2006

The Application Of "crashing" A Project Network To Solve The Time/cost Tradeoff In Recapitalization Of The Uh-60a Helicopter

Gregory Fortier
University of Central Florida

STARS Citation
Fortier, Gregory, "The Application Of "crashing" A Project Network To Solve The Time/cost Tradeoff In Recapitalization Of The Uh-60a Helicopter" (2006). *Electronic Theses and Dissertations*. 1038.
https://stars.library.ucf.edu/etd/1038

THE APPLICATION OF “CRASHING” A PROJECT NETWORK TO SOLVE THE TIME-COST TRADEOFF IN RECAPITALIZATION OF THE UH-60A HELICOPTER

by

GREGORY S. FORTIER
B.S. United States Military Academy, West Point 1996

A thesis submitted in partial fulfillment of the requirements
for the degree of Master of Science
in the Department of Industrial Engineering and Management Systems
in the College of Engineering and Computer Science
at the University of Central Florida
Orlando, Florida

Fall Term
2006

ABSTRACT

Since the beginning of project management, people have been asked to perform “more with less” in expeditious time while attempting to balance the inevitable challenge of the time/cost tradeoff. This is especially true within the Department of Defense today in prosecuting the Global War on Terrorism both in Afghanistan and Iraq. An unprecedented and consistent level of Operational Tempo has generated heavy demands on current equipment and has subsequently forced the need to recapitalize several legacy systems until suitable replacements can be implemented.

This paper targets the UH-60A:A Recapitalization Program based at the Corpus Christi Army Depot in Corpus Christi, Texas. More specifically, we examine one of the nine existing project sub-networks within the UH-60A:A program, the structural/electrical upgrade phase. In crashing (i.e. adding manpower or labor hours) the network, we determine the minimal cost required to reduce the total completion time of the 68 activities within the network before a target completion time. A linear programming model is formulated and then solved for alternative scenarios. The first scenario is prescribed by the program manager and consists of simply hiring additional contractors to augment the existing personnel. The second and third scenarios consist of examining the effects of overtime, both in an aggressive situation (with limited longevity) and a more moderate situation (displaying greater sustainability over time).

The initial linear programming model (Scenario 1) is crashed using estimates given from the program scheduler. The overtime models are crashed using reduced-time crash estimates.

For Scenarios 2 and 3, the crashable times themselves are reduced by 50% and 75%, respectively.

Initial results indicate that a completion time of 79.5 days is possible without crashing any activities in the network. The five-year historical average completion time is 156 days for this network. We continue to crash the network in each of the three scenarios and determine that the absolute shortest feasible completion times, 73 days for Scenario 1, 76 days for Scenario 2, and 77.5 days for Scenario 3. We further examine the models to observe similarities and differences in which activities get targeted for crashing and how that reduction affects the critical path of the network.

These results suggests an in-depth study of using linear programming and applying it to project networks to grant project managers more critical insight that may help them better achieve their respective objectives. This work may also be useful as the groundwork for further refinement and application for maintenance managers conducting day-to-day unit level maintenance operations.

ACKNOWLEDGMENTS

I would like to first thank God for giving me the strength and opportunity to spend a wonderful year at the University of Central Florida. Special thanks to Mrs. Jackie Gibson, Mr. Brandon McCraw, MAJ Russ Dunford, Mr. Eric Edwards, and Mr. Steve Foster for granting me unlimited access to the UH-60A:A Recapitalization program data. Thank you to Dr. Charles H. Reilly for his faith in God, his love of country, and his impeccable knowledge, mentorship, and guidance throughout the process. Finally, I would like to thank my wonderfully supportive wife and her willingness to pack up the house every 18 months so that I could fulfill a dream of serving in the United States Army.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AVIM – Aviation Intermediate Maintenance

ASM – American Society for Materials Engineers

CAPPB – Computer-Assisted Planning, Programming, Budgeting System

CCAD – Corpus Christi Army Depot

CPM – Critical Path Method

DOD – Department of Defense

FCS – Future Combat Systems

GAO – Government Accountability Office

GWOT – Global War on Terrorism

LP – Linear Programming

OCM – On Condition Maintenance

OEM – Original Equipment Maintenance

OPTEMPO – Operational Tempo

O&S – Operations and Support

PEO – Program Executive Office

PERT – Program Evaluation and Review Technique

TAT – Turn Around Time

TRACE – Total Risk Assessing Cost Estimate

UH-60A – Sikorsky’s “Blackhawk” Utility Helicopter

VERT – Venture Evaluation Review Technique

WIP – Work in Progress

LIST OF DEFINITIONS

Activities – Specific jobs or tasks that are components of a project. Activities are represented by nodes in a project network.

Immediate predecessors – The activities that must be completed immediately prior to the start of a given activity.

Project network – A graphical representation of a project that depicts the activities and shows the predecessor relationships among activities.

Critical path – The longest path with respect to time in a project network.

Critical activities – The activities on the critical path.

Slack – The length of time an activity can be delayed without affecting the project completion time.

Crashing – The shortening of activity times by adding resources and hence usually increasing cost.

CHAPTER 1: OVERVIEW

1.1 Introduction

Both in February and March, 1999, the Honorable Paul J. Hoeper, Assistant Secretary of the Army and Army Acquisition Executive, addressed the 106th Congress detailing the significant modernization challenges facing the United States Army. With modernization funding at an all time low (65% decrease from the funding supplied in 1985 and the lowest "real term" level since 1960 (Hoeper, 1999)), Mr. Hoeper first addressed the funding challenges stretching programs to great lengths and beyond. He described the struggle of sustaining and recapitalizing selected equipment (i.e. tanks, helicopters, vehicles) while simultaneously developing complementary replacements in the early part of the 21st Century. This ominous and continuous challenge, also called the "death spiral," exists because aging equipment invariably requires additional maintenance thereby increasing critical operations and support costs (O&S) that ultimately drain the modernization budget. Lieutenant General John C. Coburn, added that "the issue is so serious that, if not properly addressed and corrected, it will inevitably result in degradation in the Army's ability to maintain its readiness." (Hoeper, 1999)

Dr. Jacques Gansler, an expert in acquisition matters, offered that the key to avoiding this "death spiral" comes in the way of acquisition reform – a critical component to increase the efficiencies of the Army's internal operations to produce savings that could be applied in modernization efforts. In optimizing its overall performance, a program could now generate its own savings and provide an overarching benefit to the Army's collective effort. Seven years following his comments, we are now beginning to realize the power of Dr. Gansler's ideas.

Two years later, and four months prior to terror attacks of September 11, 2001, the Vice Chief of Staff of the Army approved a program specifically targeting the recapitalization of the UH-60A "Blackhawk" helicopter. Little did he know at the time the importance of this program for accomplishing the following mission statement.

Mission: UH-60A:A Recapitalization Program produces 20 aircraft per year within the parameters of a $1.3 Billion Dollar Budget, a 12 year schedule (2002-2013), and various performance measures such as managing the recapitalization baseline and providing overhauled components to the UH-60 fleet.

Endstate: A total of 193 UH-60A:A aircraft are recapitalized.

Executing five years of the UH-60A:A Program in parallel to the prosecution of the Global War on Terrorism has validated LTG Coburn's claim that meeting equipment challenges is every bit as serious as fighting a tough and determined enemy on many fronts. If you do not address the former, you most certainly cannot succeed in the latter. Unprecedented operational tempo over the past five years has demanded a significant increase of maintenance requirements on an already aging fleet of UH-60 Sikorsky aircraft, the largest fleet of aircraft in the Army (1585 Helicopters).

Today, the UH-60A:A Program attacks the inevitable and day-to-day "death spiral" within the framework of the Army Modernization Plan and National Sustainment Maintenance to address readiness within fiscal constraints and maintenance workload management, respectively. In doing so, project managers strive to balance rising O&S costs, the need for modernizing equipment, and the demands of maintaining a readiness posture suitable to prosecuting the Global War on Terrorism.

Army Modernization Plan

The UH-60 “Blackhawk,” Army Aviation’s workhorse in its 28th year of production, has flown well over 200,000 flight hours in support of Operation Enduring Freedom and Operation Iraqi Freedom.

Figure 1: Soldiers prepare to board a UH-60A in support of Operation Iraqi Freedom

Each year, over twenty aircraft are inducted into the UH-60A:A program for overhaul. Simultaneously, twenty aircraft are scheduled to be released back into the operating forces after recapitalization completion. More often than not, this is accomplished by executing the “more with less” maxim in solving the aforementioned dilemma. A program manager’s ability to effectively balance cost constraints, a demanding schedule, and various performance measures in the most effective manner is vital to protecting our nation's interests and sustaining land force dominance.

The Army's Modernization Plan addresses the critical balance of current and future readiness within fiscal constraints by emphasizing recapitalization of our aging equipment. The UH-60A:A Program addresses three of the five major goals in the Army Modernization Plan. By performing structural and component upgrades to five different parts of the aircraft, the program ensures compliance with Goal #1: to maintain combat overmatch. Goal #2, recapitalize the force, is achieved by extending the service life of the aircraft by 10-15 years. Finally, this program successfully accomplishes Goal #3 by integrating active and reserve components by servicing each organization and the airframes that accompany them. Achieving each of these three goals mitigates the readiness impact by aging equipment through reduction in O&S costs and improvement of current readiness through timely delivery of overhauled airframes.

National Sustainment Maintenance (NSM)

The NSM is an overarching maintenance management umbrella to distribute maintenance workload executed above the tactical level, affording the United States government the ability to efficiently workload its depots in recapitalizing the aging equipment fleet (Hoeper, 1999). This aggressive program targets O&S costs directly to target reduction through sustainment efforts on the remanufacture, rebuilding, and overhaul of systems. Further, it provides significant and lasting benefits by optimizing the core depot capability.

Corpus Christi Army Depot (CCAD), a successful depot executing a sound national sustainment maintenance program, improves overall reliability, reduces O&S costs, and provides opportunities and efficiencies for technology insertion in accordance with the recapitalization initiative. By performing range of maintenance from minor repair through complete overhaul of equipment not reparable by unit/intermediate maintenance, the depot relieves a significant maintenance manpower burden from the war fighter. The depot also performs original equipment manufacturer (OEM) maintenance and other specific actions that cannot be completed at the unit level based on maintenance policies.

Recapitalization

Without question, the need to retain legacy UH:60A's equates to an overall increase in average age of the airframe. Although an increasing average age of aircraft is inversely proportional to the decreasing overall performance edge, the Army must continue to address the issues at hand. The UH-60A:A Program recapitalizes its equipment through a combination of refurbishment and replacement initiatives that comprise 9 sub-networks (in a large overall project network) to extend useful life and reduce O&S costs. Each of the sub-networks is listed below, and heretofore referred to as a numbered network for the remainder of this paper.

.

- **Network 1**: Disassembly **Network 2**: Clean / PMB **Network 3**: PSA
- **Network 4**: Struct/Elect **Network 5**: Prime Paint **Network 6**: Assembly
- **Network 7**: Final Paint **Network 8**: Flight Test **Network 9**: Delivery

This paper specifically targets “Network 4” (Structural/Electrical) to reduce the total cost in reducing network turn-around-time (TAT) through the application of a linear programming model for project crashing. By crashing various activities in the project network, valuable insight into the optimal time/cost tradeoff is presented. A five-year performance summary of TAT by fiscal year is presented in Table 1. Although the overall Program TAT average has been decreasing consistently, there is still room for improvement within a few specified networks.

Table 1: Five Year Turn Around Time Summary of UH-60A:A Recap Program (Days)

Network	**5-Year Average**	**FY02**	**FY03**	**FY04**	**FY05**	**FY06**
1	15	16	16	18	13	11
2	17	13	14	21	17	19
3	11	8	8	17	10	11
4	***156***	***251***	***207***	***144***	***101***	***129***
5	17	36	27	8	11	8
6	97	82	119	91	80	51
7	7	12	8	7	7	7
8	27	38	27	22	32	30
9	9	8	11	9	8	4
TOTAL	345	449	437	337	274	252

We target Network 4 (Structural/Electrical) because of its variability and overall program contribution. First, significant variability exists with respect to TAT over the course of the past five reporting years. Secondly, and most importantly, improving Network 4 yields the highest improvement dividends as it is the most influential aspect of the program network, with 46% of the entire program time processed resting within its 68 activities. To gain a better understanding of the many factors influencing this network, we further consider three other factors that impact the total number of days to complete the process.

Table 2: Five Year Summary of Network 4

Network 4	**5- Year Average**	**FY02**	**FY03**	**FY04**	**FY05**	**FY06**
Structural/Electrical	113	138	150	97	87	98
Network Total	156	251	207	144	101	129

Three additional sub-categories within Network 4, “excess work in progress”, “work stoppage”, and “over and above,” are not shown in Table 2 but account for the discrepancy between the Structural/Electrical totals and the Network Total. The difference will be discussed in detail in Chapter 6 of this paper. For example, the FY02 data shows a large increase from structural/electrical to network total. This is mostly attributed to excessive work stoppage due to a lagging logistics system as the program transitioned from a truly infant state. Although this is a large factor in any aircraft maintenance scenario, 48 month’s worth of successful lean events from the depot, more proactive parts tracking from the Program Executive Office (PEO), and better understanding of the requirements in supporting the Global War on Terrorism have matured with time and have mitigated its overall impact.

1.2 Goals of the Present Study

Even if all of the modernization and recapitalization programs achieve 100% success over the next 20 years, it is critically important to understand that 70% of the Army's total force structure in 2020 will be comprised of legacy systems (Hoeper, 1999). Therefore, it is unrealistic to believe that the "death spiral" dilemma will truly ever be solved. With that understanding, the goal of this study is two-fold.

First, we seek to apply a methodology of linear programming for project scheduling that is applicable to any project with an existing network structure consisting of numerous interrelated activities. The goal is to schedule the activities in the network to achieve the least costly completion of the project by a specified deadline. Using this approach, we supply "crash" time estimates to normal activity times in order to achieve project completion by a specified time at minimum cost. With the existing project structure, we create a network representation of the constituent activities to identify critical tasks, key in subsequent analysis as these tasks may change as crashing begins. Although the number of scenarios one could consider is virtually limitless, we address three scenarios (Scenario #1 driven from the program manager and Scenarios #2 and #3 offered as alternatives developed in consultation with the program manager).

- Scenario #1: Crash the existing network by hiring 55 additional contractor employees. This course of action is the current accepted practice as CCAD is pursuing hiring additional contractors to work on the program. The activity crash estimates are provided from the master scheduler for the program. The cost is measured in labor costs with respect to 2006 wage rates by grade.

- Scenario #2: Crash the existing network using overtime (60 total work hours per person per week). This course of action examines using the existing work force in an overtime scenario to avoid paying exorbitant contractor costs. The activity crash estimates are derived by decreasing the contractor crash estimates by 50% as approved by the master scheduler for the program. The cost is measured in labor costs times 1.5 to address overtime hours (i.e. hours worked in excess of 40/week).

- Scenario #3: Crash the existing network using overtime (50 total work hours per person per week). This course of action examines using the existing work force in a reduced overtime scenario to avoid paying exorbitant contractor costs. The activity crash estimates are derived by reducing the contractor crash estimates by 75% as approved by the master scheduler for the program. The cost is measured in labor costs times 1.5 to address overtime hours (i.e. hours worked in excess of 40/week).

Through these three scenarios we seek to provide enough information in addressing the critical tradeoffs between time and cost – applicable in any project in any program.

