewness	-0.0415	0.0118
Kurtosis	2.9250	2.9591
Values	1000	1000

Table 8. Cumulative Probability Distribution Statistics: Comparison of Time Required (Blue is Fixed Design, Red is Flexible Resource Allocation Design)

With 1000 trials in the simulation, the flexible resource allocation design (in red) had a mean makespan of 34.5 shifts versus 36.5 shifts for the fixed design. This was a savings in overall time of 5.5%. The minimum was 27 shifts for the flexible design compared to 32 shifts for the fixed design, an improvement of 15.6%.

b. *Evaluation of Multiple Criteria*

As can be seen in Table 9, the flexible design has a clear advantage in the primary objective function of minimizing the number of shifts to complete the work. Also, it reduces the idle time in the shop. Graphs of makespan, shop idle time, number of workers, and overall task time (in man hours) are shown in Appendix C for both the fixed and flexible resource allocation designs. However, more workers (36 versus 43) is required to achieve this flexibility. This would be balanced by data on the actual resource constraints available at a public shipyard. As opposed to private shipyards that may have larger personnel swings, the public shipyards have a more steady personnel level. Flexibility with manning may be more likely at a private shipyard for surge capacity. However, public shipyards share personnel to help provide some similar flexibility.

	Fixed Design	**Flexible Resource Allocation Design**
Minimum Time Required (shifts)	32	27
Average Time Required (shifts)	36.502	34.518
Max. Time Required (shifts)	42	41
Time Required, P5	34	31
Time Required, P95	39	38
Average Shop Idle Time	102.012	93.787
Average Number of Workers	36 (Constant)	43

Table 9. Results with Multiple Criteria, Fixed versus Flexible Design

Again, since the actual work schedule has 4,038 tasks, the model described in this section is a first-step simplification. This model could be applied to select portions of the schedule network, such as the critical path or to weekly periods of work. Other model adjustments to increase fidelity would be to adjust the number of tasks, match the number of actual trade skill worker categories to the shipyard manning (around 30 different trade skills), or adjust the decision rules. A more complex model would require details for the data set that would include more than the given task's job order code and nominal task duration. A task's work summary sheet for each task would be needed to ensure resource allocation decisions in the optimization would have the desired effect.

B. OVERALL RESULTS

As discussed in Chapter II, Section D, the data shows how the project system is nonlinear. A variation in 10 percent of all individual task durations resulted in a finish date duration of only plus or minus 2.9 percent. Varying just the top 10 critical tasks by 20 percent resulted in a finish date duration of plus or minus 2.7 percent.

The experiment on optimizing resource allocation to minimize the makespan showed an improvement versus the fixed resource allocation design. Unfortunately, this method cannot be carried out on all 4038 tasks since adding additional resources does not necessarily result in a linear reduction in the duration. Again, a more detailed data set would be needed that includes task descriptions. In the pubic shipyards, this is generally part of the Availability Work Package. However, the trial experiment demonstrates the use of a genetic algorithm, included in the Evolver software, successfully applied to the given data.

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VI. CONCLUSIONS

A. PIE STUDY IMPACT

This thesis shows that existing commercial off the shelf tools can have an impact to better understand the complex dynamics of schedules in ship repair. The specific application to U.S. public shipyards described below has relevance to the RCSP and project management.

B. APPLICABILITY

1. Applicability to U.S. Public Shipyards

Clearly, the results of this study are applicable to the four public U.S. Naval Shipyards. The use of @Risk with Microsoft Project offers a new capability for project managers to evaluate the variability of their schedules. As discussed in Chapter II, Section B, seven years ago the shipyard required 17 individual files within Microsoft Project to capture one maintenance project. This thesis demonstrated that Microsoft Project 2010 can accommodate the data set the Navy provided to test the Primavera software.

For maintenance availabilities longer than six months in duration, the project manager and scheduler are assigned to the project one year in advance to begin planning. Other project members begin staffing the project six months before the start of the availability. During this time, the use of @Risk or similar software would prove valuable for the project team in understanding the dynamics of the project schedule. Currently, the project schedule is made of thousands of point-estimates for the duration of individual tasks. With probabilistic scheduling tools, the project team could better plan for the possible schedule outcomes.

The sensitivity analysis demonstrated with tornado diagrams shows how crucial tasks can be identified that have large impact on the overall project duration. Most project management practices focus on the critical path. However, with the large scale and duration in submarine maintenance projects, the critical path or near-critical path can consist of thousands of tasks. Merely identifying the critical path may not provide managers the ability to “focus” on thousands of items. Instead, tornado diagrams generated in planning could identify tasks that are not only on the critical path but are particularly crucial due to their ties within the network. Simulation can help identify these chokepoints to allow project management focus and action.

The Navy’s analysis of Primavera, offered some “tangible benefits” to shifting to a commercial scheduling tool. Many of the benefits repeated below would apply equally to use of @Risk and Microsoft Project for scheduling submarine maintenance availabilities:[69]

- A single repository for Business Unit programs
- All programs in the system present data in a consistent format making analysis easier
- The tracking of program attributes and visibility of summary data will provide additional ways for executives and other managers to analyze the portfolio of each Business Unit’s programs, thereby increasing the information used in decision making.
- Executives and Manages can create multiple portfolios and scenarios to determine the impact of focusing key resources on a specific set of programs
- Visibility to key milestones and program events is available
- Time is saved in the preparation of reports and presentations for Program status as it can quickly be gathered and/or presented from a single source
- Program and Resource Managers will have information on the timelines for their programs and the usage of resources at a role level required to complete those programs. This will:
    - Allow them to understand the resource impacts to their program and their Business Unit’s resource pool in as a whole

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[69] *Architectural Documentation for Primavera P6* (Washington, D.C.: 2011), Section 6.1.

