NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

THE ROLE OF HIGH PERFORMANCE COMPUTING IN SIMULATION BASED ACQUISITION: A CASE STUDY BASED ON EXPERIENCES IN THE RAH-66 COMANCHE PROGRAM

by

Denice P. Brown

June 2001

Thesis Advisor:	Thomas W. Crouch
Associate Advisor:	Andrew Mark

Approved for public release; distribution is unlimited.

20011108 159

REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE June 20001	3. REPORT TYPE AND DATES COVERED Master's Thesis

4. TITLE AND SUBTITLE: The Role of High Performance Computing in Simulation Based Acquisition: A Case Study Based on Experiences in the RAH-66 Comanche Program	**5. FUNDING NUMBERS**
6. AUTHOR(S) Brown, Denice P.	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000	**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A	**10. SPONSORING / MONITORING AGENCY REPORT NUMBER**

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION / AVAILABILITY STATEMENT	12b. DISTRIBUTION CODE
Approved for public release; distribution is unlimited.	

13. ABSTRACT *(maximum 200 words)*

This thesis endeavors to determine how effective a role high performance computing played in the Program Definition and Risk Reduction (PDRR) and early Engineering and Manufacturing Development (EMD) phases of the RAH-66 Comanche program. In so doing, the various modeling and simulation efforts used in the Comanche program are explored and their utility and efficacy determined. This study provides insights into the places to insert high performance computing into the simulation based acquisition process for best effect. In addition, it uncovers the best uses of modeling and simulation in the Comanche program, which can serve as a guide for other simulation based acquisition programs.

14. SUBJECT TERMS	15. NUMBER OF PAGES 76
RAH-66 Comanche, Simulation Based Acquisition, Modeling and Simulation, Simulation Based Design, High Performance Computing, Computer Aided Design, Computer Aided Engineering, Computer Aided Manufacturing, Virtual Prototyping, Virtual Manufacturing, Virtual Environments	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release; distribution is unlimited

THE ROLE OF HIGH PERFORMANCE COMPUTING IN SIMULATION BASED ACQUISITION: A CASE STUDY BASED ON EXPERIENCES IN THE RAH-66 COMANCHE PROGRAM

Denice P. Brown
Civilian, United States Army Research Laboratory
B.S., Pennsylvania State University, 1975

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN PROGRAM MANAGEMENT

from the

NAVAL POSTGRADUATE SCHOOL
June 2001

Author: Denice P. Brown

Approved by: Thomas W. Crouch, Thesis Advisor

Andrew Mark, Associate Advisor

Kenneth J. Euske, Dean
Graduate School of Business and Public Policy

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

This thesis endeavors to determine how effective a role high performance computing played in the Program Definition and Risk Reduction (PDRR) and early Engineering and Manufacturing Development (EMD) phases of the RAH-66 Comanche program. In so doing, the various modeling and simulation efforts used in the Comanche program are explored and their utility and efficacy determined. This study provides insights into the places to insert high performance computing into the simulation based acquisition process for best effect. In addition, it uncovers the best uses of modeling and simulation in the Comanche program, which can serve as a guide for other simulation based acquisition programs.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

I. INTRODUCTION 1
- A. BACKGROUND 1
- B. PURPOSE 1
- C. SCOPE AND METHODOLOGY 1
- D. ORGANIZATION OF STUDY 2

II. BACKGROUND 5
- A. SIMULATION BASED ACQUISITION 5
- B. MODELING AND SIMULATION 7
  - 1. Computer Aided Design (CAD) 8
  - 2. Computer Aided Engineering (CAE) 9
  - 3. Computer Aided Manufacturing (CAM) 9
  - 4. Virtual Prototyping 10
  - 5. Virtual Environments 10
  - 6. Virtual Manufacturing 10
- C. HIGH PERFORMANCE COMPUTING 11
- D. RAH-66 COMANCHE PROGRAM 12

III. DATA 15
- A. MODELING AND SIMULATION EFFORTS 15
  - 1. Resin Transfer Molding 15
  - 2. "Mockpit" 16
  - 3. Aft Fuselage Design 17
  - 4. Ballistic Vulnerability Forecasting 21
  - 5. Avionics Software 21
  - 6. Lean Manufacturing 22
  - 7. On-board Test and Training Instrumentation System (OTTIS) 23
  - 8. Comanche Portable Cockpit (CPC) 24
- B. CATEGORIZATION OF THE EFFORTS 24
  - 1. Types of Modeling and Simulation 24
  - 2. Use of High Performance Computing 25

IV. ANALYSIS 27
- A. EFFICACY OF CAD 27
- B. EFFICACY OF CAE 27
- C. EFFICACY OF CAM 28
- D. EFFICACY OF VIRTUAL PROTOTYPING 28
- E. EFFICACY OF VIRTUAL MANUFACTURING 28
- F. EFFICACY OF VIRTUAL ENVIRONMENTS 29
- G. EFFICACY OF HIGH PERFORMANCE COMPUTING 29

V. CONCLUSIONS AND RECOMMENDATIONS 31
- A. CONCLUSIONS 31

B. RECOMMENDATIONS 32
C. SUMMARY 33

APPENDIX. INTERVIEW QUESTIONS AND RESULTS 35
A. INTERVIEW QUESTIONS AND APPROACH. 35
B. INTERVIEW RESULTS 38
1. Interview with Mr. Dale Shires 38
2. Interview with Mr. Stephen Law 41
3. Interview with Mr. Phillip Lang 42
4. Interview with Mr. Melvin Niederer 43
5. Interview with Mr. Frank Sum 45
6. Interview with Mr. Bruce Cramer and Mr. G. Randall Wichmann 46
7. Interview with MAJ Vincent Tobin 48

LIST OF REFERENCES 51

BIBLIOGRAPHY 55

INITIAL DISTRIBUTION LIST 57

LIST OF TABLES

Table 1. Categorization of Efforts by Modeling and Simulation Category 25
Table 2. Categorization of Efforts by Use of High Performance Computing 26
Table Appendix-1. Synopsis of Interview with Mr. Dale Shires.....40
Table Appendix-2. Synopsis of Interview with Mr. Stephen Law 42
Table Appendix-3. Synopsis of Interview with Mr. Phillip Lang 43
Table Appendix-4. Synopsis of Interview with Mr. Melvin Niederer.....44
Table Appendix-5. Synopsis of Interview with Mr. Frank Sum.....46
Table Appendix-6. Synopsis of Interview with Messrs. Cramer and Wichmann 48
Table Appendix-7. Synopsis of Interview with MAJ Vincent Tobin.....49

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF ACRONYMS AND ABBREVIATIONS

AATD	Aviation and Applied Technology Directorate
AGES	Air Ground Engagement System
AHPCRC	Army High Performance Computing Research Center
AOA	Analysis of Alternatives
ARL	Army Research Laboratory
ATCOM	Aviation and Troop Command
AWE	Army Warfighting Experiment
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacturing
CATIA	Computer Aided Three-Dimensional Interactive Application
COMPOSE	COmposite Manufacturing PrOcess Simulated Environment
CPC	Comanche Portable Cockpit
DoD	Department of Defense
DoDD	Department of Defense Directive
EMD	Engineering and Manufacturing Development
ENIAC	Electronic Numerical Integrator and Computer
FEM	Finite Element Mesh
GB	Gigabytes
GF	Gigaflops
GPS	Global Positioning System
HE	High Explosive
HPC	High Performance Computing
IPT	Integrated Product Team
LHX	Light Helicopter Family
LTG	Lieutenant General
M&S	Modeling and Simulation
MAJ	Major
MD	Maryland
MILES	Multiple Integrated Laser Engagement System
MRP	Material Requirements Planning
MRP II	Manufacturing Resource Planning
MSC	MacNeil-Schwendler Corporation
NPS	Naval Postgraduate School
OTTIS	On-board Test and Training Instrumentation System
PC	Personal Computer
PDM	Product Data Manager
PDRR	Program Definition and Risk Reduction
PMO	Program Management Office
RTM	Resin Transfer Molding
SBA	Simulation Based Acquisition

SGI	Silicon Graphics Inc.
SMART	Simulation and Modeling Acquisition Requirements Training
STEP	Simulation Test and Evaluation Process
TTP	Tactics, Techniques, and Procedures
VE	Virtual Environments
VM	Virtual Manufacturing
VP	Virtual Prototyping

ACKNOWLEDGMENTS

First and foremost, I would like to thank Shannon Brown, my loving husband, whose moral support and confidence in my abilities enabled me to persevere and finish this degree program. I would, also like to thank LTC Thom Crouch, my thesis advisor, and Dr. Andrew Mark, my associate advisor, for the assistance they gave me in this endeavor. In addition, I would like to thank MAJ Vincent Tobin and MAJ Brian Shoop of the RAH-66 Comanche Program Office for giving me contacts to pursue and answering a myriad of my questions. I would like to thank Mr. William Hunter, who arranged all my interviews with Boeing personnel as well as all my interviewees, namely: Messrs. Dale Shires, Stephen Law, Phillip Lang, Melvin Niederer, Frank Sum, Bruce Cramer, and G. Randall Wichmann.

THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION

A. BACKGROUND

Simulation based acquisition is a buzzword to some and a firm method to others. This thesis endeavors to discover what simulation based acquisition and all its modeling and simulation efforts can do for the Department of Defense (DoD) acquisition program manager. Specifically, it looks at the modeling and simulation efforts in relation to their use of high performance computing to determine how they can help the program manager acquire a system that is more reliable and cost effective.

B. PURPOSE

The purpose of this thesis is to provide insights into the places to insert high performance computing into the simulation based acquisition process for best effect. In addition, it endeavors to uncover the best uses of modeling and simulation in the Comanche program, which can serve as a guide for other simulation based acquisition programs.

C. SCOPE AND METHODOLOGY

The scope of this thesis examines the modeling and simulation activities employed in the RAH-66 Comanche program during the Program Definition and Risk Reduction (PDRR) and early Engineering and Manufacturing Development (EMD) phases of the acquisition process.

It includes the following: 1) a review of the various modeling and simulation areas and their need for high performance computing, 2) a determination of which were used and on what platforms in the RAH-66 Comanche program, 3) an exploration of the

utility and efficacy of these modeling and simulation efforts on the Comanche, and 4) the need for additional or different modeling and simulation efforts using high performance computing. The thesis does not include any material requirements planning (MRP) or manufacturing resource planning (MRP II) efforts as part of the modeling and simulation that was done.

The methodology used in this thesis research consists of the following steps:

1) Conduct a literature search of books, magazine articles, the web, and other library information resources for information on simulation based acquisition, modeling and simulation, high performance computing, and the RAH-66 Comanche aircraft.
2) Conduct a review of the various modeling and simulation areas, including computer aided design, computer aided engineering, computer aided manufacturing, virtual prototyping, virtual manufacturing and virtual environments.
3) Conduct interviews with the Comanche Program Management Office (PMO) staff, Boeing-Sikorsky, and others deemed appropriate to determine which modeling and simulation efforts were used in the PDRR and early EMD phases, including their utility, efficacy, and need for high performance computing based on the research questions.
4) Make recommendations to other simulation based acquisition programs on which Comanche modeling and simulation efforts worked best and where the use of high performance computing may have improved the results.

D. ORGANIZATION OF STUDY

The study begins with background information regarding simulation based acquisition, modeling and simulation, high performance computing, and the RAH-66

Comanche. Next, various modeling and simulation efforts used on Comanche are described and categorized. The efficacy of the modeling and simulation efforts is analyzed. From this information, conclusions and recommendations are made.

THIS PAGE INTENTIONALLY LEFT BLANK

II. BACKGROUND

A. SIMULATION BASED ACQUISITION

Simulation Based Acquisition is an "acquisition process in which DoD and Industry are enabled by robust, collaborative use of simulation technology that is integrated across acquisition phases and programs." (Lavine, 2000) It includes all aspects of the acquisition life cycle including: top level system requirements, conceptual development, functional design, physical hardware and software system design, engineering and manufacturing development, test and evaluation, operations, logistics, and training, cost, schedule, and program management. It was promulgated in 1997 and, in May 1999, changes to DOD 5000.2R elevated modeling and simulation (M&S) to a key element of and incorporated Simulation Test and Evaluation Process (STEP) into the acquisition strategy. (Lavine, 2000).

The Defense Acquisition System encourages program managers to apply simulation based acquisition techniques to their programs. Department of Defense Directive (DoDD) 5000.1 states the following:

> 4.5.4. Simulation-Based Acquisition. Program managers shall plan and budget for effective use of modeling and simulation to reduce the time, resources, and risk associated with the entire acquisition process; increase the quality, military worth and supportability of fielded systems; and reduce total ownership costs throughout the system lifecycle. (DoDD 5000.1, 2000)

In addition, the program manager is enjoined to use modeling and simulation as a tool to aid in decision making:

> 4.7.1.2. Extensive use of modeling, simulation, and analysis should be used throughout the acquisition process to integrate the activities of the principal decision support systems by creating information for decision-makers. Modeling and simulation (M&S) is useful in representing conceptual systems that do not exist and extant systems that cannot be subjected to actual environments because of safety requirements or the limitations of resources and facilities. The Program Manager should plan for the integrated use of M&S that maximizes the use of existing M&S before developing program unique products. (DoDD 500.1, 2000)

In the Army, Simulation Based Acquisition equates to SMART (Simulation and Modeling Acquisition Requirements Training). The SMART moniker was developed to avoid confusion of Simulation Based Acquisition (SBA) with the Small Business Administration. SMART is defined as:

> ... a process in which we capitalize on Modeling and Simulation (M&S) technology to address the issue of system development and life-cycle costs through the combined efforts of the requirements, training, and acquisition communities. (Lanceford, 2000)

The SMART vision, espoused by LTG Larry R. Ellis, Deputy Chief of Staff for Operations and Plans, LTG Paul J. Kern, Military Deputy to the Assistant Secretary of the Army (Acquisition, Logistics, and Technology), and Mr. Walter W. Hollis, Deputy Under Secretary of the Army (Operations Research), is to

> Be a world leader in Modeling and Simulation to continuously improve Army effectiveness through a disciplined collaborative environment in partnership with industry, government, and academia. (Lanceford, 2000)

With SMART, collaborative engineering environments are developed. A key one is the integrated digital environment consisting of distributed product description, data protection/security, data access and causal networking. This integrated digital environment enables all system stakeholders to access the digital system designs and assess the impact of any design changes on their particular function. In this manner,

system design can be optimized across all functions instead of at the expense of one function over another. (Lanceford, 2000)

B. MODELING AND SIMULATION

Modeling and Simulation (M&S) is defined as "the use of models, including emulator, prototypes, simulators and stimulators, either statistically or over time, to develop data as a basis for making managerial or technical decisions" (Defense Acquisition Deskbook, 2000). A model is defined as "a physical, mathematical, or otherwise logical representation of a system, entity, phenomenon, or process." (DoD 5000.59-M, DoD Modeling and Simulation (M&S) Glossary, 1997) A simulation is defined as "a method for implementing a model over time." (DoD 5000.59-M, DoD Modeling and Simulation (M&S) Glossary, 1997)

Modeling and Simulation are not new concepts in the defense acquisition process. They have been used for a long time. Every hardware mockup of a weapon system is a model. Every mathematical formula that describes a physical law related to it is, also, a model. Simulations became easier with the advent of computers. The U.S. Army's and world's first electronic computer, the ENIAC (Electronic Numerical Integrator and Computer), was specifically designed by the University of Pennsylvania during World War II for the Army to produce firing tables for the various weaponry. Using results from actual firing tests, firings under other conditions were determined by interpolating and extrapolating the known data and applying the laws of physics, yielding the first computer-aided simulations. These simulations produced singular values that were tabulated to produce the firing tables. Although they did not produce the conceptual or

scientific visualizations that one pictures when using the word simulation today, they were simulations nonetheless. (Moye, 1996)

Today's digital simulations can provide even more insight. Paul J. Hoeper, Assistant Secretary of the Army (Acquisition, Logistics, and Technology) has stated that "If a picture is worth a thousand words, then a digital simulation is worth a thousand pictures!" (Kern, 1999) Although today's acquisition members have better simulations, their counterparts in the 1940's probably felt the same way about their firing tables.

Modeling and simulation can be categorized into various types, including the following: Computer Aided Design (CAD), Computer Aided Engineering (CAE), Computer Aided Manufacturing (CAM), Virtual Prototyping (VP), Virtual Environments (VE), and Virtual Manufacturing (VM). Each is described below in more detail. Some of these modeling and simulation areas require high performance computer while others require just office personal computers. Each is important in its own right.

1. Computer Aided Design (CAD)

CAD can be defined simply as "the use of computer system to assist in the creation, modification, analysis or optimization of a design" (Naval Postgraduate School, 1997). It involves the construction of models of the various parts and components of an item using special software systems which enable the quick rendering of the item, including its dimensions, and storage of the geometric and other information in a central database, usually, available to all involved in the design. It has taken the place of manual drafting. It enables the designer to check tolerances and fit between components and feed the design information into engineering analysis programs, scientific visualizations, and other simulations.

2. Computer Aided Engineering (CAE)

Computer Aided Engineering includes "analysis of part weight, center of gravity, and moment of inertia calculations. Finite element analysis enhances thermal and mechanical stress analysis" (Naval Postgraduate School, 1997). CAE looks at whether the design from the CAD system can perform the function for which it was intended given the basic physical laws and engineering practices. CAE enables the designer to perform "what if" scenarios to determine if design changes are needed to meet the change conditions engendered by the scenario. If such changes are needed, the CAD design can be adjusted to meet the physical demands, re-tested with the CAE model, and repeated as necessary. This enables the designer to optimize the design to meet the physical demands on the item before a prototype or production item is created. Of course, after each design change, tolerances and fit must be checked with other items to which the part interfaces as well as any impact the design change has made to the engineering capability of the other items. Many CAE efforts require the use of high performance computers.