In accomplishing the first goal, we desire to achieve a second goal of providing a simplistic and user-friendly methodology for use within the operating forces of the United States Army for future applications. We utilize Microsoft Project and Microsoft Excel because of their availability, ease of use, and universal familiarity with the target audience of the United

States Army. Although this study is focused on Army helicopters, this model and this approach can be applied to any system with a set of interdependent tasks to better solve the challenges presented in the “death spiral.”

1.3 Organization of Thesis

The remainder of this document is divided into five additional chapters. Chapter 2 primarily addresses an accompanying literature review with respect to linear programming and the critical path method, the cost of crashing various activities in the network, and its applications within the Department of Defense and United States Army Aviation. We further address various aviation maintenance challenges that rest within a depot maintenance facility. Chapter 3 discusses and defines the proposed model to solve this problem, the derivation of the input parameters and a supporting explanation of data collection. Chapter 4 focuses solely on the three scenarios evaluated within the framework of the linear programming model, while Chapter 5 examines the results, primarily focusing on the investigation of how each model targets the crash variables within the network and the associated critical path for each scenario as we attempt to find the best tradeoff between cost, schedule, and performance. Finally, Chapter 6 summarizes the findings while providing recommendations, conclusions, and suggestions for future work.

CHAPTER 2: LITERATURE REVIEW

Although the United States Army and the Department of Defense has been utilizing linear programming for a variety of purposes for many years, very little evidence exists within the context of applying a linear program to an existing aviation maintenance schedule to minimize program cost while reducing total TAT. This is, in large part, because historical deterministic CPM presents few problems of interest (Haga, 2004). We, for the purposes of this study, feel differently and hope to lay the framework for an eventual application adopted by the mainstream maintenance managers across the Army.

Over the past several years, the distinction between the PERT and CPM approaches have become increasingly blurred. Surprisingly, little work has been done in the area of the time-cost tradeoff problem (Haga, 2004), even though PERT and CPM have been around since the 1950's. Therefore, the following literature review offers a basic history and understanding of linear programming and some of the key findings over the past 60 years that are pertinent to this work. The remainder of the review consists of various key snapshots of historical Department of Defense applications and a recent history of depot level maintenance and the associated challenges dealing with the time/cost balance. Each of the topics presented are applicable to the areas of emphasis targeted by this study.

2.1 History of Linear Programming

Any historical summary of linear programming (LP) must first begin with Professor George B. Dantzig as he contributed more than any other researcher to this discipline's development. The problem that started his research is still one that we grapple with today – the problem of planning or scheduling dynamically over time. Dantzig's background in the Department of Defense is of particular interest in this case, as he was addressing one of the same issues (rapid computation of time-staged development, training and logistical supply program) that effects the project presented in this paper (Lenstra, 2002). In fact, the somewhat confusing name of "linear programming" is based on the military definition of program (Lenstra, 2002).

Dantzig's simplex algorithm solves LP problems by constructing an admissible solution at a vertex of the polyhedron, and then moving along its edges to the vertices with successively higher values of the objective function until the optimal solution is reached. Many successful applications of LP are found in the literature.

Van Slyke (1963) demonstrated several advantages of applying simulation techniques to PERT, including more accurate estimates of true project length. This is especially applicable in this case as the linear program is only as good as the "crash estimates" provided from the scheduler. Although our study is not a simulation, much can be learned from Van Slyke's work in overall understanding of a scientific way to estimate project completion time. Instead of using a simplistic "trial and error" approach, Van Slyke offered various distributions for activity times and a way to calculate "criticality indexes."

Karmarkar (1984) proposed the first algorithm for LP that performs well both in theory and in practice. This method falls within the class of interior point methods and was the first reasonably efficient algorithm that solves LP problems in polynomial time. Since then, many interior point methods have been proposed and analyzed as alternatives to the simplex method.

Ramini (1986) proposed an algorithm for crashing PERT networks with the use of criticality indices, but no results were ever reported. The most important takeaway from this work is that it did not account for bottlenecks. Every schedule has bottlenecks, including the schedule examined in this study. However, even when project managers build time buffers into their completion time estimates, the potential for late projects still exists largely because of deviation from timetables and budget constraints. Both of these areas will be addressed later in this chapter.

Ameen’s (1987) work with computer assisted PERT simulation actually inspired and refined this study. It is first important to understand that there are numerous critical paths within a given project schedule, once that schedule becomes subject to crashing its activities. Because crashing a given activity by one time period will not necessarily reduce the completion time of the project by one time period, it is critical to utilize Ameen’s instructional tool to teach project management techniques. This is clearly the crux of the time-cost problem and the need to understand the relationships and tradeoffs for each project manager.

Four years later, Badiru (1991) developed another simulation program called STARC that affords the user the opportunity to calculate the probability of completing the project by a specified deadline. This speaks more to pessimistic and optimistic estimates and again affords insight into the overall complexity of executing a program schedule. For purposes of this paper, we utilized the crash estimates given by the program scheduler as well as the five-year historical data to obtain the most feasible TAT completion target goal.

Feltz (1970) presents an interesting application of the critical path method to explore the overall cost of crashing. He determined that the critical path method was the most likely management technique for controlling costs and deadlines because CPM provided the opportunity to separate planning and scheduling functions. He uses a sequential algorithm for selecting the activities of achieving a target for total project duration. He then sequentially expedites activities on the critical path in the order of increasing cost rates. Although not applied in this case, this method could be applied to delve deeper into a better understanding of the cost of crashing.

Nearly thirty years later, Roemer and Ahmadi (2000) refined Feltz’s model to present a formal model that addressed both the overlapping of development stages and crashing of development times with respect to product development. This application may apply if this study were addressing the entire nine phase program and offers future potential for research as Roemer and Ahmadi’s results exhibited the necessity of addressing overlapping and crashing concurrently as well as general characteristics of optimal overlapping/crashing policies.

Premachandra (1992) presents a goal-programming model for activity crashing in project networks that speaks specifically to the importance of understanding the goals of a respective PERT/CPM problem. Because project management often has several objectives, goal programming is utilized to handle multi-criteria situations within the general framework of linear programming. This is especially important in providing the project manager options in crashing various activities in the network because often it is not responsible to assume that equal priority is given to crash each activity. With respect to minimizing cost, an LP model may provide a solution which falls outside of the intended budget or project cost. This model considers both under- and overachievement for each of the specified goals as well as assigning a priority factor for each goal. The result is a solution requiring multiple interpretations to ensure the specified goals were properly addressed. Again, this is extremely valuable in situations where managers make decisions subject to many criteria to obtain a more practically feasible solution to the program manager.

Love and Drew (2000) examine the effects of progressively long overtime that generates quality problems like rework and the commitment of additional resources. For purposes of this study, we assume an overall low rework percentage although there is currently no measure in place to accurately present the total amount of rework performed per year in the UH-60A:A Program. With that said, there is validity in modeling the complex nature of attaining a tradeoff between working overtime and the procurement of additional resources such as hiring contractors. Love and Drew use system dynamics modeling to examine the effects of overtime work on project cost and quality.

Love and Drew (2000) conclude that prolonged overtime working may cause declines in productivity and performance and those findings drove us to refine our original crash estimates in both overtime scenarios. Love and Drew's paper was the first attempt to analytically determine the effects of overtime and can be used to mitigate delays of large projects and projects with confined shifts and sites, projects like UH-60A:A. Determining the most appropriate combination of prescribing overtime work and injecting additional resources is very significant and often will determine the level to which cost savings are achieved.

This study focuses on one of the special cases of linear programming in addressing a network scheduling problem, a topic that led to research on many of the previously presented specialized algorithms. The current common opinion is that the efficiency of good implementation of the simplex-based methods and interior point methods is similar for routine applications of linear programming. Even though there are a multitude of LP solvers to address various problems in industry, we have chosen the Microsoft Excel compatible Premium Solver developed by Frontline Systems.

2.2 Department of Defense Applications

Early applications of PERT within the Department of Defense can be traced back to the Polaris Project in the 1950's and the Army LANCE missile system. A study presented in 1964 regarding the LANCE project highlights the early beginnings of the same challenges we continue to grapple with today: defining and serving organizational goals in concert with a program mission statement while simultaneously reducing cost and continually redesigning a project network (Borgman, 1975). The application of PERT aided greatly in the redesign of the missile container system within the LANCE project.

Whiton (1971) offers interesting insight into the four major large-scale linear programming models in current usage 30 years ago within the Department of Defense. Each of these models displays the baseline PERT models employed at the highest levels within the DOD specifically targeting personnel assignments, resource allocations for training, logistics issues in streaming the supply chain, and other large scale decisions involving base realignment and closure (Whiton, 1971). We learn a great deal from the past as he offers key analysis on the developmental problems encountered between the early model developers and the users. He also speaks to the various applications of extensions from the four large-scale models discussed in the paper.

Parallel work from the Department of the Army was also performed in 1975 with their advent of the Total Risk Assessing Cost Estimate (TRACE) program whose goal was to develop a new program cost-estimation procedure for research, development, test and evaluation cost realism (Cockerham, 1976). Although not applied to an existing production network, this approach is applicable in this study as it addresses uncertainties that could possibly be applied to current schedules. Applying the essential elements of the TRACE concept yields two very important models: a cost impact model and a schedule variance model. Each and every schedule possesses variance within the estimates and the UH-60A:A Program could benefit from researching variance models in refining the network. Additional applications of this procedure exist within the NASA/Army Tilt Rotor Research Aircraft Project back in 1975.

In 1987, the United States Army Logistics and Management Center at Fort Lee, Virginia, developed an application with PERT principles called the Venture Evaluation Review Technique (VERT). This valuable management tool focused on modeling program cost, schedule, and performance risk (McGowen, 1987). Although very similar in concept, VERT, a computer-supported network modeling and simulation technique, possesses far greater modeling and analysis capabilities to PERT. McGowen (1987) presents VERT's capabilities in comparison to PERT techniques in addition to offering the latest version of VERT, VERT-PC, for review.

Like the Logistics and Management Center at Fort Lee, the United States Army Corps of Engineers Construction Engineering Research Lab continues to utilize and develop PERT systems. In 1994, they developed an information system called CAPPB (Computer-Assisted Planning, Programming, and Budgeting System). CAPPB assists in gathering and providing detailed resource programming information for the military engineer to plan and defend resource requirements (Goettel, 1994). The single biggest strength of this application is that it includes links to several other Army systems to improve data consistency and to avoid duplication of data entry. In our study, we utilize the Premium

Solver package developed by Frontline Systems as it is embedded in the widely utilized Microsoft Excel software.

In 1999, the United States Army deployed and tested a multiple objective model for manpower planning in a company-sized, 100-soldier, military reserve unit. This model involved 5 objectives and consisted of over 1,150 decision variables and 650 constraints over a 12-month planning horizon (Reeves, 1999). Although our model is reduced in scale, this research and application is very applicable to our study as it generated model solutions using two different procedures, providing valuable insight to the employment of reserve personnel. Ironically, this information proved critical given the role of the United States reserve forces in support of the Global War on Terrorism. Instead of learning through the painful experience of the past, we envision using the current wartime setting to establish a credible model that provides the decision maker with as much pertinent information as possible to handle any contingency and any challenge regarding time and money. Ultimately, this manpower model was extremely effective in solving manpower challenges.

2.3 Depot Level Maintenance

Over the past 10 years, there has been a series of reports published by the General Accounting Office (GAO), the investigative arm of Congress charged with examining matters relating to the receipt and payment of public funds. The GAO has published reports highlighting deficiencies in the spare parts supply system, as well as the management of government funding to effectively achieve the collective mission of depot level maintenance repairs such as recapitalization.

Although the practice of “cannibalizing” aircraft parts from one aircraft to another has been around since the advent of Army Aviation, the most recent literature addressing this phenomenon is found in 2001. This practice, valuable in limited situations, ultimately causes many second and third order effects and eventually creates more problems than it solves. The primary effect from these practices results in higher maintenance costs due to increased mechanics' workloads (Curtin, 2001). This is especially important when dealing with the size and scope of the mission statement presented in Chapter 1. Even if a program has the money to offset the higher labor costs, they can expect an overall reduction in performance from the work force due to decreased morale. It is extremely frustrating for a maintainer to enter “work stoppage” on a task due to limited parts. It is even more frustrating for that same maintainer to work additional man hours in removing a functional part from another aircraft and then reinstalling that same part on the aircraft in maintenance. Lastly, and most importantly, cannibalization may solve a problem in the short-term, but ultimately the long-term result will be extensive delays in multiple aircraft, therefore failing to accomplish the mission that cannibalization was supposed to originally solve.

However, it is important to study and review this aspect of the literature because strong incentives exist for cannibalizing aircraft. Often, maintenance managers are so discouraged with the supply system that they lose the vision necessary to identify the shortfalls and use cannibalization as a crutch to meet readiness and operational needs (Curtin, 2001). Using linear programming to better understand a schedule will ultimately channel the energy toward addressing logistics shortfalls and developing specific strategies to reduce cannibalizations and the associated maintenance hours.

Just two months after the UH-60A:A program was initiated, the GAO further highlighted maintenance shortcomings in the military’s ability to carry out future operational missions. Because we cannot predict when and where we, as a nation, go to war, it is crucial to identify and source the proper number of adequate spare parts within the supply system for all levels of maintenance and repairs.

From a financial perspective, the GAO concludes that parts shortages are a key indicator that the billions of dollars being spent on these parts are not being used effectively, efficiently, and economically. For many years, including 2001, Congress continually supplied additional funding to aid in the money intensive arena of aviation maintenance (Warren, 2001). This report further highlights spare parts shortages for many aircraft including the UH-60 Blackhawk and further addresses the issue of cannibalization as an inefficient practice that results in double work for the maintenance personnel, masks parts shortages, and lowers morale.

The “parts problem” has been around for decades and can be attributed to many things including higher-than-expected demand, delays in obtaining factory direct parts, and various problems with overhaul and maintenance. Moreover, the Army’s inability to forecast and obtain parts for aging fleets whose original providers have long since gone out of business represents another key factor (Warren, 2001). In late 2001, the Army and the Defense Logistics Agency went “under the microscope” to improve the availability of aviation spare parts, subject to periodic review from the GAO. The improvement has been slow and steady at best.

Nearly three years and two wars later, the Defense Department began to come to grips with the massive maintenance demands produced from one year’s worth of consistent combat operations. This is not surprising because they never truly had the peacetime solution. Why should we expect them to possess the wartime solution? In 2004, the GAO concluded that it will take “months or years to get aircraft fleets back to acceptable levels” (Wall, 2004). The U.S. Army is feeling the greatest burden as they are maintaining the delicate balancing act in running a massive repair and overhaul effort for helicopters returning from the combat zone, while continuing to operate more than 600 aircraft in Iraq and Afghanistan (Wall, 2004). These operational demands prevented the UH-60A:A program from getting the jumpstart it needed and can be directly cited for the program’s overall sluggish start with respect to higher than necessary TAT.

In aggressively attacking Secretary Hoeper’s challenging “death spiral,” the GAO further cited in 2004, that the U.S. Army was borrowing production money from its next five-year budget plan to pay development costs for an additional four programs in its Future Combat System (FCS) project (Fulgham, 2004). This is yet another example of the challenges that exist on a day-to-day basis as the FCS initial budget for design and development was twenty times greater than the entire UH-60A:A Program. Army leadership, heavily criticized in the past for its long-term neglect of aviation modernization and for using aviation funding to pay for other high-profile programs such as armor, reshuffled four programs and accelerated four additional programs to combat the discrepancy (Fulgham, 2004).