    - Provide the ability to perform what-if scenarios to address resource conflicts
        - Shifting an entire program's timeline or a portion of it to determine changes to resource changes
        - Modifying resource allocations within a program to correct small resource conflicts
    - Track hours resources are charging to each program to ensure resources are correctly allocated to high priority or key programs
    - With better understanding of internal resource usage, this information can be used to determine if internal resources can replace contractors on specific work, resulting in savings to the company
- System users, such as Program Managers and Resource Managers, will begin to learn the system in preparation for the future when more detailed planning and analysis are required

2. Applicability to Private Shipyards

Although this study reviewed a schedule of the repair of a submarine, the tools and methods discussed are applicable to private shipyards. As discussed in Chapter II, section A.3, repair schedules of a submarine are some of the most complex schedules seen in project management. The system complexity, the tight spaces, the nuclear reactor, the challenges inherent in repair, and resource competition all contribute to a dense integrated schedule. The tools demonstrating improved scheduling in submarines will also aid project management scheduling problems such as new construction. Generally, the variability in repair is seen as the biggest factor that leads to variability in the given data set.

A rule of thumb for modern modular ship construction is the "1-3-8" rule. This rule emphasizes how much more efficient work is off-hull vice inside the vessel. A task that would take eight hours inside the ship, would take only three hours off-hull in an outfitting building, or only one hour on the shop floor. Therefore, modern shipyards greatly emphasize scheduling construction work in the shop. According to the winter 2011 Undersea Warfare magazine, “the shipbuilders are pursuing an ambitious effort to optimize the entire construction process and significantly shorten construction time.”[70] This thesis offers tools and suggestions to support that effort.

3. Applicability to General Scheduling Problems

For general scheduling problems, using the tools provided is not necessarily unique. The @Risk software has many features dedicated to solving project management schedules. However, through the literature search, the application of these software tools does not appear to have been executed on similar realistic schedules.

C. FUTURE WORK

To minimize the makespan of the entire submarine overhaul, each task in the data set would need to have a model for the relationship between duration and the number of workers. With this extended data set, the genetic algorithm executed to minimize the makespan for the 25 sample tasks could be applied to the entire overhaul. However, the answer generated would still face the uncertainty of the assumed available resources, since projects occur not in isolation but in the context of other projects at the shipyard. When taken in small subsets over short time periods, such as done in Chapter IV, the prediction for available resources is more reliable. Assumptions about resources available over a two year period face greater uncertainty.

Gabriel Burnett’s 2011 work on RCSP for new construction of Virginia submarines addressed multiple projects worked in parallel. As he notes, “multiple objective versions of the problem [RCSP] have not been well studied.”[71] Applying a methodology similar to his work to the data set from this thesis would be a worthwhile future effort. The conflicts of resource management under the uncertainty of repair are

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[70] John Holmander and Thomas Plante, "The Four-Module Build Plan,” (Undersea Warfare Nov. 2011) 7.

[71] Gabriel Burnett, “*Multiple Objective Assembly Scheduling with Spatial Resources and Recurring Tasks,”* (Pennsylvania State University, 2011), 18.

likely more problematic for maintenance than the more deterministic schedule in new construction shipyards.

If doing multiple projects, another data source that would be valuable is a snapshot of actual resource pools available at a U.S. public shipyard. Using real historic resource pools incorporated into the simulation would provide more accurate conclusions in a multi-project RCSP.

Gaining new construction data would allow a comparison between the maintenance data in this thesis. However, knowledge of the data set and the details of the schedule are essential when solving a RCSP. Also, as shown in Chapter III, the data will likely have to be formatted to fit the selected analysis algorithm. Managing the schedule for multi-year projects in new construction and maintenance of ships currently requires dozens of managers. The data must be accompanied by significant background research and access to experienced managers. For instance, reducing the makespan requires knowledge of each individual task to understand how increasing resources impacts duration.

Future data sources include new construction of other U.S. Naval combatants. Data on Virginia submarine construction used at Pennsylvania State's Applied Research Lab is being vetted by Electric Boat for release to MIT's PIE study. Other data could include a released version of a baseline Availability Work Package from the Submarine Maintenance Engineering Planning and Procurement Activity (SUBMEPP). SUBMEPP prepares the baseline AWP for all submarine maintenance availabilities. This central activity could be tasked to do more detailed simulations in the early pre-planning stages to better predict the durations of submarine maintenance schedules.

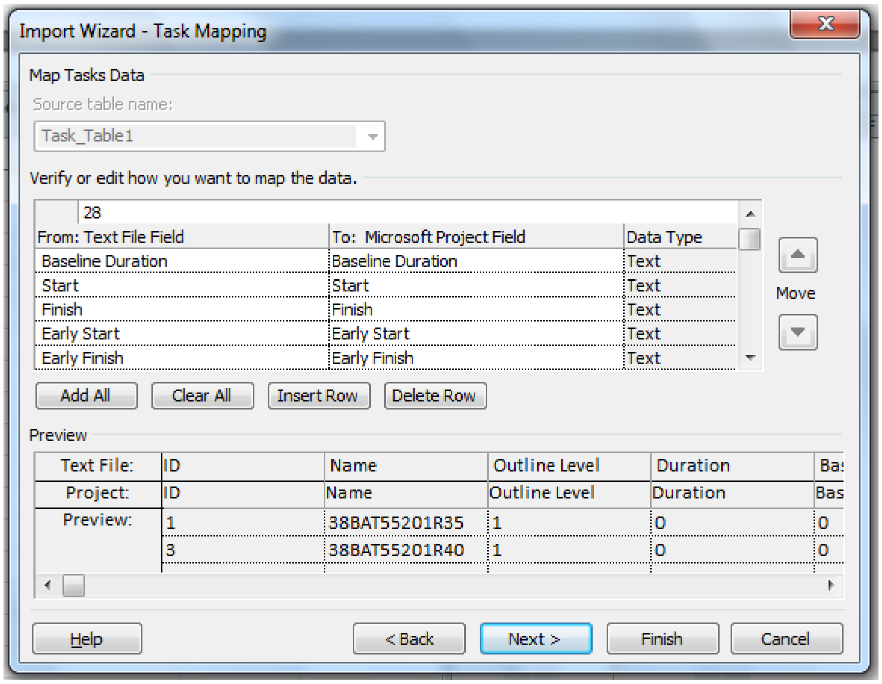
The literature review shows that many academic attempts at project management problems are not implemented due to a lack of "real-world" capability. Too often, real world constraints, resource allocation limits, or other variables are over-simplified in the academic solutions. However, the complex project management scheduling issues seen in real world applications are often kept in proprietary hold out of reach of academia. The data set analyzed in this thesis was a notional submarine overhaul schedule.

