AN APPLICATION OF THE SYSTEMS ENGINEERING PROCESS TO THE EVALUATION AND SELECTION OF AN ARCHITECTURAL COMPUTER AIDED DESIGN SYSTEM

by

Kristen S. Rindin

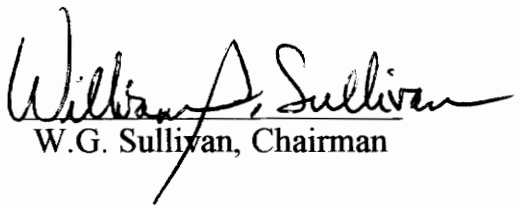
Project and report submitted to the faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

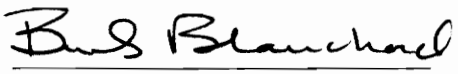
in

Systems Engineering

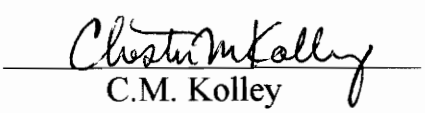
APPROVED:



W.G. Sullivan, Chairman



B.S. Blanchard



C.M. Kolley

2 December 1993

Blacksburg, Virginia

C.2

LD
5655
V851
1993
R563
c. 2

AN APPLICATION OF THE SYSTEMS ENGINEERING PROCESS TO THE EVALUATION AND SELECTION OF AN ARCHITECTURAL COMPUTER AIDED DESIGN SYSTEM

by

Kristen S. Rindin

Committee Chairman: Professor William G. Sullivan

(ABSTRACT)

The Systems Engineering Process has been applied to the evaluation and selection of a Computer Aided Design system for AER Architects to automate the design and drafting process, establish computer-based compatibility with contractors and vendors, and improve productivity.

A needs analysis establishes the architecture firm's desire to produce higher quality drawings in a reduced time schedule. Detailed functional, operational, and maintenance requirements are developed through interactive meetings with the Principal Architect, and a set of desired advanced software capabilities is identified. Alternative CAD software packages are compared, and two packages are selected for further evaluation. A brief discussion of decision making models is included, with justification for the utilization of the Analytic Hierarchy Process model. The two CAD software packages are evaluated against the objective and subjective attributes defined by the Principal Architect through the use of Automan, a software package developed by Stephen F. Weber of the National Institute of Standards and Technology.

ACKNOWLEDGMENTS

I wish to acknowledge the valuable assistance of my committee chairman, Professor William G. Sullivan, in completing this project. His knowledge of the systems engineering process kept me on track. I'd also like to acknowledge the persistent guidance of committee member Chet Kolley. Chet spent a significant amount of his personal time reviewing each revision for continuity and clarity, which helped produce a quality report. Dean Blanchard should be recognized for his valuable assistance during my graduate student career for the last three years, as well as on this project. I am deeply indebted to the Principal Architect of AER Architects for assisting me with all phases of this project during the last four months.

Finally, special recognition goes to Jeffrey A. Rindin, my patient husband, who has weathered the last three years of classes two nights a week and the significant stress level introduced by the challenges of this Masters Degree Program. I am thankful for the assistance Jeff provided on this project, and for his support during the last two months.

Table of Contents

Section	Title	Page
	Abstract	ii
	Acknowledgments	iii
	List of Figures	vii
	List of Tables	viii
1	**Introduction**	**1**
1.1	Background Information	1
1.2	Project Objectives	4
1.3	Definition of Need	6
1.4	Feasibility Study	9
2	**The Systems Engineering Process**	**13**
2.1	Introduction	13
2.2	Conceptual Design Phase	14
2.3	Preliminary Design Phase	17
2.4	Detail Design Phase	20
2.5	Summary	22
3	**Development of System Requirements**	**22**
3.1	Requirements Definition Process	23
3.1.1	Requirements Collection Process	23
3.2	Operational Concept and Requirements	26
3.2.1	Operational Use Requirements	28
3.2.2	Operational Requirements Flow Diagrams	30

Table of Contents, continued

Section	Title	Page
3.3	Maintenance Concept and Requirements	34
3.3.1	Maintainability of CAD Software	41
3.4	Functional Analysis and Requirements	42
3.4.1	Description of Required CAD Software Capabilities	50
3.4.2	Compatibility Functional Requirements	51
3.4.3	Operational Life Cycle of the CAD Software	53
3.4.4	Effectiveness Factors	53
3.5	Definition of System Support Requirements	54
3.5.1	Training Requirements	54
3.5.2	Vendor Requirements	55
3.6	Summary and Allocation of Requirements	57
4	**Analysis and Evaluation of Alternatives**	**60**
4.1	Discussion of the Multiattribute Decision Analysis	60
4.1.1	Sequential Elimination Methods	62
4.1.2	Graphical Techniques	63
4.1.3	Weighted Evaluation of Alternatives	65
4.2	Application of Multiattribute Decision Analysis	67
4.3	Life Cycle Cost Analysis of Preferred Alternatives	71
4.3.1	Assumptions	72
4.3.2	Equivalent Worth Calculations for Alternatives	73
4.3.3	Results of Equivalent Economic Worth Calculations	81

Table of Contents, continued

Section	Title	Page
4.4	Description of Analytic Hierarchy Process	82
4.5	Application of Analytic Hierarchy Process	85
4.6	Results of Analytic Hierarchy Process	86
5	**Future Study Recommendations**	**87**
5.1	Hardware Study and Evaluation	87
5.1.1	Hardware Operating Environment	89
5.1.2	Benchmark Hardware System	89
5.1.3	Hardware Life Cycle Cost Analysis	92
5.2	Networking	93
5.3	Productivity Measurement	94
6	**Conclusions**	**95**
6.1	Summary of the Application of the System Engineering	95
Appendix A	Summary of Software Packages Reviewed	97
Appendix B	Summary of Automan Computer Output	109
Appendix C	Automan Sensitivity Analysis	118
	Footnotes	140
	References	142
	Vita	144

List of Figures

Figure	Title	Page
1	CAD System Conceptual Design Phase	16
2	CAD System Preliminary Design Phase	19
3	CAD System Detail Design Phase	21
4	Weekly System Usage Scenario	29
5	Operational Functional Flow Diagram	31
6	Operational Functional Flow Diagram, cont.	32
7	Operational Functional Flow Diagram, cont.	33
8	Top Level Maintenance Functional Flow Diagram	37
9	First Level Maintenance Functional Flow Diagram	38
10	First Level Maintenance Functional Flow Diagram, cont.	39
11	CAD System Maintenance Policies	40
12	Top Level Requirements Functional Flow Diagram	44
13	First Level Requirements Functional Flow Diagram	45
14	Second Level Requirements Functional Flow Diagram	46
15	Second Level Requirements Functional Flow Diagram, cont.	47
16	Second Level Requirements Functional Flow Diagram, cont.	48
17	Second Level Requirements Functional Flow Diagram, cont.	49
18	Graphical Evaluation Technique	64
19	Schematic Model of Alternative 1 Costs	76
20	Schematic Model of Alternative 2 Costs	79
21	Analytic Hierarchy Process Model	84
22	Proposed System Hardware Configuration	88

List of Tables

Table	Title	Page
1	Survey of Architecture Firm Results	10
2	Summary and Allocation of Requirements	58-9
3	Attribute Score Scale for Alternatives	69
4	Summary of Alternative Evaluations	70
5	Summary of Cost Data for Alternative 1	75
6	Summary of Cost Data for Alternative 2	78
7	Summary of Equivalent Economic Worth Calculations	81

CHAPTER ONE

INTRODUCTION

1.1 Background Information

The computer aided design (CAD) field has expanded exponentially with affordable and powerful software packages in the past five years. Architecture firms wishing to adopt computer aided design tools and techniques must do so carefully, only after establishing a budget, identifying and reaffirming their goals and objectives, defining their requirements and thoroughly analyzing the alternatives. While the number of CAD software packages designed for architectural applications continues to skyrocket, firms are finding that they do not have the resources or time to perform a complete analysis of the software and hardware comprising the computer aided design systems on the market. In general, architects do not possess the computer hardware or software knowledge and are unable to distinguish between product capabilities to select a CAD system. (1) The systems engineering process is a valuable methodology to employ in this situation to assist architecture firms in making an educated decision regarding which CAD system will best satisfy their needs.

An example of this dilemma facing many architecture firms forms the basis for this project. AER Architects, a small architecture firm in Alexandria, Virginia, has requested a systems engineering analysis to evaluate several computer aided design software packages. The Principal

Architect of AER is aware of the difficulties of venturing into an unknown market, and has expressed a wariness of over-zealous salespersons and vendors wishing to profit from his lack of computer knowledge. This past year was profitable for AER, and the Chief Financial Officer has budgeted $ 8,000 for the procurement of the CAD hardware and software required to establish a CAD system at the request of the principal architect. The budget is allocated for the purchase, installation, and training on the operation of the complete CAD system.

Many articles printed in architecture trade magazines have documented measurable productivity gains made by firms adopting the computer aided design tools. In the September 1993 issue of Architectural Record, the article "ADD Inc. Opts for No CAD Operators" describes how the firm has eliminated the CAD operators to allow the architects to create their own drawings. ADD Inc. has experienced improvements in the quality of their drawings and in the time required to create the drawings by removing the middleman, both of which are measurable forms of productivity improvement by the firm. They have also significantly improved their ability to create "extraordinary marketing presentations" leading to an increase in the new business generated and a greater output of designs by the firm. (2)

Measuring the exact amount of productivity improvement is a time intensive task. A CAD Productivity Study performed by Hampton R. Liggett and Steven R. Foster in 1986 at The University of Tennessee's

Center for Computer Integrated Engineering and Manufacturing documents two procedures developed to measure productivity improvement ratios. (3) These procedures can be implemented during the selection of CAD systems or after a system has been purchased and installed. Both procedures require keeping accurate records of the time used to perform design tasks using manual design and drafting techniques prior to the installation of the CAD system, as well as efforts using the CAD system after its installation. Unfortunately, AER Architects has not maintained accurate records of the time spent creating and editing recent architectural projects. The measurement and evaluation of the productivity improvements are not made in this paper due to the lack of required data. The assumption is made in this paper that AER Architects will realize a significant productivity gain if suitable training on the system is provided following its installation. Liggett and Foster state in their study that "the amount of training provided to CAD personnel will often be the difference between marginally successful users and an exceptionally productive, highly motivated CAD team." (4) In addition, interviews with architecture firms that have adopted CAD tools during the last two years indicate that the firms have shown great improvement in productivity when measured by the number of projects produced per time period and the time required per project. (5)

1.2 Project Objective

This report summarizes the activities required to assist an architecture firm in automating its design and drafting process. Incorporating automation into other small architecture firms has resulted in a significant improvement in the productivity of the architects, as estimated by the architecture project managers. (6) The CAD system will enhance the principal architect's ability to complete multiple drawings in the time it used to require to complete a single drawing. In addition, the editing process will be shortened by providing the architect with the capability to quickly manipulate the drawing in softcopy and print out a modified drawing.

The objective of this project is to apply the systems engineering process as described by Blanchard and Fabrycky in their book, Systems Engineering and Analysis, to the evaluation and selection of a computer aided design software package based on the automation requirements of an architecture firm. (7) The paper presents a needs analysis in Chapter One that establishes the architecture firm's desire to implement a cost effective CAD system to reduce the cycle time of producing quality designs and drawings. The paper then applies the systems engineering process to the system design in Chapter Two. An approach is described for completing the design phases of the engineering process, including the Conceptual Design, Preliminary Design, and the Detail Design Phases.

This report addresses the Conceptual and Preliminary Design Phases of the CAD hardware and software life cycle analysis. The analysis establishes the CAD system's conceptual design in Chapter Three by developing the system's functional and operational requirements, conducting a functional analysis, and deriving the system's configuration using preliminary design information obtained from a variety of vendors. The paper then presents a description and application of the Analytic Hierarchy Process decision making model to evaluate the alternative software packages that satisfy the CAD requirements of AER Architects as described in Chapter Four. A life cycle cost analysis is also conducted and used in the decision making model as an evaluation attribute. In Chapter Five, the paper then concludes with a summary of topics recommended for future study that fall outside the scope of this project. An analysis of the success of applying the systems engineering process to the topic of selecting a CAD system for an architecture firm is presented in the conclusion in Chapter Six.

1.3 Definition of Need

The Principal Architect of AER Architects is currently performing all architectural design work using manual design techniques. Proposed designs are drafted by the architect, a task that requires many hours of tedious labor and reduces available design hours. Quality sketches to demonstrate conceptual designs for proposals result in significant cost to AER in terms of available time. Creating a typical concept drawing of a single family house requires nearly 16 hours of manual drafting, which results in only 2.5 concept drawings per week. A CAD System would greatly increase the speed with which the drawings are produced, resulting in a predicted rate of over 5 concept drawings per week. Repetitive and standard features such as windows and doors are common to nearly all designs, yet they must be laboriously re-drawn by hand on each new design. A CAD System would allow the architect to quickly insert common features using symbol buttons, resulting in a time savings of 8 hours per week. Uniformity of lettering and architectural symbols are difficult to maintain using manual drafting. These items demonstrate the quality of drawings the architecture firm produces, and studies have shown that higher quality drawings result in increased business. This is a key concern to a small firm owner. Finally, the editing of projects to meet customer change requests is often time consuming and repetitive. A CAD system will shorten the "turn-around" time from 8 hours to only 1 hour on the typical single family house design. Many computer aided design software

packages provide these basic capabilities to the architects using the software.

The Principal Architect of AER Architects has also seen some demonstrations of the advanced capabilities of CAD systems, and is interested in acquiring a fast system that will improve the firm's ability to quickly create presentation quality drawings in 3D with a minimum of required software add-on packages. In addition, AER Architects has heard that CAD systems have a proven potential based on previous experience by other architects to greatly improve productivity. AER Architects believes that acquiring a CAD system will help maximize profitability and ultimately make AER Architects a stronger firm.

AER Architects has recently felt increasing pressure from the multiple clients, vendors, contractors and collaborating firms it works with on a daily basis to become compatible via the computer. Compatibility via the computer can be achieved through the CAD software package's ability to read and write common file formats that are used by most firms, clients, and vendors. Pressure from these organizations has led AER Architects to consider purchasing a computer aided design system to foster improved compatibility. Compatibility will result in an estimated 20 % increase in business, based on the output potential of skilled architects using a powerful CAD System.

The factors listed above, coupled with the desire of AER to move into the 1990's computer aided design (CAD) arena, comprise the definition of need that has launched this project.

1.4 Feasibility Study

Following the definition of need, a survey of architecture firms and a market study was completed to determine the feasibility of automating an architecture firm's design and drafting capabilities to improve productivity. The initial survey based on a random selection of 15 firms found that 60 % of the small to midsize architecture firms have automated capabilities with varying degrees of sophistication. Interviews with nine (9) small to midsize architecture firms using CAD systems revealed an industry that was quickly becoming reliant on the technology and the functionality it provides. The firms are all located in the Washington, D.C. area, and employ anywhere from one (1) to twenty-seven (27) architects. The average number of architects employed by the nine firms using automated CAD systems was eight (8). Many of the firms had obtained CAD systems during the last three years, with the exception of one firm, ADD Incorporated, the employer of twenty-seven (27) architects, that began using CAD in 1988. A table of the architecture firm survey results is located in Table 1. The products used by some of the firms are included in the list of alternatives evaluated through the systems engineering analysis in Chapter Four.

TABLE 1. RESULTS OF ARCHITECTURE FIRM SURVEY

Architecture Firm	Number of Architects	CAD Capable?	Since Date	Which Software?	Which Hardware?
Kohler and Associates	4	Yes	May '93	DataCAD	PC Clone
Hickock and Warner	6	Yes	July '93	AutoCAD	PC Clone
ADD, Incorporated	27	Yes	1988	AutoCAD	Macintosh
Architectural Design Team	12	Yes	Dec. '91	Microstation	PC Clone
BDR Architects	4	Yes	May '91	AutoCAD	PC Clone
Cole & Lenny, Incorporated	2	Yes	Aug. '92	VersaCAD	PC Clone
Nora Design	4	Yes	Nov. '90	Microstation	PC Clone
Sasaki Associates Architects	5	Yes	Jan. '91	AutoCAD	PC Clone
Metcalf Torey & Partners	9	Yes	Sept. '92	Microstation	PC Clone
SLM Group	6	No			
Stephen B. Smith	1	No			
Harry J. Graef	1	No			
The Tucson Group	4	No			
Laurel Consortium	2	No			
Elliott Architects	3	No			

Additional software products were reviewed to determine if they should be included in the evaluation of alternatives during a market study. The market study was conducted to assess if any commercial off-the-shelf (COTS) products (not identified by the architecture firms during the user survey) existed to satisfy the computer aided design requirement. Appendix A shows the list of Architectural CAD packages that were selected for the initial evaluation, and includes the manufacturer data. The market study resulted in a plethora of ten (10) design packages. The initial evaluation served a valuable purpose by significantly reducing the field to a more manageable number of software products. Two software packages met the criteria and requirements identified in Chapter Three, which will be further described and evaluated in Chapter Four.