In 2005, the GAO took a hard look at the activities involved within depot maintenance. GAO identified four management weaknesses that are impairing the efficiency and effectiveness of Army depot maintenance operations. The activity group's average sales price increased from $111.87 per hour for fiscal year 2000 to $147.07 per hour for fiscal year 2005--a 31 percent increase (21 percent if adjusted for inflation) (Kutz, 2005). An increase in material costs was the major driver of the sales price increase. The Army has identified some causes of the higher material costs, but it has not completed a comprehensive analysis of material cost increases. Consequently, the Army failed to take proactive steps to control rising material costs. This finding further validates the notion of reducing total labor costs as a means for acquisition programs to help their potential funding problems.

GAO analysis showed that in setting future prices, the Army spread depot maintenance reported gains and losses across all depots rather than allocating them to the individual depot that incurred the gains or losses (Kutz, 2005). While DOD policy does not specify how to allocate gains and losses at the depot level, this practice does not provide the right incentives to the depots to set prices correctly. This larger problem and root cause of setting prices correctly will continue to fester and create heartache within the program until remedied.

Figure 2: Forward View of Electrical Upgrades to UH-60A

2.4 Time/Cost Challenge

As stated, the cost of prosecuting the Global War on Terrorism on two fronts has challenged every arm of the Department of Defense. *Aviation Week and Space Technology* cited a GAO estimate that the DOD was overspending its $65 billion appropriation for the fiscal year 2004 by $12.3 billion, or nearly 19% (Bond, 2004). Each of the four major services' operations and maintenance accounts were overrunning and subsequently demanding a deferral of additional activity to fiscal year 2005. This is a common practice with the Department of Defense and often one way to deal with the time/cost challenge. Program managers must understand this tactic and safeguard against it. For if their respective program is not on time and on budget at each critical point of the year, then they may miss critical performance goals and measures. Often, the first to feel the effects of cutbacks to compensate for overspending is peacetime operations, depot maintenance, and contractor logistics support (Bond, 2004). Cuts in depot maintenance and contractor logistics support have impacted depot programs like UH-60A:A, regardless of the services they perform.

Therefore, within an aviation maintenance situation like UH-60A:A, it is even more critical to produce "more with less" for as fast and as long as you can. For the GAO's chief concern of deferrals causing second and third order effects haunts every project manager. These effects could fester into a "bow wave" of unfinished business extending past the subsequent fiscal year, ultimately resulting in a collective "two footed" leap into the inevitable "death spiral."

CHAPTER 3: PROPOSED MODEL

3.1 Justification for Proposed Model

This problem addresses the inevitable challenge facing every program manager in the world: What is the optimum balance between expediting an existing schedule and its corresponding impact on the framework of a fixed budget? Although not necessarily constrained to a tangible fixed monetary budget, this dilemma can be extended to the desk of nearly every maintenance manager in every aircraft hangar in the United States Army. Although these problems could be and are often modeled analytically using mean values, common knowledge, and the ever scientific “this is how we did it last time approach,” a decision model using a common and existing software package like Microsoft Excel could prove invaluable in maximizing total efficiency within any project network. This model aims to provide realistic and easily interpreted results while holding true to critical factors like system variability and flexibility to input a large number of diverse input parameters.

The overarching intent of the model is to present an approach that is mathematical in nature and logical in its approach. Additionally, the aforementioned model must be “experimentally friendly” in affording the user a complete understanding of the model’s power with limited training. Once this understanding is gained, the user possesses the ability to change input parameters quickly and efficiently to draw critical conclusions about enhancing the performance of the given network. These conclusions afford the user the ultimate ability to implement necessary, priority-driven changes necessary to achieve optimal results.

Linear programming is extremely applicable in the PERT/CPM type applications like project networks where a series of interdependent tasks are performed simultaneously in order to achieve a common end state. The notion of critical path is also applicable in these types of scenarios as much can be learned from its examination and understanding the tradeoff between time and cost.

3.2 Description of Proposed Model

After an initial dialogue from March, 2006 to May 2006, we gained approval to model portions of the UH-60A:A Program from the product manager for UH-60A/L, Mr. Eric Edwards, located in Huntsville, AL and the Program Manager, Mrs. Jackie Gibson, located in Corpus Christ, TX. The following represents the step by step process of developing the linear programming model in accordance with the methods presented by Anderson, Sweeney, and Williams (2005).

Step 1 – Description and Definition of Targeted Network

As stated, the focus of this effort is to model the aforementioned “Network 4” within the UH-60A:A Recapitalization Program. This 68-task (activity) network is comprised of structural and electrical upgrades and replacements as well as various modifications and/or improvements to extend the service life of the airframe 10 to 15 years. The completion times of these tasks were defined as the “decision variables” and labeled with corresponding X1 through X68 nomenclature (See Appendix A for a list of decision variables.) Telephone calls, email consultation, and two on-site visits with the program manager and chief project scheduler in Corpus Christi, TX aided in accomplishing the next several steps of the process.

Currently, the UH-60 A:A Program consists of two eight-hour shifts manned with 53 workers on first shift and 52 workers on second shift. For purposes of discussion, we have grouped the 105 workers into one pool for analysis. There are two types of workers from four different pay grades who are about evenly distributed over eight different work teams. The first type of worker represents the government employees (63 total) who earn one of three wages in accordance of their classification, either Wage Grade 5, Wage Grade 8, or Wage Grade 10. The second type of worker represents contracted civilian employees (42 total) who earn a different flat rate fee per hour. Each worker performs 40 hours of work in a given work week without any scheduled overtime. Table 3 details the total personnel breakdown by team and wage as well as current wage rates for government employees and contractors. It is assumed that each team works on different aspects of the network within the hangar floor and, if there is any work stoppage in a given area, that the workers are redistributed to the most critical aspect of the program within the given time.

Table 3: 2006 Wage Rates for Government Employees and Contracted Civilians

	Grade 5	Grade 8	Grade 10	Contractor
Wage Rate/Hr	$18.29	$21.45	$23.47	$128.70
Team 1	1	1	6	5
Team 2	1	1	6	5
Team 3	1	1	6	5
Team 4	1	1	6	5
Team 5	1	1	6	5
Team 6	1	1	6	5
Team 7		2	6	6
Team 8		2	5	6
TOTALS	6	10	47	42

Source: DoD Civilian Personnel Management Federal Wage Table (2006), CCAD

Step 2 – Derivation of the Network Diagram, Determination of Predecessors

After inputting the network data (normal activity start times, normal activity finish times, and immediate predecessors) into Microsoft Project 2003, we then determined the network diagram as well as the critical path and associated critical activities. This accurate network diagram highlighted the immediate predecessors necessary for deriving the constraints for the linear program. Understanding the critical path is essential and an integral step in proceeding with the analysis of the results, as this path will most likely change for each of the three scenarios. Detailed analysis of the critical path will be presented in Chapter 6.

Step 3 – Estimation of Activity Completion Times in a Normal Environment

With the network diagram complete (See Appendix B for network diagram) and the normal activity start and finish times known, the framework for the derivation of the constraints was in place. The program scheduler estimated the "activity normal times" (An) for each task.

Step 4 – Estimation of Activity Completion Times in a "Crashed" Environment

The program scheduler then identified 24 of the 68 tasks in the network that could be crashed by applying additional resources (manpower) to complete the task faster. It is important to note that we define "crashing" as allocating additional resources to a specific activity of the network to reduce overall completion time. Table 4 depicts the activity normal completion times (An) (in hours) for each task as well as the "crashed" activity completion times (Ac) (in hours) for each of the previously identified 24 activities or tasks for Scenario 1. The variables associated with activities that may be crashed are highlighted in bold.

Table 4: Summary of Activity Normal Times (hours) and Activity Crash Times (hours)

Variable	Normal Time (Hrs)	Crash Time (Hrs)	Variable	Normal Time (Hrs)	Crash Time (Hrs)	Variable	Normal Time (Hrs)	Crash Time (Hrs)
X1	8		X24	32		X47	24	
X2	8		X25	8		X48	24	
X3	8		X26	24		X49	24	
X4	**16**	**12**	X27	24		X50	32	
X5	56		X28	56		X51	40	
X6	104		X29	152		**X52**	**24**	**16**
X7	**8**	**6**	**X30**	**24**	**15**	**X53**	**24**	**16**
X8	16		**X31**	**24**	**16**	**X54**	**8**	**6**
X9	16		X32	16		**X55**	**24**	**16**
X10	24		**X33**	**8**	**6**	**X56**	**16**	**10**
X11	80		**X34**	**8**	**6**	**X57**	**16**	**10**
X12	**16**	**12**	X35	24		**X58**	**8**	**6**
X13	**64**	**56**	X36	32		**X59**	**40**	**32**
X14	24		**X37**	**24**	**16**	**X60**	**4**	**3**
X15	72		**X38**	**24**	**16**	X61	32	
X16	48		X39	56		**X62**	**4**	**3**
X17	240		X40	32		**X63**	**80**	**60**
X18	8		**X41**	**8**	**6**	X64	8	
X19	24		X42	56		X65	8	
X20	8		**X43**	**16**	**10**	X66	8	
X21	48		X44	40		**X67**	**16**	**12**
X22	32		X45	16		X68	4	
X23	64		X46	8				

Step 5 – Calculation of the Normal Cost/Hr Worked and Crash Cost/Hr Worked

With the estimates for activity completion times under normal and "crashing" conditions complete, we now must calculate the average cost/hr worked under both normal and crashed conditions. In accordance with guidance from the program manager, we examined Scenario 1 (Crashing the Network by hiring 55 additional contractors to the existing eight teams). First, we had to compute the "total cost per hour worked under normal conditions" per team (Ctn). Once computed, we summed the eight values for Ctn to find the value for Cn (total network cost per hour worked under normal conditions). The actual values for calculating Cn are listed in Table 5 below.

Table 5: Derivation of Total Network Cost per Hour Worked under Normal Conditions

	WGrade 5 Total Cost	WGrade 8 Total Cost	WGrade 10 Total Cost	Contractor Total Cost	Hourly Team Cost
Team 1	$18.29	$21.45	$140.82	$643.50	$824.06
Team 2	$18.29	$21.45	$140.82	$643.50	$824.06
Team 3	$18.29	$21.45	$140.82	$643.50	$824.06
Team 4	$18.29	$21.45	$140.82	$643.50	$824.06
Team 5	$18.29	$21.45	$140.82	$643.50	$824.06
Team 6	$18.29	$21.45	$140.82	$643.50	$824.06
Team 7		$42.90	$140.82	$772.70	$955.92
Team 8		$42.90	$117.35	$772.70	$932.45
TOTALS					**$6,832.73**

Ctn = #WG5*$18.29 + #WG8*$21.45 + #WG10*23.47 + #Cont*$128.70

Cn = Ctn1 + Ctn2 + Ctn3 + Ctn4 + Ctn5 + Ctn6 + Ctn7 + Ctn8 = $6,832.73

Once calculated, we applied the Cn value to each of the tasks to determine the total task cost under normal conditions. This value will be critical when determining the total crash cost per hour.

The additional 55 contractors were distributed across each of the eight teams and the "total cost per hour worked under crash conditions per team" (Ctc) was computed, yielding an increased cost for contractor column of the aforementioned table. Once Ctc was computed, we summed the eight values for Ctc to find the value for Cc (total network cost per hour worked under crashed conditions). The actual values for calculating Cc is listed in Table 6 below.

Table 6: Derivation of Total Network Cost per Hour Worked under Crashing Conditions

	WGrade 5 Total Cost	WGrade 8 Total Cost	WGrade 10 Total Cost	Contractor Total Cost	Hourly Team Cost
Team 1	$18.29	$21.45	$140.82	$1,544.40	$1,724.96
Team 2	$18.29	$21.45	$140.82	$1,544.40	$1,724.96
Team 3	$18.29	$21.45	$140.82	$1,544.40	$1,724.96
Team 4	$18.29	$21.45	$140.82	$1,544.40	$1,724.96
Team 5	$18.29	$21.45	$140.82	$1,544.40	$1,724.96
Team 6	$18.29	$21.45	$140.82	$1,544.40	$1,724.96
Team 7		$42.90	$140.82	$1,544.40	$1,856.82
Team 8		$42.90	$117.35	$1,673.10	$1,833.35
TOTALS					**$14,039.93**

Ctc = #WG5*$18.29 + #WG8*$21.45 + #WG10*23.47 + #Cont*$128.70

Cc = Ctc1 + Ctc2 + Ctc3 + Ctc4 + Ctc5 + Ctc6 + Ctc7 + Ctc8 = $14,039.93

Tables 7 outlines the total overtime cost utilized in Scenarios 2 and 3. We simply multiply each of the WGrade hourly costs listed above by 1.5 to account for overtime pay. The contractor hourly cost is multiplied by 1.8 to account for overtime and other benefit costs not associated with government workers.

Table 7: Derivation of Total Network Cost per Hour Worked under Normal Conditions

	WGrade 5 Total Cost	WGrade 8 Total Cost	WGrade 10 Total Cost	Contractor Total Cost	Hourly Team Cost
Team 1	$27.44	$32.18	$211.23	$1158.30	$1429.14
Team 2	$27.44	$32.18	$211.23	$1158.30	$1429.14
Team 3	$27.44	$32.18	$211.23	$1158.30	$1429.14
Team 4	$27.44	$32.18	$211.23	$1158.30	$1429.14
Team 5	$27.44	$32.18	$211.23	$1158.30	$1429.14
Team 6	$27.44	$32.18	$211.23	$1158.30	$1429.14
Team 7		$64.32	$211.23	$1389.96	$1665.54
Team 8		$64.32	$176.03	$1389.96	$1630.34
TOTALS					**$11,870.72**

Ctc = #WG5*$27.44 + #WG8*$32.18 + #WG10*35.21 + #Cont*$231.66

Cc = Ctc1 + Ctc2 + Ctc3 + Ctc4 + Ctc5 + Ctc6 + Ctc7 + Ctc8 = $11,870.72

Once we have derived the three cost values (Normal Labor, Crash Contractor Labor, and Overtime Labor) we can now present the crash costs for each of three scenarios listed in Table 8 below.

Table 8: Summary of Crash Costs for Each Scenario

	Normal Cost	Contractor Cost	Overtime Cost	Total Crash Cost
Scenario 1	$6,832.73	$14,039.93	N/A	$14,039.93
Scenario 2	$6,832,73	N/A	$11, 870.72	$8,512.06
Scenario 3	$6,832.73	N/A	$11, 870.72	$7,840.33

The total crash cost values for Scenario 2 and Scenario 3 are computed by multiplying the applicable percentage of each value worked within the outlined parameters.

Scenario 2 = .66($6,832.73) + .33($11,870.72) = $8,512.06

Scenario 3 = .80($6,832.73) + .20($11,870.72) = $7,840.33

Step 6 – Calculation of Maximum Reduction in Time (M) and Crash Cost/Hr (K)

Combining the computed data of normal cost per hour (Cn) and crash cost per hour (Cc) with the estimates for activity normal time (An) and activity crash time (Ac) allows us the opportunity to compute the maximum reduction in time (M) and then subsequently compute the crash cost/hour (K) for each crashable activity. The equations used for calculating maximum reduction time (M) and crash cost per hour (K) are listed below.