NAVSEA provided the data for Oracle to test Primavera software as a trial for future Navy projects. However, the data is incomplete in its current form. Attempts by the PIE study to gain new construction data for U.S. naval ships remains ongoing. The scope of these project management scheduling problems require a broad scope of individuals with the proper clearance, management background, and academic research capability. Executing these large projects requires dozens of managers. Fully analyzing such a project will require considerable effort. Clearly though, any progress in improving the scheduling of a submarine maintenance project will have demonstrated benefits to all of project management.

APPENDIX A. FORMATTING DATA

In order to use the data, the csv files had to be opened within Microsoft Project. The public shipyards use a macro program written to import the csv files from PSS directly into Microsoft Project. That macro converted the csv file into the 2007 version of Microsoft Project; however it failed when executed in the newer software version. To remedy this, the first step was to take the two csv files, constraints and precedents, and combine them into one csv file for upload.

Then, when importing the csv data into Microsoft Project, the headers from the csv data were mapped to appropriate headers in Project. A screen capture is shown in Figure 15 and Table 10 summarizes the changes in column headings and the general description of each column.



Source table name: Task_Table1

Verify or edit how you want to map the data.

28

From: Text File Field	To: Microsoft Project Field	Data Type
Baseline Duration	Baseline Duration	Text
Start	Start	Text
Finish	Finish	Text
Early Start	Early Start	Text
Early Finish	Early Finish	Text

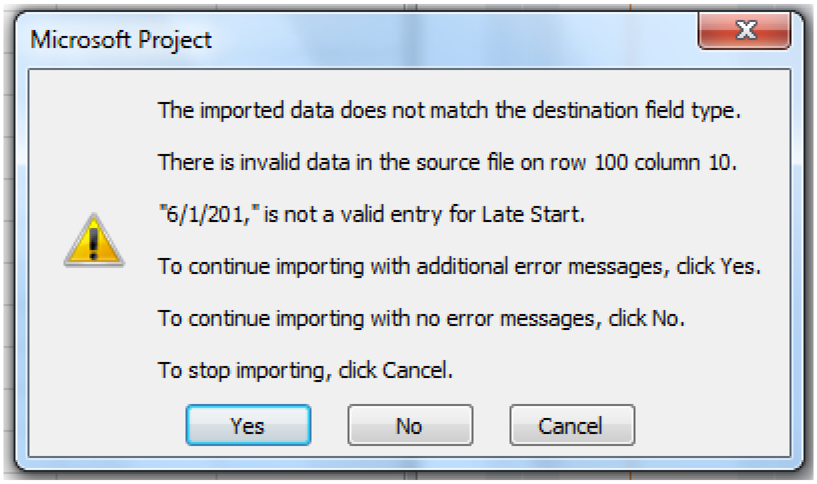
Text File:	ID	Name	Outline Level	Duration	Ba
Project:	ID	Name	Outline Level	Duration	Bas
Preview:	1	38BAT55201R35	1	0	0
	3	38BAT55201R40	1	0	0

Figure 15. Import Wizard Showing Mapping of Data Headings

Original Shipyard Data Headings	**Modified Headings for MS Project**	**Comment**
Number1	ID	"ID" used by MS Project to identify tasks
Name	Name	
Outline Level	Outline Level	
Duration	Duration	
Baseline Duration	Baseline Duration	
Start Date	Start	"Start" vice "Start Date" used by MS Project
Finish Date	Finish	"Finish" vice "Finish Date" used by MS Project
Early Start	Early Start	
Early Finish	Early Finish	
Late Start	Late Start	
Late Finish	Late Finish	
Free Slack	Free Slack	
Total Slack	Total Slack	
Percent Complete	% Complete	"% Complete" used by MS Project
Actual Start	Actual Start	
Actual Finish	Actual Finish	
Baseline Start	Baseline Start	
Baseline Finish	Baseline Finish	
Priority	Priority	
Milestone	Milestone	
Notes	Notes	
Constraint Type	Constraint Type	All entries are constrained with "Start no Earlier Than"
Constraint Date	Constraint Date	
Text5	Resource Names	Supervisor Name
Text6	Text6	Ships Work List Item Number (SWLIN)
Text7	Text7	Component Unit Identifier (CUI) – item being worked
Predecessors	Predecessors	
Deleted Columns: "Text1", "Text2", "Text3", "Text4" (all entries were blank)		

Table 10. Mapping Data from csv Format to Microsoft Project

Next, once the import wizard began importing the csv file into Project, a number of errors were identified. A total of 38 errors were attributed to improper comma separation in the data. For instance, a start date would be listed as "6/3/20128/5/2102." This would create more errors as each following entry for that task would be in the wrong format. These errors had to be manually corrected in the source data.



The imported data does not match the destination field type.

There is invalid data in the source file on row 100 column 10.

"6/1/201," is not a valid entry for Late Start.

To continue importing with additional error messages, click Yes.

To continue importing with no error messages, click No.

To stop importing, click Cancel.

Figure 16. Example Error Generated When Importing csv Data

Note, when changing the heading of the first column from "Number1" to "ID" it generated an error in Excel when trying to open the subsequent csv file. This is a known error with Excel in misidentifying csv files as "sylk" file format.[72] Instead, the csv file was saved with the title "Number1" in the first column and the data was mapped to "ID" using the Microsoft Project import wizard.

When importing the csv data, another error created was the creation of tasks without other information. The csv data had task IDs that were not sequential. For instance, there was no task ID 138, but Microsoft Project reserved a task ID with that identifier. Of the 4038 tasks, the tasks numbered from 1 to 11761, therefore Microsoft Project generated 7723 blank entries. This is seen in Figure 17.