A minimal amount of deliberation was given to the build or buy decision. Past experience with complex graphical user interface software development efforts has proven to be valuable in understanding the labor hours required to complete such a task. Hence, custom development of an architectural design package was not considered as an viable option for this project due to the overwhelming procurement cost and schedule, as well as significant operational costs required for maintenance. Estimates for a simple graphical package (primitive compared to the CAD software meeting AER Architect's requirements) and its development effort have been well over $ 100,000.

After evaluating the definition of need and the results of the feasibility study, it is believed that the goal of providing a commercial off-the-shelf computer aided design system for an architecture firm is very realistic.

CHAPTER TWO

THE SYSTEMS ENGINEERING PROCESS

2.1 Introduction

The systems engineering process provides a logical approach to evaluate the options available to an architecture firm wishing to automate its design and drafting capabilities. The process coordinates engineering activities that start after establishing the need for the system and identifying system functional and operational requirements to satisfy the need. The systems engineering process uses analytical techniques to establish and continually evaluate the system's design, operation, and maintenance throughout its life-cycle. The activities conducted as part of the systems engineering process correspond to life-cycle activities such as the Conceptual Design, Preliminary Design, Detail Design, Construction, Operation, and Retirement Phases as described by Blanchard and Fabrycky (8).

This chapter outlines the design and development activities that apply to defining and evaluating the alternatives for automating AER Architects' designing techniques, including the Conceptual Design, Preliminary Design, and Detail Design Phases. The results of these activities are documented within Chapters Three and Four.

2.2 Conceptual Design Phase

The needs analysis established AER Architects' desire to improve the drafting capability of the Principal Architect by automating the design and drafting process. The analysis identified a CAD System as the method of choice for automation. Figure 1 summarizes the activities associated with the Conceptual Design Phase.

The Conceptual Design Phase starts by reviewing current trends of computer aided design in the architecture field and collecting related information. The analysis determines the availability of computer aided design software packages designed specifically for architecture firms to help the architects improve the quality and quantity of designs they produce. Analysis of the trends in the architectural drafting industry and interviews with architects and vendors revealed information on the capabilities of the CAD software packages. Additional studies were completed to assess the availability of small personal computer systems that could be purchased in a single system configuration and would run CAD software. Large scale workstations and operating systems were not considered because they were cost prohibitive, with several workstations priced in the $ 50,000 range.

Multiple meetings with the Principal Architect of AER Architects were held to elicit and capture the preferences and requirements for the CAD hardware and software system. Quality Functional Deployment

(QFD), an inter functional design approach developed in 1972 was implemented in a modified format to ensure that the customer requirements and preferences are considered during the design process. The modified QFD approach used during the Conceptual Design Phase is described in more detail in Section 3.1.1, the Requirements Collection Process. The systems engineering process uses the information obtained from this research to develop the operational requirements and a maintenance concept for both the computer hardware and the CAD software package. The requirements provide the foundation for performing a functional analysis and evaluation of alternatives. Following the Conceptual Design Phase, the design of the CAD system moves into the Preliminary Design Phase of the life-cycle analysis.

The detailed description of the application of the Conceptual Design Phase is contained within Chapter Three.

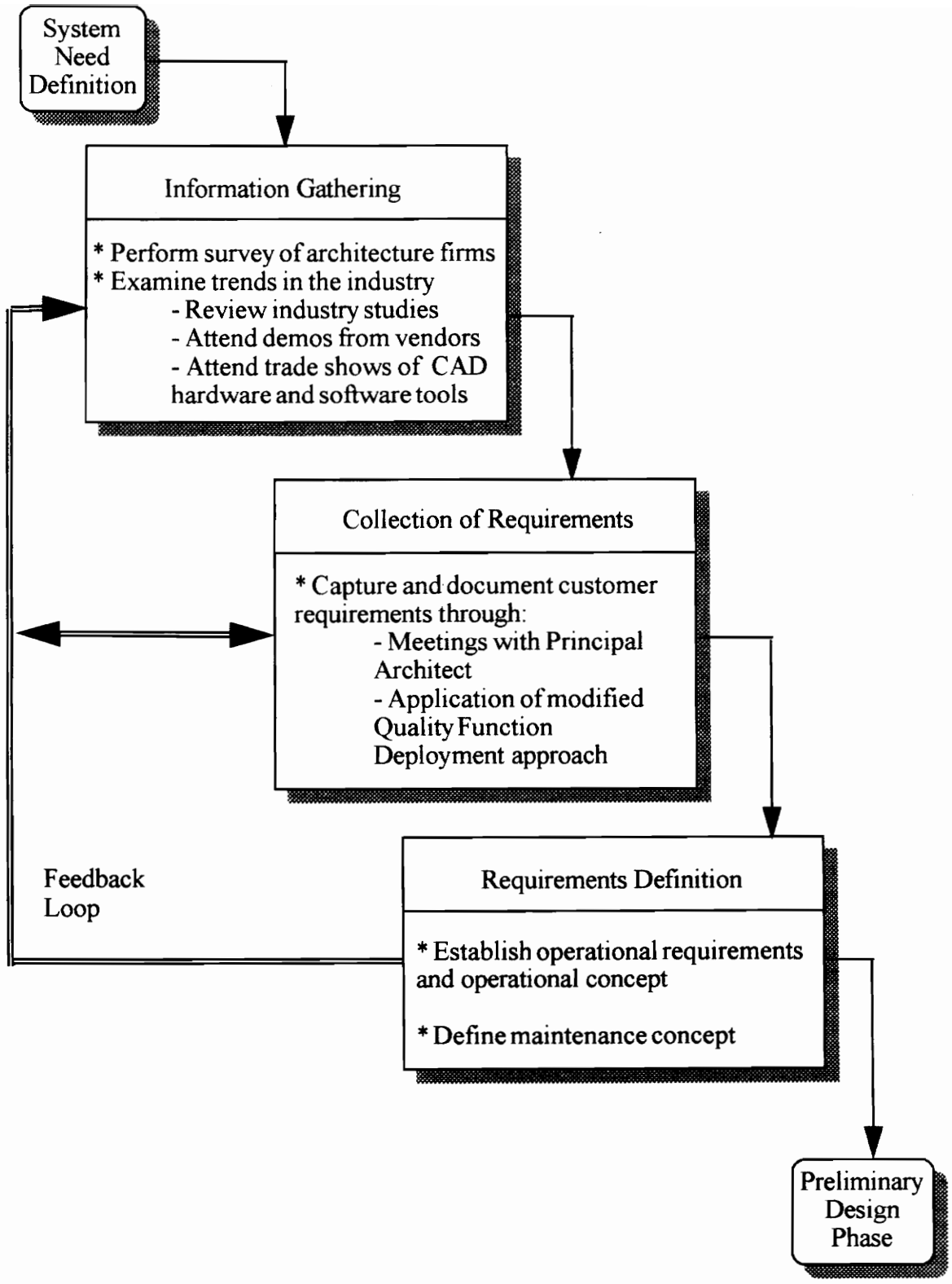


FIGURE 1. CAD SYSTEM CONCEPTUAL DESIGN PHASE

2.3 Preliminary Design Phase

The Preliminary Design Phase refines the CAD system's high-level requirements and conducts a functional analysis to establish the CAD system's functional requirements and maintenance concept more thoroughly. The functional and operational requirements are allocated to hardware and software subsystems. The allocated requirements provide a template or benchmark for the identification of multiple alternative software selections. The systems engineering process develops the system functional requirements in more detail through an iterative analysis shown by the feedback loops in Figure 2. The iterative process for capturing the functional requirements follows a customer requirements gathering technique modified from the Quality Function Deployment approach described further in Chapter Three.

The CAD system synthesis process identifies several alternative CAD software packages that satisfy four of the functional, operational, and maintenance requirements. Once the field of alternative CAD software packages is narrowed to two "preferred" alternatives, a more detailed evaluation of the packages is conducted to determine which CAD software package satisfies the greatest percentage of the weighted objective and subjective requirements.

The Preliminary Design Phase software optimization step includes activities that lead to the selection of the optimal CAD system software

package through a multiattribute evaluation technique called Analytic Hierarchy Process (AHP). Economic goals and specific system functional and operational requirements comprise the evaluation attributes and subattributes. The selected CAD software package is has operational specifications that are critical to the next stage of the CAD system's development, the Detail Design Phase, where detailed hardware component specifications will be established.

Definition of alternative CAD hardware systems and optimization of the hardware are not presented in this project. Once the operational and functional requirements of the hardware and software are defined, the project focuses on the optimization and evaluation of the CAD software package. The activities comprising the Preliminary Design Phase are contained within Chapters Three and Four. The hardware optimization and selection activities are described in more detail in Chapter Five.

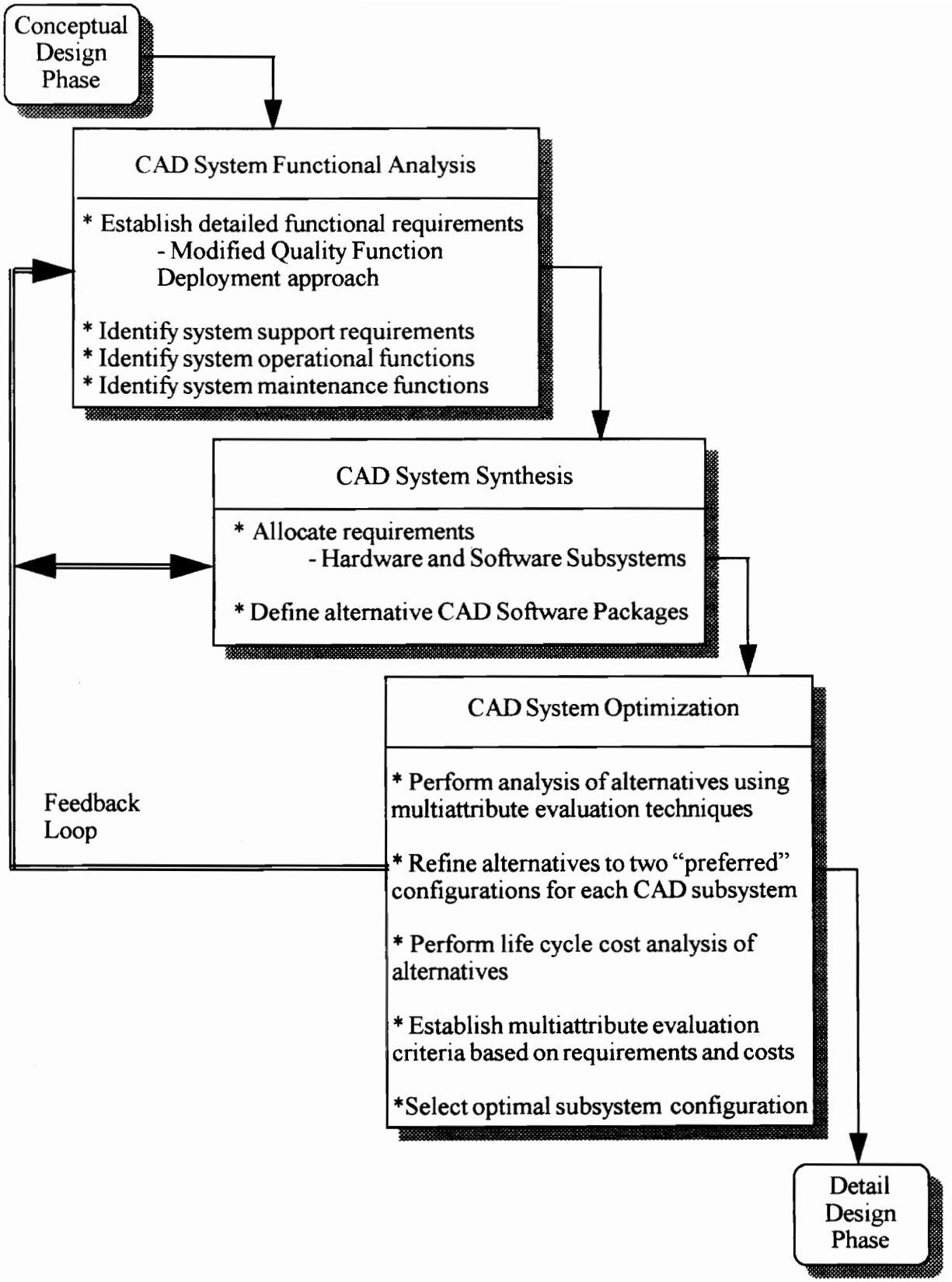


FIGURE 2. CAD SYSTEM PRELIMINARY DESIGN PHASE

2.4 Detail Design Phase

The Detail Design Phase of the CAD system's life-cycle, shown in Figure 3, completes development of the CAD system through additional analysis and design. Specific activities associated with the Detail Design Phase include designing the system and its components in more detail, evaluating the suitability of the design, and modifying the design of the components, as necessary. Some examples of the activities that occur in this phase of the design process include developing detailed maintenance procedures; designing operational office layout configurations; and establishing the system support requirements. In addition, the integration of the CAD system hardware and software should be planned for during the Detail Design Phase. A complete system evaluation should also be performed, including a major design review, hands-on demonstrations of vendor products for the Principal Architect of AER Architects, a complete system analysis, and preparation for a productivity study to evaluate design and drafting capabilities following the selection, procurement, and installation of the complete system. Chapter Five provides additional information and recommendations for these system design and evaluation activities and their impact on the CAD system's design and development.

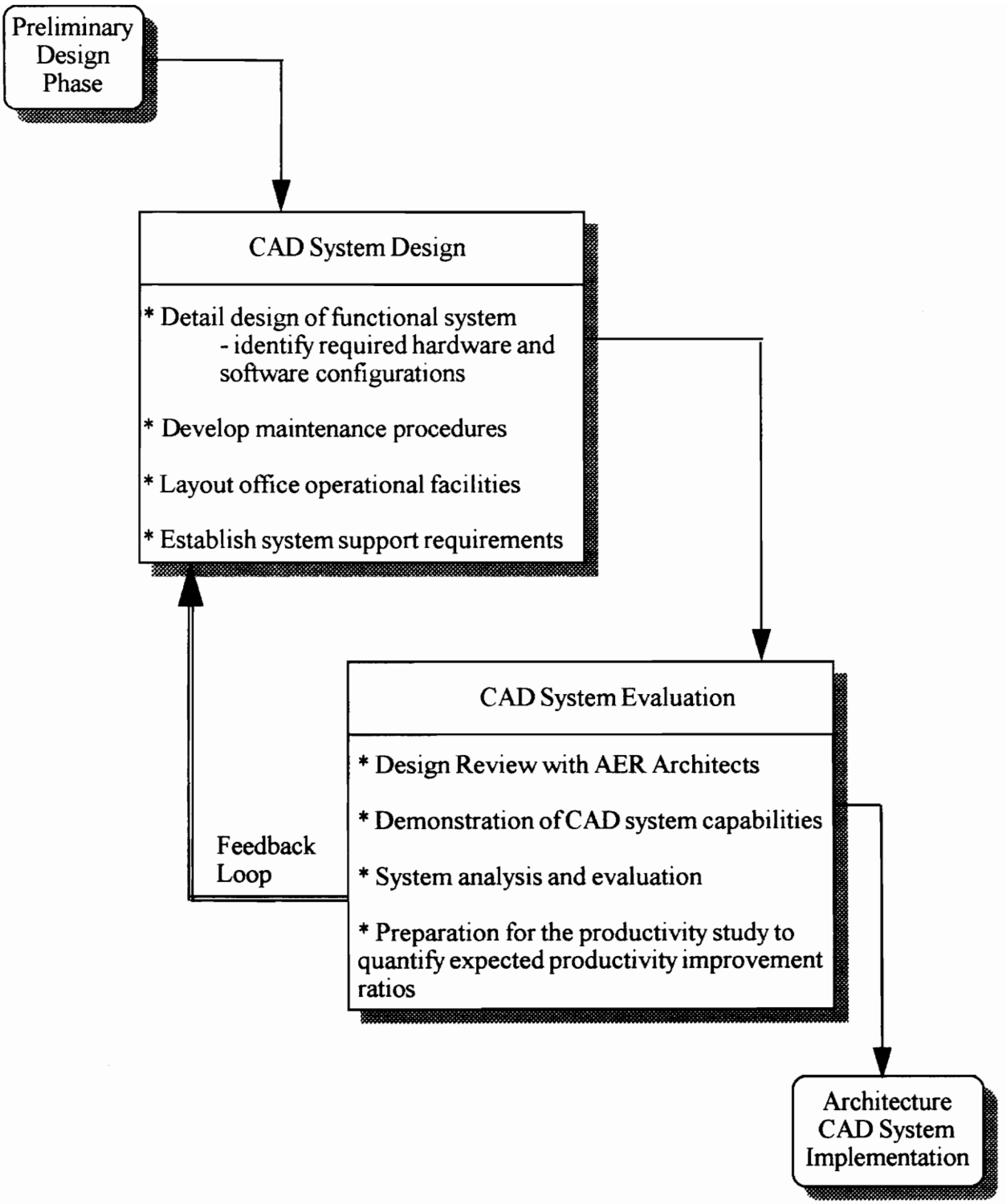


FIGURE 3. CAD SYSTEM DETAIL DESIGN PHASE

2.5 Summary

The activities outlined for these design phases provide the high-level guidance to select the CAD software and hardware system for AER Architects. However, this paper describes the application of a modified process tailored from Blanchard and Fabrycky for the CAD system's Conceptual and Preliminary Design Phases only. The modified process allows for the collection and analysis of the requirements, and the identification of a CAD software package that provides the most satisfaction for the architects that provided the requirements and will eventually use the complete system. (9) Future study recommendations are provided in Chapter Five, and are intended to satisfy some of the hardware related Preliminary Design Phase activities, and all of the Detail Design Phase activities.