- M = An – Ac
- K = (Cc – Cn)/M

Tables 9, 10, and 11 listed below detail the data used for Scenarios 1, 2, and 3

Table 9: Summary of Scenario 1

Task	M	Cc ($)	Cn ($)	K ($)	Task	M	Cc ($)	Cn ($)	K ($)
X1	0	112319.44	54661.84		X35	0	336958.32	163985.52	
X2	0	112319.44	54661.84		X36	0	449277.76	218647.36	
X3	0	112319.44	54661.84		X37	8	224638.88	163985.52	7581.67
X4	4	168479.16	109323.68	14788.87	X38	8	224638.88	163985.52	7581.67
X5	0	786236.08	382632.88		X39	0	786236.08	382632.88	
X6	0	1460152.72	710603.92		X40	0	449277.76	218647.36	
X7	2	84239.58	54661.84	14788.87	X41	2	84239.58	54661.84	14788.87
X8	0	224638.88	109323.68		X42	0	786236.08	382632.88	
X9	0	224638.88	109323.68		X43	6	140399.30	109323.68	5179.27
X10	0	336958.32	163985.52		X44	0	561597.20	273309.20	
X11	0	1123194.40	546618.40		X45	0	224638.88	109323.68	
X12	4	168479.16	109323.68	14788.87	X46	0	112319.44	54661.84	
X13	8	786236.08	437294.72	43617.67	X47	0	336958.32	163985.52	
X14	0	336958.32	163985.52		X48	0	336958.32	163985.52	
X15	0	1010874.96	491956.56		X49	0	336958.32	163985.52	
X16	0	673916.64	327971.04		X50	0	449277.76	218647.36	
X17	0	3369583.20	1639855.20		X51	0	561597.20	273309.20	
X18	0	112319.44	54661.84		X52	8	224638.88	163985.52	7581.67
X19	0	336958.32	163985.52		X53	8	224638.88	163985.52	7581.67
X20	0	112319.44	54661.84		X54	2	84239.58	54661.84	14788.87
X21	0	673916.64	327971.04		X55	8	224638.88	163985.52	7581.67
X22	0	449277.76	218647.36		X56	6	140399.30	109323.68	5179.27
X23	0	898555.52	437294.72		X57	6	140399.30	109323.68	5179.27
X24	0	449277.76	218647.36		X58	2	84239.58	54661.84	14788.87
X25	0	112319.44	54661.84		X59	8	449277.76	273309.20	21996.07
X26	0	336958.32	163985.52		X60	1	42119.79	27330.92	14788.87
X27	0	336958.32	163985.52		X61	0	449277.76	218647.36	
X28	0	786236.08	382632.88		X62	1	42119.79	27330.92	14788.87
X29	0	2134069.36	1038574.96		X63	20	842395.80	546618.40	14788.87
X30	9	210598.95	163985.52	5179.27	X64	0	112319.44	54661.84	
X31	8	224638.88	163985.52	7581.67	X65	0	112319.44	54661.84	
X32	0	224638.88	109323.68		X66	0	112319.44	54661.84	
X33	2	84239.58	54661.84	14788.87	X67	4	168479.16	109323.68	14788.87
X34	2	84239.58	54661.84	14788.87	X68	0	56159.72	27330.92	

Table 10: Summary of Scenario 2

Task	M	Cc ($)	Cn ($)	K ($)	Task	M	Cc ($)	Cn ($)	K ($)
X1	0	68096.48	54661.84		X35	0	204289.44	163985.52	
X2	0	68096.48	54661.84		X36	0	272385.92	218647.36	
X3	0	68096.48	54661.84		X37	4	170241.20	163985.52	1563.92
X4	2	119168.84	109323.68	4922.58	X38	4	170241.20	163985.52	1563.92
X5	0	476675.36	382632.88		X39	0	476675.36	382632.88	
X6	0	885254.24	710603.92		X40	0	272385.92	218647.36	
X7	1	59584.42	54661.84	4922.58	X41	1	59584.42	54661.84	4922.58
X8	0	136192.96	109323.68		X42	0	476675.36	382632.88	
X9	0	136192.96	109323.68		X43	3	110656.78	109323.68	444.37
X10	0	204289.44	163985.52		X44	0	340482.40	273309.20	
X11	0	680964.80	546618.40		X45	0	136192.96	109323.68	
X12	2	119168.84	109323.68	4922.58	X46	0	68096.48	54661.84	
X13	4	510723.60	437294.72	18357.22	X47	0	204289.44	163985.52	
X14	0	204289.44	163985.52		X48	0	204289.44	163985.52	
X15	0	612868.32	491956.56		X49	0	204289.44	163985.52	
X16	0	408578.88	327971.04		X50	0	272385.92	218647.36	
X17	0	2042894.40	1639855.20		X51	0	340482.40	273309.20	
X18	0	68096.48	54661.84		X52	4	170241.20	163985.52	1563.92
X19	0	204289.44	163985.52		X53	4	170241.20	163985.52	1563.92
X20	0	68096.48	54661.84		X54	1	59584.42	54661.84	4922.58
X21	0	408578.88	327971.04		X55	4	170241.20	163985.52	1563.92
X22	0	272385.92	218647.36		X56	3	110656.78	109323.68	444.37
X23	0	544771.84	437294.72		X57	3	110656.78	109323.68	444.37
X24	0	272385.92	218647.36		X58	1	59584.42	54661.84	4922.58
X25	0	68096.48	54661.84		X59	4	306434.16	273309.20	8281.24
X26	0	204289.44	163985.52		X60	0	34048.24	27330.92	
X27	0	204289.44	163985.52		X61	0	272385.92	218647.36	
X28	0	476675.36	382632.88		X62	0	34048.24	27330.92	
X29	0	1293833.12	1038574.96		X63	10	595844.20	546618.40	4922.58
X30	4.5	165985.17	163985.52	444.37	X64	0	68096.48	54661.84	
X31	4	170241.20	163985.52	1563.92	X65	0	68096.48	54661.84	
X32	0	136192.96	109323.68		X66	0	68096.48	54661.84	
X33	1	59584.42	54661.84	4922.58	X67	2	119168.84	109323.68	4922.58
X34	1	59584.42	54661.84	4922.58	X68	0	34048.24	27330.92	

Table 11: Summary of Scenario 3

Task	M	Cc ($)	Cn ($)	K ($)	Task	M	Cc ($)	Cn ($)	K ($)
X1	0	62722.64	54661.84		X35	0	188167.92	163985.52	
X2	0	62722.64	54661.84		X36	0	250890.56	218647.36	
X3	0	62722.64	54661.84		X37	2	172487.26	163985.52	4250.87
X4	1	117604.95	109323.68	8281.27	X38	2	172487.26	163985.52	4250.87
X5	0	439058.48	382632.88		X39	0	439058.48	382632.88	
X6	0	815394.32	710603.92		X40	0	250890.56	218647.36	
X7	.5	58802.48	54661.84	8281.27	X41	.5	58802.48	54661.84	8281.27
X8	0	125445.28	109323.68		X42	0	439058.48	382632.88	
X9	0	125445.28	109323.68		X43	1.5	113684.79	109323.68	2907.40
X10	0	188167.92	163985.52		X44	0	313613.20	273309.20	
X11	0	627226.40	546618.40		X45	0	125445.28	109323.68	
X12	1	117604.95	109323.68	8281.27	X46	0	62722.64	54661.84	
X13	2	486100.46	437294.72	24402.87	X47	0	188167.92	163985.52	
X14	0	188167.92	163985.52		X48	0	188167.92	163985.52	
X15	0	564503.76	491956.56		X49	0	188167.92	163985.52	
X16	0	376335.84	327971.04		X50	0	250890.56	218647.36	
X17	0	1881679.20	1639855.20		X51	0	313613.20	273309.20	
X18	0	62722.64	54661.84		X52	2	172487.26	163985.52	4250.87
X19	0	188167.92	163985.52		X53	2	172487.26	163985.52	4250.87
X20	0	62722.64	54661.84		X54	.5	58802.48	54661.84	8281.27
X21	0	376335.84	327971.04		X55	2	172487.26	163985.52	4250.87
X22	0	250890.56	218647.36		X56	1.5	113684.79	109323.68	2907.40
X23	0	501781.12	437294.72		X57	1.5	113684.79	109323.68	2907.40
X24	0	250890.56	218647.36		X58	.5	58802.48	54661.84	8281.27
X25	0	62722.64	54661.84		X59	2	297932.54	273309.20	12311.67
X26	0	188167.92	163985.52		X60	0	31361.32	27330.92	
X27	0	188167.92	163985.52		X61	0	250890.56	218647.36	
X28	0	439058.48	382632.88		X62	0	31361.32	27330.92	
X29	0	1191730.16	1038574.96		X63	5	588024.75	546618.40	8281.27
X30	2.25	178367.51	163985.52	11505.59	X64	0	62722.64	54661.84	
X31	2	172487.26	163985.52	4250.87	X65	0	62722.64	54661.84	
X32	0	125445.28	109323.68		X66	0	62722.64	54661.84	
X33	.5	58802.48	54661.84	8281.27	X67	1	117604.95	109323.68	8281.27
X34	.5	58802.48	54661.84	8281.27	X68	0	31361.32	27330.92	

Step 7 – Definition of the Crash Variables

As previously stated, the decision variables for this problem have been defined as X1 through X68 for each of the 68 activities in the network. Now, we must also define the crash variables as they will also impact the constraints. For ease and consistency, we have identified the letter "y" to denote a crash variable. Referencing Table 4 above, we simply then append the corresponding "x" number to the crash letter y to derive the following 24 crash variables. In total, there are 92 decision variables for this problem in the following nomenclature:

X1, X2, X3,….., X66, X67, X68 and Y2, Y4, Y8, Y9, Y11, Y12, Y13, Y14, Y16, Y17, Y19, Y20, Y21, Y22, Y23, Y24, Y26, Y27, Y28, Y30, Y32, Y37, Y40, Y42

Complete description and definition of all decision variables is listed in Appendix A.

Step 8 – Definition of the Constraints

With all variables defined, all activity normal times specified, and all activity crash times estimated for each scenario, we can now define each of the constraints for this problem. In this case, the constraints are classified in three categories: "crash constraints," "interference constraints," and "TAT constraint."

First, the crash constraints simply represent a mathematical way to express that each of the 24 crash variables cannot exceed the maximum estimated allowable crash time for each of their respective activities. For example, if Activity 2 can be crashed a maximum of 4 total hours, then $Y2 \leq 4$ must be enforced. Tables 12, 13, and 14 detail the crash constraints for each scenario. Each scenario possesses a different set of crash constraints.

On the other hand, the interference constraints are all based on the activity normal time and therefore remain consistent throughout each of the scenarios. When deriving the interference constraints, we reference activity finish time, earliest start time and activity normal time. Consider Activity 7, an activity that cannot be crashed. It takes 8 hours to complete, and its earliest start time is the completion time for its predecessor, Activity 6. In this case, the finish time must be greater than or equal to the sum of the earliest start time and the activity time for the given task. Because we do not know ahead of time whether an activity will start at its earliest start time, we use an inequality of the greater than or equal to variety. For clarity, the constraint is listed below.

$$X7 \geq X6 + 8 \text{ simplified to } X7 - X6 \geq 8$$

For activities that can be crashed, consider Activity 8, an activity that can be crashed by 20 hours, takes 80 hours to complete, and whose earliest start time is the completion of its predecessor, Activity 7. The same rules apply except for the addition of a parenthetical expression for the difference between the normal time for the activity and the amount that the activity is crashed. There are a total of 103 constraints for this problem. The constraint described is listed below.

$$X8 \geq X7 + (80 - Y8) \text{ simplified to } X8 - X7 + Y8 \geq 80$$

Lastly, we must add the final TAT constraint. This is simply one constraint that targets our goal of reducing the total TAT of the project. For purposes of each scenario, we are using 80 days or 640 hours as the maximum amount of time for the completion of all activities within the network. Therefore, our final task, represented by X68, must be completed within the target time of 640 hours. This constraint is consistent for each scenario and will be modified accordingly as we examine just how far this network can be crashed and still maintain a feasible solution. This constraint is listed last in Tables 12, 13, and 14.

Figure 3: UH-60A Aft View with Tail Boom Detached

Table 12: Constraints for Scenario 1

X3 – X1	≥ 8	X32 – X23	≥ 16	X63 – X62 +Y63	≥ 80
X4 – X1 + Y4	≥ 16	X33 – X30 + Y33	≥ 8	X65 – X63	≥ 8
X2 – X3	≥ 8	X46 – X45	≥ 8	X64 – X63	≥ 8
X2 – X4	≥ 8	X36 – X28	≥ 32	X67 – X65 +Y67	≥ 16
X5 – X3	≥ 56	X44 – X29	≥ 40	X67 – X64 +Y67	≥ 16
X5 – X4	≥ 56	X34 – X31 + Y34	≥ 8	X66 – X64	≥ 8
X6 – X3	≥104	X35 – X32	≥ 24	X68 – X67	≥ 4
X6 – X4	≥104	X47 – X46	≥ 24	X68 – X66	≥ 4
X7 – X2 + Y7	≥ 8	X39 – X36	≥ 56	X62 – X61 +Y62	≥ 4
X8 – X2	≥ 16	X48 – X44	≥ 24	Y4	≤ 4
X9 – X2	≥ 16	X37 – X35 + Y37	≥ 24	Y7	≤ 2
X10 – X2	≥ 24	X50 – X47	≥ 32	Y12	≤ 4
X11 – X2	≥ 80	X42 – X39	≥ 56	Y13	≤ 8
X18 – X5	≥ 8	X51 – X48	≥ 40	Y30	≤ 9
X25 – X6	≥ 8	X38 – X37 + Y38	≥ 24	Y31	≤ 8
X12 – X7 + Y12	≥ 16	X53 – X50 + Y53	≥ 24	Y33	≤ 2
X13 – X7 + Y13	≥ 64	X49 – X42	≥ 24	Y34	≤ 2
X14 – X8	≥ 24	X55 – X51 + Y55	≥ 24	Y37	≤ 8
X15 – X9	≥ 72	X40 – X38	≥ 32	Y38	≤ 8
X16 – X10	≥ 48	X56 – X53 + Y56	≥16	Y41	≤ 2
X19 – X18	≥ 24	X52 – X49 + Y52	≥ 24	Y43	≤ 6
X26 – X25	≥ 24	X57 – X55 + Y57	≥ 16	Y52	≤ 8
X20 – X13	≥ 8	X41 – X40 + Y41	≥ 8	Y53	≤ 8
X17– X14	≥ 240	X54 – X52 + Y54	≥ 8	Y54	≤ 2
X24 – X15	≥ 32	X43 – X41 + Y43	≥ 16	Y55	≤ 8
X21 – X16	≥ 48	X58 – X20 + Y58	≥ 8	Y56	≤ 6
X27 – X22	≥ 24	X58 – X34 + Y58	≥ 8	Y57	≤ 6
X27 – X21 + Y27	≥ 24	X58 – X56 + Y58	≥ 8	Y58	≤ 2
X23 – X19	≥ 64	X58 – X57 + Y58	≥ 8	Y59	≤ 8
X29 – X25	≥104	X58 – X54 + Y58	≥ 8	Y60	≤ 1
X30 – X26 + Y30	≥ 24	X58 – X43 + Y58	≥ 8	Y62	≤ 1
X45 – X17	≥ 16	X59 – X58 + Y59	≥ 40	Y63	≤ 20
X28 – X24	≥ 56	X60 – X59 + Y60	≥ 4	Y67	≤ 4
X29 – X21	≥ 152	X60 – X33 + Y60	≥ 4	TAT Constraint	
X31 – X27 + Y31	≥ 24	X61 – X60	≥ 32	Y68	≤ 640