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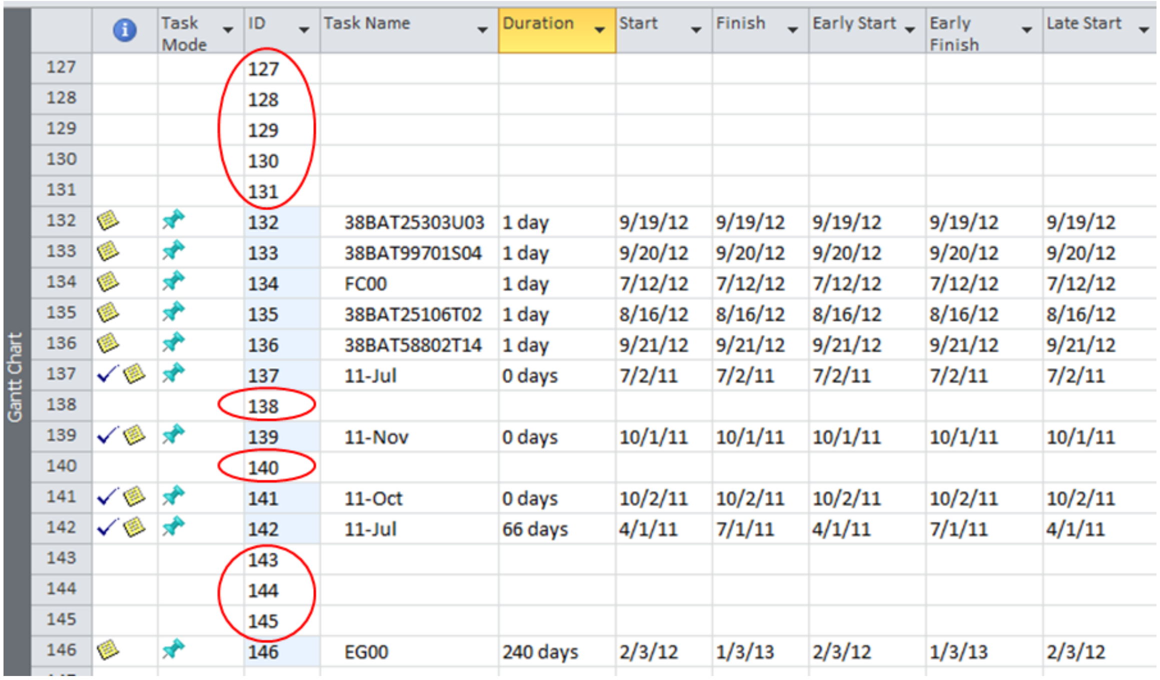
[72] http://support.microsoft.com/kb/215591



	ⓘ	Task Mode	ID	Task Name	Duration	Start	Finish	Early Start	Early Finish	Late Start
127			127							
128			128							
129			129							
130			130							
131			131							
132	📝	📌	132	38BAT25303U03	1 day	9/19/12	9/19/12	9/19/12	9/19/12	9/19/12
133	📝	📌	133	38BAT99701S04	1 day	9/20/12	9/20/12	9/20/12	9/20/12	9/20/12
134	📝	📌	134	FC00	1 day	7/12/12	7/12/12	7/12/12	7/12/12	7/12/12
135	📝	📌	135	38BAT25106T02	1 day	8/16/12	8/16/12	8/16/12	8/16/12	8/16/12
136	📝	📌	136	38BAT58802T14	1 day	9/21/12	9/21/12	9/21/12	9/21/12	9/21/12
137	✓📝	📌	137	11-Jul	0 days	7/2/11	7/2/11	7/2/11	7/2/11	7/2/11
138			138							
139	✓📝	📌	139	11-Nov	0 days	10/1/11	10/1/11	10/1/11	10/1/11	10/1/11
140			140							
141	✓📝	📌	141	11-Oct	0 days	10/2/11	10/2/11	10/2/11	10/2/11	10/2/11
142	✓📝	📌	142	11-Jul	66 days	4/1/11	7/1/11	4/1/11	7/1/11	4/1/11
143			143							
144			144							
145			145							
146	📝	📌	146	EG00	240 days	2/3/12	1/3/13	2/3/12	1/3/13	2/3/12

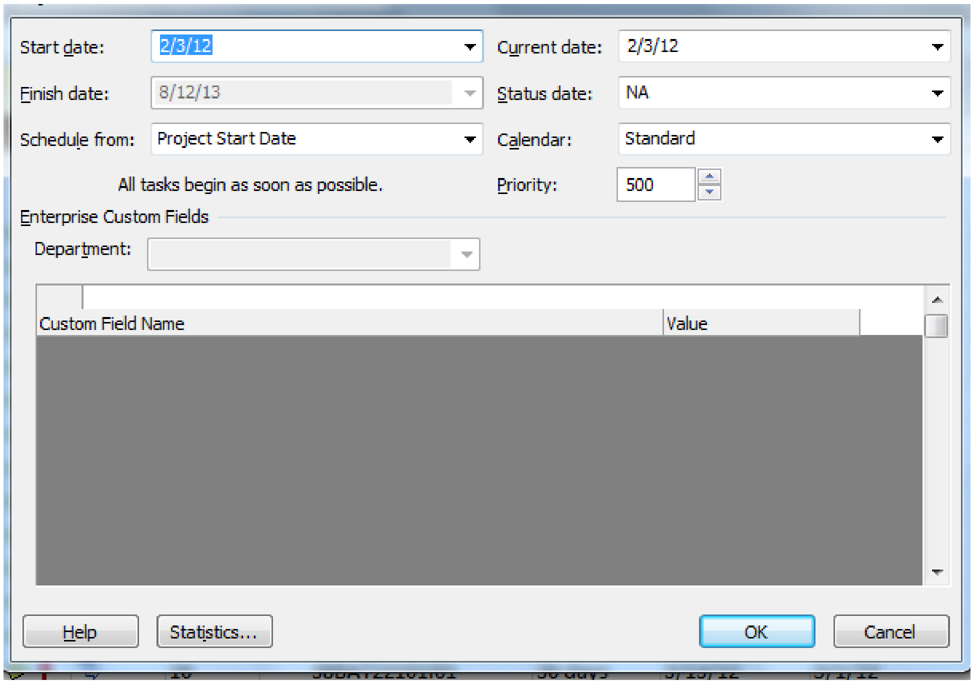
Figure 17. Microsoft Project's Creation of "Empty" Tasks Circled Above

Some of the tasks that Microsoft Project created were not just empty cells, but contained dates and other entries. These entries had dates that did not match the imported csv data. To fix this, the task mode was manually changed to "inactivate task." There were 97 such entries that all had Early Start, Early Finish, Late Start, and Late Finish dates that matched the current date. Microsoft Project has default actions when reading the csv data and made assumptions for dates to match the current date.