CHAPTER THREE

DEVELOPMENT OF SYSTEM REQUIREMENTS

3.1 Requirements Definition Process

Blanchard and Fabrycky state that the technical parameters for system design evolve from an analysis of the need. (10) Many questions regarding the operational concept of the CAD system are asked of the Principal Architect of AER Architects in order to facilitate the establishment of the system operational requirements in accordance with the steps in the Conceptual Design Phase.

3.1.1 Requirements Collection Process

Interactive meetings were held between the Principal Architect and the system engineer to discuss the desired capabilities of the CAD system. The meetings were designed to follow a modified system design process known as Quality Function Deployment (QFD) and were used to capture the operational and functional requirements during both the Conceptual and Preliminary Design Phases. QFD is a management approach developed at one of Mitsubishi's ship yards in 1972 aimed at improving the design of products by incorporating customer input. Planning and communication routines form the basis of QFD, and are used to channel the skills within the engineering organization to result in an inter-functional design that achieves both customer and engineering goals. The design effort is a team

effort. Products are designed "to reflect the customers' desires and tastes" as described by John R. Hauser and Don Clausing in the Harvard Business Review article, "The House of Quality." (11)

Hauser and Clausing propose that the design process "begins with the customer, whose requirements are called customer attributes (CAs) - phrases customers use to describe products and product characteristics." (12) The Principal Architect of AER Architects described many of the characteristics he wished to have in an architectural CAD system. His requirements were for both hardware and software, and were functional and operational. The system engineer captured the 'customer attributes' described and translated them into 'engineering characteristics' (identified as ECs in the Hauser and Clausing article) or requirements that can be satisfied by many of the CAD systems in the marketplace, with the Principal Architect's consent at each step of the process. This process was iterative, and the Principal Architect provided enough CAs to allow them to be bundled into primary groupings of requirements, which are presented in the requirements functional flow diagrams found in later in this Chapter.

Once bundled, the ECs, or requirements, were ranked and weighted by the Principal Architect and documented here in this report. The evaluations that are performed on the variety of software packages are based solely on the information provided and approved by the eventual user of the CAD system. All of the requirements that were collected and

recorded directly affect the Principal Architect's perceptions of the CAD system and its ability to address his desires and tastes.

While the 'quality function deployment' approach, as described in "The House of Quality", was not used in its complete format, a modified approach, as described above, was applied to accurately elicit and capture the engineering characteristics of the CAD system hardware and software from the primary end user, the Principal Architect of AER Architects. One goal of this project is to focus on achieving customer satisfaction through careful application of the system engineering process.

3.2 Operational Concept and Requirements

Defining the operational concept must occur during the Conceptual Design Phase, prior to the generation of the operational requirements. This section details many of the desired operational capabilities of the CAD system as expressed by the Principal Architect during the interactive meetings with the system engineer. The operational concept addresses issues including the prime operating mission of the proposed CAD system and a desired hardware computer configuration for the operation of the CAD system software.

The prime operating mission of the CAD system for AER Architects is to provide a method for the Principal Architect to create and store computer representations of newly initiated project designs, existing designs, or concept designs. The CAD system shall automate many of the manual drawing functions performed by the Principal Architect during the creation of a set of project plans, elevations, sections and detail views. The CAD system shall display designs in 2-D and provide a capability for 3-D rendering as well. The rendering features built into the software will allow the Principal Architect to move through the designs as if to "walk through" or "fly through" and inspect the designs from a virtual reality point-of-view. The CAD system shall also provide the architect with the ability to print out high-quality drawings for use in client meetings, proposals, and demonstrations. The CAD system shall be "user-friendly", as determined by the evaluating architect, and the Principal Architect will require basic,

intermediate, and possibly advanced training on the CAD system to become a skilled and knowledgeable user.

The proposed CAD system shall be assembled of a powerful software package capable of satisfying the operational requirements, and one complete personal computer whose physical and performance parameters shall be defined by the selected CAD software package. The personal computer shall be defined as a Computer Processing Unit (CPU), a color monitor, a small black and white monitor (optional), a keyboard, a mouse, and a black and white printer. Only one CAD system is required for deployment to the AER Architects' office at this time.

The Principal Architect of AER Architects has established specific requirements that the new CAD system be a PC based system, and use the DOS operating system, paired with a Microsoft Windows interface. Both the Principal Architect and the CFO are familiar and comfortable with the Microsoft Windows interface, and have taken training courses for word processing on Microsoft Word for Windows 2.0. The Principal Architect and the system engineer believe that installing a Windows based CAD system will maintain the existing level of software comfort.

3.2.1 Operational Use Requirements

The CAD system is to be used by the Principal Architect of AER Architects. Interviews with the Principal Architect to capture the required operational use periods resulted in the operational usage scenarios in Figure 4. The required CAD system usage is 56.5 hours per week. This includes weekday and weekend usage of the CAD system to maximize output capacity. The shaded areas on the Figure represent the planned operational use periods during a typical week, as defined by the Principal Architect.

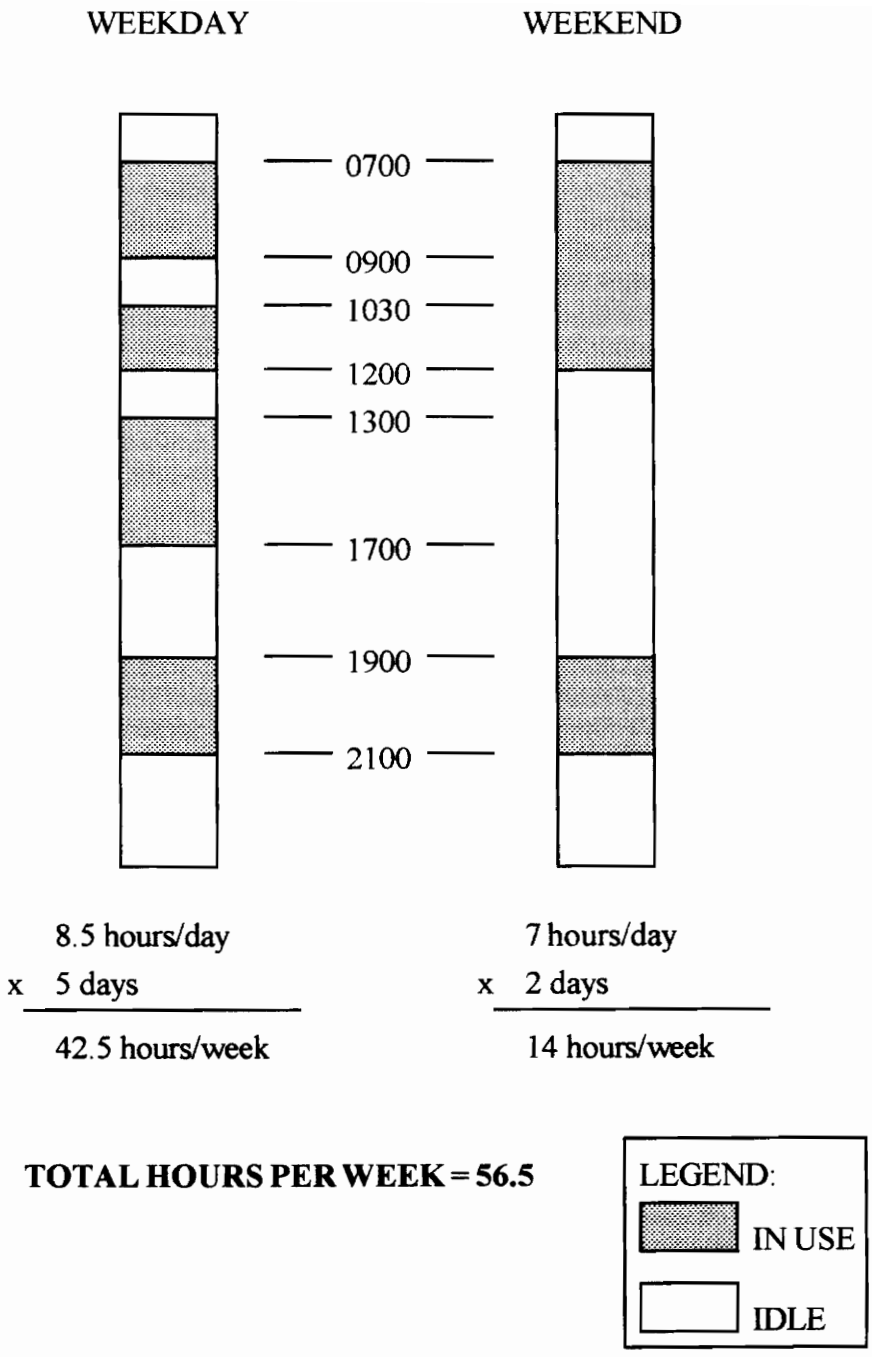


FIGURE 4. WEEKLY SYSTEM USAGE SCENARIO

3.2.2 Operational Requirements Flow Diagrams

The high level operational activities of the CAD system operator are presented in Figures 5 through 7. The operational functional flow diagrams provide a format for portraying the steps required to operate the CAD system, the feedback loops, and the operational interactions within the system. Three levels of detail are presented in the operational flow diagrams, progressing from the top level definition to more detailed definitions on each lower level. The levels are linked with progression and feedback loops depending on the nature of the function. The numbering scheme provides a reference to identify the functions for traceability between levels.

Details about the capabilities of the CAD software program are developed through the functional analysis in the Preliminary Design Phase. The functional analysis serves to further describe the desired requirements of the CAD software according to the Principal Architect of AER Architects. Section 3.4 documents the functional requirements.