3. Computer Aided Manufacturing (CAM)

Computer Aided Manufacturing is the "application or use of the computer to perform any manufacturing process, system or operation" (Naval Postgraduate School, 1997). It is often combined with CAD and stated as CADCAM. CADCAM includes the elements of CAD and CAE and the addition of planning and scheduling, and fabrication – the CAM portion. Planning includes process planning and factory management tools including material requirements planning (MRP) and manufacturing resource planning (MRP II) systems. CAM in fabrication includes such things as computer numerical control machines, robots, and flexible manufacturing cells and systems. Computer integrated manufacturing is another buzz word that falls under the CAM umbrella.

4. Virtual Prototyping

Virtual prototyping (VP) is the application of virtual reality to design. It is not a new idea. It has been used as long as computer simulation for design has been employed. The difference today is that it is a much cheaper endeavor. It previously required supercomputers or high-end computer workstations to use. Now, VP products are available that run on the standard office computer, thus bringing VP to the smaller companies. (Bury, 2000), (Simulation Based Design Center, 2000)

5. Virtual Environments

Virtual reality enables the end user to immerse himself in a synthetic environment, or virtual environment, rendered through computer software with whatever attributes are desired. The immersion often includes a three-dimensional viewing capability using special eye glasses or head-mounted displays. Haptic devices, e.g., wands or gloves, can be used to capture the tactile sense of the virtual objects. (Simulation Based Design Center, 2001) This type of environment enables the end user to try out the virtual prototype of the design under various conditions without having to actually have a physical prototype available. It can be used quite effectively to determine human factor impact for persons of various heights, weights, etc. before a design is finalized. Training simulators fall into this category.

6. Virtual Manufacturing

Virtual manufacturing uses software tools to design a production line and determine if the positioning, footprint and flow are what are desired. The ability to gain access to the equipment for maintenance can be determined and verified. Even virtual people can be inserted into the design to see if there are any human factors issues that will impact the operator or operation.

C. HIGH PERFORMANCE COMPUTING

High Performance Computing (HPC) is difficult to define, since it changes as time marches on. Today's desktop computer was yesterday's high performance computer. At any point in time, high performance computing represents the leading edge of computing technology – the computer systems with the highest peak speeds (in floating point operations per second). Systems such as the IBM 360, CDC 7600, Cray 1, DEC Vax 780, Cray X-MP, Cray 2, Cray T90, Thinking Machine CM-1, Cray T3E, SGI Origin 2000, IBM SP2, for example, have all been considered high performance computers, or supercomputers, of their day. (Johnson, McKeon, and Szanto, 1998) Silicon Graphics Inc. (SGI) defines supercomputers as:

> ... a class of computers that are recognized as delivering industry-leading performance, in terms of computational abilities (both number of processors and performance), bandwidth, memory capacity, storage capacity and visualization. (Baker, November 2000)

According to Cray Henry of the DoD HPC Modernization Office, "any computer that costs more than a million dollars is considered a supercomputer." (Baker, November 2000) Currently in the DoD High Performance Computing Modernization Program, an HPC project is defined as one that:

> ... meets at least one of the following thresholds: 1) a system speed requirement of 1 gigaflops (GF, billion floating point operations per second), 2) an integrated overall computational requirement of 1,000 GF-hours over a year, 3) a memory requirement of 512 megabytes, 4) an on-line storage requirement of 10 gigabytes (GB), 5) an archival storage requirement of 50 GB. (DoD High Performance Computing Modernization Office, 2001)

Therefore, a computing system today that meets the first, third, and fourth threshold would definitely be considered an HPC system. As an HPC system, it is a "technology for producing more computations more quickly" (Feinberg, 2000) to aid in faster modeling and simulation.

D. RAH-66 COMANCHE PROGRAM

The RAH-66 Comanche program began its acquisition life as the Light Helicopter Family (LHX) with the Concept Exploration phase of Preliminary Design studies in 1983. The first Program Manager was assigned in January 1984 and the Program Office established in October 1984. The original acquisition plan, approved in August 1984, anticipated that the LHX would enter production by FY90. Funding shortfalls and resultant acquisition plan changes have lengthened that schedule considerably so that, today, the RAH-66 Comanche program is only in the Engineering and Manufacturing Development (EMD) phase. (Galindo, 2000)

The Comanche is a reconnaissance/attack helicopter set for initial operating capability in FY2006. It is a two-seater with twin turbine engines. Its rotor system consists of both a five-bladed bearingless main rotor, and a FANTAIL anti-torque system. Other key features include the following: low workload crew station, triple redundant fly-by-wire flight control system, wide field-of-view (35 x 52 degrees) helmet-mounted display, low observables (radar, infrared, acoustic), and simple remove-and-replace maintenance. (Boeing, 2001) Comanche can cruise at 161 knots with the ability to dash to 172 knots. It can fly both sideways and backwards at 70 mph. Snap turns can be executed in 4.5 seconds. (Sikorsky, 2001)

The aircraft is being developed by Team Comanche, a consortium of companies led by The Boeing Company in Philadelphia, Pennsylvania and United Technologies' Sikorsky Aircraft in Stratford, Connecticut. The Boeing Company is responsible for the mission equipment package integration, the flight controls, the aft fuselage, and the rotor blades. Sikorsky Aircraft is responsible for airframe integration, dynamics, rotor hub, and the crew station design. They are assisted by 1,100 major subcontractors and suppliers, which are located in 45 states. (Boeing-Sikorsky, 2001)

The Comanche program has utilized a simulation based acquisition strategy for its development from the beginning. Its key simulation requirements include the following:

> 1) Design and development, 2) Pilot Vehicle Interface Analysis, 3) Test and Evaluation, 4) Tactics Techniques and Procedures (TTP) Development, 5) Concept Exploration Programs, 6) AWE Support, 7) Individual Training, 8) Collective Training, 9) Support Requirements Determination, 10) Digital Interoperability (System Development), and 11) Demonstrations. (RAH-66 Comanche Simulation Support Plan, 1999)

Team Comanche has split the responsibilities for the M&S efforts between the two prime contractors. Boeing is responsible for constructive, training, and flight controls simulation. Sikorsky is responsible for virtual aircraft and crew station vehicle simulations. (RAH-66 Comanche Simulation Support Plan, 1999)

THIS PAGE INTENTIONALLY LEFT BLANK

III. DATA

A. MODELING AND SIMULATION EFFORTS

1. Resin Transfer Molding

The US Army, under the auspices of the Army High Performance Computing Research Center (AHPCRC) and the Army Research Laboratory (ARL), has done research in the physical process modeling of the resin transfer molding (RTM) process for composite manufacturing, a VM area. During resin transfer molding, dry spots, also known as voids, can develop which ruin the composite being formed. Being able to model the resin transfer process and determine where to position the injection points to eliminate voids can save valuable time, money, and resources when the final product is manufactured. An example of RTM for RAH-66 Comanche is the 24-foot keel beam. (Mark, Mohan, Tamma, 1999)

This keel beam has been problematic to build in one piece. A smaller 10-foot keel beam was created successfully using the RTM process; however, the larger one was just too big and had many voids. Currently, the Comanche keel beams have been made as hard lay-ups, which are costly, time consuming and non-repetitive. (Mohan, Shires, Mark, Tamma, Ngo, 1998) RTM works quite well for smaller parts; although Sikorsky had some problems, initially, with the Comanche gear box. The Aviation and Applied Technology Directorate (AATD) at Fort Eustis became aware of the Sikorsky's plight and contacted ARL to see if it could assist. (Shires, Mohan, Mark, 2000), (Shires, 2001)

The ARL code, COMPOSE (COmposite Manufacturing PrOcess Simulated Environment), which simulates the RTM process, was run on the gear box design. After

several simulations, an optimal design for the injection ports was determined and delivered to Sikorsky. Sikorsky successfully manufactured the gear box out of composites, using ARL's suggestions. Having a gear box made solely from composites saves both weight and money. (Shires, 2001)

COMPOSE runs on LINUX, UNIX, and Windows environments from desktop personal computers (PCs) through High Performance Computers. The size and complexity of the design and urgency of the results determines the platform choice. For example, the gear box simulations were done on an SGI O2 workstation; whereas, the 24-foot keel beam simulations required an HPC platform, such as the SGI Origin 2000. (Shires, 2001)

2. "Mockpit"

The RAH-66 Comanche benefited not only from RTM modeling but also from the use of human engineering models and simulations. The Transom Jack model developed by the Natick Research, Development and Engineering Center enabled designers to place human figures of various sizes within the simulated Comanche cockpit drawn using the CATIA (Computer Aided Three-Dimensional Interactive Application) data to determine if there were any problems that needed design rework. Later, a virtual cockpit, named the "mockpit," was created using an SGI O2 computer and virtual prototyping software. This set-up included reusable crew station simulation code written in C++ that could be mailed on a CD-ROM as an executable file to all "mockpit" locations. Crews could "fly" the Comanche, using this simulation software, months before it would be put into the real aircraft. (Chase, Copeland, and Ferrell, 2000)