	ⓘ	Task Mode	ID	Task Name	Duration	Start	Finish	Early Start	Early Finish	Late Start	Late Finish
1	📝	📌	1	38BAT55201R35	1 day	2/3/12	2/3/12	2/3/12	2/3/12	2/3/12	2/3/12
2		📌?	2					3/14/13	3/14/13	3/14/13	3/14/13
3	📝	📌	3	38BAT55201R40	1 day	9/25/12	9/25/12	9/25/12	9/25/12	9/25/12	9/25/12

Figure 18. Microsoft Project's Creation of False Tasks Circled Above

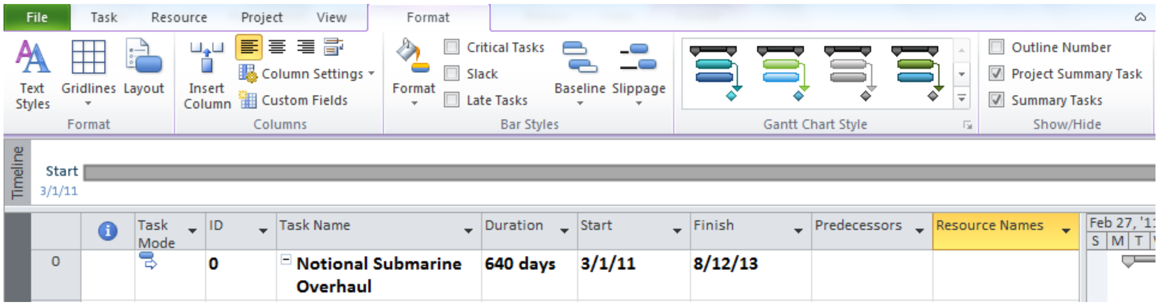
Next, the project start date had to be adjusted since the project data provided was in the past. This was done under the "Project Information" tab as shown in Figure 19. Finally, the last step was to create a "Project Summary Task" as shown in Figure 20. This allowed one entry to record the start and finish dates of the overall project. The duration and finish dates of this Project Summary task were identified as outputs of the simulation.



Start date: 2/3/12
Current date: 2/3/12
Finish date: 8/12/13
Status date: NA
Schedule from: Project Start Date
Calendar: Standard
All tasks begin as soon as possible.
Priority: 500
Enterprise Custom Fields
Department:

Custom Field Name	Value

Figure 19. Updating the Start Date and Current Date in the Project Information



☐ Critical Tasks
☐ Slack
☐ Late Tasks
☐ Outline Number
☑ Project Summary Task
☑ Summary Tasks

		Task Mode	ID	Task Name	Duration	Start	Finish	Predecessors	Resource Names
0			0	**Notional Submarine Overhaul**	**640 days**	**3/1/11**	**8/12/13**		

Figure 20. Selecting a Project Summary Task

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APPENDIX B. SCHEDULE AUDIT RESULTS

As discussed in Chapter III, Section C, the @Risk audit tool identified three "error" types: 1) No successor tasks, 2) No predecessor tasks, and 3) Tasks out of sequence.

ID	Task	ID	Task	ID	Task
No successor task was assigned to this task. During simulation, simulated schedule changes for this task will not delay other tasks. Check if task dependencies are missing.					
5	End Guarantee Period	6997	38BAT55506T25	8665	38BAT53407R02
806	38BAT77201S01	6998	38BAT55506R52	8668	38BAT53407R02
2662	38BAT12303R12	7001	38BAT55506R28	8904	38BAT13001R12
3017	38BAT25801H07	7002	38BAT55506R29	8908	38BAT13001R12
6190	38BAT55507T04	7006	38BAT55506T34	9180	38BAT12305P01
6240	38BAT55503T20	7191	38BAT55505T07	9181	38BAT12305P01
6242	38BAT55503T26	7226	38BAT55505T07	9182	38BAT12305P02
6674	38BAT55505T02	7227	38BAT55505T08	9183	38BAT12305P02
6683	38BAT55506R29	7228	38BAT55505T09	9835	38BAT25402R04
6684	38BAT55506T12	7399	38BAT12303R21	9861	38BAT25803R05
6698	38BAT55506R52	7404	38BAT12303R18	9922	38BAT22101R25
6712	38BAT65102T01	7405	38BAT12303R19	9923	38BAT22101R25
6720	38BAT99213R09	7406	38BAT12303R20	10055	38BAT22102R17
6736	38BAT99213R09	7420	38BAT12303R18	10310	38BAT22102R17
6895	38BAT55506R15	7421	38BAT12303R19	10332	38BAT31202A01
6896	38BAT55506R16	7422	38BAT12303R20	10333	38BAT31202A01
6897	38BAT55506R17	7423	38BAT12303R21	10474	38BAT22101R28
6898	38BAT55506R18	7425	38BAT12303R14	10857	38BAT53404R02
6900	38BAT55506R21	7437	38BAT12303R14	10960	38BAT53405R02
6982	38BAT55506T10	7619	38BAT49505T02	10961	38BAT53405R02
6983	38BAT55506T11	7620	38BAT49505T02	11255	38BAT25106R06
6984	38BAT55506T12	8327	38BAT25401R01	11257	38BAT25106R06
6988	38BAT55506R15	8331	38BAT25401R01	11556	38BAT24301T02
6989	38BAT55506R16	8333	38BAT25402R04	11641	38BAT45403R05
6990	38BAT55506R17	8337	38BAT25402R04	11642	38BAT45403T01
6991	38BAT55506R18	8561	38BAT64402T01	11648	38BAT45403R05
6993	38BAT55506R20	8563	38BAT64402P02	11684	38BAT45403T01
6994	38BAT55506R21	8565	38BAT64402P02	11693	38BAT24301T02
6995	38BAT55506T23				