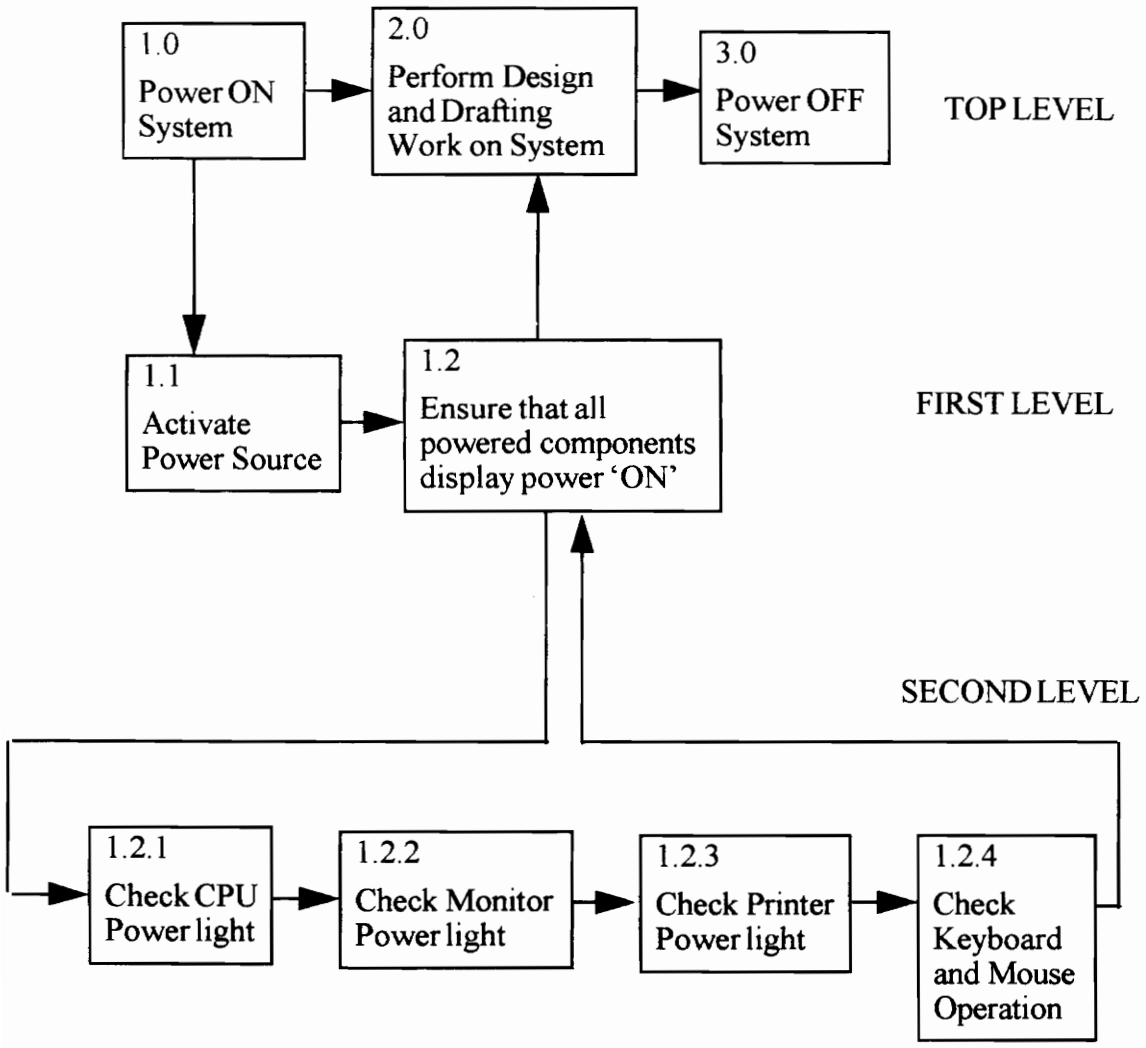


FIGURE 5. OPERATIONAL FUNCTIONAL FLOW DIAGRAM

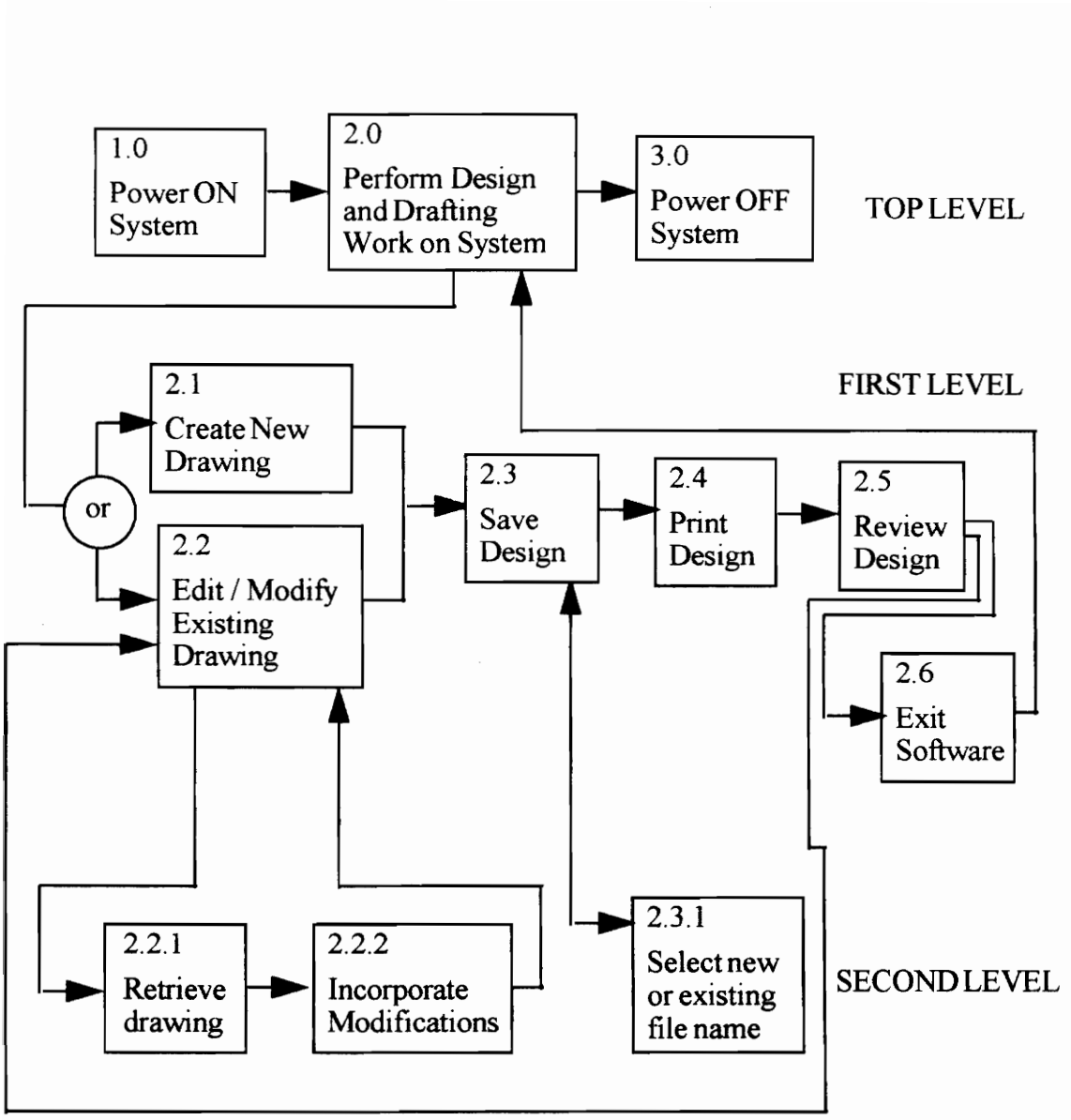


FIGURE 6 . OPERATIONAL FUNCTIONAL FLOW DIAGRAM

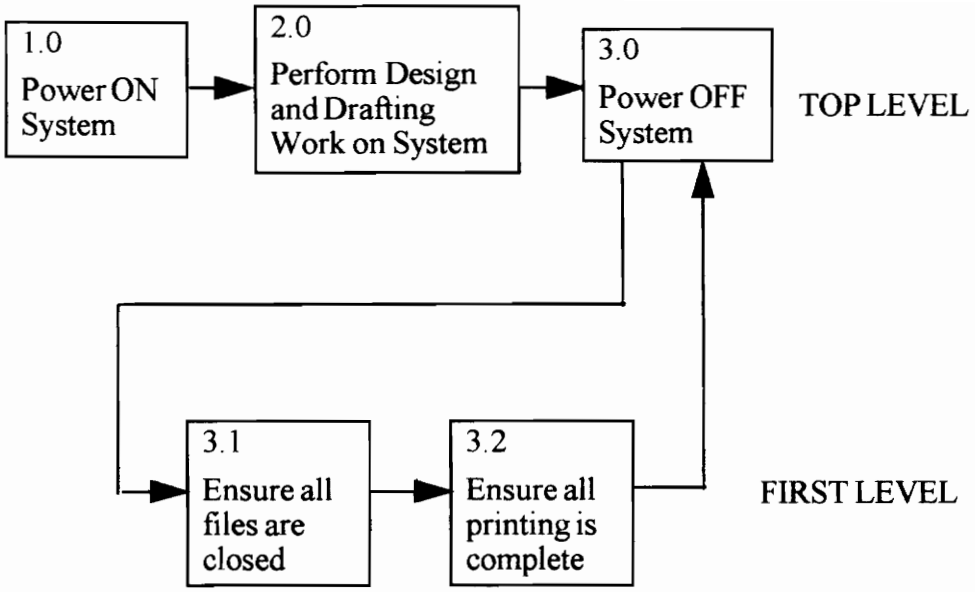


FIGURE 7. OPERATIONAL FUNCTIONAL FLOW DIAGRAM

3.3 Maintenance Concept and Requirements

The anticipated levels of maintenance support for the selected CAD system are defined in the CAD system maintenance concept. Blanchard and Fabrycky specify that the maintenance concept must define the policies that establish the suitability of repairing and replacing system components; identify responsible parties for conducting maintenance actions; and specify the logistical support requirements. (13) Figures 8 through 10 present the functional flow diagrams for the maintenance activities. The top level and first level of the required maintenance activities are shown for monitoring equipment operation, performing preventive maintenance, and performing corrective maintenance.

The maintenance concept defined here will establish the high-level support for maintaining an operational CAD system. The concept identifies maintenance tasks, frequency of accomplishing preventive and corrective maintenance actions, and the level of support assigned to complete the action. This concept specifies two levels of maintenance support: AER Architects, the procuring organization; and the vendor who sells the CAD system to AER Architects.

AER Architects will complete organizational maintenance actions, including hardware and software component inspections and checkouts during system startup; monitor CAD system activity and component status during equipment operation to verify operational functionality; and identify

CAD system malfunctions and initiate corrective actions following component failures. AER Architects will perform corrective and preventive maintenance on the CAD system components, to the limit of their ability. AER Architects will notify the vendor in the event that the required maintenance actions or diagnostic skills are beyond AER Architects' computer hardware technical capabilities.

AER Architects will enter contractual agreements with the vendor operational support organizations during the life-cycle of the CAD system. A warranty on the system components for a minimum of the first year will be provided by all component vendors, which will further protect AER Architects from poorly manufactured hardware or software not meeting the operational capabilities advertised by the vendor company.

Logistical support of replacement parts needed to perform corrective and preventative maintenance will be coordinated by the vendor support organization. The only replacement part that will be kept at the AER Architect office is one (1) printer cartridge replacement. On site maintenance will be conducted in the CAD systems operational area, unless more room is required for disassembly of the hardware components. Disassembly of the hardware will be completed on the floor of the office area. In the event that more space is required by the vendor during a corrective or preventive maintenance activities, the vendor will perform the maintenance action on the CAD system component at the vendor's office location. Figure 11 describes the CAD system maintenance policies

describing which organization will perform the maintenance, where it shall be performed, and what types of activities are planned.

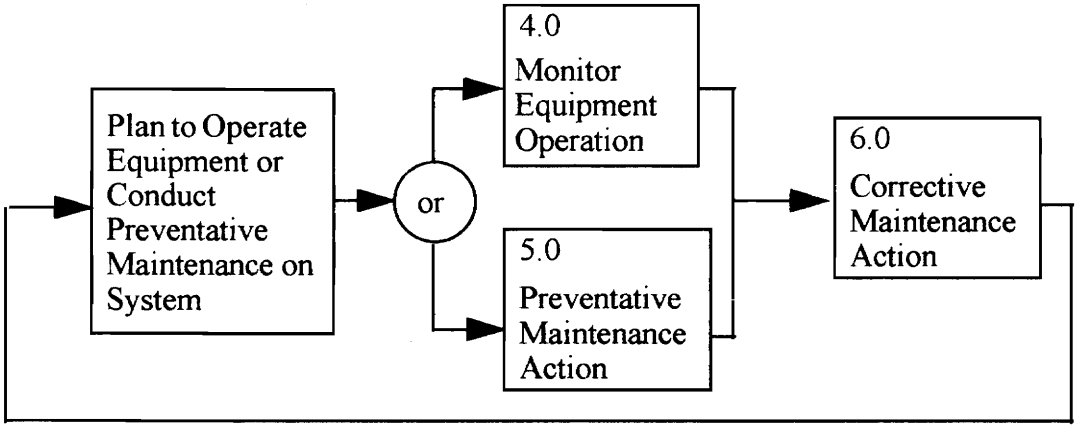


FIGURE 8. TOP LEVEL MAINTENANCE FUNCTIONAL FLOW DIAGRAM

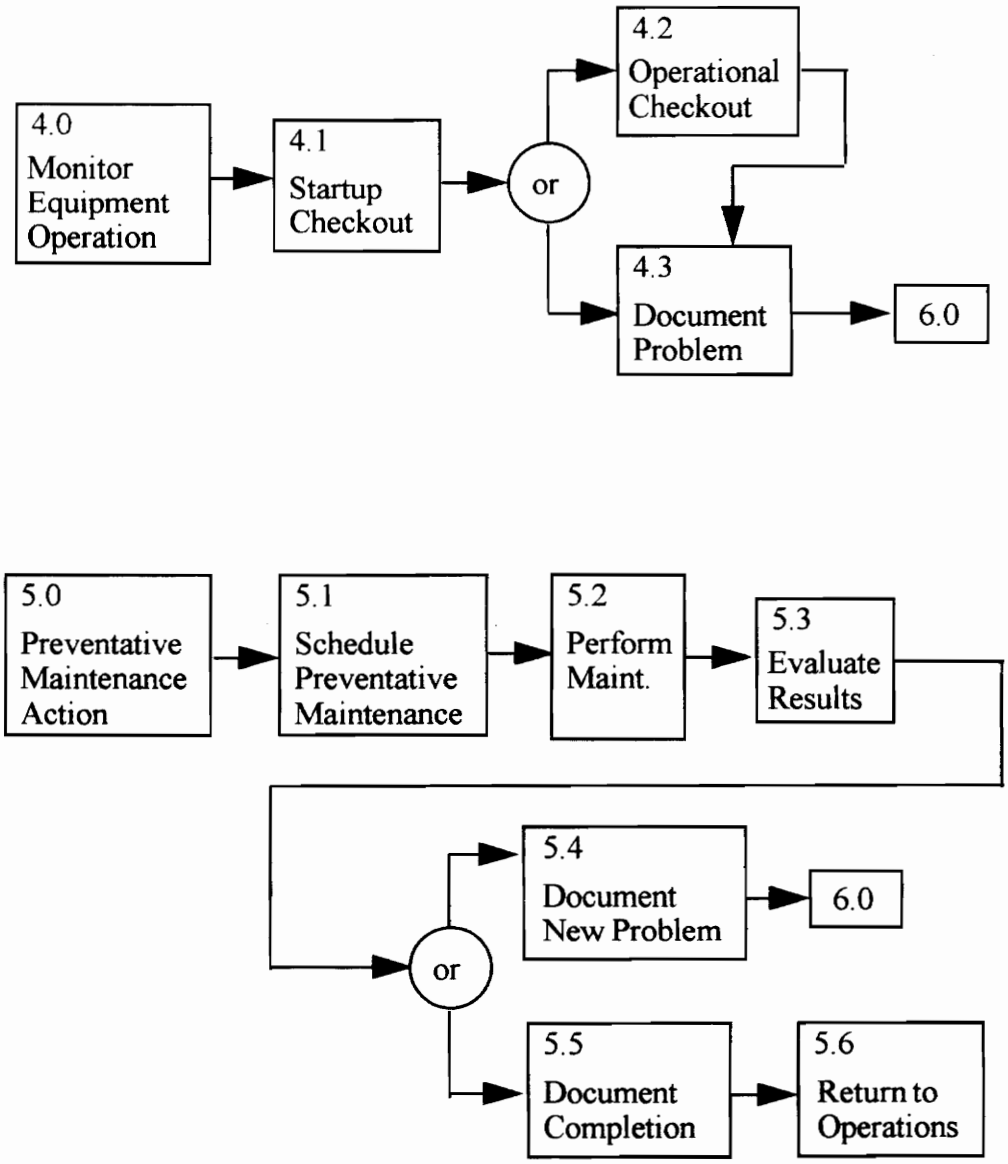


FIGURE 9. FIRST LEVEL MAINTENANCE FUNCTIONAL FLOW DIAGRAM

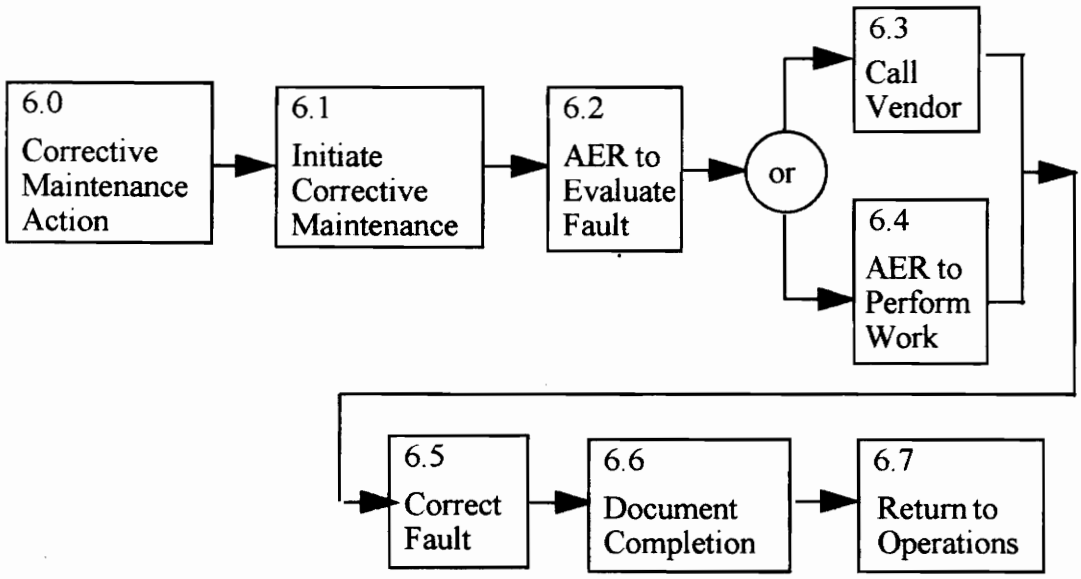


FIGURE 10. FIRST LEVEL MAINTENANCE FUNCTIONAL FLOW DIAGRAM

	AER Maintenance	Vendor Maintenance
Location:	AER Office	AER Office or Vendor Facility
Performer:	AER Architect	Vendor Personnel
Activities:	Visual Inspection	Detailed Inspection and system checkout
	Operational Checkout	Equipment Repair
	Monitor Operation	Preventive Maintenance
	Schedule Maintenance	Overhaul Components
	Minor Preventive and Corrective Maintenance on some components - Clean components - Use dust covers - Avoid food consumption near CAD system - Install new printer ink cartridge or ribbon	Major System Modifications - Install new software versions - Reconfigure system for new components Warranty Work

FIGURE 11. CAD SYSTEM MAINTENANCE POLICIES

3.3.1 Maintainability of CAD Software

Several additional requirements are needed to address the maintainability issues related to the CAD system software. The most critical maintainability requirement to AER Architect's Principal Architect is that the CAD software shall provide for upgrades that are transparent to the user and do not require total system reconfiguration. This can best be described in terms of the next release of the software, and that its installation is easily made and does not require the Principal Architect or vendor to spend several days modifying the CAD software to achieve operational status again.

The second most critical maintainability issue also involves new releases of the CAD software. New releases should be "upward compatible", i.e., a new release should have at least the same functionality as the previous version. None of the capabilities of the software should be discontinued; only new capabilities may be added.

As mentioned earlier, the software should be purchased with a specific warranty effective for at least one year. Any software release during the warranty period should be provided by the vendor or manufacturer to AER Architects at no cost. New version releases of software programs generally correct manufacturer or developer "bugs" that are missed during the manufacturer's integration tests.

3.4 Functional Analysis and Requirements

Once the operational concept and requirements and the maintenance concept have been defined during the Conceptual Design Phase, the project moves into the Preliminary Design Phase. The first activity of the Preliminary Design Phase is for the systems engineer to conduct the CAD system functional analysis. Blanchard and Fabrycky define a "function" as "a specific or discrete action required to achieve a given objective." (14) Functional analysis is described as the systematic approach used to design and develop a system. It is intended to facilitate the process in a logical and complete manner. The functional analysis is based on the operational concept and the maintenance concept. Functional flow diagrams are used in the Preliminary Design Phase for the purpose of structuring system requirements into functional terms. It is important to justify the need for CAD system hardware or software capabilities prior to defining which hardware or software is desired.

The functional requirements of the CAD system as defined by the Principal Architect were captured as part of the Preliminary Design Phase. Functional flow diagrams provide a format for portraying the functions a system performs, the feedback loops, and the functional interactions within the system. The requirements functional flow diagrams progress from the top level definition to more detailed definitions on each lower level. The levels are linked with progression and feedback loops depending on the

nature of the function. The numbering scheme provides a reference to identify the functions for traceability between levels.

Figures 12 through 17 show the multi-level functional requirements of the CAD system hardware and software. For the purposes of this discussion, a drawing of a single family home is used as the function to be performed by the AER architect. These functional flow diagrams were created through iterative discussions and reviews with AER Architects' Principal Architect to define the mission definition, performance parameters, use requirements, operational deployment, operational life cycle predictions, desired effectiveness factors, and the expected operating environment. Each flow diagram has been approved by the Principal Architect. The requirements functional flow diagrams are defined in terms of mission capabilities that the CAD system software and hardware will be required to perform. Please note that the 2.X family forms the requirements for the CAD system software, while the 3.X family defines the CAD system hardware functional requirements.