3. Aft Fuselage Design

The Boeing engineers have used modeling and simulation heavily in the design of the aft fuselage both during the PDRR and early EMD phases of the Comanche program. CATIA is the workhorse software package for the design effort in both. Currently in EMD, virtual reality design reviews are conducted several times each week that are attended by the engineering and manufacturing departments. The EAI software package is employed to take all the mathematics out of the CATIA and then to display the results on a large screen in three-dimensional format. The virtual reality engine is an SGI Onyx machine, a low-end high performance computer. (Law, 2001)

The actual engineering design is conducted interactively using CATIA on IBM RS/6000 UNIX workstations. The data is stored on central servers, accessible by all the engineers. Not only the aft fuselage but also all other parts of the aircraft are designed using CATIA. Although few paper drawings of the aircraft are needed, those that are can be drawn directly from the CATIA data with no human intervention, thus eliminating a source of error. (Law, 2001)

Manufacturing uses the CATIA data to build the parts. Vendor sub-contractors will be given access in the near future to those portions of the CATIA database relevant to the parts each is building. During the design phase, engineers from the vendor sub-contractors are expected to help with the design in a true Integrated Product Team (IPT) fashion. (Law, 2001)

The CATIA data has made the Comanche manufacturing process much easier than for previous rotary aircraft, especially regarding the engineering drawings:

> It took 38 Sikorsky draftsmen approximately six months to develop working drawings of the CH-53E Super Stallion's outside contours. In contrast, using modeling and simulation one engineer was able to accomplish the same task for the Comanche helicopter in just one month. (Sanders, 1997)

In addition, the process to join the fuselage and tailboom was streamlined and produced a better fit:

> ... for joining the fuselage and tailboom this facilitated a two-step tooling process versus an eight-step process as experienced in the CH-53 program without use of CATIA. It also achieved 95% first time fit versus 35% in previous processes...." (Sanders, 1996)

The Boeing Company recently started using the Product Data Manager (PDM) to store all data about the aircraft. If anything changes, quick fixes can be done to maintenance manuals, instead of redrawing pen-and-ink drawings again. The goal is to have a single source of data for engineering. With PDM, each part has its own folder in which not only the CATIA data can reside but also spread sheets, documents, stress information, etc. Even PC users can use PDM to access the CATIA model of a part by using a low-end viewer that runs on their Windows NT computers. The low-end viewer has the ability to zoom in or out and to rotate the part for viewing just as on the IBM workstations. (Law, 2001)

During PDRR, the CATIA product was not as robust and feature-rich as it is today. The solid modeling aspects are relatively new. Some of the design of the PDRR version of the aft fuselage was too complicated to do in solid models of the CATIA product of that time. Surface modeling of the outside contours was used instead whereby the piece is defined as an infinitely thin sheet of aircraft skin. (Law, 2001)

The design efforts using CATIA are extremely useful; however, the engineers need to know whether the parts can perform the functions for which they were intended under the stresses and strains they will experience. To accomplish this, the CATIA solid and suface models are used by other engineers to create finite element meshes of the design. These meshes are used in various CAE models, including MacNeil-Schwendler Corporation (MSC) NASTRAN, MSC PATRAN, IDEAS, and ANSYS. MSC PATRAN works very well with the CATIA data. The finite element mesh work is done locally on IBM RS/6000 workstations. (Lang, 2001)

To create the finite element meshes, the engineer picks only certain features to model eliminating some of the finer details. A finite mesh is created from the grosser design. The material properties of the components (e.g., whether a piece is steel or graphite) are, also, determined and added. MSC NASTRAN is run on a two-processor HP server. The results of these runs are brought back to the local workstation for viewing. If deformation occurred, then design changes are made, the mesh re-done, and MSC NASTRAN re-run. MSC PATRAN is run on the local workstations. (Lang, 2001)

During PDRR, a Sun system was used for the workstation. In addition, the software packages IDEAS and CAEDS, a predecessor to IDEAS, were run on an IBM mainframe. (Lang, 2001)

Boeing engineers were not the only ones designing the aft fuselage of the Comanche during PDRR. Students at the Naval Postgraduate School (NPS) analyzed potential design modifications to the tail as well. The 1996-version of the Comanche did not meet the Army's requirement for radar signature. One student examined various structural design modifications to determine if the tailcone design could meet both its

structural and radar signature requirements. He discovered that his proposed geometry changes did increase stiffness when using the original materials; however, they decreased stiffness when using radar cross section compliant materials. His design efforts were done using the MSC NASTRAN (Version 69) and MSC PATRAN (Version 6.0) software packages running on a UNIX workstation. The MSC NASTRAN package uses the finite element method with meshes to do the analysis. The MSC PATRAN package serves as a pre- and post-processor for finite element codes such as NASTRAN. It enables the user to view structures from various angles and zoom in for more detail as needed. It, also, can create the finite element meshes needed by the finite element codes. (Tobin, 1997)

Another student continued the work of the first to see if any other modifications would provide the stiffness needed in the tail when using radar-absorbing materials. In addition, he designed and analyzed proposed structural modifications to the horizontal and vertical stabilizers to accommodate Boeing–proposed tail-fold design changes. The best modifications to the tailcone did increase stiffness, especially when applied to the previous NPS modifications. However, the addition of the radar-absorbing material to the modifications decreased stiffness. The decrease was not as great, though, as that seen by just applying the radar-absorbing material to the baseline aircraft. His changes to the horizontal and vertical stabilizers not only increased structural stiffness but also reduced the weight of the tail-fold design. He used the same version of MSC NASTRAN for his analysis; however, he used a newer version (6.2) of MSC PATRAN. (Shoop, 1997) (Shoop, 2001)

4. Ballistic Vulnerability Forecasting

Ballistic vulnerability forecasting for the Comanche is another area that used extensive modeling and simulation efforts. The Boeing Company worked with the Army Research Laboratory to assess the ballistic vulnerability of the Comanche. Six, high explosive rounds were fired at a static test article of the Comanche aft fuselage at Aberdeen Proving Ground, MD during August 1999. The stresses and strains experienced by the test article during the shots were measured and recorded. (Niederer, 2001)

Simulations of the test firings were, also, run on a detailed, finite element model of the aft fuselage using the software package, MSC-DYTRAN. MSC-DYTRAN handles shock well; however the interaction of fluids and structures is still in developmental stages. The Boeing Company received good correlation between the MSC-DYTRAN results and the actual test firings; although in the process, some bugs were found in the MSC-DYTRAN code, which were corrected swiftly by the software company in the release now in use. The Boeing Company runs MSC-DYTRAN on a 650 MHz PC as well as on an HP Unix server and a 32-processor, SGI Origin 2000 high performance computer. MSC-DYTRAN is a very cpu-intensive model requiring run times of 1.5 to 5 days on the SGI Origin 2000 HPC system. (Niederer, 2001)

5. Avionics Software

The avionics software for the Comanche system runs on a mission computer cluster of which there are two per system. Although there are two clusters, they are not redundant. If one cluster goes down, the other takes over the critical duties, but not all the duties, resulting in the system being considered in a degraded mode. The data

processing modules in each mission computer cluster use 133 MHz Pentium processors that were selected four years ago. The avionics software is being developed for these Windows NT Pentium processors. (Sum, 2001)

The Boeing Company developed its own simulations for the avionics software; however, Lockheed Martin provided the target acquisition and radar simulations and TRW provided the communications network simulations. The avionics software group at Boeing uses the following software packages to aid in their efforts: 1) ADA Assure, 2) ADA Cast for unit testing, 3) PV-Wave for flight test data and integration issues data analyses, 4) AONIX for requirements modeling, 5) TEAMWORK for requirements model interfaces, 6) DOORS for requirements traceability, and 7) C-Tool for generating coherent output from the integrated products. These products run on Unix workstations and the HP UNIX server. The PV-Wave product is usually run on an SGI system. They do not run any of these on high performance computers. Higher speed computers do not help their development efforts. Higher speed networks would, since the network has been a bottleneck in their simulations. (Sum, 2001)

6. Lean Manufacturing

The Boeing Company has embraced lean manufacturing as a company and applied it to its efforts in the RAH-66 Comanche program. It uses the product CITIS to provide a secure mailbox with reverse proxy for pick up of the latest information (e.g., models, documentation, etc.) that members of Team Comanche need. The Lean Manufacturing group are change agents for the company. Their job is to provide processes and tools that encourage the behavioral changes to make Lean Manufacturing succeed. (Cramer, Wichmann, 2001)