Table 11. No Successor Defined for 85 Tasks

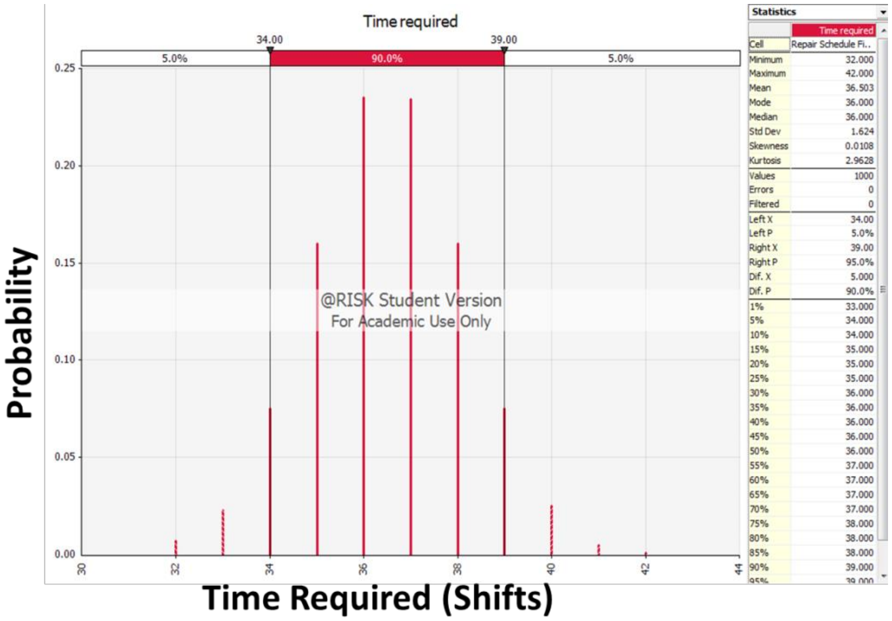
ID	Task
No predecessor task was assigned to this task. During simulation, simulated changes to schedules will not affect this task. Check if task dependencies are missing.	
8	38BAT81304S06
808	38BAT77201H01
1492	FC49
6710	38BAT55507T01
6993	38BAT55506R20

Table 12. No Predecessor Defined for 5 Tasks

ID	Task	Field Contents
This task starts earlier than its predecessor, even though it has a Finish to Start dependency with that task. Check if task dependency logic is correct.		
230	38BAT56102S02	166
1913	CA00	8
2715	FC05	1179
3869	EG00	5058
3869	EG00	5059
3869	EG00	5060
3869	EG00	5061
3869	EG00	5094
3870	EG00	5094
4140	HX00	8
4227	HX00	3892
4227	HX00	6713
4618	38BAT12310A02	4616
4621	UD02	4611
4622	UD02	4612

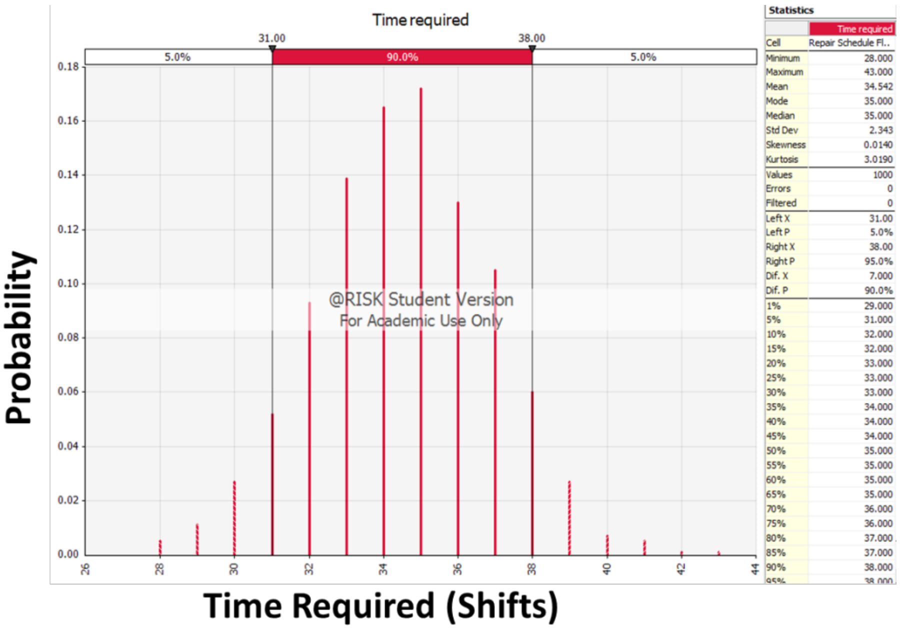
Table 13. Tasks Out of Sequence (15 Total)

APPENDIX C. GRAPHS FOR OPTIMIZING RESOURCE ALLOCATION TO MINIMIZE THE MAKESPAN



Statistics	Time required
Cell	Repair Schedule Fi..
Minimum	32.000
Maximum	42.000
Mean	36.503
Mode	36.000
Median	36.000
Std Dev	1.624
Skewness	0.0108
Kurtosis	2.9628
Values	1000
Errors	0
Filtered	0
Left X	34.00
Left P	5.0%
Right X	39.00
Right P	95.0%
Dif. X	5.000
Dif. P	90.0%
1%	33.000
5%	34.000
10%	34.000
15%	35.000
20%	35.000
25%	35.000
30%	36.000
35%	36.000
40%	36.000
45%	36.000
50%	36.000
55%	37.000
60%	37.000
65%	37.000
70%	37.000
75%	38.000
80%	38.000
85%	38.000
90%	39.000
95%	39.000