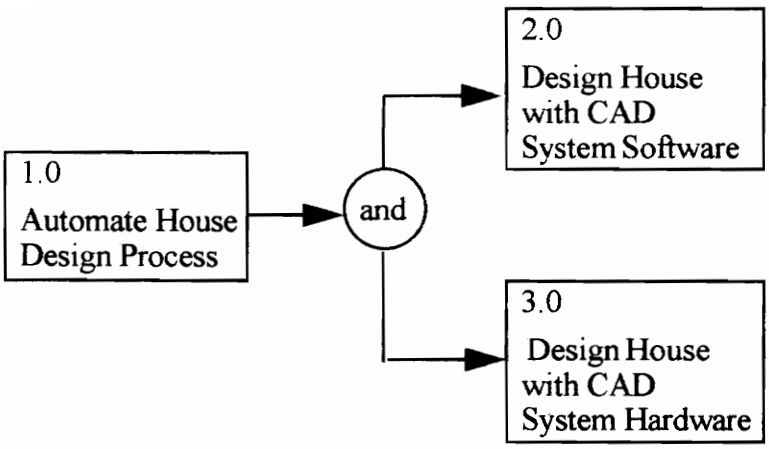


FIGURE 12. TOP LEVEL REQUIREMENTS FUNCTIONAL FLOW DIAGRAM

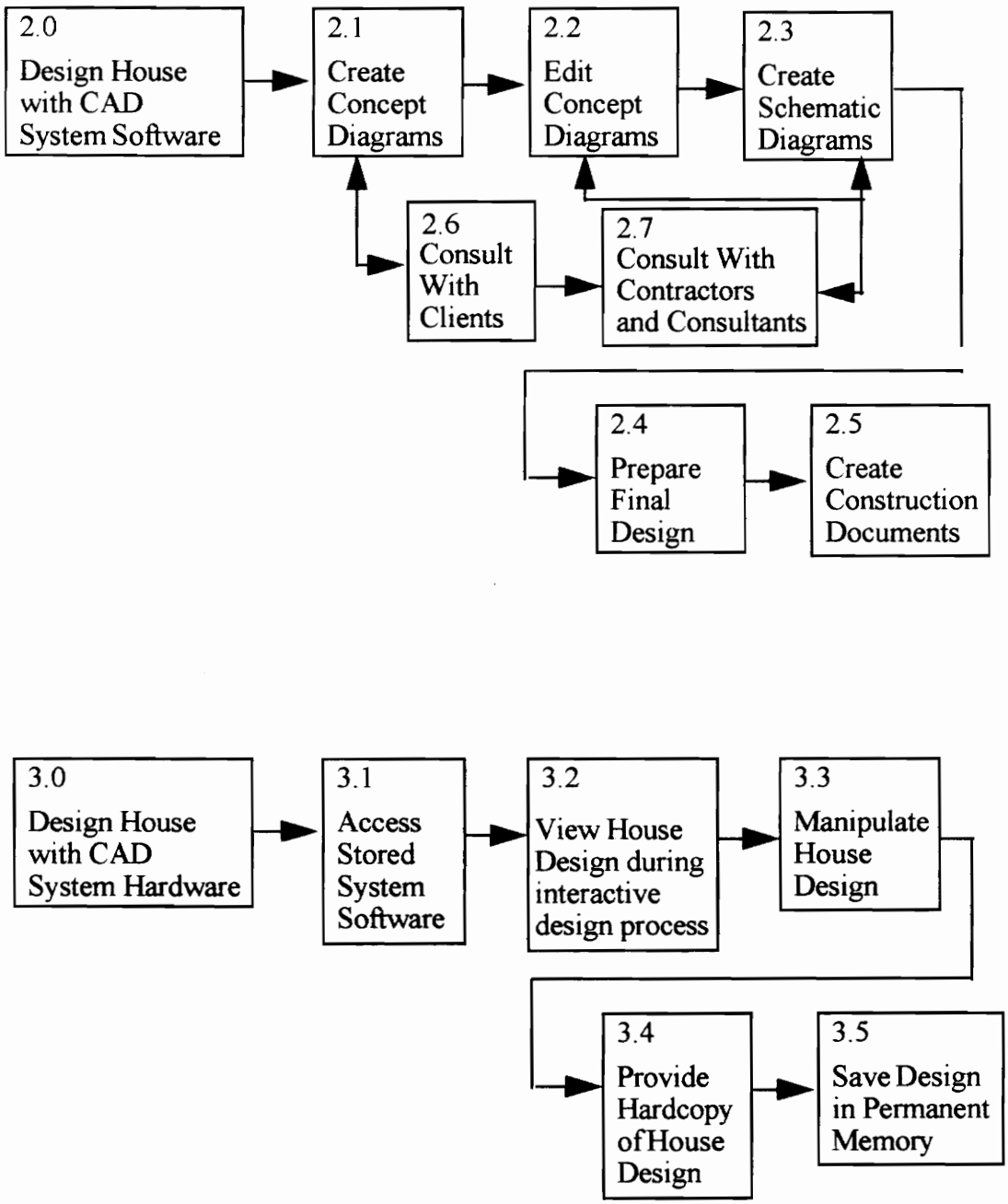


FIGURE 13. FIRST LEVEL REQUIREMENTS FUNCTIONAL FLOW DIAGRAM

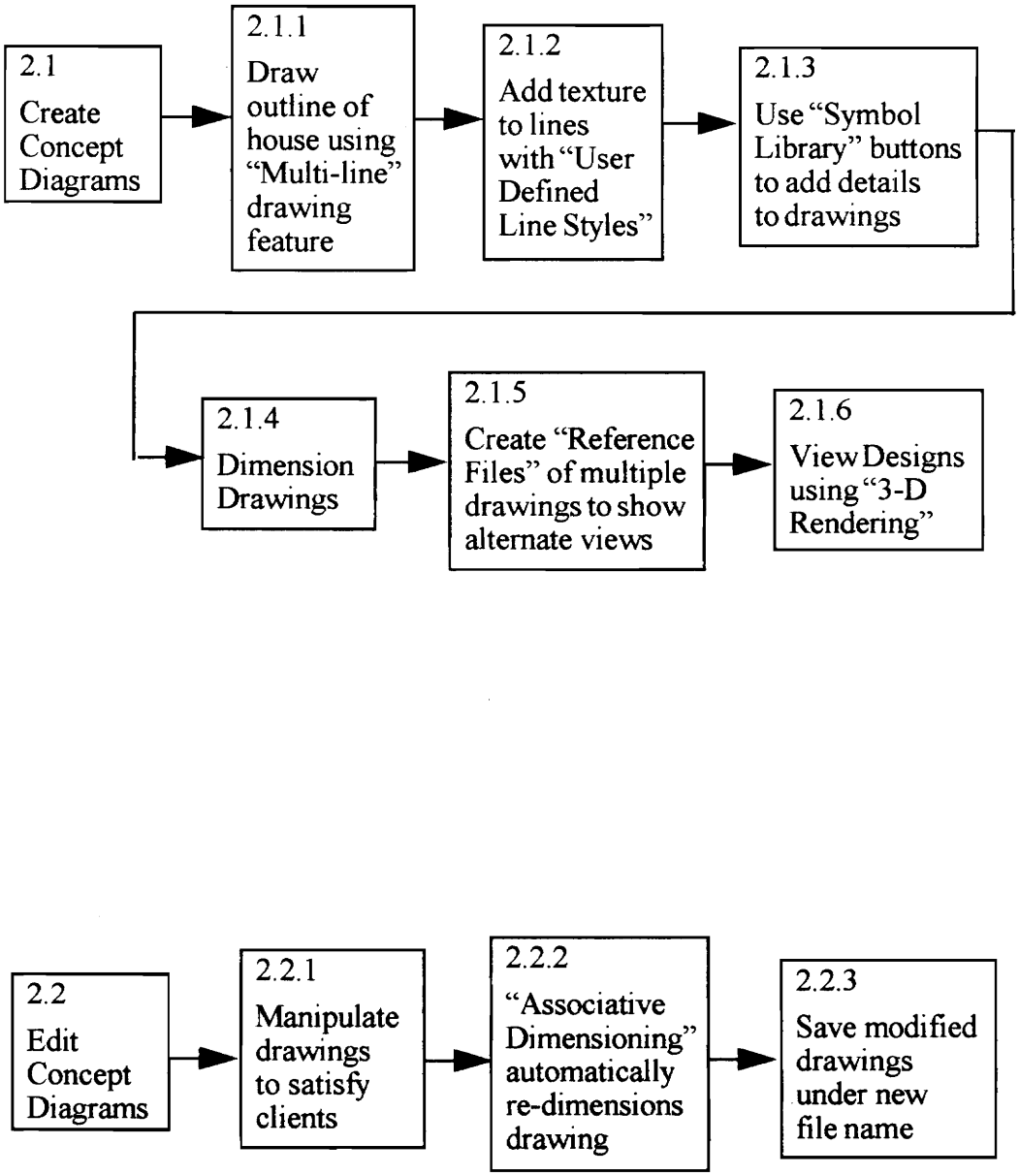


FIGURE 14. SECOND LEVEL REQUIREMENTS FUNCTIONAL FLOW DIAGRAM

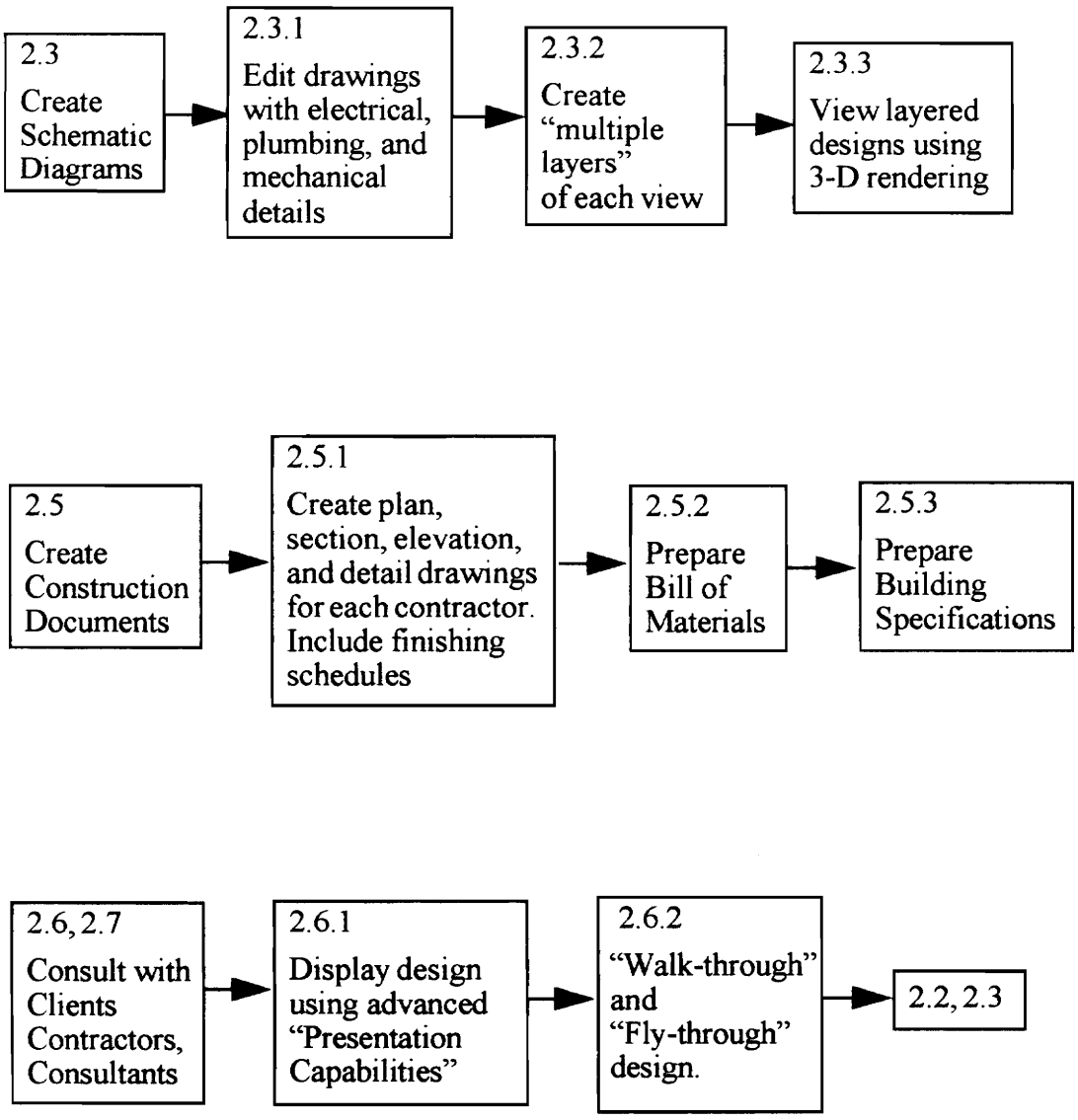


FIGURE 15. SECOND LEVEL REQUIREMENTS FUNCTIONAL FLOW DIAGRAM

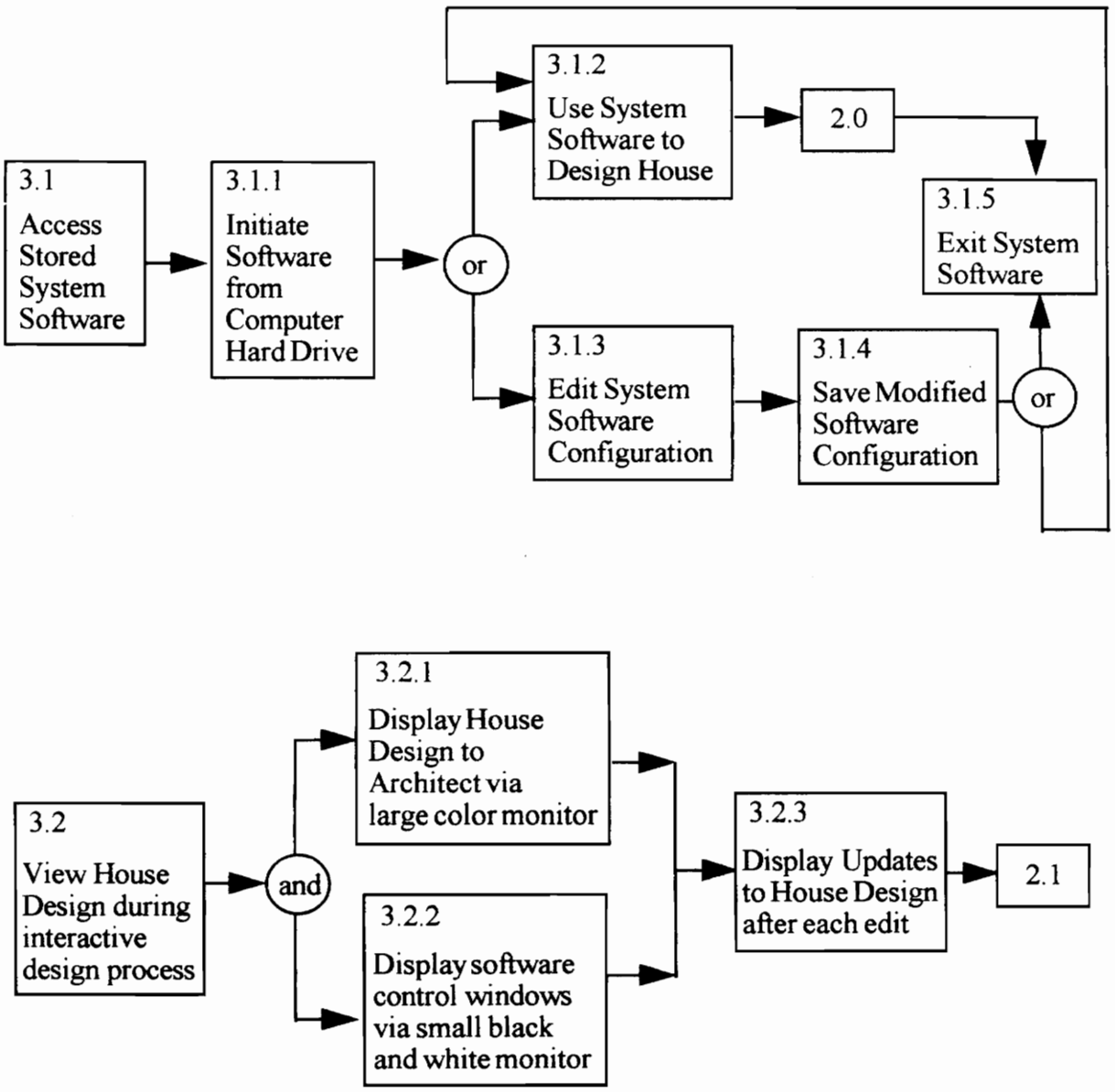


FIGURE 16. SECOND LEVEL REQUIREMENTS FUNCTIONAL FLOW DIAGRAM

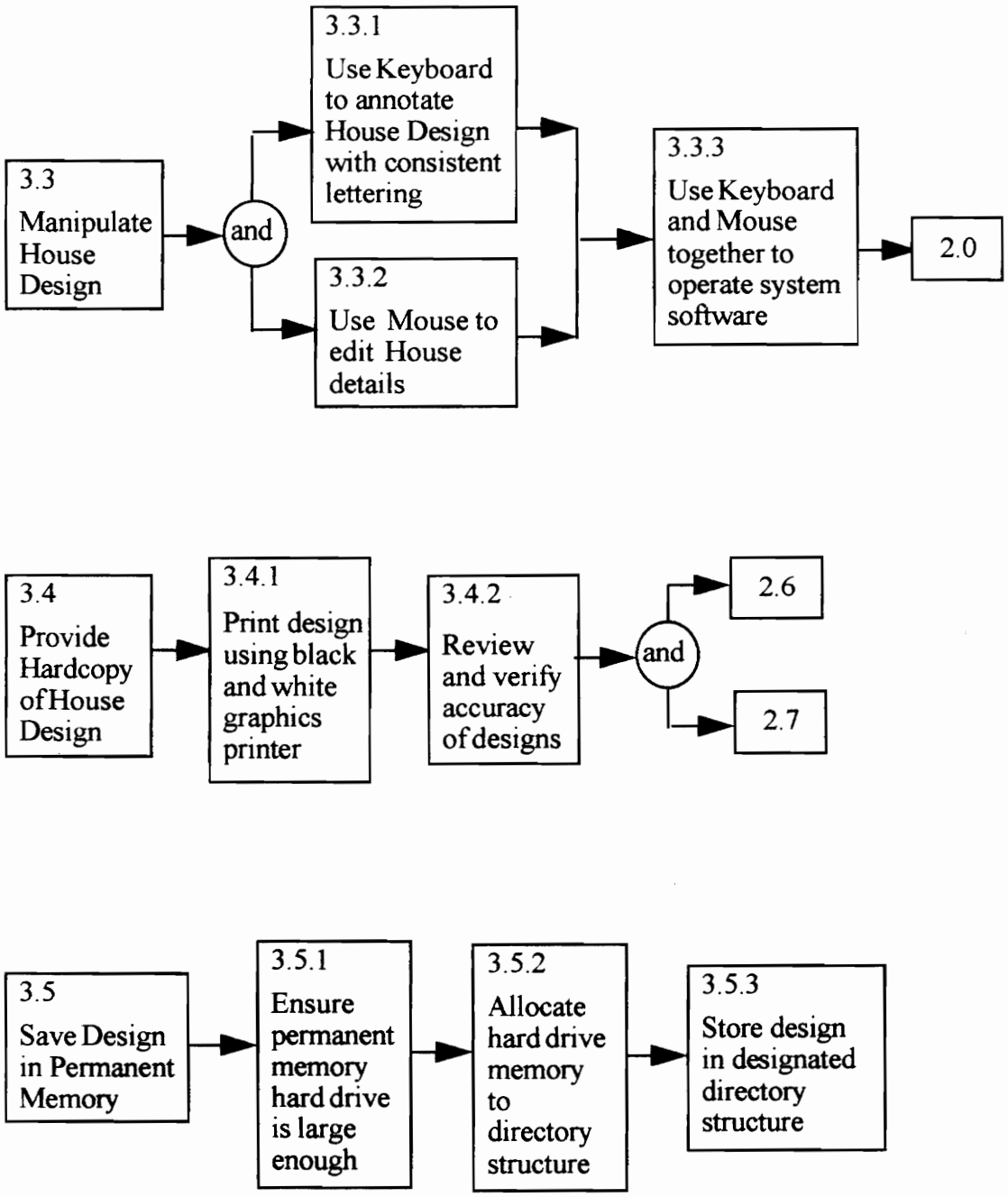


FIGURE 17. SECOND LEVEL REQUIREMENTS FUNCTIONAL FLOW DIAGRAM

3.4.1 Description of Required CAD Software Capabilities

The CAD software package shall provide the set of standard computer aided design capabilities, as well as those functions specific to architectural drafting, including the capability to draw double lines and multiple lines. The required advanced capabilities and features of the CAD system per the Principal Architect's functional requirements and the description are as follows. These requirements are listed in the priority order as identified by the Principal Architect.

1. Applicability to architecture right out of the box, prior to "add-ons". This requirement is intended to identify the best "pure" architectural CAD system software. CAD design engines that require multiple "add-on" packages to provide the required architectural functionality may introduce significant added costs to the life cycle cost estimates.

2. Multiple reference files associated to one drawing. This requirement will allow the Principal Architect to examine multiple views simultaneously, and to manipulate the multiple views with relative ease.

3. 3-D Rendering. This requirement will allow the Principal Architect to view the design in three dimensions, a feature that greatly enhances the architect's and client's understanding of how the finished project will look and feel.

4. Presentation Capabilities. This requirement will provide the Principal Architect with the ability to create visually pleasing presentations using the graphical capabilities of the CAD software. Presentations are vitally important to the clients who want to "see" what designs the firm has done previously, and to "view" their projects from realistic perspectives.

5. User defined line styles. This requirement will allow the Principal Architect to specify two points and a material for the line connecting the two points, and the CAD system software will insert the specified texture for the line.

6. Multi-line capability. This requirement will allow the Principal Architect to draw more than 2 lines simultaneously with different colors and textures, resulting in reduced design time.

3.4.2 Compatibility Functional Requirements

Compatibility requirements as described by the Principal Architect include the requirement that the CAD system software shall provide the ability to read and write multiple file formats. This will enhance the Principal Architect's ability to be compatible via the computer. Manipulation of multiple file formats allows other vendor CAD software products to be compatible with the selected CAD software. This is the most critical compatibility requirement because all clients, contractors and consultants use different CAD software packages, and being able to read

and write to many of the other packages will result in greater communicability of designs.

Compatibility with third party vendors is the second most important compatibility requirement according to the Principal Architect. While this is related to the previous requirement, it also is a measure of the number of third party software "add-ons" that are available for the selected CAD software engine. Some CAD software packages provide the base computer aided design and drafting capabilities, and require "add-ons" to gain further, specialized functionality. For example, many CAD software packages do not have 3D rendering capabilities, and, to accommodate users that require this capability, they offer an "add-on" that is easily integrated with the main package. Specialized libraries of architectural symbols are a popular type of "add-on" software product for CAD systems.

The last major compatibility requirement specified by the Principal Architect is that the CAD software shall be configured with built-in database macros to allow the Principal Architect to store drawings in a database file structure. Most CAD software packages do not have a built in database and often require an "add-on" to gain this functionality. However, a macro that is already built-in or installed in the CAD software allows for an easy adaptation of the "add-on" database package. Special databases are required after the architect has created numerous designs, and requires additional storage assistance.

3.4.3 Operational Life Cycle of the CAD Software

The operational life cycle for this evaluation project will be designed to be four years. Reviews of the computer technology turnover rates indicate that the current capabilities and capacities will be significantly replaced every four years. Hypothetical upgrades to the CAD system software shall be included in this paper in the cost analysis only. An assumption will be made that the next version release date for the alternative software packages will be 24 months in the future, based on the release date of the evaluated package. Estimated cost impacts for the purchase of upgraded software will be included in the cost analysis section of Chapter Four.

3.4.4 Effectiveness Factors

The effectiveness factors included within the scope of this project are limited to the operator skill levels, the CAD system use times, the mean time between maintenance, and the maximum allowable maintenance downtime. These factors are established as requirements to be met during the detail design phase of the CAD system. The operators shall be trained at the advanced level through vendor training courses. The planned usage of the CAD system shall be 56.5 hours per week, as specified by the Principal Architect. The CAD system shall support a mean time between maintenance of 1000 hours, and the maximum allowable down time shall be one day.

3.5 Definition of System Support Requirements

System support requirements are also defined during the Preliminary Design Phase and the system functional analysis. One of the purposes of the functional analysis is to identify additional system related requirements that fall outside the software capabilities arena. Both training and the vendor support and viability were identified by the system engineer as critical requirements that must be considered when evaluating software packages. The Principal Architect did not state these as functions or requirements during the interactive discussions that resulted in the functional flow diagrams. Nonetheless, he agrees they are important and should be included. Brief descriptions of the support related requirements are contained in this section.

3.5.1 Training Requirements

The most critical training requirement is the availability of the training courses for the Principal Architect. Classes shall be scheduled frequently and will address the beginner, intermediate, and advanced levels of training. This requirement will ensure that the Principle Architect shall become skilled on the CAD software at his earliest convenience.

The effectiveness of the training shall be determined based on the evaluations given by previous students. This requirement is critical in determining the value of the training class and the associated costs. The

Principle Architect will be able to gauge his learning progress through the planned use of the CAD software following each training session.

The convenience of the training is also an important factor to consider. The training shall be located close to or in AER Architects' office and require a minimum of travel and living costs while attending the training courses.

The training shall include a variety of training methods, including videos, live instruction, guide books, and on-line self-paced computer based training. Variety in the training methods will allow the Principal Architect to determine which training technique is preferred and most effective.

3.5.2 Vendor Requirements

The viability and support capabilities of the CAD software vendor are important requirements that are to be included in the evaluation of the CAD software packages. In order of decreasing importance, the following are the vendor related requirements.

The CAD software vendor shall have a qualified technical staff sufficient to perform the product development and maintenance, and not be top-heavy with sales persons who promise more than the technical staff can deliver. The percentage of technical staff indicates the commitment a vendor makes to the quality of the software product.

The vendor shall provide installation support, both on-site and via a telephone hot-line. The installation support is essential for AER Architects to activate the CAD system. The Principal Architect is unfamiliar with the technical aspects of configuring a CAD software package.