Table 13: Constraints for Scenario 2

X3 – X1	≥ 8	X32 – X23	≥ 16	X63 – X62 +Y63	≥ 80
X4 – X1 + Y4	≥ 16	X33 – X30 + Y33	≥ 8	X65 – X63	≥ 8
X2 – X3	≥ 8	X46 – X45	≥ 8	X64 – X63	≥ 8
X2 – X4	≥ 8	X36 – X28	≥ 32	X67 – X65 +Y67	≥ 16
X5 – X3	≥ 56	X44 – X29	≥ 40	X67 – X64 +Y67	≥ 16
X5 – X4	≥ 56	X34 – X31 + Y34	≥ 8	X66 – X64	≥ 8
X6 – X3	≥104	X35 – X32	≥ 24	X68 – X67	≥ 4
X6 – X4	≥104	X47 – X46	≥ 24	X68 – X66	≥ 4
X7 – X2 + Y7	≥ 8	X39 – X36	≥ 56	X62 – X61 +Y62	≥ 4
X8 – X2	≥ 16	X48 – X44	≥ 24	Y4	≤ 2
X9 – X2	≥ 16	X37 – X35 + Y37	≥ 24	Y7	≤ 1
X10 – X2	≥ 24	X50 – X47	≥ 32	Y12	≤ 2
X11 – X2	≥ 80	X42 – X39	≥ 56	Y13	≤ 4
X18 – X5	≥ 8	X51 – X48	≥ 40	Y30	≤ 4.5
X25 – X6	≥ 8	X38 – X37 + Y38	≥ 24	Y31	≤ 4
X12 – X7 + Y12	≥ 16	X53 – X50 + Y53	≥ 24	Y33	≤ 1
X13 – X7 + Y13	≥ 64	X49 – X42	≥ 24	Y34	≤ 1
X14 – X8	≥ 24	X55 – X51 + Y55	≥ 24	Y37	≤ 4
X15 – X9	≥ 72	X40 – X38	≥ 32	Y38	≤ 4
X16 – X10	≥ 48	X56 – X53 + Y56	≥16	Y41	≤ 1
X19 – X18	≥ 24	X52 – X49 + Y52	≥ 24	Y43	≤ 3
X26 – X25	≥ 24	X57 – X55 + Y57	≥ 16	Y52	≤ 4
X20 – X13	≥ 8	X41 – X40 + Y41	≥ 8	Y53	≤ 4
X17– X14	≥ 240	X54 – X52 + Y54	≥ 8	Y54	≤ 1
X24 – X15	≥ 32	X43 – X41 + Y43	≥ 16	Y55	≤ 4
X21 – X16	≥ 48	X58 – X20 + Y58	≥ 8	Y56	≤ 3
X27 – X22	≥ 24	X58 – X34 + Y58	≥ 8	Y57	≤ 3
X27 – X21 + Y27	≥ 24	X58 – X56 + Y58	≥ 8	Y58	≤ 1
X23 – X19	≥ 64	X58 – X57 + Y58	≥ 8	Y59	≤ 4
X29 – X25	≥104	X58 – X54 + Y58	≥ 8	**Y60**	**≤ 0**
X30 – X26 + Y30	≥ 24	X58 – X43 + Y58	≥ 8	**Y62**	**≤ 0**
X45 – X17	≥ 16	X59 – X58 + Y59	≥ 40	Y63	≤ 10
X28 – X24	≥ 56	X60 – X59 + Y60	≥ 4	Y67	≤ 2
X29 – X21	≥ 152	X60 – X33 + Y60	≥ 4	TAT Constraint	
X31 – X27 + Y31	≥ 24	X61 – X60	≥ 32	Y68	≤ 640

Table 14: Constraints for Scenario 3

X3 – X1	≥ 8	X32 – X23	≥ 16	X63 – X62 +Y63	≥ 80
X4 – X1 + Y4	≥ 16	X33 – X30 + Y33	≥ 8	X65 – X63	≥ 8
X2 – X3	≥ 8	X46 – X45	≥ 8	X64 – X63	≥ 8
X2 – X4	≥ 8	X36 – X28	≥ 32	X67 – X65 +Y67	≥ 16
X5 – X3	≥ 56	X44 – X29	≥ 40	X67 – X64 +Y67	≥ 16
X5 – X4	≥ 56	X34 – X31 + Y34	≥ 8	X66 – X64	≥ 8
X6 – X3	≥104	X35 – X32	≥ 24	X68 – X67	≥ 4
X6 – X4	≥104	X47 – X46	≥ 24	X68 – X66	≥ 4
X7 – X2 + Y7	≥ 8	X39 – X36	≥ 56	X62 – X61 +Y62	≥ 4
X8 – X2	≥ 16	X48 – X44	≥ 24	Y4	≤ 1
X9 – X2	≥ 16	X37 – X35 + Y37	≥ 24	Y7	≤ .5
X10 – X2	≥ 24	X50 – X47	≥ 32	Y12	≤ 1
X11 – X2	≥ 80	X42 – X39	≥ 56	Y13	≤ 2
X18 – X5	≥ 8	X51 – X48	≥ 40	Y30	≤ 2.25
X25 – X6	≥ 8	X38 – X37 + Y38	≥ 24	Y31	≤ 2
X12 – X7 + Y12	≥ 16	X53 – X50 + Y53	≥ 24	Y33	≤ .5
X13 – X7 + Y13	≥ 64	X49 – X42	≥ 24	Y34	≤ .5
X14 – X8	≥ 24	X55 – X51 + Y55	≥ 24	Y37	≤ 2
X15 – X9	≥ 72	X40 – X38	≥ 32	Y38	≤ 2
X16 – X10	≥ 48	X56 – X53 + Y56	≥16	Y41	≤ .5
X19 – X18	≥ 24	X52 – X49 + Y52	≥ 24	Y43	≤ 1.5
X26 – X25	≥ 24	X57 – X55 + Y57	≥ 16	Y52	≤ 2
X20 – X13	≥ 8	X41 – X40 + Y41	≥ 8	Y53	≤ 2
X17– X14	≥ 240	X54 – X52 + Y54	≥ 8	Y54	≤ .5
X24 – X15	≥ 32	X43 – X41 + Y43	≥ 16	Y55	≤ 2
X21 – X16	≥ 48	X58 – X20 + Y58	≥ 8	Y56	≤ 1.5
X27 – X22	≥ 24	X58 – X34 + Y58	≥ 8	Y57	≤ 1.5
X27 – X21 + Y27	≥ 24	X58 – X56 + Y58	≥ 8	Y58	≤ .5
X23 – X19	≥ 64	X58 – X57 + Y58	≥ 8	Y59	≤ 2
X29 – X25	≥104	X58 – X54 + Y58	≥ 8	**Y60**	**≤ 0**
X30 – X26 + Y30	≥ 24	X58 – X43 + Y58	≥ 8	**Y62**	**≤ 0**
X45 – X17	≥ 16	X59 – X58 + Y59	≥ 40	Y63	≤ 5
X28 – X24	≥ 56	X60 – X59 + Y60	≥ 4	Y67	≤ 1
X29 – X21	≥ 152	X60 – X33 + Y60	≥ 4	TAT Constraint	
X31 – X27 + Y31	≥ 24	X61 – X60	≥ 32	Y68	≤ 640

Step 9 – Definition of the Objective Function of the Linear Program

The final step in this process is to develop the objective function for the model. In this case, we desire to minimize the total cost required to complete the network by the specified TAT. Since we estimated the hourly crash cost per task, we can then determine the total cost required to achieve that level of reduction. The objective function for each of the three scenarios is listed in Tables 15, 16, and 17 below.

Table 15: Objective Function for Scenario 1 (Minimize Total Cost)

Variable	Coefficient
All X Values (X1..X68)	0
Y4 = Inventory Upgrade Kits	14788.87
Y7 = Remove Landing Gear	14788.87
Y12 = Inspect Landing Gear Fittings	14788.87
Y13 = Inspect Reassemble Landing Gear	43617.67
Y30 = Recheck Structural – Nose Section	5179.27
Y31 = Recheck Structural – Cockpit Section	7581.67
Y33 = Recheck Electrical – Nose Section	14788.87
Y34 = Recheck Electrical – Cockpit Section	14788.87
Y37 = Recheck Structural – Roof Section	7581.67
Y38 = Structural Repair – Firewalls	7581.67
Y41 = Recheck Structural – Firewalls	14788.87
Y43 = Recheck Electrical – Roof Section	5179.27
Y52 = Recheck Structural – Tail Cone Section	7581.67
Y53 = Recheck Structural – Transition Section	7581.67
Y54 = Recheck Structural – Tail Cone Section	14788.87
Y55 = Recheck Structural – Cabin	7581.67
Y56 = Recheck Electrical – Transition Section	5179.27
Y57 = Recheck Electrical – Cabin	5179.27
Y58 = Remove Fuselage from Work Stands	14788.87
Y59 = Wire Alignment	21996.07
Y60 = All Structural Repairs Complete	14788.87
Y62 = Move Fuselage to Final ATC	14788.87
Y63 = Final ATC	14788.87
Y67 = Clean and Close	14788.87

Table 16: Objective Function for Scenario 2 (Minimize Total Cost)

Variable	Coefficient
All X Values (X1..X68)	0
Y4 = Inventory Upgrade Kits	4922.58
Y7 = Remove Landing Gear	4922.58
Y12 = Inspect Landing Gear Fittings	4922.58
Y13 = Inspect Reassemble Landing Gear	18357.22
Y30 = Recheck Structural – Nose Section	444.37
Y31 = Recheck Structural – Cockpit Section	1563.92
Y33 = Recheck Electrical – Nose Section	4922.58
Y34 = Recheck Electrical – Cockpit Section	4922.58
Y37 = Recheck Structural – Roof Section	1563.92
Y38 = Structural Repair – Firewalls	1563.92
Y41 = Recheck Structural – Firewalls	4922.58
Y43 = Recheck Electrical – Roof Section	444.37
Y52 = Recheck Structural – Tail Cone Section	1563.92
Y53 = Recheck Structural – Transition Section	1563.92
Y54 = Recheck Structural – Tail Cone Section	4922.58
Y55 = Recheck Structural – Cabin	1563.92
Y56 = Recheck Electrical – Transition Section	444.37
Y57 = Recheck Electrical – Cabin	444.37
Y58 = Remove Fuselage from Work Stands	4922.58
Y59 = Wire Alignment	8281.24
Y60 = All Structural Repairs Complete	0.00
Y62 = Move Fuselage to Final ATC	0.00
Y63 = Final ATC	4922.58
Y67 = Clean and Close	4922.58

Table 17: Objective Function for Scenario 3 (Minimize Total Cost)

Variable	Coefficient
All X Values (X1..X68)	0
Y4 = Inventory Upgrade Kits	8281.27
Y7 = Remove Landing Gear	8281.27
Y12 = Inspect Landing Gear Fittings	8281.27
Y13 = Inspect Reassemble Landing Gear	24402.87
Y30 = Recheck Structural – Nose Section	11505.59
Y31 = Recheck Structural – Cockpit Section	4250.87
Y33 = Recheck Electrical – Nose Section	8281.27
Y34 = Recheck Electrical – Cockpit Section	8281.27
Y37 = Recheck Structural – Roof Section	4250.87
Y38 = Structural Repair – Firewalls	4250.87
Y41 = Recheck Structural – Firewalls	8281.27
Y43 = Recheck Electrical – Roof Section	2907.40
Y52 = Recheck Structural – Tail Cone Section	4250.87
Y53 = Recheck Structural – Transition Section	4250.87
Y54 = Recheck Structural – Tail Cone Section	8281.27
Y55 = Recheck Structural – Cabin	4250.87
Y56 = Recheck Electrical – Transition Section	2907.40
Y57 = Recheck Electrical – Cabin	2907.40
Y58 = Remove Fuselage from Work Stands	8281.27
Y59 = Wire Alignment	12311.67
Y60 = All Structural Repairs Complete	0.00
Y62 = Move Fuselage to Final ATC	0.00
Y63 = Final ATC	8281.27
Y67 = Clean and Close	8281.27

Step 10 – Compute the Cost using the Objective Function of the Linear Program

In order to discuss the time/cost tradeoff, we must utilize the objective function for each of the scenarios. A generic approach is presented below including only the 24 crash variables within the problem. Crash cost per hour (K) was already computed in Step 6 and is now utilized to determine the overall increase to the project given the solution from Step 9. Cost results for each of the three scenarios are presented in Chapter 5. Before we attempt to solve this 92-variable, 103-constraint deterministic linear programming model using the premium Microsoft Excel Solver, we must first revisit each of the input parameters, a general mathematic formulation, and some thoughts about the critical path.

3.3 Summary of Input Parameters

An = Activity Normal Completion Time (in hours) for each activity in the Network

Ac = Activity Crash Completion Time (in hours) for each activity in the Network

Ctn = Total Cost per Hour Worked by team under Normal Conditions

Cn = Total Network Cost per Hour Worked under Normal Conditions

Cc/hr = Activity Cost/hour (in dollars) for 105 workers to work 1 hour in the Network

Ctc = Total Cost per Hour Worked by team under Crash Conditions

Cc = Total Network Cost per Hour Worked under Crash Conditions

M = Maximum Reduction in Time (in hours) for each activity in the Network

K = Crash Cost per Hour (in dollars) for each activity in the Network

3.4 General Mathematic Formulation

A general mathematic formulation to outline the mechanics of this study is offered below using the nomenclature defined in paragraph 3.3 above. Recall that x_i is defined as the finish time for activity i and y_i is defined as the time by which activity i is crashed.

$$
\begin{aligned}
\text{Minimize} \quad & Z = \sum_i \left(\frac{Cc_i - Cn_i}{An_i - Ac_i} \right) y_i \\
\text{Subject to} \quad & y_i \le An_i - Ac_i, \quad \forall i \\
& x_{last} \le TAT_{\max} \\
& x_i, y_i \ge 0, \quad \forall i
\end{aligned}
$$

Further clarification is given below with respect to the constraints and how they were derived using the network diagram. In total, this problem included 103 constraints, 54 using the framework of the “beginning” nodes, and 24 using the framework of the precedence nodes listed below.

$$
\begin{aligned}
& \text{"Beginning" nodes:} \\
& x_i \ge An_i - y_i \ \text{ or } \ x_i + y_i \ge An_i
\end{aligned}
$$

$$
\begin{aligned}
& \text{If activity } k \text{ must precede activity } \ell: \\
& x_\ell \ge x_k + (An_\ell - y_\ell) \ \text{ or } \ x_\ell + y_\ell - x_k \ge An_\ell
\end{aligned}
$$

3.5 Critical Path

Although one could compute the critical path manually, we choose to utilize the associated network diagram in Microsoft Project to analyze the initial critical path. In computing the critical path, the software traverses all paths in the network in order to complete the project, searching for the paths that consume the most time. It does this because all other paths are shorter in duration and the longest path determines the total time to complete the project. If the activities residing on the longest path are delayed, then the project is delayed. The activities on the critical path can also be referred to as critical activities. As we crash the network, we may or may not see a change in the critical path for the given scenario. The initial critical path is presented in Chapter 5 along with the associated critical path for each of the scenarios at their shortest completion time.

The premium version of Microsoft Excel Solver is capable of solving problems with up to 200 decision variables and 200 constraints. A complete summary of results for each of the three scenarios is discussed in Chapter 4. It is important to note that the linear programming solution provides the revised activity times. From these times, a revised schedule must be developed and a new critical path must be calculated.

CHAPTER 4: EXPERIMENTS

4.1 Assumptions

Before we provide an overview of the results for the three scenarios, we first present some overall considerations for optimization using linear programming and address four implicit assumptions; proportionality, additivity, divisibility, and deterministic.