Figure 21. Fixed Design, Time Required (Makespan)



Statistics	Time required
Cell	Repair Schedule Fl..
Minimum	28.000
Maximum	43.000
Mean	34.542
Mode	35.000
Median	35.000
Std Dev	2.343
Skewness	0.0140
Kurtosis	3.0190
Values	1000
Errors	0
Filtered	0
Left X	31.00
Left P	5.0%
Right X	38.00
Right P	95.0%
Dif. X	7.000
Dif. P	90.0%
1%	29.000
5%	31.000
10%	32.000
15%	32.000
20%	33.000
25%	33.000
30%	33.000
35%	34.000
40%	34.000
45%	34.000
50%	35.000
55%	35.000
60%	35.000
65%	35.000
70%	36.000
75%	36.000
80%	37.000
85%	37.000
90%	38.000
95%	38.000

Figure 22. Flexible Resource Allocation Design, Time Required (Makespan)

Statistics

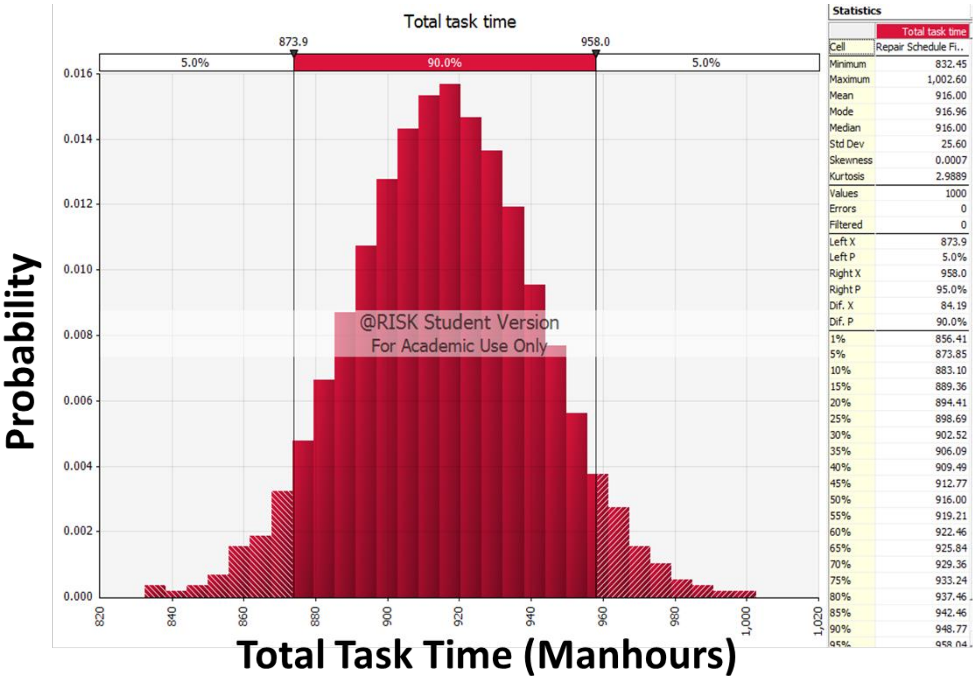
	Total Shop Idle time
Cell	Repair Schedule Fi..
Minimum	84.000
Maximum	124.000
Mean	102.012
Mode	100.000
Median	100.000
Std Dev	6.498
Skewness	0.0108
Kurtosis	2.9628
Values	1000
Errors	0
Filtered	0
Left X	92.00
Left P	5.0%
Right X	112.00
Right P	95.0%
Dif. X	20.000
Dif. P	90.0%
1%	88.000
5%	92.000
10%	92.000
15%	96.000
20%	96.000
25%	96.000
30%	100.000
35%	100.000
40%	100.000
45%	100.000
50%	100.000
55%	104.000
60%	104.000
65%	104.000
70%	104.000
75%	108.000
80%	108.000
85%	108.000
90%	112.000
95%	112.000

Figure 23. Fixed Design, Total Shop Idle Time

Statistics

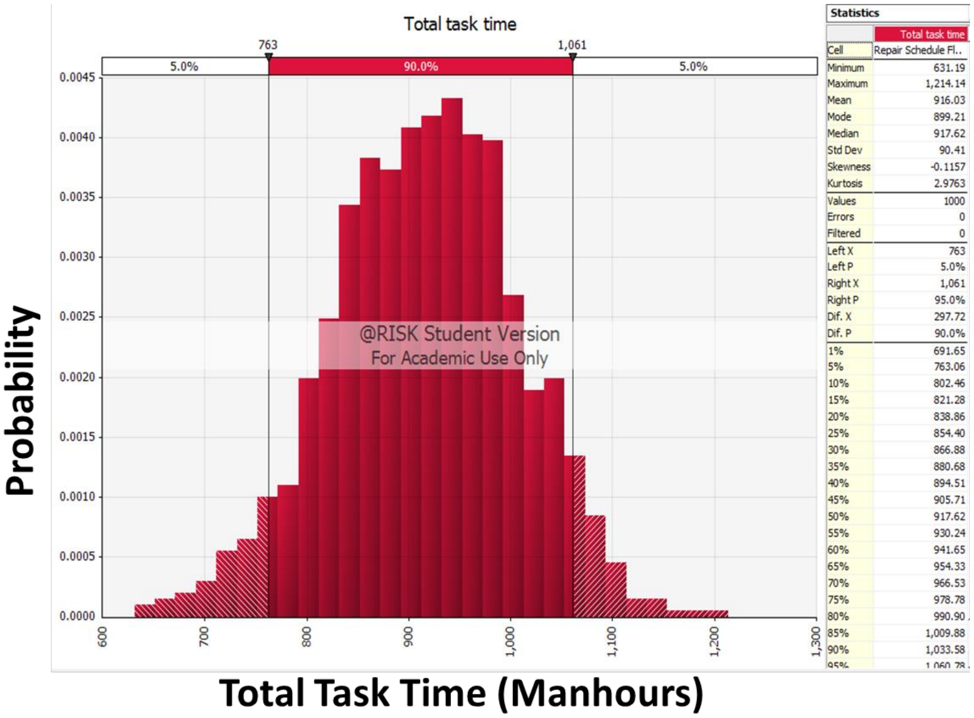
	Total Shop Idle time
Cell	Repair Schedule Fl..
Minimum	66.000
Maximum	126.000
Mean	93.787
Mode	98.000
Median	94.000
Std Dev	9.480
Skewness	0.0910
Kurtosis	2.9742
Values	1000
Errors	0
Filtered	0
Left X	78.0
Left P	5.0%
Right X	110.0
Right P	95.0%
Dif. X	32.000
Dif. P	90.0%
1%	71.000
5%	78.000
10%	82.000
15%	84.000
20%	86.000
25%	87.000
30%	89.000
35%	90.000
40%	91.000
45%	92.000
50%	94.000
55%	95.000
60%	96.000
65%	98.000
70%	99.000
75%	100.000
80%	102.000
85%	104.000
90%	106.000
95%	110.000