The CAD software vendor shall provide operational support, both on-site and via the telephone hot-line. The vendor shall have a well established record of prompt responses to problem reports. Operational support is a critical step towards ensuring that the CAD system will be successfully integrated into the daily routine at AER Architects.

The vendor shall have an ongoing program to enhance the users understanding of the CAD software product's capabilities in the form of a newsletter and free seminars. "User groups" are another form of communication between the vendor and the users that helps enhance the useability of the CAD software.

Finally, the vendor shall be a mature and stable company, with several years in the CAD software industry. Maturity in the CAD industry indicates that the vendor is well known and their software is reliable.

3.6 Summary and Allocation of Requirements

The requirements that have been identified in Chapter Three comprise the metrics that will be used in Chapter Four to evaluate CAD packages. A complete list of the requirements in provided in Table 2. The requirement numbers were derived from the paragraph numbers in Chapter Three where the requirements were stated. The column labeled "allocated to" indicates to which subsystem (software or hardware) and which attribute within the subsystem each requirement is allocated. The hardware requirements are not defined to the attribute level in Chapter Three. This task is recommended as a future study in Chapter Five.

TABLE 2. SUMMARY AND ALLOCATION OF REQUIREMENTS

Requirement Number	Requirement	Allocated to
3.2.a	The CAD System shall automate the manual drawing functions performed by the Principal Architect	System
3.2.b	The CAD System shall be "user-friendly" as determined by the evaluating architect	System
3.2.c	Only one CAD System is required at this time	System
3.2.d	The CAD System software shall be compatible with Microsoft Windows on a DOS Operating System	System
3.4.4.a	The CAD System shall support a mean time between maintenance of 1000 hours	System
3.4.4.b	The maximum allowable down time shall be 1 day	System
3.3.1.a	The CAD software shall provide for upgrades that are transparent to the user and do not require total system reconfiguration	SW.Maintainability
3.3.1.b	New releases of the CAD software shall be upward compatible	SW.Maintainability
3.3.1.c	The warranty on the CAD software shall be effective for at least one year	SW.Maintainability
3.4.1.a	The CAD software shall be applicable to the architecture discipline, prior to adding additional packages	SW.Capabilities
3.4.1.b	The CAD software shall provide the capability to store multiple reference files associated to one drawing	SW.Capabilities
3.4.1.c	The CAD software shall provide advanced 3D rendering capabilities	SW.Capabilities
3.4.1.d	The CAD software shall provide the ability to create visually pleasing presentations	SW.Capabilities
3.4.1.e	The CAD software shall provide the capability for user defined line styles	SW.Capabilities
3.4.1.f	The CAD software shall provide the capability for drawing more that two lines simultaneously	SW.Capabilities
3.4.2.a	The CAD software shall read and write multiple file formats	SW.Compatibility

TABLE 2. SUMMARY AND ALLOCATION OF REQUIREMENTS, CONT'D

Requirement Number	Requirement	Allocated to
3.4.2.b	The CAD software shall be compatible with third party packages	SW.Compatibility
3.4.2.c	The CAD software shall have built in macros to allow easy access to database packages	SW.Compatibility
3.5.1.a	The CAD software training courses shall be scheduled frequently and shall address the beginner, intermediate, and advanced levels of training	SW.Training
3.5.1.b	The CAD software training courses shall be rated effective by previous students	SW.Training
3.5.1.c	The CAD software training shall be located close to or in AER Architects' office and shall require a minimum of travel and living costs while attending the training courses	SW. Training
3.5.1.d	The CAD software training shall include a variety of training methods	SW.Training
3.5.2.a	The CAD software vendor shall have a qualified technical staff sufficient to perform the product development and maintenance	SW.Vendor
3.5.2.b	The CAD software vendor shall provide installation support, on-site and via the telephone hot-line	SW.Vendor
3.5.2.c	The CAD software vendor shall provide operational support	SW.Vendor
3.5.2.d	The CAD software vendor shall have an on-going program of user communications	SW.Vendor
3.5.2.e	The CAD software vendor shall be a mature and stable company	SW.Vendor
3.4.1.a	The CAD software shall be stored on a Computer Hard Drive	HW
3.4.1.b	A large color Monitor shall be used to display the designs to the Architect	HW
3.4.1.c	A Keyboard and a Mouse shall be used to mainpulate the designs	HW
3.4.1.d	A Printer shall be used to create design hardcopies	HW

CHAPTER FOUR

ANALYSIS AND EVALUATION OF ALTERNATIVES

4.1 Discussion of the Multiattribute Decision Analysis

Following the definition of the requirements for AER Architect's CAD system software, a list of ten candidate software packages was compiled from the interviews, survey, and market study of architecture firms and their principal architects. The decision making process is an orderly and quantifiable process of eliminating alternatives and identifying the CAD software package that most closely satisfies the Principal Architect's requirements. Multiple techniques exist for performing evaluations similar to this, including simple studies addressing one or two of the more critical requirements, or decision making based on price alone. In a situation where there are many quantifiable requirements, Canada and Sullivan state that the "multiattribute decision techniques seem to provide an easily understood, yet comprehensive, set of quantitative/qualitative approaches" to select computer aided design software systems. (15) The multiattribute decision techniques have many variations that can be tailored for use in comparing and eliminating alternatives of CAD software packages.

Whichever method is selected for use during this evaluation, the act and process of making the decision will allow the following benefits for all involved parties. The decision making process will:

1. Force focus on the objectives, alternatives, attributes and risks of selecting CAD software.
2. Facilitate communication between the architect(s), systems engineer, analysts, and chief financial officer of AER Architects.
3. Promote a more developed evaluation procedure.
4. Encourage generation of new alternatives and requirements.
5. Assist the selling of the final recommendation based on a rational decision making process.

Identification of the attributes is a critical step to be taken prior to analyzing alternative CAD system software packages. The most critical restriction in the identification of attributes is that they be independent of one another, according to Canada and Sullivan. Selecting key attributes that are likely to differ between the alternatives allows the decision making techniques to be used efficiently, without becoming cluttered or confused with inconsequential details. Avoiding this common trap provides the decision maker with more time and effort with which to possibly identify better alternatives. Canada and Sullivan recommend starting with a few attributes and performing an initial analysis. Future, in-depth, analyses

should be performed using a more diverse number and range of attributes to help eliminate alternatives. This process was used to narrow the field of ten CAD system software packages to the best candidates that deserve added consideration.

Methods used for such evaluations include sequential elimination methods, graphical techniques and weighted evaluation of attributes. Brief descriptions of the various techniques are provided in the next several sections.

4.1.1 Sequential Elimination Methods

Sequential elimination methods are useful decision rules to help eliminate several alternatives and narrow the field of candidates. This method can be used when the attributes and alternatives are easily specified by a numerical value. The attributes are not weighted when employing the sequential elimination methods. In addition, the attributes are described by Canada and Sullivan as "noncompensatory", which indicates that trade-offs among the attributes across the alternatives are not recognized. Variations of the sequential elimination methods compare attributes against attributes and alternatives against alternatives. Each variation of the method requires that values be determined for each alternative, and that the alternatives are then compared against each other or against a fixed standard. A choreographed process of elimination is then followed to identify the most preferred alternative.

4.1.2 Graphical Techniques

The graphical techniques allow the decision makers to readily absorb large amounts of information when presented in a powerful format. Similar to the sequential elimination methods, the graphical techniques do not include weightings of attributes. This can be advantageous because the weightings can sometimes be non-exact and vary among the decision makers. Shaded circles are a popular means of portraying relative evaluations of alternatives with respect to identified attributes. While this is not the method used in the analysis and display of the CAD system software results, a example of the shaded circles is in Figure 18.