Regarding proportionality, we assume that increasing a decision variable by an amount, q, will affect the objective function and constraints proportionally with respect to q. Additionally, we assume that the total contribution of the variables in the objective function and the constraints is the sum of the individual contributions for the objective function and the constraints, respectively.   Further, we assume that fractional values are acceptable for decision variables.   Lastly, we assume that all data are known, and there are no probabilistic or stochastic elements in the problem. This is especially applicable in terms of the various crashing estimates for each activity.

4.2 General Overview

The purpose of this problem is to provide insight on the time/cost tradeoff with respect to project management. Understanding that there are an infinite number of possibilities to consider, we defined the scenarios to capture two different options in attacking the primary controllable variables that affect the program budget – the work force. In examining the work force, there are truly only two options that exist to a program manager: 1) Hire additional contractors, or 2) Work the current force additional hours. Because both situations represent an increase in cost, we chose to compare the two scenarios by incorporating realistic cost estimates into alternative linear programming model formulations. The ultimate practical feasibility of these overtime approaches may be dependent on their extended sustainability.

4.3 Normal Activity Model "Crashed" with CCAD Estimates

Scenario 1 addresses the current program request of examining the addition of 55 contracted civilians to the project, increasing the total personnel from 105 to 160. This assumes an even division of the workers across the 8 teams performing duties over two identical eight hour shifts. The crash estimates were provided from the program scheduler at Corpus Christi Army Depot.

4.4 Normal Activity Model “Crashed” with Extensive Overtime

Scenario 2 consists of adding pure man hours in the form of an aggressive overtime plan. This scenario utilizes the existing 105 workers about evenly divided across 8 teams by increasing the total number of hours worked per week. Instead of working the current work week of four identical ten-hour days, we examined a scenario of increasing the number of workdays to five and the number of work hours per day to 12. This applies 60 hour workweeks to the problem and dictates an increase in total pay. We applied time-and-a-half to each of the 20 hours worked past the original 40 hours. With respect to crash estimates, we hypothesized decreases in the maximum crash time for each of the activities referencing in Scenario 1 of 50%. For example, if a task in Scenario 1 could be crashed 4 hours, we estimated that it could be crashed 2 hours in Scenario 2. We further apply the opinions of the project manager and experience of the work force to justify these estimates. The initial crash estimates were approved by the program scheduler at Corpus Christi Army Depot. This scenario is most likely not sustainable for extended periods of time, but provides the program manager appreciates the flexibility to understand the time/cost tradeoff in mass production situations.

4.5 Normal Activity Model “Crashed” with Moderate Overtime

Scenario 3 also examines the notion of adding man hours, this time in the form of a moderate overtime plan. In this case, we again utilize the current manpower of 105 workers about evenly divided across 8 teams and increase their total hours worked per week. Instead of working the current work week of four identical ten-hour days, we examined a scenario of increasing the number of workdays to five while holding the current man hours per day constant. This applies 50 hour workweeks to the problem and dictates an increase in total pay. We applied time-and-a-half rates to each of the 10 hours worked past the original 40 hours. With respect to crash estimates, we simply decreased the maximum crash time for each of the activities referenced in Scenario 1 by 75%. For example, if a task in Scenario 1 could be crashed 4 hours, we estimated that it could be crashed 1 hour in Scenario 3. As with the logic presented in reducing crash estimates from Scenario 1 to Scenario 2, we again apply the same approach from Scenario 2 to Scenario 3, assuming that utilizing the same workforce for an extended period of time would, on average, show inferior performance to an increased number of skilled workers who performed duties over a shorter period of time. These crash estimates were also approved by the program scheduler at Corpus Christi Army Depot.

CHAPTER 5: RESULTS

Before the results of the three aforementioned scenarios are presented, we offer a summary of each course of action with respect to the total number and types of workers as well as a composite hourly wage rate for all workers involved. Recall that Scenario 1 adds additional employees to the existing workforce while Scenarios 2 and 3 do not.

The linear program will determine the minimum crash cost with respect to a specified reduction in the time to complete the project network. We present a summary of the total time reduction for each scenario. Understanding the results offer insight into just how quickly this network can be realistically completed. If every activity were crashed by its maximum value, we could reduce the entire project duration no more than 17.13 days as illustrated in Table 18 for Scenario 1. However, the LP model must find feasible solutions and will most likely yield a time reduction value much smaller than the aforementioned 17.13 days. Table 18 highlights the scenario summary data.

Table 18: Scenario Summary Data

	Scenario #1 Add Contractors	*Scenario #2 Aggressive OT*	*Scenario #3 Moderate OT*
# Government Employees	63	63	63
# Contracted Employees	97	42	42
Average Hourly Wage Rate	$14,039.93	$8,512.06	$7,840.33
Maximum Reduction Time	137 Hours (17.13 Days)	67.5 Hours (8.44 Days)	32.75 Hours (4.09 Days)

The computation of the average hourly wage rates was outlined in Chapter 3. In dealing with the overtime scenarios, we applied the normal rate ($6,832.73) to the first 40 hours and the overtime rate ($11,870.72) to the last 10 or 20 hours, respective to each scenario.

Quickly viewing Table 18 may lead one to infer that Scenario 3 will always cost less than the other two scenarios based on it possessing the smallest average hourly rate. Similarly, one may infer that Scenario 1 > Scenario 2 > Scenario 3 in all cases. However, we observe fluctuation based on the desired TAT end state throughout each of the trials. In fact, throughout each incremental reduction, each of the three scenarios is most expensive at least once compared to the other two. This occurs for a few reasons.

First, we must understand how the "K" values are calculated because each of the K values dictates the overall cost within each scenario. The denominator of each K value is based on maximum crash time compared to the normal activity time. In our case, we have systematically reduced the maximum crash time from Scenario 1 to Scenario 2 by 50% and from Scenario 2 to Scenario 3 by another 50%. Therefore, Scenario 1's maximum crash time is four times greater than Scenario 3 and the overall cost relationship between the three scenarios is 1:1/2:1/4 for Scenario 1, Scenario 2, and Scenario 3, respectively. In order to observe the inferred dominance relationship between each scenario 100% of the time, we would have to expect the numerator (based on cost) to hold the similar 1:1/2:1/4 relationship.

Within our work, it is impossible for the numerators of our K values to hold that relationship because the average hourly crash costs for each scenario do not hold the 1:1/2:1/4 relationship. Our crash costs ($14,039, $8,512, $7,840) hold a 1:60/100:55/100 relationship.

These types of observations further substantiate the overall importance and value of this work to any program manager.

The initial TAT target value (i.e. maximum network completion time) given from the program manager was 80 days. Since many of the activities could only be reduced by hours instead of days, we converted that value and utilized the target value of 640 total work hours. Given that value, the linear program presented an optimal solution of 636 hours (79.5 work days) without “crashing” any additional tasks. This finding, referred to as Finding 1, will be further analyzed in Chapter 6 of this document. After acknowledging Finding 1, we then began to reduce the maximum completion time in increments of 8 hours for each of the three scenarios until the linear program could no longer find a feasible solution. A complete summary of each scenario is listed in Table 19.

Table 19: Consolidated Summary of Results

	Scenario #1 *Add Contractors*	*Scenario #2* *Aggressive Overtime*	*Scenario #3* *Moderate Overtime*
632 Hrs (79 Days)	$20,717.08	$6,255.69	$25,064.27
624 Hrs (78 Days)	$119,808.84	$45,636.33	$91,314.49
616 Hrs (77 Days)	$238,119.80	$85,016.97	$124,439.51 *620 Hours*
608 Hrs (76 Days)	$356,430.76	$134,473.59	No Feasible Solution
600 Hrs (75 Days)	$474,741.72	No Feasible Solution	No Feasible Solution
592 Hrs (74 Days)	$593,052.68	No Feasible Solution	No Feasible Solution
584 Hrs (73 Days)	$769,021.24	No Feasible Solution	No Feasible Solution
580 Hrs (72 Days)	No Feasible Solution	No Feasible Solution	No Feasible Solution

5.1 Scenario 1

Before we present the observations in each of the three Scenarios, we observe that each of the three models only chooses to crash 9 of the 24 “crash variables” available, with seven of the nine crashed variables residing at the tail end of the network. This is consistent throughout all three scenarios and will be highlighted further as Finding 2 in Chapter 6.

On average, Scenario 1 is the most costly and most flexible of the three scenarios. The maximum completion time for the network can be reduced by up to 7 days more than the target goal of 80 days, and an additional 3 extra days more than any other scenario in the study. However, the exceptionally high wage rate for the contractors drives the additional cost significantly as the model squeezes every piece of available slack time from non-binding activities. It is interesting to note that it is cheaper than Scenario 2 for the first iteration. This is a direct result of each model (with different crash costs) targeting different crash variables to reach the optimal solution of 79 days.

In total, this scenario has 69 of its 103 constraints binding. This number is ultimately increased to a total of 80 of 103 binding constraints at 584 hours or 73 days. Table 20 below summarizes a snapshot of the priority activities targeted by the model in reducing the total time (shown in hours) within the framework of an optimal solution for each duration (in days). As each iteration (defined as a reduction in 8 hours project time) is processed, you will notice which variables the model targets to achieve the desired reduction.

Table 20: Summary of Target Variables

Days	Y4	Y54	Y57	Y58	Y59	Y60	Y62	Y63	Y67
79			4						
78			6					6	
77		2	6	2		1		1	8
76	4		6	2				20	
75			6	2		1		19	8
74	4		6	2		1	1	20	8
73	4	2	6	2	8	1	1	20	8

We then classified each of the values listed above in a “priority framework” in order to illustrate to the program manager which activities and at what levels could be targeted for reduction. Although not true sensitivity analysis by definition, we can learn a great deal from observing the pattern listed in Table 20. The “tiered” priorities are listed in Table 21. We will draw additional conclusions when comparing each of the priority tier lists for each of the three scenarios considered.

Table 21: Priority Tier List for Crash Variables in Scenario 1

Priority Tier 1: Y57
Priority Tier 2: Y63
Priority Tier 3: Y58, Y60, Y67
Priority Tier 4: Y4, Y62
Priority Tier 5: Y54
Priority Tier 6: Y59

Although the model targets Y54 (Final/Recheck Electrical – Tail Cone Section) in the "third iteration," we list that activity as priority tier 5 because the model does not hold that reduction consistent from iterations 3 to 7, instead choosing to utilize slack from Y63 (Final ATC) to fill the void. We also classify Y63 in priority tier 2 because the model does not begin to consistently rely on its slack until iteration 4.

Therefore, if looking to reduce maximum completion time in Scenario 1, we first look to activity Y57 (Final Recheck-Cabin). As duration reduction, resources, time, and priority dictates, we recommend stepping down the priority tiers listed in Table 21 until the desired results are achieved. It is important to note that the activity with the least priority for crashing is Y59 (Wire Alignment) and should only be addressed if absolutely necessary.

Lastly, we examine the critical path in both the maximum and minimum TAT for Scenario 1. As you can see in Table 22, the critical path does not change even after the network is crashed to its maximum limit and TAT is reduced to 73 days. This is somewhat surprising because activities X4, X54 and X57 are not on the critical path in any of the iterations within the scenario. Further, crashing the variables listed in Table 20 does not yield any change in the critical path.

Table 22: Critical Path Analysis for Scenario 1

Sequence	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
640 Hrs	X17	X45	X46	X47	X50	X53	X56	X58	X59	X60	X61	X62	X63	X64	X65	X67	X68
584 Hrs	X17	X45	X46	X47	X50	X53	X56	X58	X59	X60	X61	X62	X63	X64	X65	X67	X68

5.2 Scenario 2

As previously stated, Scenario 2 represents an aggressive overtime scenario that is simply designed to offer an alternative in situations where large quantities of work are required in less than optimal amounts of time. When presenting the results for this course of action, we once again revisit portions of Table 19 in Table 23 to note observations.

First, we notice that the aggressive overtime scenario, assumedly not sustainable over periods longer than one month, is actually the cheapest scenario for overall project time reduction. In total, it is an average of 65% less cost than Scenario 1 and 53% less cost than Scenario 3. However, the maximum reduction time for the network bottoms out at a value of 76 days as there is no feasible solution when reducing the target completion time in this scenario to 75 days.

Table 23: Consolidated Summary of Results (632 Hours to 600 Hours)

	Scenario #1 *Add Contractors*	*Scenario #2* *Aggressive Overtime*	*Scenario #3* *Moderate Overtime*
632 Hrs (79 Days)	$20,717.08	$6,255.69	$25,064.27
624 Hrs (78 Days)	$119,808.84	$45,636.33	$91,314.49
616 Hrs	$238,119.80	$85,016.97	$124,439.51

(77 Days)			***620 Hours***
608 Hrs (76 Days)	$356,430.76	$134,473.59	No Feasible Solution
600 Hrs (75 Days)	$474,741.72	No Feasible Solution	No Feasible Solution

As we did above in Scenario 1, we again look at how the model chooses to target the slack activities in attempting to reach the maximum reduction of total completion time.

Table 24: Summary of Target Variables

Days	Y4	Y54	Y57	Y58	Y59	Y60	Y62	Y63	Y67
79			3					1	
78			3			Constraints		1	8
77	2		3	1		Not		10	6
76	2	1	3	1	3	Crashable		10	8
75									
74	NO FEASIBLE SOLUTION EXISTS								
73									

Unlike the values presented in Scenario 1, Scenario 2 presents a different strategy and different set of priorities. First, we notice fewer priority tiers (4) in this model compared to the 6 presented in Scenario 1. This is expected for many reasons. First, we notice that there are two less variables to choose from in this scenario as the X60 and X62 activities are not reducible in each of the overtime scenarios. Further, this model possesses an overall reduced flexibility attributed to less flexible (reduced) crash estimates and an overall larger maximum reduction time value of 76 days.

Table 25: Priority Tier List for Crash Variables in Scenario 2

Priority Tier 1: Y57, Y63
Priority Tier 2: Y67

Priority Tier 3: Y4, Y58
Priority Tier 4: Y54, Y59

Just like Scenario 1, Scenario 2’s model tells us to first focus on Y57 (Final Recheck – Cabin). However, this model also immediately targets Y63 (Final ATC) in the first iteration assigning it equal priority for attention. We observe one additional similarity in the task of Y59 (Wire Alignment) resting in the lowest priority for the model. We further observe that Y54 (Final/Recheck Electrical – Tail Cone Section) and Y4 (Inventory Upgrade Kits) are also a relatively low priority for reduction and therefore should not be reduced unless the program manager determines it is critical to do so.

Critical path analysis in this scenario is a bit different than Scenario1 in that an additional variable X66 (Install EMI Filters) is added to the critical path of the network. As you notice in Table 26, this scenario, although not crashed as heavily, adds activity X66 to increase the critical path to 18 activities within the network of 68 activities. No increase in Scenario 1 and a minor increase in Scenario 2 imply an overall stability of the network and the soundness of the schedule.

Table 26: Critical Path Analysis for Scenario 2

Sequence	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
640 Hrs	X17	X45	X46	X47	X50	X53	X56	X58	X59	X60	X61	X62	X63	X64	X65	X67	X68	
608 Hrs	X17	X45	X46	X47	X50	X53	X56	X58	X59	X60	X61	X62	X63	X64	X65	X66	X67	X68

Figure 4: UH-60A Undergoing Structural Upgrades

5.3 Scenario 3

The last scenario observed in this study is an additional overtime study, this time representing a more feasibly sustainable situation. When presenting the results for this course of action, we once again revisit portions of Table 19 in Table 27 to note observations.