Figure 24. Flexible Resource Allocation Design, Total Shop Idle Time



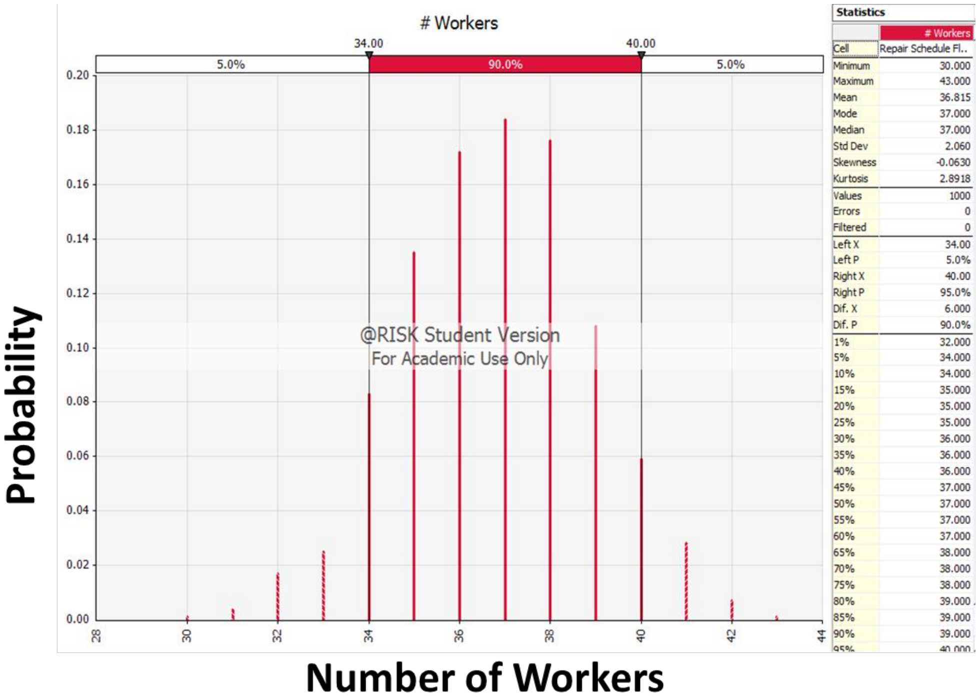
Statistics	Total task time
Cell	Repair Schedule Fi..
Minimum	832.45
Maximum	1,002.60
Mean	916.00
Mode	916.96
Median	916.00
Std Dev	25.60
Skewness	0.0007
Kurtosis	2.9889
Values	1000
Errors	0
Filtered	0
Left X	873.9
Left P	5.0%
Right X	958.0
Right P	95.0%
Dif. X	84.19
Dif. P	90.0%
1%	856.41
5%	873.85
10%	883.10
15%	889.36
20%	894.41
25%	898.69
30%	902.52
35%	906.09
40%	909.49
45%	912.77
50%	916.00
55%	919.21
60%	922.46
65%	925.84
70%	929.36
75%	933.24
80%	937.46
85%	942.46
90%	948.77
95%	958.04

Figure 25. Fixed Design, Total Task Time



Statistics	Total task time
Cell	Repair Schedule Fl..
Minimum	631.19
Maximum	1,214.14
Mean	916.03
Mode	899.21
Median	917.62
Std Dev	90.41
Skewness	-0.1157
Kurtosis	2.9763
Values	1000
Errors	0
Filtered	0
Left X	763
Left P	5.0%
Right X	1,061
Right P	95.0%
Dif. X	297.72
Dif. P	90.0%
1%	691.65
5%	763.06
10%	802.46
15%	821.28
20%	838.86
25%	854.40
30%	866.88
35%	880.68
40%	894.51
45%	905.71
50%	917.62
55%	930.24
60%	941.65
65%	954.33
70%	966.53
75%	978.78
80%	990.90
85%	1,009.88
90%	1,033.58
95%	1,060.78

Figure 26. Flexible Resource Allocation Design, Total Task Time



Statistics

	# Workers
Cell	Repair Schedule Fl..
Minimum	30.000
Maximum	43.000
Mean	36.815
Mode	37.000
Median	37.000
Std Dev	2.060
Skewness	-0.0630
Kurtosis	2.8918
Values	1000
Errors	0
Filtered	0
Left X	34.00
Left P	5.0%
Right X	40.00
Right P	95.0%
Dif. X	6.000
Dif. P	90.0%
1%	32.000
5%	34.000
10%	34.000
15%	35.000
20%	35.000
25%	35.000
30%	36.000
35%	36.000
40%	36.000
45%	37.000
50%	37.000
55%	37.000
60%	37.000
65%	38.000
70%	38.000
75%	38.000
80%	39.000
85%	39.000
90%	39.000
95%	40.000

Figure 27. Flexible Resource Allocation Design, Number of Workers (Fixed set at 36 Workers)

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