As part of the Lean Manufacturing effort, the Boeing Company uses virtual reality, virtual prototyping, and virtual environments to achieve results. In the St. Louis office, virtual reality with haptic devices is employed to aid in design efforts. Virtual prototyping is used across the board on all parts. Both high-end and low-end viewing packages are used depending on the context. Translations occur between the modeling tools (e.g., CATIA) and the visualization tools. Virtual environments are employed in the Virtual Design Reviews, which are daily reviews of the current designs. During the Virtual Design Reviews, the latest design is brought up and manipulated by rotating and zooming to ensure that everything fits and makes sense. The software packages used for these reviews include the following, which are run on various computer platforms: 1) CATIA, 2) Unigraphics, and 3) Pro-E. The computers used include those in the $1M, HPC range. (Cramer, Wichmann, 2001)

7. On-board Test and Training Instrumentation System (OTTIS)

The purpose of OTTIS is to exploit both training and testing requirements through a common instrumentation suite. It is the Apache Longbow upgrade for MILES/AGES (Multiple Integrated Laser Engagement System/Air Ground Engagement System). It utilizes a global positioning system (GPS) and a smart modem. Target adjudication exists for both direct and indirect fire. Geometric positioning is used to determine kills. If a kill occurs, a radio message is sent, which activates the virtual kill indicator light. This same system can be used for training purposes for Comanche. This is especially critical, since there is a limited number of aircraft for user tests. The Comanche can use its telemetry antenna as a conduit between the real and virtual world. Two Comanche

Portable Cockpits can be used with terrain databases to run a four-ship mission with two systems in the real world and two in the virtual. (Tobin, 2001)

8. Comanche Portable Cockpit (CPC)

The Comanche Portable Cockpit simulator, which is built by Sikorsky Aircraft Inc., is transported in a customized trailer and includes both cockpits of the RAH-66 Comanche in a side-by-side configuration. These can be operated on or off the trailer. The single, rack-mount SGI computer, which runs the simulator, resides on the trailer as well. It uses an Aviation and Troop Command (ATCOM) model that was used in the Milestone II Analysis of Alternatives (AOA) for the Comanche program. The fidelity is high enough that the CPC can be used as a flight simulator. The fidelity can be lowered so that force-on-force modeling can be done. All tactics, techniques, and procedures for the Comanche have been done with the CPC. Its most important feature, however, is its ability to get pilots ready to fly Comanche before the aircraft is available. (Jane's, 1999), (Tobin, 2001)

B. CATEGORIZATION OF THE EFFORTS

1. Types of Modeling and Simulation

Table 1 summarizes and categorizes the efforts described above into the various modeling and simulation categories described earlier.

Effort	CAD	CAE	CAM	VP	VM	VE
Resin Transfer Molding	X	X		X	X	
"Mockpit"				X		

Aft Fuselage Design	X	X	X	X		
Ballistic Vulnerability Forecasting		X				
Avionics Software				X		
Lean Manufacturing			X	X	X	X
OTTIS						X
CPC						X

Table 1. Categorization of Efforts by Modeling and Simulation Category (Source: Researcher)

Several of the efforts fall into multiple categories due to their comprehensive nature and dependence on the other categories.

2. Use of High Performance Computing

Table 2 categorizes the efforts by their use of high performance computing based either on the interviews or on what could be gleaned from the research articles.

Effort	Use of HPC
Resin Transfer Molding	Yes
"Mockpit"	No
Aft Fuselage Design	Yes

Ballistic Vulnerability Forecasting	Yes
Avionics Software	No
Lean Manufacturing	Yes
OTTIS	No
CPC	No

Table 2. Categorization of Efforts by Use of High Performance Computing (Source: Researcher)

IV. ANALYSIS

A. EFFICACY OF CAD

The Computer Aided Design efforts in the Comanche program are its linchpin. Other modeling and simulation efforts use the CAD data as their basis. The Computer Aided Engineering efforts need the CAD data to create the finite element meshes that are used in the CAE analyses, including: 1) resin transfer molding, 2) aft fuselage design, and 3) ballistic vulnerability forecasting. The Computer Aided Manufacturing efforts use the CAD data for part sizing and fit. This lead to a 95% first-time fit when the fuselage and tailboom of the Comanche were first joined, which was a substantial increase from 35% for previous, non-CAD efforts. Maintenance manuals are readily updated when changes are made because the CAD drawings can be rendered directly into the manuals vice having to be re-drawn by hand.

The CAD efforts, also, drive the virtual prototyping, virtual environments, and virtual manufacturing efforts. In some cases, the extensive details available in the CATIA-based CAD designs are presented in lower fidelity to allow more individuals access to the information on lower-end computing platforms, e.g., desktop PCs. In other cases, the full fidelity is maintained and three-dimensional views and haptic devices are added to increase the realism. In any case, without the accurate CAD data, the other modeling and simulation efforts would suffer.

B. EFFICACY OF CAE

The Computer Aided Engineering efforts associated with the Comanche program are key to the structural integrity of the aircraft design. The stresses and strains on the

aircraft can be duly rendered and impacts of other design changes evaluated for continued integrity. Ballistic vulnerability can be assessed and designs re-done to ameliorate the effects. Components made out of composites can be manufactured without the voids that so often happen. All these make for a better aircraft.

C. EFFICACY OF CAM

Computer Aided Manufacturing owes its success to the ability to get the dimensional data for the components directly from one machine (the computer) to another (the assembly line). The elimination of a human being between the two machines results in a more error-free transit of the information.

D. EFFICACY OF VIRTUAL PROTOTYPING

Virtual Prototyping is providing needed insight into the aircraft design by allowing various individuals the capability to see the designs and verify form, fit and function before any metal is cut or composite molded. In addition, early training simulations, like the "mockpit," can be utilized to test out key flight features. The avionics software can be simulated and its integration with communication network and target acquisition and radar simulations verified. All this can be done without committing to a final design mock-up.

E. EFFICACY OF VIRTUAL MANUFACTURING

Virtual Manufacturing aids the manufacturer to try out the process before committing to the final configuration. This is, especially, true with the resin transfer molding. The use of modeling and simulation to design the location of injection ports in the composite mold so that voids were eliminated has been useful. The gear box assembly was, thus, able to be designed totally out of composites resulting in weight savings. The use of the Product Data Manager (PDM) at Boeing is helping to make the

manufacturing process seamless by providing a ready access point for all data about each part for Team Comanche personnel.

F. EFFICACY OF VIRTUAL ENVIRONMENTS

Virtual Environments have proven especially useful at Boeing in the Virtual Design Reviews. The ability to zoom in and out and rotate the three-dimensional images provides unique insights to the designers, manufacturers, and maintainers. Impacts on other parts or functions can be determined swiftly before the design is set. ATCOM and the CPC provide the Comanche pilots the unique opportunity to test the tactics, techniques, and procedures they will use. It, also, provides the ability for pilots to train in advance of receipt of aircraft.

G. EFFICACY OF HIGH PERFORMANCE COMPUTING

When High Performance Computing was used, it was quite effective. It was used in four of the eight efforts described. Of these, only a few of the modeling and simulation efforts used the multi-processor, high-end, high performance computers. The remainder used the lower-end, HPC systems as visualization servers to display the virtual prototyping, virtual manufacturing and virtual environments information.

THIS PAGE INTENTIONALLY LEFT BLANK

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

This thesis uncovered some of the modeling and simulation efforts supporting the simulation based acquisition effort in the RAH-66 Comanche Program. The RAH-66 Comanche Program is an excellent example of SMART acquisition. The ongoing efforts of Boeing to provide a centralized repository for all data about each part will definitely enhance the SMART process. The answers to the Supplemental Research Questions of this thesis solidify the conclusions.

Supplemental Research Question #1. What types of modeling and simulation efforts (e.g., Computer Aided Design, Computer Aided Engineering, Computer Aided Manufacturing, Virtual Prototyping, Virtual Environments, Virtual Manufacturing) were employed in the RAH-66 Comanche Program? Modeling and simulation efforts in all these areas have been employed on the RAH-66 Comanche Program. Resin transfer molding, "mockpit", aft fuselage design, ballistic vulnerability forecasting, avionics software, lean manufacturing and On-board Test and Training Instrumentaiton System are just some of the efforts uncovered. The Computer Aided Design efforts serve as the linchpin for all the others by providing the dimensional data needed.

Supplemental Research Question #2. Did they employ high performance computing? Yes, four of the eight modeling and simulation efforts employed high performance computing. Surprisingly, most of the high performance computing efforts

employed the low-end HPC system instead of the high-end, multi-processor HPC systems.

Supplemental Research Question #3. How useful and effective were they? All the modeling and simulation efforts have proved useful to the Comanche program. The use of the CATIA CAD package enabled the drawings for the Comanche to be done in a month vice 38 man-months for previous rotary aircraft. These data enabled the manufactured parts to go together with 95% fit on first try vice 35% on previous systems.

Supplemental Research Question #4. Would more or different modeling and simulation efforts with high performance computing have helped? Some of the engineers felt that more modeling with the higher speed computers would have helped, especially, with the CAE efforts in aft fuselage stress dynamics and in balisstics vulnerability. The avionics software, in contrast, would have benefited from higher network speeds.