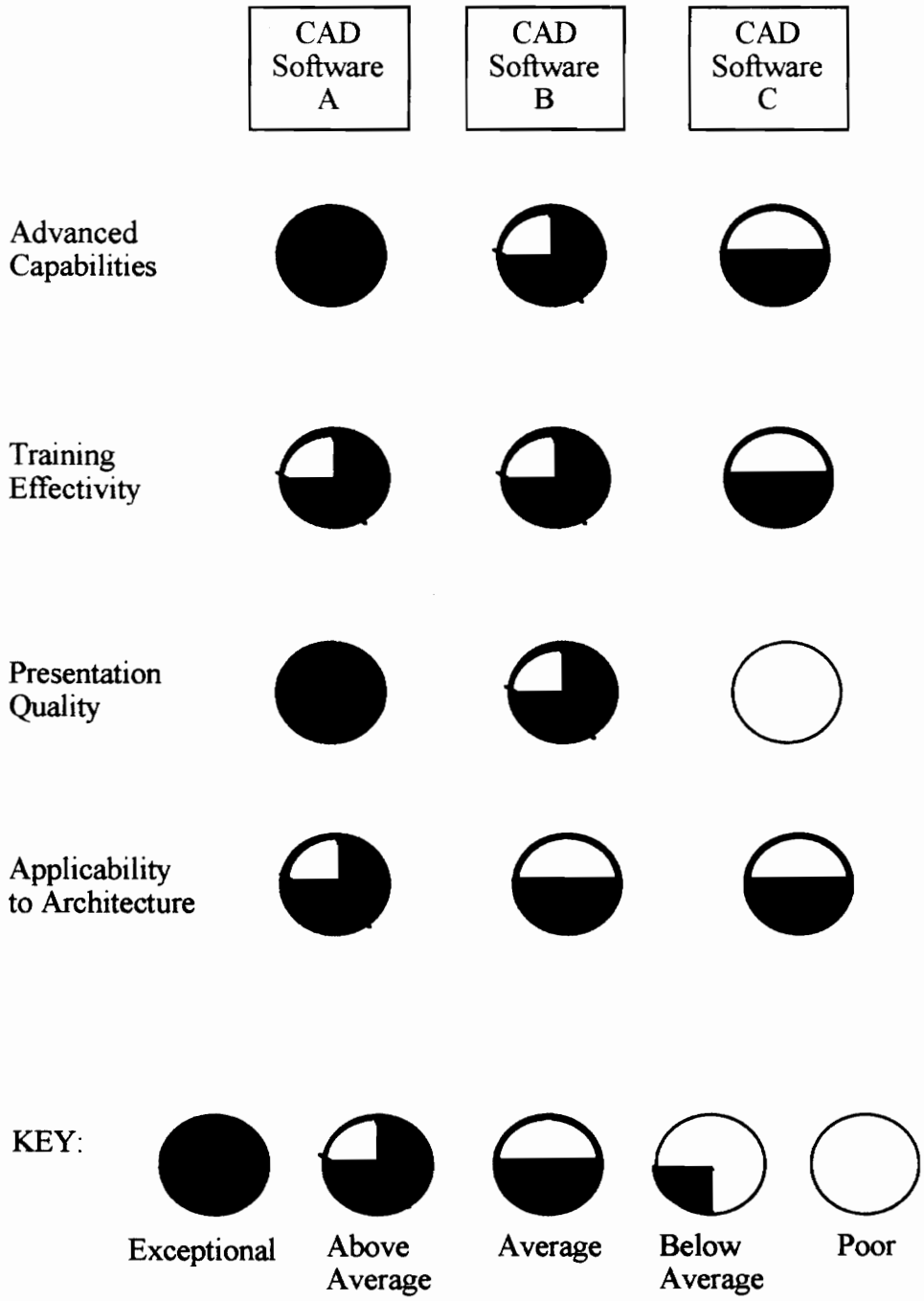


FIGURE 18. GRAPHICAL EVALUATION TECHNIQUE

4.1.3 Weighted Evaluation of Alternatives

The weighted evaluation of alternatives involves the ranking of attributes and the weighting of attributes. Prior to ranking the attributes, the decision maker must align them in order of decreasing preference, with the most preferable attributes listed first. Pairwise comparisons among the attributes helps one determine the order of importance, and results in a comparative summary of the attributes. The mathematical symbols <, =, and > are used to indicate the degree of preference.

Weighting the attributes requires quantification of the relative importance of each attribute with respect to each other attribute. The steps to be taken by the decision maker to perform the weighting is as listed below:

1. Assign values to the ranked list of attributes, usually 0 to 100.
2. Validate the assigned weightings to each attribute through internal comparisons to the other attributes' assigned weighting values.
3. Normalize the weightings using a simple summation equation.

Once all attributes have assigned weights, the decision maker must record values for each alternative representing the level to which the alternative satisfied each attribute. This task can be completed for the CAD system software packages with assistance from the Principal Architect or the surveyed architects who are very familiar with the software capabilities. Gathering the data can be time consuming, but it is critical to the thorough evaluation of the CAD software packages. The values assigned to each of the four attributes were selected using a rating scale of 1 to 10.

4.2 Application of Multiattribute Decision Analysis

A worksheet has been developed for the evaluation of each of the ten CAD software packages identified in Appendix A. Several key attributes have been selected for this first evaluation, which is aimed at eliminating many of the alternatives and narrowing the field of candidates. The Principal Architect reviewed each of the packages against these four attributes that were selected because they provide a good initial indication of how well a CAD software package will satisfy all the requirements documented in Chapter Three.

The weighted attribute evaluation technique will be used for this first elimination round. The four attributes each package will be evaluated against are listed below, along with their respective weightings and normalized weightings. The rank order and weightings were determined by the process defined by Canada and Sullivan, which is summarized in Section 4.1.3.

	Initial Weighting Assignment	**Normalized Factor Weight**
Runs on a PC with Windows	100	30
Compatibility with other products	90	27
3-D Rendering	80	24
User Defined Line Styles	65	19
	Sum = 335	**Sum = 100**

The tables in Appendix A show the calculations involved in evaluating which packages should be considered for the further studies. Please note that the scores for the alternatives against the four attributes clearly identify whether each CAD software package provides the required capabilities as defined by the attributes. The scores are the result of the Principal Architect reviewing the package and determining how well the software achieved the required attributes.

The scale used to evaluate each software package against the criteria is shown in Table 3. The summary in Table 4 at the conclusion provides a concise look at the scores. Only two packages received weighted evaluation scores above 84: **Autodesk Inc. AutoCAD Release 12 for Windows,** and **Intergraph's MicroStation PC Version 5**. These two preferred alternatives will be evaluated using more quantitative and in-depth techniques to determine which is the best CAD software package for AER Architects based on their requirements.

TABLE 3. ATTRIBUTE SCORE SCALE FOR ALTERNATIVES

Attribute	Weighting Scale				
	0	**2.5**	**5**	**7.5**	**10**
Runs on a PC with Windows	Neither		PC Only		Both
Compatible with other Vendors and Products	None	Few	Many	Dozens	Hundreds
3-D Rendering	None	Below Average	Average	Above Average	Excellent
User Defined Line Styles	None	Below Average	Average	Above Average	Excellent

TABLE 4. SUMMARY OF ALTERNATIVE EVALUATIONS

Alternative Evaluated	Score
DesignCAD 2D	44.75
AutoCAD R12	84.5
Generic CADD	44.75
DataCAD	56
Drawbase	44
Claris CAD	23
VersaCAD	38
PowerDraw	22.25
MicroStation V. 5	93.25
Cadvance	65

4.3 Life Cycle Cost Analysis of Preferred Alternatives

The economic considerations of purchasing CAD software are very important to the decision making role of the systems engineering analysis. Comparing the two alternative CAD software packages on the basis of the identified costs is an essential step towards selecting the best package. Life cycle cost is a critical attribute to be considered during a complete multiattribute analysis of the two preferred alternatives. The equivalent cost is not considered as the primary decision making criteria, and it will be used in following sections that detail the multiattribute analysis. The goal is to identify the equivalent worth costs of the two CAD software alternatives and incorporate that information into the decision making process.

This section of the paper details the assumptions made prior to the life cycle cost analyses for the two preferred alternatives, and the application of the equivalent worth methods to the life cycle cost data.

4.3.1 Assumptions

Several assumptions are made prior to performing the economic analysis.

First, all calculations will be made using before tax equivalent worth methods.

Second, both alternatives are assumed to have the same benefits, hence only the costs are considered.

Third, the interest rate used in all equivalent worth calculations is 10 %.

Fourth, the life of both alternatives is the same, and is assumed to be four years.

Fifth, neither alternative has a salvage value.

4.3.2 Equivalent Worth Calculations for Alternatives

The procedure utilized for systematically comparing the two alternatives' equivalent worth is outlined as shown:

1. Identify the alternatives
2. Specify the evaluation period
3. Estimate the cash flows for each alternative
4. Specify the interest rate
5. Calculate the equivalent worth
6. Compare the alternatives

Blanchard and Fabrycky identify three factors that must be known prior to determining equivalent sums of money: " (1) the amount of the sums, (2) the time occurrence of the sums, and (3) the interest rate." (16) The economic equivalence function is defined symbolically by

E = f (F, i, n) **Equation 1**

where E = present, annual, or future equivalent worth

F = the sum of money, either positive or negative,
at the end of the year

i = annual interest rate

n = number of years for evaluation.

For convenience, all costs that occur during the year are assumed to occur at the start of the next year. Blanchard and Fabrycky indicate that this assumption introduces an insignificant error when compared to the typical errors made in the initial estimates. (17)

Two equivalence evaluations were performed for each alternative using the available cost data. The Present Equivalent Evaluations allow for the comparison of the alternatives on the basis of equivalent cost at the present time, which is assumed to be January 1, 1994 in this study. The Annual Equivalent Evaluation calculates the annual equivalent cost series over the life of the CAD software, which is expected to be three years. The data required to perform the equivalent cost calculations is presented in Tables 5 and 6. The series of calculations and the results are detailed on the next few pages. Schematic models for the money flow over time are presented for both alternatives in Figures 19 and 20. Downward arrows in the schematic models are commonly used to represent disbursements or expenses.

Alternative 1

Package Name:	**AutoCAD Release 12 for Windows**
Manufacturer:	Autodesk Incorporated
Vendor:	CAD Microsystems, Incorporated 6183 Grovedale Court, Suite 200 Alexandria, Virginia 22310
Cost Data:	See Table 5

Table 5. Summary of Cost Data for Alternative 1

Acquisition Cost:	$ 2,745.00
Training Fees:	$ 750.00
Travel for Training:	$ 15.00
Installation:	$ 200.00
Hot Line Support:	$ 375.00 / year
Maintenance:	$ 100.00 / year
Upgrade Cost:	$ 475.00 in Jan. 1996
Salvage Value:	$ 0.00

Alternative 1: AutoCAD Release 12 for Windows

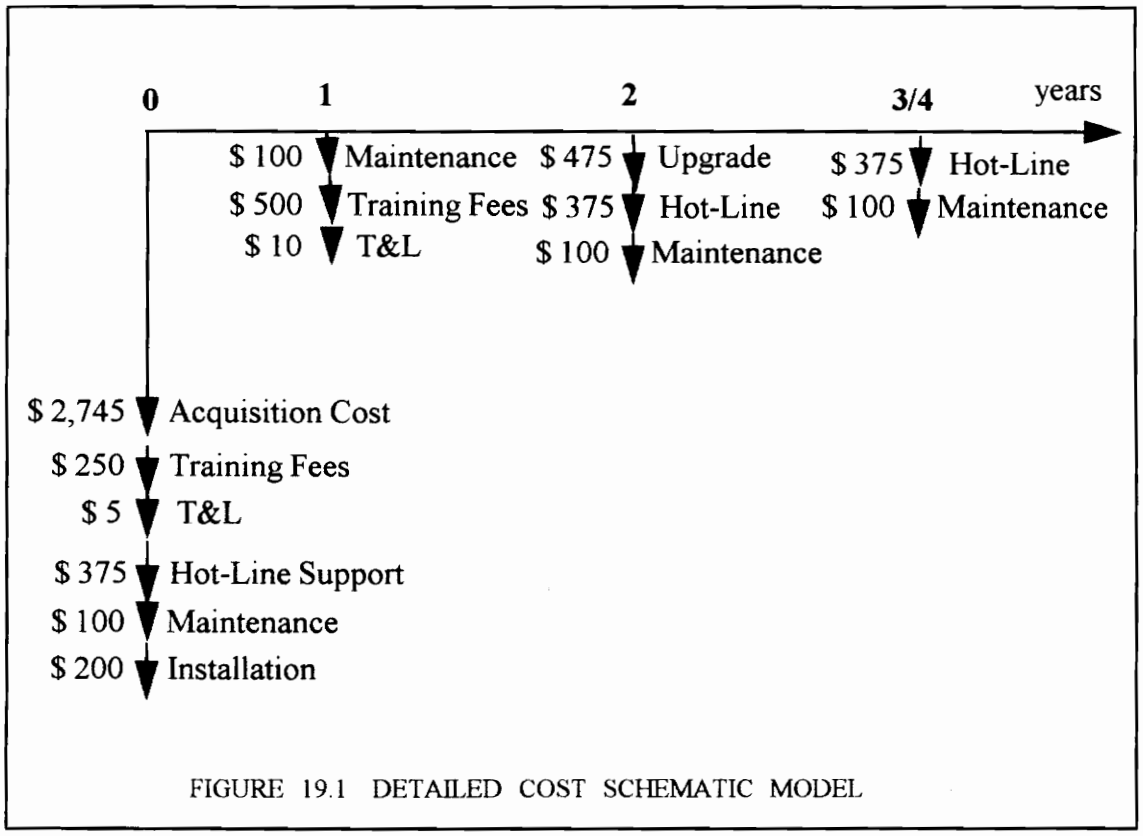


FIGURE 19.1 DETAILED COST SCHEMATIC MODEL

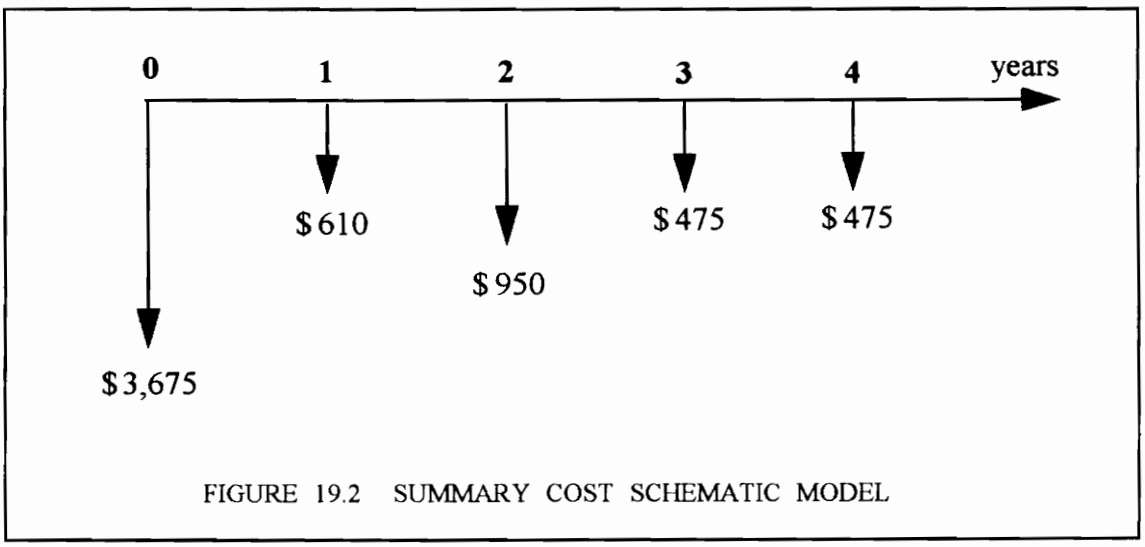


FIGURE 19.2 SUMMARY COST SCHEMATIC MODEL

FIGURE 19. SCHEMATIC MODEL OF ALTERNATIVE 1 COSTS

Reviewing the schematic model of the life cycle costs for Alternative 1, the present worth cost (PW-C) and equivalent uniform annual cost (EUAC) calculations are performed as follows:

Present Worth Cost: (PW-C)

$$PW\text{-}C = 3675 + 610 (P/F, 10\%, 1) + 950 (P/F, 10\%, 2) + 475 (P/F, 10\%, 3) + 475 (P/F, 10\%, 4)$$