First, this scenario offers the least amount of flexibility in that it only reduces the optimal solution by 2.5 days or 20 hours to a total network completion time of 77.5 days. This scenario is the second cheapest of those studied, but only for TAT times of 78 days or less. Over the course of the three iterations down from 636 to 620 hours, this scenario is an average of more than twice as expensive as Scenario 2.

Table 27: Consolidated Summary of Results (632 Hours to 608 Hours)

	Scenario #1 *Add Contractors*	*Scenario #2* *Aggressive Overtime*	*Scenario #3* *Moderate Overtime*
632 Hrs (79 Days)	$20,717.08	$6,255.69	$25,064.27
624 Hrs (78 Days)	$119,808.84	$45,636.33	$91,314.49
616 Hrs (77 Days)	$238,119.80	$85,016.97	$124,439.51 ***620 Hours***
608 Hrs (76 Days)	$356,430.76	$134,473.59	No Feasible Solution

As we did above in the previous two scenarios, we again look at how the model chooses to target the various slack activities in attempting to reach the maximum reduction of total completion time. We expect the same or even fewer priority levels in this scenario given its overall inflexible nature in addition to the overall reduction of crash variables due to Y60 and Y62 being unchanged during the crash estimates.

Table 28: Summary of Target Variables

Days	Y4	Y54	Y57	Y58	Y59	Y60	Y62	Y63	Y67
79			1.5			Constraints		2.5	
78			1.5	.5		Not		5	5
77	1	.5	1.5	.5		Crashable		5	7.5
76	NO FEASIBLE SOLUTION EXISTS								
75									
74									
73									

In examining Table 28 above, we observe commonality among this model and the others with respect to Y63 (Final ATC) as it is placed in the top priority tier. However, unlike the other models, Y59 (Wire Alignment) is never targeted in any iteration.

Table 29: Priority Tier List for Crash Variables in Scenario 3

Priority Tier 1: Y57, Y63
Priority Tier 2: Y58, Y67
Priority Tier 3: Y4, Y54,
Not Targeted by this Model: Y59

Further, it is important to note that this model does also attack Y57 (Final Recheck Electrical Cabin) in the first iteration. However, unlike the approach in Scenario 1 and Scenario 2, this model cannot find a feasible solution using the 9 or 7 crash variables, respectively. We note the absence of a feasible solution before the exhaustion of each crash variable. These observations reveal another piece of analysis that will be addressed as Finding 3 in Chapter 6.

As was the case in Scenario 2, the critical path added one activity (X66) in the maximum crash iteration. This again supports stability in the network and is interesting when combined with the analysis of how the model attacks various activities differently between each of the three scenarios.

Table 30: Critical Path Analysis for Scenario 3

Sequence	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
640 Hrs	X17	X45	X46	X47	X50	X53	X56	X58	X59	X60	X61	X62	X63	X64	X65	X67	X68	
618 Hrs	X17	X45	X46	X47	X50	X53	X56	X58	X59	X60	X61	X62	X63	X64	X65	X66	X67	X68

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

In Section 6.1, we present analysis and conclusions regarding the results and findings listed in Chapter 5. Section 6.2 offers commentary presented in the format of Issue/Discussion/Recommendation in order to generate additional dialogue regarding this applicable and real-world problem. Section 6.3 offers final thoughts and recommendations for future work.

6.1 Conclusions

Finding 1

The current schedule of activities for Network 4, modeled by the linear program presented above, yielded a minimal solution time of 636 work hours or 79.5 days at no additional cost to the program. As evident in Table 31, the shortest completion time for activities in Network 4 to date equaled no better than 87 days (FY05), not including the three additional subcategories affecting network completion time.

Table 31: External Factors adding to increased Turn Around Time for Network 4

Network 4	**5- Year Average**	**FY02**	**FY03**	**FY04**	**FY05**	**FY06**
Structural/Electrical	113	138	150	97	87	98
Excess WIP	21	0	30	31	3	10
Work Stoppage	8	**90**	8	0	0	7
Over and Above	14	23	19	16	11	14
Total	156	251	207	144	101	129

Excess WIP

Over the past five years, excess WIP (work in progress) has added additional time to complete the network. The majority of this can be attributed to unforeseen delays in replacing and/or repairing specialty parts. For example, the installation of certain structural beams on the UH-60A is not always a clean and predictable process for all aircraft in the fleet. Therefore, possible delays result depending on the complexity of the particular installation. Like the logistics challenges, CCAD has improved greatly in this area over the past two fiscal years.

Work Stoppage

Any maintenance environment relies heavily on parts availability and a seamless logistical supply chain to sustain a consistent work flow. This is especially critical in an aviation environment whose target airframe is nearly 20 years old. We understand this phenomenon and acknowledge its impact on overall project completion time. We also acknowledge previous issues dealing with an overall lack of Class IX critical parts as these parts are often exhausted within the logistics supply chain. This challenge is further exacerbated by a constant modification of Congressional budgets leading to continuous starting and stopping due to funding. However, as the program has matured, we have noticed an overall decrease in work stoppage days caused by impacts from incomplete structural kits, timeliness and availability of Class IX parts, and other factors contributing to an overall halt in network flow.

Over and Above

Periodically throughout the project, workers will perform duties outside of the previously agreed upon work breakdown structure. This work, classified as “over and above” is significant in that it adds overall time to the completion of the project. Over the past 5 years, the completion of over and above tasks has added an additional three work weeks worth of man hours to the overall network equation. However, these services are critical to the overarching intent of the program (i.e. to provide the best possible product to the war fighter). The program manager must decide whether to “band aid” a repair at CCAD or to utilize precious time and resources to ensure the strongest possible service life upon departure. Mostly, the project manager expends the resources in order to accomplish the task 100% correctly, the first time, thereby avoiding potential second and third order effects. This is especially necessary when speaking of electrical repairs that may fester for years if not addressed properly at the depot level.

Table 32: Average of Annual Over and Above Work Performed (FY04-FY06)

Total Labor Hours Expended	10,563 Hours
Total Labor Cost per Year	$7,216,416
Total Time Delay per Year	15.2 Days
Total Number of Aircraft Serviced per Year	21

The data presented in Table 32 is significant in that it draws resources (time and money) from the program. However, the completion of this work is necessary for schedule completion and is an inevitable aspect of a successful and thorough maintenance program. Alarmingly, the total number of aircraft serviced per year equals the total number of aircraft completed per year by the program, ultimately proving that 100% of all aircraft receive some sort of over and above work.

Consequently, if we disregard the additional impacts made by the three previously described external factors, we still notice that the primary network can be refined to achieve the optimal state of 79.5 days. At present, the three year average, although much improved, is missing this target goal by three full work weeks. Some of this may be attributed to residual impacts felt from servicing excess WIP, work stoppage, and/or over and above requirements. However, we understand that some challenges are outside of the purview of the program manager and often require higher level command emphasis.

Finding 2

Before we proceed to Finding 3, we must first present a consolidated list of the activities in the network that could be "crashed" to examine their impact on the models in each of the three scenarios. Table 33 below details the list of "crashable" activities. The activities highlighted in bold represent the activities crashed in each of the three models.

Table 33: The 24 "crashable" activities listed in the Structural/Electrical Network

Activity	Priority Tier
Y4 = Inventory Upgrade Kits	**4th, 3rd, 3rd**
Y7 = Remove Landing Gear	
Y12 = Inspect/Repair Landing Gear Fittings	
Y13 = Inspect/Repair/Reassemble Landing Gear	
Y30 = Final/Recheck Structural – Nose Section	
Y31 = Final/Recheck Structural – Cockpit Section	
Y33 = Final/Recheck Electrical – Nose Section	
Y34 = Final/Recheck Electrical – Cockpit Section	
Y37 = Final/Recheck Structural – Roof Section	
Y38 = Structural Repair - Firewalls	
Y41 = Final/Recheck Structural – Firewalls Section	
Y43 = Final/Recheck Electrical – Roof Section	
Y52 = Final/Recheck Structural – Tail Cone Section	
Y53 = Final/Recheck Structural – Transition Section	
Y54 = Final/Recheck Electrical – Tail Cone Section	**Last in all Scenarios**
Y55 = Final/Recheck Structural - Cabin	
Y56 = Final/Recheck Electrical – Transition Section	
Y57 = Final/Recheck Electrical – Cabin Section	**First is all Scenarios**
Y58 = Remove Fuselage from Work Stands	**3rd, 3rd, 2nd**
Y59 = Wire Alignment	**Last in all Scenarios**
Y60 = All Structural Repairs Complete	**2nd in Scenario 1**
Y62 = Move Fuselage to Final ATC	**4th in Scenario 1**
Y63 = Final ATC	**2nd, 1st, 1st**
Y67 = Clean and Close	**3rd, 2nd, 2nd**

In examining the activities above, we first notice that the linear program chose to target only 9 of the 24 tasks considered before it could no longer find a feasible solution. We also notice that the majority of the tasks are targeted at the end of the network structure within the framework of the schedule. This is encouraging in some regard in that this affords the program manager maximum flexibility as various aircraft flow through the schedule and shows that the network is well constructed in the initial phases, affording clean entry as it enables initial success upon induction.

It is also clear that X4, X54 and X59 are not very significant during the crashing iterations in each scenario. Scenario 3 never targets X59 in any of the iterations prior to failing to reach a feasible solution. On the contrary, X57, X63, and X67 are very significant as they are targeted early and often throughout the process.

Furthermore, 13 of the 24 tasks involve a final inspection and/or recheck of the electrical and structural portion of the airframe. Our first inclination is that these tasks, although critical to the schedule, are built in with additional time assigned to provide additional flexibility to the program manager. This additional time is often necessary and “untouchable” if a program manager intends to accomplish the schedule on time and budget. However, various situations may require that the program manager cut time off an activity in order to achieve program goals. This is a challenging decision and situation and will be addressed further in Section 6.2.

Finding 3

Building on what was already presented in Finding 2; we examine the inconsistency between where each model attacks each respective crash variable. This implies potential schedule revisions, the existence of multiple optimal solutions, and the need to take a closer look at activity completion times. We do not necessarily believe that each of the variables should rest within the identical target priorities of the other. However, the inversion and fluctuating targeting of some of the variables like Activity X54 and Activity X57 requires additional consideration. Additionally, we recommend revisiting the entire schedule of 68 activities and reviewing which can be crashed may further aid in gaining an even better understanding of how to reduce completion time while minimizing cost.

Figure 5: UH-60A Prepares for Flight Test

6.2 Recommendations

Issue: Budget

Discussion: In any type of program, cost and fiscal responsibility is paramount. Prosecuting the Global War on Terror may have presented a skewed reality of funding applied to the program as the need for refurbished helicopters dictates significant funding. The inclusion of the National Guard as a relevant contributor to the Global War on Terror further validates this point. To date, this program has served National Guard aircraft from 14 states and has provided critical upgrades to the fleet. Ultimately, most military programs endure reductions in budget once they begin to achieve steady state program maturity, regardless of the war time conditions. It is important that the UH-60A:A program continues to safeguard and plan accordingly for inevitable reductions in their annual budget.

Recommendation: Continue to contingency plan for pending annual reductions in budget while attempting to maximize overall program output. To date, this program has exceeded the mission statement and has provided 64 completed airframes over the course of five years. For every aircraft produced outside of the target goal, they are reducing the overall budgeting requirements in concert with the “more with less” maxim. Again, mastering the tricky balance between time and cost ultimately determines success and/or failure. It is clear that this is the strength of this program.

Issue: Overtime vs. Contracted Employees

Discussion: Much like the delicate balance between time and cost, a similar balance exists between balancing working overtime with the existing force workforce or simply hiring additional high-priced contractors to augment the schedule in limited duration. Of the many considerations in this dilemma, the notion of cost, the duration of new employees and overall worker expertise represent the critical contributing factors within this issue.

Most likely, the primary consideration in this case is overall schedule performance. If the program begins to lag and a backlog of various activities is present, the program manager must choose between hiring expertise in the form of contracted workers and pushing the existing force into an aggressive overtime scenario. If the latter is chosen, one could expect second and third order effects on the network as those workers rebound from the aggressive schedule. In cases of schedule backlog, cost becomes a secondary consideration and therefore this study is useful in minimizing the total cost incurred in crashing the schedule. Further, the notion of hiring additional government employees becomes eliminated from the equation based on the urgency of the situation. Ultimately, this level of the urgency dictates the flexibility in the hiring process.

Recommendation: This paper does not intend to make recommendations on how to run an already existing and very successful program. Rather, we focus simply on highlighting the challenges and presenting all of the possible outcomes for each case.

Issue: Chrome 6 and a Corrosive Environment

Discussion: Although we primarily addressed the reduction of cost in expediting the network, it is important to understand the critical importance of reducing the time exposed to the corrosive environmental elements inherent in the climate in Corpus Christi, TX. Hangar #47, the primary hangar used for completion of Network 4, rests less than one tenth of one mile from the Corpus Christi Bay and the immense amount of salt water that it holds. Couple that location with the consistently tropical climate and there is significant cause for concern when dealing with aircraft electronics and structural components subject to corrosion. Although the labor cost figures presented may seem large, they pale in comparison to the overall potential cost incurred by reworking a corrosion infected aircraft due to delays in overall completion time.

ASM International present a report entitled, “The Effects and Economic Impact on Corrosion" that states “the annual costs of metallic corrosion were estimated to be about 4.2 percent of the Gross National Product.” (Bradford, 1998) The United States spends $350 million annually to combat this significant threat and its associated ills.

Recommendation: Currently, CCAD and UH-60A:A is doing an outstanding job with their corrosive protection program. ASM further stated that “$139 billion (40 %) of the corrosion costs could be avoided through application of *existing* technologies and best know practices.” (Bradford, 1998) CCAD utilizes these practices daily and is well aware of this very important reason in expediting airframes through the existing schedule.

Issue: Time/Cost Tradeoff

Discussion: Much like the overtime vs. contracted employee dilemma, a similar and always present challenge exists between schedule performance within a given budget. Knowing when and how to inject additional cost into a lagging program is perhaps one of the most critical attributes of any program manger. In times of war, this may not be such an issue as supplemental funding at the end of a fiscal year is used to account for any budget inefficiencies. However, as the program reaches steady state in concert with a reduction or steady state wartime funding, this issue takes greater significance.

In situations where cost is not measured (i.e. on every aircraft maintenance hangar within the Department of Defense), this issue is also crucial to project completion. Unlike a predominantly civilian manned organization working a consistent schedule, the average maintenance maintainer rarely enjoys the consistency of a certain number of workers performing within the framework of an established schedule. As a result, this study is also very applicable in understanding the schedule and what is required to expedite the completion of any large scale maintenance task, such as a phase program, internal reset program, or various other large scale AVIM tasks.

Recommendation: As previously stated, the secondary goal of this study was to further develop a system that could be applied to the field army maintenance teams to better understand and manage their respective programs. Understanding the time/cost tradeoff is the first core step in gaining this overall mastery and improving upon the existing practice. We speak more to this in the section 6.3.

6.3 Final Thoughts

The single greatest value of project scheduling is that all of the activities, their relationships, and their durations must be determined or estimated. Every program manager, maintenance manager, or individual responsible for completing a given set of tasks desires to complete an entire project in a reasonable time. Learning how to minimize the time and reduce the cost is the key to a successful program.