B. RECOMMENDATIONS

The RAH-66 Comanche Program should not discontinue any of the modeling and simulation efforts ongoing. They should support the efforts involving the Product Data Manager so that a centralized repository of all information about each part on the aircraft is securely and readily available to all Team Comanche Program Integrated Product Team (IPT) members. The Virtual Design Reviews should be encouraged so that all IPT members can quickly determine if a change impacts their function.

The RAH-66 Comanche Program should encourage the use of higher fidelity models that require HPC systems so that designs are optimum. If schedule constraints tighten, HPC capability can be used to speed up the modeling and simulation efforts for some of the lower fidelity models and those that do not normally require HPC.

C. SUMMARY

This thesis endeavored to answer the following Primary Research Question: How effective a role did high performance computing play in simulation based acquisition for the RAH-66 Comanche Program? High Performance Computing played an effective role in the RAH-66 Comanche Program; however, it was just one of the computer platforms used for the modeling and simulation. The computer aided engineering efforts and the virtual prototyping, virtual manufacturing and virtual environments used the HPC systems effectively and the most. Other modeling and simulation efforts employed lower-end systems, which provided the needed utility.

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX. INTERVIEW QUESTIONS AND RESULTS

A. INTERVIEW QUESTIONS AND APPROACH.

The following questions were used in the conduct of the interviews:

1. Was Computer Aided Design (CAD) used?
2. If CAD was used, on which parts was it used?
3. If CAD was used, what computer software packages or programs were used?
4. If CAD was used, what types of computers were used?
5. If CAD was used, were the CAD data shared with all parties involved in the acquisition, (e.g., Comanche PMO, Boeing-Sikorsky, and sub-contractors)?
6. If CAD was used, how useful and effective was it?
7. Was Computer Aided Engineering (CAE) used?
8. If CAE was used, on which parts was it used?
9. If CAE was used, what computer software packages or programs were used?
10. If CAE was used, what types of computers were used?
11. If CAE was used, were the CAE data shared with all parties involved in the acquisition, (e.g., Comanche PMO, Boeing-Sikorsky, and sub-contractors)?
12. If CAE was used, how useful and effective was it?
13. Was Computer Aided Manufacturing (CAM) used?
14. If CAM was used, on which parts was it used?
15. If CAM was used, what computer software packages or programs were used?
16. If CAM was used, what types of computers were used?

17. If CAM was used, were the CAM data shared with all parties involved in the acquisition, (e.g., Comanche PMO, Boeing-Sikorsky, and sub-contractors)?
18. If CAM was used, how useful and effective was it?
19. Was Virtual Prototyping (VP) used?
20. If VP was used, on which parts was it used?
21. If VP was used, what computer software packages or programs were used?
22. If VP was used, what types of computers were used?
23. If VP was used, were the VP data shared with all parties involved in the acquisition, (e.g., Comanche PMO, Boeing-Sikorsky, and sub-contractors)?
24. If VP was used, how useful and effective was it?
25. Were Virtual Environments (VE) used?
26. If VE were used, on which parts/functions was it used?
27. If VE were used, what computer software packages or programs were used?
28. If VE were used, what types of computers were used?
29. If VE were used, were the VE data shared with all parties involved in the acquisition, (e.g., Comanche PMO, Boeing-Sikorsky, and sub-contractors)?
30. If VE were used, how useful and effective were they?
31. Was Virtual Manufacturing (VM) used?
32. If VM was used, on which parts/manufacturing lines was it used?
33. If VM was used, what computer software packages or programs were used?
34. If VM was used, what types of computers were used?
35. If VM was used, were the VM data shared with all parties involved in the acquisition, (e.g., Comanche PMO, Boeing-Sikorsky, and sub-contractors)?

36. If VM was used, how useful and effective was it?

37. How could simulation based acquisition have been done differently in the Comanche Program in PDRR?

38. How was high performance computing used in the Comanche Program?

39. Would more high performance computing have helped?

40. What VV&A tools were used to validate the software employed?

As one can see, the 40 questions are not totally unique. The first 36 questions repeatedly address the same six issues as they apply to the six, modeling and simulation categories. Because of this redundancy, each interviewee did not answer all 40 questions. Instead, he only answered those questions for which he had cognizance.

Each interview began with the interviewee describing his modeling and simulation efforts. As his tale unfolded, many of the answers naturally fell out without the need for specific questioning later. As the interviewee spoke, the author was able to determine into which M&S category his efforts fell. The author verified the correct categorization with the interviewee and asked the specific questions for that category (if not already answered) as well as the last four questions. If an interviewee's efforts or knowledge fell into more than one category, then the questions for the appropriate categories were asked, too. The interviewee may not have responded to all questions asked.

For those efforts gleaned from research material, the author determined the categorization and searched for the answers to her specific questions in the material. The answers may not have been available to all the questions, however. She inferred some answers based on the information provided, e.g., specific mention of running simulation

on SGI O2 workstation, a personal desktop computer, led her to negate the need for high performance computing.

B. INTERVIEW RESULTS

1. Interview with Mr. Dale Shires

Mr. Dale Shires is a Computer Scientist with the US Army Research Laboratory. His M&S effort area is Resin Transfer Molding.

Question	Synopsis of Answer
1	Yes, CAD was used.
2	Keel beam and gear box assemblies
3	Pro-Engineer, CATIA (Computer Aided Three-Dimensional Interactive Application)
4	N/A
5	Yes
6	Pretty effective
7	Yes, CAE was used.
8	Keel beam and gear box assemblies
9	COMPOSE (Composite Manufacturing PrOcess Simulated Environment)
10	Runs on LINUX, UNIX, Windows from desktop computers through HPCs.
11	Yes

12	Very effective when used. Could have done more. People good at doing stress analysis. More aggressive efforts needed with manufacturing.
19	Yes
20	Keel beam and gear box assemblies
21	COMPOSE
22	Runs on LINUX, UNIX, Windows from desktop computers through HPCs.
23	Data shared except for information considered proprietary by vendor. If vendor has a proprietary process, it may not tell surface tension parameters, for example.
24	Useful and effective
31	Yes, can do parametric studies to find optimal solution for automating manufacturing process. Sikorsky had problems with gear box assembly using composites. AATD pointed Sikorsky to ARL for help. Modeling done which enabled gear box to be made totally out of composites, thus decreasing weight and money spent.
32	Keel beam and gear box assemblies
33	COMPOSE
34	Runs on LINUX, UNIX, Windows from desktop computers through HPCs.
35	Yes

36	Useful and effective
37	Hard to integrate it all. Boeing's idea, a web site that is an FTP server in which you can put files for others to read, is a good one. Need an intelligent system to catalog items. Then, when someone makes changes, it automatically checks on load bearing or manufacturability with either an alert to individual or better yet automatically runs the needed analyses. Not going to get there right away -- big task. More could be done, but need global acceptance of Simulation Based Acquisition, because a weak link brings it down. Individuals need to realize what each does can affect lots of others.
38	HPC was used on the keel beam and when true three-dimensional view with thermal data is needed, which quadruples the computing requirement. Using a single cpu HPC system, like an SGI Origin 2000, the 24-ft keel beam results take 1 week; whereas, using 64-128 cpus of same system, results come out in hours. Can, also, use HP workstations and SGI O2 workstations for smaller designs like the gear box.
39	More horsepower would not have helped. The SBA structure is more important.
40	Validated experimentally and numerically. Symmetric circular pattern match is valid for flat panel and box experiments for permeability. Compared videotaped resin molding process from Boeing with computer runs as well.

Table Appendix-1. Synopsis of Interview with Mr. Dale Shires

2. Interview with Mr. Stephen Law

Mr. Stephen Law is an Airframe Design Engineer and Lead for the tailcone for the Boeing Company. His M&S effort area is the aft fuselage.

Question	Synopsis of Answer
1	Yes, CAD was used.
2	Used for all of the aircraft and to create paper drawings that were needed in PDRR
3	CATIA (version 4.2.2) and earlier versions for design in both PDRR and early EMD. Earlier PDRR version not as robust in solid modeling as current version. Surface models of outside contours used with the piece defined as an infitnitely thin sheet of aircraft skin. Product Data Manager (PDM) to store all the data (e.g., CATIA data, spread sheets, documents, stress information), which, when items change, allows a quick fix to maintenance manuals without redrawing, for example. PDM is a more recent addition to software. It includes a low-end viewer, which can zoom in/out and rotate, to see CATIA model of part visualized on Windows NT personal computer. Also, use IMAN and Unigraphics in conjunction with PDM. For Virtual Reality reviews, use EAI software package that takes CATIA data, removes the mathematics, and displays all parts on big screen in 3D.

4	Use IBM RS/6000 UNIX workstations to do design with all data stored on servers. The Virtual Reality reviews use an SGI Onyx, a low-end HPC system.
5	Data is shared; however, direct access to PDM by sub-contractors and Comanche Program Manager is still being developed. Goal is to have web-based access to PDM for these groups. Sub-contractors will be limited to their particular parts; whereas, Program Manager will have access to all the aircraft.
6	Extremely useful and effective, especially given the odd angles in the design to provide stealth capability. These would be very difficult to model otherwise. Three-dimensional CAD extremely helpful.
38	HPC is used in the Virtual Reality reviews of the CAD designs conducted several times per week.
40	Fit of aircraft parts in manufacture.

Table Appendix-2. Synopsis of Interview with Mr. Stephen Law

3. Interview with Mr. Phillip Lang

Mr. Phillip Lang is an Associate Technical Fellow in Dynamics Technology with the Boeing Company. His M&S effort area is the aft fuselage.

Question	Synopsis of Answer
7	Yes, CAE was used.

8	On all parts
9	Currently, use MSC PATRAN, IDEAS, and ANSYS. MSC PATRAN works well with CATIA to create finite element mesh (FEM) of key features that need to be modeled. Use MSC NASTRAN to determine stresses, strains, or deformations that may occur based on the FEM and material properties of the particular parts. If a problem, re-design part and iterate process. In PDRR, used IDEAS and CAEDS (predecessor to IDEAS).
10	Currently, MSC PATRAN, IDEAS and ANSYS are run on an IBM RS/6000 UNIX workstation. MSC NASTRAN is run on a 2-cpu HP server, which is soon to be upgraded to a newer model that will be in the HPC category. During PDRR, used a Sun system and an IBM mainframe.
11	Shared with Sikorsky, Lockheed Martin, and the US Army
12	Very effective and amazing. Great to be able to look at model and get animation. Can explain to others why changes are needed. Could not imagine doing without it.
38	Used for some portions of CAE effort.
39	Would probably have allowed for faster turn-around times.

Table Appendix-3. Synopsis of Interview with Mr. Phillip Lang

4. Interview with Mr. Melvin Niederer

Mr. Melvin Niederer is Lead Engineer for Comanche Airframe Stress at the Boeing Company. His M&S effort area is ballistic vulnerability forecasting.

Question	Synopsis of Answer
8	Yes, CAE was used in ballistics analysis
9	MSC DYTRAN is used for detailed finite element modeling for the blast models, since it does shock very well. Its interactions of fluid and structures is in development. Very cpu-intensive with model needing 1.5 to 5 days on SGI Origin 2000.
10	Runs on 650 Mhz desktop PC, an HP Server and a 32-processor SGI Origin 2000, which is an HPC system.
11	Yes, the data was shared with US Army live-fire testing group, Sikorsky, the rest of Boeing, and the Program Manager.
12	Extremely useful and effective. Extremely powerful tool. Impressive technology. Does good job.
38	Used for some of the CAE ballistics analyses.
39	Yes, it probably would have helped to have higher-speed systems.
40	The software predicted the shock wave at different distances based on the test firings. The six, high explosive (HE) test firings were done at Aberdeen Proving Ground with the US Army Research Laboratory in August 1999 against the aft fuselage. Stresses and strains were measured under load. Getting good correlation between test results and software simulations.

Table Appendix-4. Synopsis of Interview with Mr. Melvin Niederer

5. Interview with Mr. Frank Sum

Mr. Frank Sum is the Avionics Software Manager, RAH-66 comanche Helicopter for the Boeing Company. His M&S effort area is avionics software.

Question	Synopsis of Answer
19	Yes, VP was used and categorizes the avionics software development
20	Used to design the avionics software, which consists of two, mission computer clusters per aircraft. There are multiple modules per cluster. The data processing modules use 133 MHz Pentium cpus selected four years ago.The two clusters are not redundant. If lose one cluster, then in a degraded mode. If lose one module, then fully capable. The avionics software is being developed for and Windows NT Pentium processor. Simulations developed themselves with target acquisition and radar simulation done by Lockheed Martin and communication network simulation done by TRW. Simulate operating system running on an NT box by using HP server. In PDRR used a VAX to simulate an Intel i960.
21	Use ADA Assure, ADA Cast for unit test, PV-Wave for flight test data analysis and integration issues data analysis (runs on SGI), AONIX to model requirements, TEAMWORK to model requirements model interfaces, DOORS for requirements traceability, and C-Tool to integrate product to generate coherent output.
22	HP server and SGI workstation. In PDRR, a VAX.

23	Yes, but mostly get data coming in for this area from the other vendors, not much going out.
24	Useful and effective
38	No
39	No, higher speed computer would not help. Need higher speed networks. Network is bottleneck – not the cpu.

Table Appendix-5. Synopsis of Interview with Mr. Frank Sum

6. Interview with Mr. Bruce Cramer and Mr. G. Randall Wichmann

Mr. Bruce Cramer is the Manager-Lean Enterprise and Mr. G. Randall Wichmann is the Manager-Information Systems Architecture for the Boeing Company. Their M&S effort area is lean manufacturing.

Question	Synopsis of Answer
19	Yes
20	Used across-the-board on all parts.
21	Use high-end and low-end viewing packages that provide translation between modeling tools (i.e., CATIA) and the visualization tools. Also, use PDM for workflow. CITIS provides a secure mailbox with reverse proxy for pick-up of latest information from IPT.
22	Use $1M UNIX computer (i.e., equates to an HPC system)
23	Data is shared with other Boeing sites and other vendors.

24	Very effective. Do not have any quantitative values, though.
25	Yes, VE were used.
26	Used in all parts.
27	Use CATIA, Unigraphics, Pro-E, and PDM. In daily Virtual Design Reviews, which started in September 2000, designs can be manipulated through rotation or zooming. Haptic devices used in St. Louis location and are anticipated for Philadelphia location this year.
28	Various systems including $1M UNIX computer (i.e., equates to an HPC system)
29	Yes
30	Very effective. Virtual Design Reviews are very important and a cultural change. The Lean group members are change agents. Collocation is critical. Job to provide tools and processes to encourage behavioral change.
31	Yes, VM is used.
32	Used on all parts.
33	CATIA, Unigraphics, Pro-E, and PDM. Continually investigating best way. Try to use COTS (Commercial-off-the-shelf), but will modify if needed. Try to minimize COTS enhancements so that can go to other vendors in future. Trying to create a framework to help with integration. Software decisions are sometimes made at a high corporate level.

34	Various systems including $1M UNIX computer (i.e., equates to an HPC system). In stress area, trying to improve MSC PATRAN and MSC NASTRAN servers to improve cycle time.
35	Yes. Getting customers and supplier in the loop sooner.
36	Want to be able to do faster, better, cheaper. VM helps with that.
37	Need to get today's tools yesterday. The earlier an implementation, the easier the implementation. If had more money to invest in process and tools, could have done sooner.
38	Used for some portions of VP, VE, and VM
39	In stress area, having HPC systems would help improve the cycle time for MSC PATRAN and MSC NASTRAN simulations.
40	Validation done via dimensions.

Table Appendix-6. Synopsis of Interview with Messrs. Cramer and Wichmann

7. Interview with MAJ Vincent Tobin

MAJ Vincent Tobin is the Assistant Program Manager for Test and Evaluation in the RAH-66 Program Manager Office. His M&S effort area is On-board Test and Training Instrumentation System (OTTIS) and Comanche Portable Cockpit.

Question	Synopsis of Answer
25	Yes, get a training opportunity out of test instrumentation.

26	Comanche Portable Cockpit (CPC), which is a tractor trailer that houses all computers and the cockpits for Comanche.
27	Uses ATCOM model that was used for Analysis of Alternatives. It has a high enough resolution for flight simulation, but can reduce fidelity to allow force-on-force simulations. Creating a replacement for MILES using a GPS and smart modem. It allows for target adjudication for direct or indirect fire and uses geometric positioning to determine kills. If a kill, send radio message to toun on the flash vest. Will use telemetry antenna as a conduit between real world and virtual world. Can use two CPCs with a terrain database to run a four-ship mission – two real and two virtual. InterCoastal Electronics, a sub-contractor to Boeing, will produce the product.
28	Single, rack-mount SGI computer
29	Yes
30	Very effective in getting pilots ready to fly before aircraft available to them. All tactics, techniques, and procedures are done with the CPC.

Table Appendix-7. Synopsis of Interview with MAJ Vincent Tobin

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF REFERENCES

Baker, Athanasia D., "High-octane computers spark scientific models, simulations," *National Defense*, Arlington, November 2000.

Boeing (A Comparative Study)," *Acquisition Review Quarterly*, Summer 1995.

The Boeing Company, [http://www.boeing.com/rotorcraft/military/rah66/], 2001.

Boeing-Sikorsky Joint Site, [http://www.rah66comanche.com/], 2001.

Bury, Scott, "More than just pretty pictures," *Advanced Manufacturing Magazine*, [http://www.advancedmanufacturing.com/November00/prototyping.htm], 1 November 2000.

Chase, Deborah J., Copeland, Robert R., Ferrell, Ronald J., "Comanche Crew Station Development," *Program Manager*, pp. 58-60, September-October 2000.