Understanding variability and its root cause within a program is also extremely important. UH-60A:A has already transitioned from an “on condition maintenance” (OCM) program to a more systematic and scheduled recapitalization program to reduce variability. UH-60A:A can further reduce variability by studying the precedence relationships between some activities and capitalizing on the completion of concurrent activities. By using the Critical Path Method they can find expected project duration, the critical activities and the critical path through the network. We also highlight the potential slack activities that are not critical to the overall project which yield various opportunities for crashing those activities in the network. This study represents a complimentary approach to the program and the next step in further understanding the network and ultimately reducing variability.

The biggest challenge for any DOD organization is accurate reporting. Often, this is an afterthought in the process and can often cause the generation of bad data or the existence of no available data presented. It is important to understand that this bad data or lack of data can easily lead to poor analysis, poor decisions, and the implementation of ineffective courses of action. Using and understanding linear programming to better understand a schedule channels collective energy toward establishing reporting procedures, addressing logistics shortfalls, and developing collective strategies to reduce the various ills that result in increased maintenance hours.

There are many additional opportunities for advancement of this work within the Department of Defense. However, it is important to remain true to its simplistic nature both with respect to the software applications as well as the methodology presented. Maintainers work best when there is a series of tasks listed in a checklist before them. Similarly, maintenance managers effectively manage their networks by understanding the critical pieces that affect performance. In refining those parameters, we can build upon the linear programming methodology to present a generically applicable model to any type of organization within the maintenance environment. The next step with this work is to apply a graphic user interface on top of the Microsoft Excel Spreadsheet to make the program more user friendly and simplified for application. Further, we would like to query actual field maintenance managers for their input in tailoring the linear programming approach to their every day business.

This work will never eliminate the challenge of cost/schedule/performance within a program, as that represents the inevitable and timeless test to any project manager.

APPENDIX A: DECISION VARIABLES

X1 = Induct Aircraft to Structural/Electrical Phase
X2 = Raise Fuselage on Work Stands
X3 = Review Work Package, Inventory OCM Parts
X4 = Inventory Upgrade Kits
X5 = Structural Repair – Roof Section
X6 = Structural Repair – Nose Section
X7 = Remove Landing Gear
X8 = Remove Electrical Interference – Transition Section
X9 = Remove Electrical Interference – Tailcone Section
X10 = Remove Electrical Interference - Cabin
X11 = Structural Repair – Cockpit Section
X12 = Inspect/Repair Landing Gear Fittings
X13 = Inspect/Repair/Reassemble Landing Gear
X14 = Structural Repair – Transition Section
X15 = Structural Repair – Tail Cone Section
X16 = Structural Repair – Cabin Under Floor
X17 = SSI 50-6 Rework of Lower Aft Transition Section
X18 = Remove Electrical Interference – Roof Section
X19 = SSI 50-15 Installation of ESSS Doublers
X20 = Install Landing Gear
X21 = Structural Repair – Cabin Overhead
X22 = SSI 50-22 Modification of Cockpit Floor and Door Posts
X23 = SSI 50-16 Rework of Upper Plating and Doubler Installation
X24 = SSI 50-9 Modification of Drive Shaft Supports
X25 = SSI 50-35 Modification of Canopy Assembly, Nose Door Hinge Access
X26 = Electrical Repair – Nose Section
X27 = Electrical Repair – Cockpit Section
X28 = SSI 50-13 Installation of Tail Cone Plating Modification Kit
X29 = SSI 50-5 Installation of Side Fuselage Structural Reinforcement
X30 = Final/Recheck Structural – Nose Section
X31 = Final/Recheck Structural – Cockpit Section
X32 = SSI 50-30 Installation of HIRSS Repair Kit

X33 = Final/Recheck Electrical – Nose Section
X34 = Final/Recheck Electrical – Cockpit Section
X35 = Electrical Repairs – Roof Section
X36 = SSI 50-17 Modification of Station 605.00 Bulkhead
X37 = Final/Recheck Structural – Roof Section
X38 = Structural Repair - Firewalls
X39 = SSI 50-24 Modification of Tail Cone
X40 = SSI 50-19 Modification of Left and Right Side Firewall Assemblies
X41 = Final/Recheck Structural – Firewalls Section
X42 = SSI 50-29 Modification of Tail Cone Shear Deck
X43 = Final/Recheck Electrical – Roof Section
X44 = SSI 50-7 Modification of Buttline 34.50
X45 = SSI 50-20 Modification of Tail Rotor Drive Shaft Support Brackets
X46 = SSI 50-34 Modification of Transition Station 485.00
X47 = SSI 50-21 Replacement of Vapor Barrier Support Structure
X48 = SSI 50-26 Modification of Station 379.00 Frame
X49 = Electrical Repair –Tail Cone Section
X50 = Electrical Repair – Transition Section
X51 = Electrical Repair – Cabin Section
X52 = Final/Recheck Structural – Tail Cone Section
X53 = Final/Recheck Structural – Transition Section
X54 = Final/Recheck Electrical – Tail Cone Section
X55 = Final/Recheck Structural - Cabin
X56 = Final/Recheck Electrical – Transition Section
X57 = Final/Recheck Electrical – Cabin Section
X58 = Remove Fuselage from Work Stands
X59 = Wire Alignment
X60 = All Structural Repairs Complete
X61 = Seam Seal Fuselage
X62 = Move Fuselage to Final ATC
X63 = Final ATC
X64 = Final Electrical Inspection

X65 = Final Structural Inspection

X66 = Install EMI Filters

X67 = Clean and Close

X68 = Move Fuselage to Retreat/Prime Paint

Y4 = The amount of time (in hours) that activity X4 can be crashed.

Y7 = The amount of time (in hours) that activity X7 can be crashed.

Y12 = The amount of time (in hours) that activity X12 can be crashed.

Y13 = The amount of time (in hours) that activity X13 can be crashed.

Y30 = The amount of time (in hours) that activity X30 can be crashed.

Y31 = The amount of time (in hours) that activity X31 can be crashed.

Y33 = The amount of time (in hours) that activity X33 can be crashed.

Y34 = The amount of time (in hours) that activity X34 can be crashed.

Y37 = The amount of time (in hours) that activity X37 can be crashed.

Y38 = The amount of time (in hours) that activity X38 can be crashed.

Y41 = The amount of time (in hours) that activity X41 can be crashed.

Y43 = The amount of time (in hours) that activity X43 can be crashed.

Y52 = The amount of time (in hours) that activity X52 can be crashed.

Y53 = The amount of time (in hours) that activity X53 can be crashed.

Y54 = The amount of time (in hours) that activity X54 can be crashed.

Y55 = The amount of time (in hours) that activity X55 can be crashed.

Y56 = The amount of time (in hours) that activity X56 can be crashed.

Y57 = The amount of time (in hours) that activity X57 can be crashed.

Y58 = The amount of time (in hours) that activity X58 can be crashed.

Y59 = The amount of time (in hours) that activity X59 can be crashed.

Y60 = The amount of time (in hours) that activity X60 can be crashed.

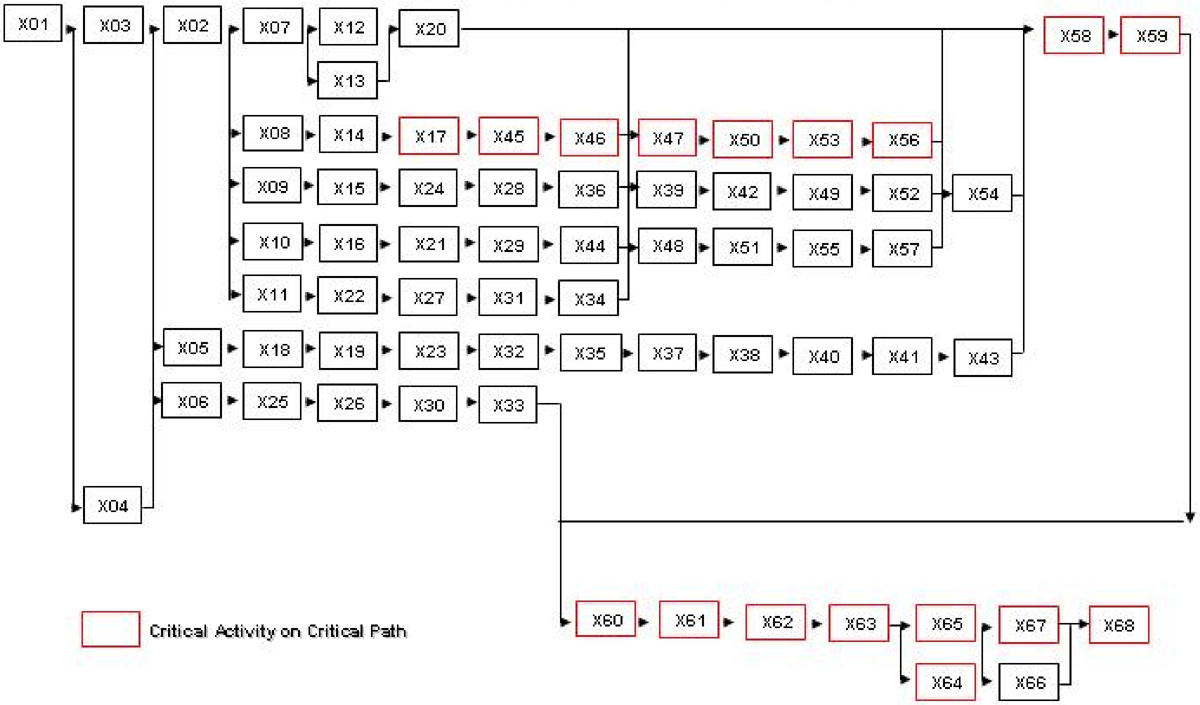
Y62 = The amount of time (in hours) that activity X62 can be crashed.

Y63 = The amount of time (in hours) that activity X63 can be crashed.

Y67 = The amount of time (in hours) that activity X67 can be crashed.

APPENDIX B: NETWORK DIAGRAM

UH-60A: A Structures/Electrical Network Diagram



LIST OF REFERENCES

Abbasi, G. Y., & Mukattash, A. M. (2001). Crashing PERT networks using mathematical programming. *International Journal of Project Management, 19*(3), 181.

Ameen, D. A. (1987). A computer assisted PERT simulation. *Journal of Systems Management, 38*(4)*,* 6-9.

Anderson, D. R., Sweeney, D. J., & Williams, T. A. (2004). *Introduction to management science* (11th Edition ed.)Thomson Learning.

Babu, A. J. G., & Suresh, N. Project management with time, cost, and quality considerations. *European Journal of Operational Research, 88*(2), 320-327.

Badiru, A. B. (1991). A simulation approach to network analysis. *Simulation, 57*(4), 245-255.

Baker, B. M. (1997). Cost/time trade-off analysis for the critical path method: A derivation of the network flow approach. *Journal of the Operational Research Society, 48*(12), 1241-1244.

Beckwith, N. E. The cost of crashing - A comment. *Journal of Marketing, 35*(4), 63-66.

Bond, D. GWOT money. *Aviation Week & Space Technology, 161*(4) 25.

Borgman, D. C., & Hwang, J. D. R&D project cost and schedule realism: A risk analysis approach. 731-733.

Cockerham, J. (1976). *U.S. army total risk assessing cost estimate (TRACE) guidelines*

Curtin, N. P. (2001). *Military aircraft: Services need strategies to reduce cannibalizations* (GAO Report No. GAO-02-86)

Dell, R. F. Optimizing army base realignment and closure. *Interfaces, 28*(6), 1-18.

Foldes, S., & Soumis, F. (1993). PERT and crashing revisited: Mathematical generalizations. *European Journal of Operational Research, 64*(2), 286-294.

Fulgham, D. A. (2004, Juggling lessons. *Aviation Week & Space Technology, 161*(7) 27-28.

Giddens, J. (2006, CCAD and lean: Through the eyes of wonder. *The Aircraftman, 4*(11) 1-7.

Goettel, B. C. (1994). Computer-assisted planning, programming, budgeting system (CAPPB). *, 1* 390-394.

Haga, W. A., & Marold, K. A. (2004). A simulation approach to the PERT/CPM trade-off problem. *Project Management Journal, 35*(2), 31-38.

Hoeper, P. J. (1999). *Statement on acquisition reform* (First Session, 106th Congress. United States Senate.

Hoeper, P. J., & Coburn, J. G. (1999). *Statement on aging military equipment* (First Session, 106th Congress, United States Senate.

Jerabeck, C. R. (2005). *Federal wage system regular and special production facilitating wage rate schedules.*

Kanda, A., & Rao, U. R. K. (1984). Network flow procedure for project crashing with penalty nodes. *European Journal of Operations Research, 16*(2), 174-182.

Karmarkar, N. (1984). A new polynomial time algorithm for linear programming. *Combinatorica, 4*(4), 373-395.

Knight, H. (2002). Crashing out. *Centaur Communications, 291*(7611), 11.

Kurtz, G. D. (2005). *Army depot maintenance: Ineffective oversight of depot maintenance operations and system implementation efforts* (GAO Report No. GAO-05-441)

Lenstra, J. K. (2002). Linear programming: George B. Dantzig. *Operations Research, 50*(1), 42-47.

Liang, T. F. (2003). A study on project crashing with multiple fuzzy goals. *Journal of the Chinese Institute of Industrial Engineers, 20*(4), 355-372.

Love, L. H., & Drew, D. S. (2000). Effects of overtime work and additional resources on project cost and quality. *Engineering Construction & Architectural Management, 7*(3), 211-221.

McGowen, J. W. (1987). VERT-PC: Placing a powerful analysis tool at the decision maker's fingertips. 274-280.

Moon, J. W., & Littlejohn, J. G. (1964). Value analysis as applied to research and development program. *Journal of Value Engineering, 2*(4), 9-12.

Peltz, E. J. (1970). The cost of crashing. *Journal of Marketing, 34*(3), 64-67.

Perera, S. (1980). Linear programming solution to network programming. *American Society of Civil Engineers, Journal of the Construction Division, 106*(3), 315-326.

Premachandra, I. M. (1993). A goal-programming model for activity crashing in project networks. *International Journal of Operations & Production Management, 13*(6), 79-85.

Pular, P. S., & Horn, S. J. (1996). Time-resource tradeoff problem. *IEEE Transactions on Engineering Management, 43*(4), 411-416.

Ramini, S. (1986). A simulation approach to the time-cost trade-off in project network. 115-120.

Reeves, G. R., & Reid, R. C. (1999). A military reserve manpower planning model. *Computers and Operations Research, 26*(12), 1231-1243.

Roemer, T. A., & Ahmadi, R. (2004). Concurrent crashing and overlapping in product development. *Operations Research, 52*(4), 606-622.

Shaing-Tai, L. (2003). Fuzzy activity times in critical path and project crashing problems. *Cybernetics and Systems, 34*(2), 161-172.

Stingel, J. D., & Componation, P. J. (2006). The utilization of modeling and simulation as a supply chain management tool for a recapitalization program. *Engineering Management Journal, 18*(2), 44-50.

Van Slyke, R. M. (1963). Monte carlo methods and the PERT problem. *Operations Research, 13*, 141-143.

Wall, R. (2004, Maintenance mountain. *Aviation Week & Space Technology, 160*(16) 69-70.

Warren, D. R. (2001). *Army inventory: Parts shortages are impacting operations and maintenance effectiveness* (GAO Report No. GAO-01-772)

Whiton, J. C. (1971). Production applications of large-scale linear programming models for optimized resource allocation within the U.S. department of defense. *Centre National De Recherches Scientifique Et Techniques Pour l'Industrie Cimentiere, Rapport De Recherche,* 43-80.