Defense Acquisition Deskbook, [http://web2.deskbook.osd.mil/], 2001.

Department of Defense, DoDD 5000.1: The Defense Acquisition System; (incorporating Change 1, January 4, 2001); 23 October 2000

Department of Defense, DoDD 5000.59-M:DoD M&S Glossary, 1997.

Department of Defense High Performance Computing Modernization Program, *FY 2000 Requirements Report*, January 2001.

Electronic mail between MAJ Brian Shoop, RAH-66 Comanche Program, and the author, 11 May 2001.

Feinberg, Jerry, "The Commercial Corner – Commercial Technologies for Modeling and Simulation," *MSIAC's (Modeling and Simulation Information Analysis Center) M&S Journal Online*, Fall 2000 Issue, Volume 2, Issue No. 1, [http://www.msiac.dmso.mil/journal/corner21.html/], Fall 2000.

Galindo, Jason L., *A Case History of the United States Army RAH-66 Comanche Helicopter*, Master's Thesis Naval Postgraduate School, Monterey, California, March 2000.

Interview between Stephen Law, Airframe Design Engineer and Lead for Comanche Tailcone, The Boeing Company, Philadelphia, PA, and the author, 8 February 2001.

Interview between Phillip Lang, Associate Technical Fellow in Dynamics Technology, The Boeing Company, Philadelphia, PA, and the author, 8 February 2001.

Interview between Melvin M. Niederer, Lead Engineer for Comanche Airframe Stress, The Boeing Company, Philadelphia, PA, and the author, 8 February 2001.

Interview between Frank Sum, Avionics Software Manager, RAH-66 Comanche Helicopter, The Boeing Company, Philadelphia, PA, and the author, 8 February 2001.

Interview between Bruce A. Cramer, Manager – Lean Enterprise, and G. Randall Wichmann, Manager – Information Systems Architecture, The Boeing Company, Philadelphia, PA, and the author, 8 February 2001.

Interview between Dale Shires, Computer Scientist, US Army Research Laboratory, and the author, 30 March 2001.

Jane's Online, "Sikorsky Comanche Portable Cockpit (CPC) simulator," Flight Simulators and Flight Training Devices, United States of America, *Jane's Simulation and Training Systems 1999-2000,* [http://fore.thomson.com/janes/], 08 December 1999.

Johnson, Sr., Michael V.R., McKeon, Mark F., and Szanto, Terence R., "Simulation Based Acquisition: A New Approach," *Report of the Military Research Fellows, DSMC 1997-1998*, Defense Systems Management College, December 1998.

Kern, LTG Paul J., "A SMART Future for Army Aviation" briefing, June 14, 1999.

Lanceford, Dell, "SMART Overview," briefing, [http://www.amsmo.mil/smart/briefs/apm-vt.ppt], February 2000.

Lavine, Michael, "Simulation Based Acquisition (SBA) A DoD and Service Perspective," briefing to ITEA Modeling and Simulation Workshop *Putting Modeling and Simulation to Work*, 6 December 2000.

Mark, A., Mohan, R.V., and Tamma, KK., "Integrated Modeling Technology for Process Simulation and Manufacture of Large Composite Structures," Army High Performance Computing Research Center, [http://www.ahpcrc.org/Com_Mec/], 1999.

Mohan, R.V., Shires, D. R., Mark, A., Tamma, K.K., and Ngo, N.D., "Manufacturing Process Flow Modeling of Large-Scale Complex Composite Army Structures: Computational Techniques and Applications," paper presented at Army Science Conference, 1998.

Moye, William T. "ENIAC: The Army-Sponsored Revolution," [http://ftp.arl.mil/~mike/comphist/96summary/], January 1996.

Naval Postgraduate School, *MN3384 Acquisition Production and Quality Management,* adapted from Defense Acquisition University *PQM 201,* Volume 3, pp. P-11, P-13, P-24, April 1997.

RAH-66 Comanche Program Manager, "RAH-66 Comanche Simulation Support Plan, September 1999.

Sanders, Patricia, "Simulation Based Acquisition – An Effective, Affordable Mechanism for Fielding Complex Technologies," *Program Manager*, pp. 72-77, September-October 1997.

Sanders, Patricia, "Study on the Effectiveness of Modeling and Simulation in the Weapon System Acquisition Process: Final Report," October 1996.

Shires, D., Mohan, R., Mark, A., "A Study of Parallel Software Development with HPF and MPI for Composite Process Modeling Simulations," paper presented at the Department of Defense High Performance Computing User Group Conference, June 2000.

Simulation Based Design Center (SBDC), *SBDC Primer on Virtual Prototyping*, [http://www.gcrmtc.org/sbdc/Services/VP/vp.html], April 2000.

Shoop, Brian P. *Structural Design Analysis of the Tail Landing Gear Bay and the Vertical/Horizontal Stabilizers of the RAH-66 Comanche Helicopter*, Master's Thesis, Naval Postraduate School, Monterey, California, September 1997.

Sikorsky, [http://www.sikorsky.com/programs/comanche/], 2001.

Telephone conversation between MAJ Vincent Tobin, Assistant Project Manager for Test and Evaluation, RAH-66 Comanche Program, and the author, 23 February 2001.

Tobin, Vincent M., *Analysis of Potential Structural Design Modifications for the Tail Section of the Rah-66 Comanche Helicopter*, Master's Thesis, Naval Postgraduate School, Monterey, California, June 1997.

THIS PAGE INTENTIONALLY LEFT BLANK

BIBLIOGRAPHY

Battershell, A. Lee, "Technology Approach: DoD Versus Boeing (A Comparative Study)," *Acquisition Review Quarterly*, Summer 1995.

Brown, C. David, Grant, Gordon, Kotchman, Donald, Reyenga, Robert, Szanto, Terence, "Building a Business Case for Modeling and Simulation," *Acquisition Review Quarterly*, Fall 2000.

Brown, David P., "Simulation Based Acquisition – Can It Live Up to Its Promises?" *Program Manager*, January-February 1999.

Delano, Kenneth J., "Identifying Factors that Contribute to Program Success," *Acquisition Review Quarterly*, Winter 1998.

Dobbins, James H., and Donnelly, Richard G., "Summary Research Report on Critical Success Factors in Federal Government Program Management," *Acquisition Review Quarterly*, Winter 1998.

Kennedy, Betty Raab, "Historical Realities of C-17 Program Pose Challenge for Future Acquisitions," *Program Manger*, November-December 1999.

Malishenko, Timothy, "C-17 Program – From the Brink of Cancellation to Baldrige National Quality Award Winner," *Program Manager*, May-June 1999.

Nissen, Mark E., Snider, Keith F., and Lamm, David V., "Managing Radical Change in Acquisition," *Acquisition Review Quarterly*, Spring 1998

O'Bryon, James F., "Meet 'Master' – Modeling & Simulation Test & Evaluation Reform," *Program Manager*, March-April 1999.

Pugh, Kari, Johnson, Collie, "Building a Simulation World to Match the Real World," *Program Manager,* January-February 1999.

RAH-66 Comanche Program Management Office, [http://www.comanche.redstone.army.mil/], 2001.

Scaachi, Walt, and Boehm, Barry, "Virtual System Acquisition: Approach and Transitions," *Acquisition Review Quarterly*, Spring 1998.

THIS PAGE INTENTIONALLY LEFT BLANK

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center 2
   8725 John J. Kingman Road, Suite 0944
   Ft. Belvoir, VA 22060-6218

2. Dudley Knox Library 2
   Naval Postgraduate School
   411 Dyer Road
   Monterey, CA 93943-5101

3. LTC Thomas W. Crouch (Code GSBPP/ct) 1
   Graduate School of Business and Public Policy
   Naval Postgraduate School
   Monterey, CA 93943-5103

4. Dr. Andrew Mark 1
   Director, US Army Research Laboratory
   ATTN: AMSRL-CI-HC
   Aberdeen Proving Ground, MD 21005-5067

5. Professor David V. Lamm (Code GSBPP/Lt) 4
   Graduate School of Business and Public Policy
   Naval Postgraduate School
   Monterey, CA 93943-5103

6. Acquisition Career Management Office (ACMO) 1
   ATTN: SAAL-ZAC
   Assistant Secretary of the Army (Acquisition, Logistics & Technology)
   2511 Jefferson Davis Highway, 10th Floor
   Arlington, VA 22202-3911

7. MAJ Brian Shoop 1
   Program Executive Office-Aviation (PEO-AVN)
   Comanche Program Management Office (PMO)
   ATTN: SFAE-AV-RAH
   Building 5681
   Redstone Arsenal, AL 35898

8. Dr. Larry Davis 1
   Deputy Director, DoD High Performance Computing Modernization Office
   1010 N. Glebe Road, Suite 510
   Arlington, VA 22201

9. Ms. Denice P. Brown 1
Director, US Army Research Laboratory
ATTN: AMSRL-CI-HS
Aberdeen Proving Ground, MD 21005-5067