Substituting values for the factor functional symbols taken from Canada and Sullivan (18):

$$= 3675 + 610 (.9091) + 950 (.8265) + 475 (.7513) + 475 (.6830)$$

PW-C= $ 5696.02

Equivalent Uniform Annual Cost: (EUAC)

$$EUAC = \{ 3675 + 610 (P/F, 10\%, 1) + 950 (P/F, 10\%, 2) + 475 (P/F, 10\%, 3) + 475 (P/F, 10\%, 4)\} (A/P, 10\%, 4)$$

$$= \{ 3675 + 610 (.9091) + 950 (.8265) + 475 (.7513) + 475 (.6830)\} (.3155)$$

EUAC = $ 1797.09

Alternative 2

Package Name:	**MicroStation PC Version 5**
Manufacturer:	Intergraph Corporation
Vendor:	HM Systems, Incorporated 18221-A Flower Hill Way Gaithersburg, Maryland 20879
Cost Data:	See Table 6

Table 6. Summary of Cost Data for Alternative 2

Acquisition Cost:	$ 2,950.00
Training Fees:	$ 1800.00
Travel for Training:	$ 30.00
Installation:	$ 200.00
Hot Line Support:	$ No charge
Maintenance:	$ 100.00 / year
Upgrade Cost:	$ 100.00 in Jan. 1996
Salvage Value:	$ 0.00

Alternative 2: MicroStation PC Version 5

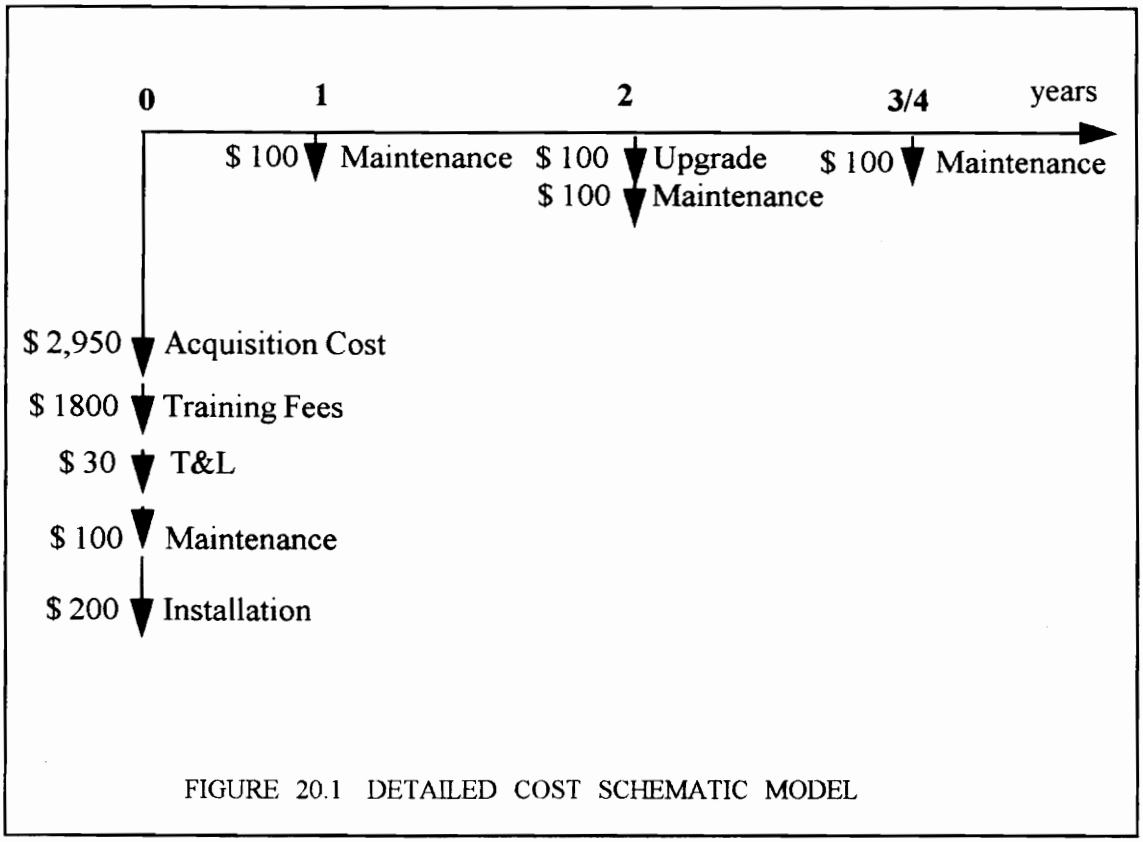


FIGURE 20.1 DETAILED COST SCHEMATIC MODEL

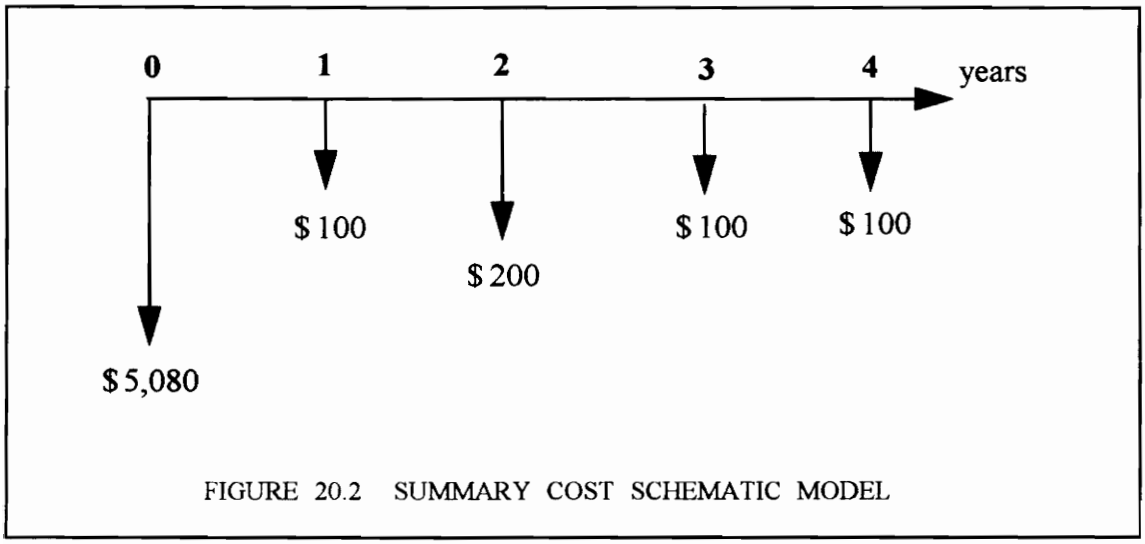


FIGURE 20.2 SUMMARY COST SCHEMATIC MODEL

FIGURE 20. SCHEMATIC MODEL OF ALTERNATIVE 2 COSTS

Reviewing the schematic model of the life cycle costs for Alternative 2, the present worth cost (PW-C) and equivalent uniform annual cost (EUAC) calculations are performed as follows:

Present Worth Cost: (PW-C)

$$PW\text{-}C = \$\ 5080 + 100\,(\ P/F,\ 10\%,\ 1\ ) + 200\,(\ P/F,\ 10\%,\ 2\ ) + 100\,(\ P/F,\ 10\%,\ 3\ ) + 100\,(\ P/F,\ 10\%,\ 4\ )$$

Substituting values for the factor functional symbols taken from Canada and Sullivan (18):

$$= \$\ 5080 + 100\,(\ .9091\ ) + 200\,(\ .8265\ ) + 100\,(\ .7513\ ) + 100\,(\ .6830\ )$$

PW-C= $ 5479.64

Equivalent Uniform Annual Cost: (EUAC)

$$EUAC = \$\{\ 5080 + 100\,(\ P/F,\ 10\%,\ 1\ ) + 200\,(\ P/F,\ 10\%,\ 2\ ) + 100\,(\ P/F,\ 10\%,\ 3\ ) + 100\,(\ P/F,\ 10\%,\ 4\ )\}\ (\ A/P,\ 10\%,\ 4)$$

$$= \$\{\ 5080 + 100\,(\ .9091\ ) + 200\,(\ .8265\ ) + 100(\ .7513) + 100\,(\ .6830\ )\}\ (\ .3155\ )$$

EUAC = $ 1728.83

4.3.3 Results of the Equivalent Economic Worth Calculations

Table 16 shows the results of the present worth equivalent cost and the annual worth equivalent cost calculations. It appears that Alternative 2, MicroStation PC Version 5 is slightly less expensive. If both CAD software packages offered the same capabilities, then these results would provide enough information to make a final choice between the two alternatives. However, since the two CAD software packages offer slightly different capabilities, a more detailed analysis is required through an application of the Analytic Hierarchy Process.

Table 7. Summary of Equivalent Economic Worth Calculations

	Alternative 1 (AutoCAD R12)	**Alternative 2** (MicroStation V5)
PW-C	**$ 5696.02**	**$ 5479.64**
EUAC	**$ 1797.09**	**$ 1728.83**

4.4 Description of Analytic Hierarchy Process

Given the broad range of attributes and requirements that are to be used to select a CAD software package, a more detailed and quantitative methodology is needed for the evaluation. The selected methodology, the Analytic Hierarchy Process (AHP), provides the decision maker with the ability to structure a complex multiattribute problem hierarchically. AHP was developed by Thomas Saaty and is described in Canada and Sullivan in Chapter 10. Figure 21 is a model of the attributes, subattributes, and alternatives to show how the problem can be structured for analysis. Comparisons of the alternatives and attributes (also referred to as elements) in a "pairwise" method promotes establishing a scale to indicate the relative strength of the elements. The scale is converted into priority weights or scores that are used in the comparison of alternatives.

The Analytic Hierarchy Process offers many benefits over other evaluation techniques. First, it is easy to understand and use. Second, AHP necessitates developing a hierarchy of attributes and subattributes, which promotes and encourages communication of the problem and the recommended solution. Finally, it offers a unique means of quantifying both subjective and objective criteria.

The calculations required by AHP are time consuming and tedious. A software program called Automan was developed by Stephen F. Weber at the National Institute of Standards and Technology that automates the

analytic hierarchy process. Automan accepts the inputs and model information, creates the AHP model, calculates the preference values, and provides a recommendation. The computer generated output from Automan for this model is located in Appendix B.

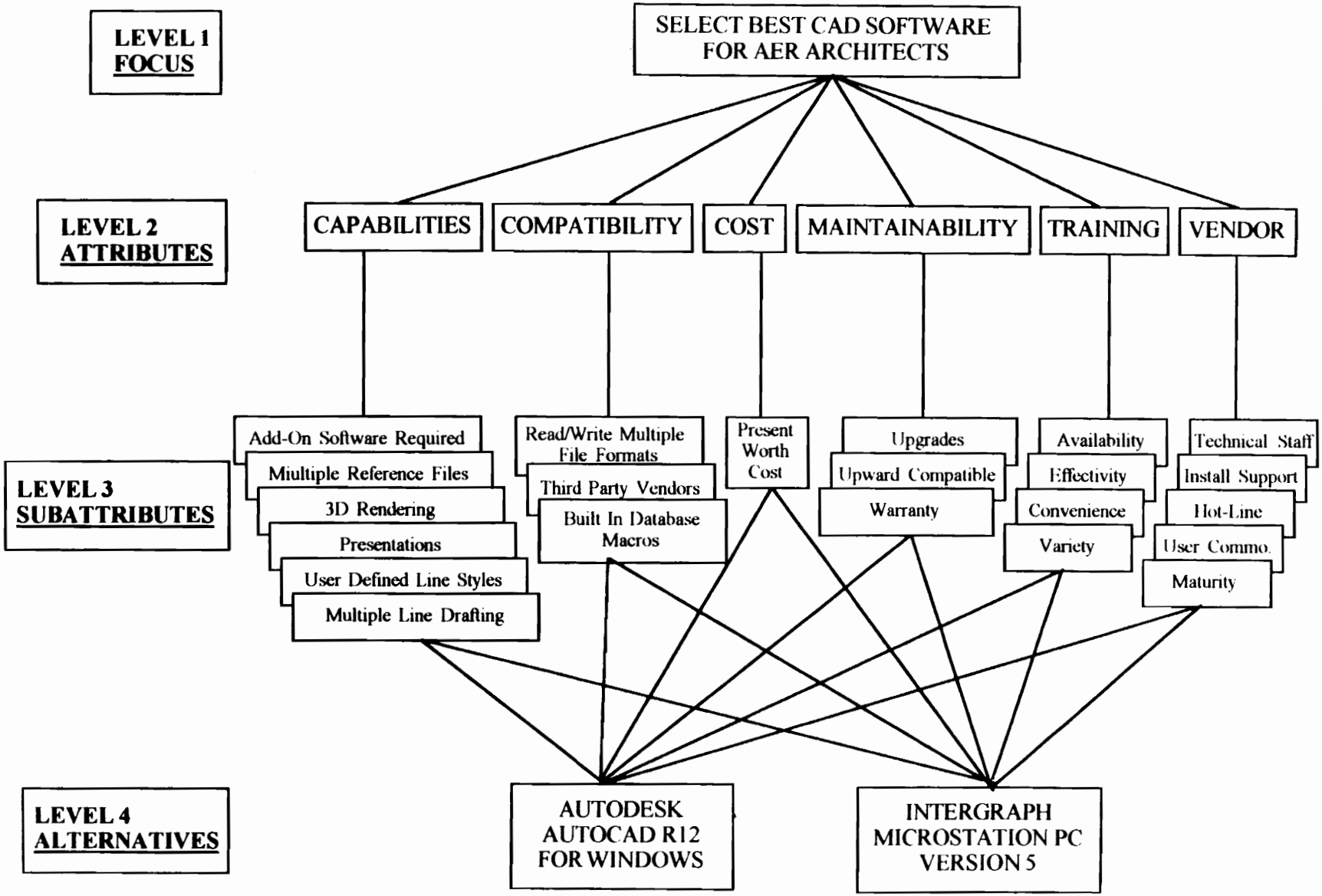


FIGURE 21. ANALYTIC HIERARCHY PROCESS MODEL

4.5 Application of Analytic Hierarchy Process

Each of the following categories were defined as critical requirements during the functional analysis activities of the Preliminary Design Phase. Each category constitutes an attribute of the CAD system software. The summary of requirements in the end of Chapter Three show which subattributes are paired with each attribute. Figure 21 also shows these relationships.

Capabilities

Compatibility

Cost

Maintainability

Training

Vendor

Pairwise comparisons between the attributes, among the subattributes within each attribute category, and between each alternative and the subattributes were generated with the Principal Architect, and were based on his familiarity with each of the "preferred" software packages. The Principal Architect had a very active role in the evaluation and comparisons of the two packages, and made multiple trips to both vendors for demonstrations, training, and product reviews. His requirements and relative ranking were translated into weightings and input into Automan. Several iterations of Automan were run until the Principal Architect was satisfied with the weightings calculated by the evaluation program. The final run produced the results located in Appendix B.

4.6 Results of Analytic Hierarchy Process

Reviewing the results in Appendix B shows a very strong preference for Intergraph's MicroStation PC Version 5. MicroStation is selected over AutoCAD by a 71% majority. The combination of the attribute weightings and the software product ratings by the Principal Architect indicate that the MicroStation software is the most satisfactory product. Based on the volume of information and requirements that were defined and input into Automan, the results are a good indication of how well the two packages would satisfy the Principal Architect. MicroStation PC Version 5 appears to be a superior product and will provide the best match for the Principal Architect's needs.

A sensitivity analysis was performed on the results of the Automan multiattribute analysis. Appendix C has the sensitivity analysis output from Automan. Review of the graphs shows that the selection of MicroStation PC Version 5 is not sensitive to minor alterations in the weightings of the attributes or subattributes. This indicates that the selection of MicroStation is a valid selection and is not easily swayed by changing one weighting. A completely different set of weightings would have to be applied to the attributes and subattributes for a different conclusion to be reached.

The Analytic Hierarchy Process shows that very complex multiattribute problems can be manipulated mathematically and reduced to simple equations to assist the evaluating party in reaching a valid decision.

CHAPTER FIVE

FUTURE STUDY RECOMMENDATIONS

5.1 Hardware Study and Evaluation

Completing the Detail Design Phase of this project will require an extensive hardware study. The selected software alternatives require a hardware configuration as described in the next few paragraphs. The identification and trade-off analysis based on a market study of hardware is beyond the scope of this project. However, it is the next step that must be completed prior to the purchase of software or hardware. The proposed "system" to satisfy AER's definition of need requires one complete Personal Computer (PC), to include a monitor (or two), central processing unit (CPU), keyboard, mouse, printer, and the computer aided software design package. Figure 22 is a conceptual drawing of the required system components.

Two monitors have been mentioned several times by the Principal Architect as a hardware requirement because the secondary monitor can be filled with the menus and icons that are used to control the software. The secondary monitor shall be a small, black and white monitor. This leaves the primary monitor free for the architectural design field. The primary monitor shall be much larger, with smaller resolution and a large color scale. The design is much easier to manipulate when it is larger and displayed in color and great detail. Several CAD systems on the market,

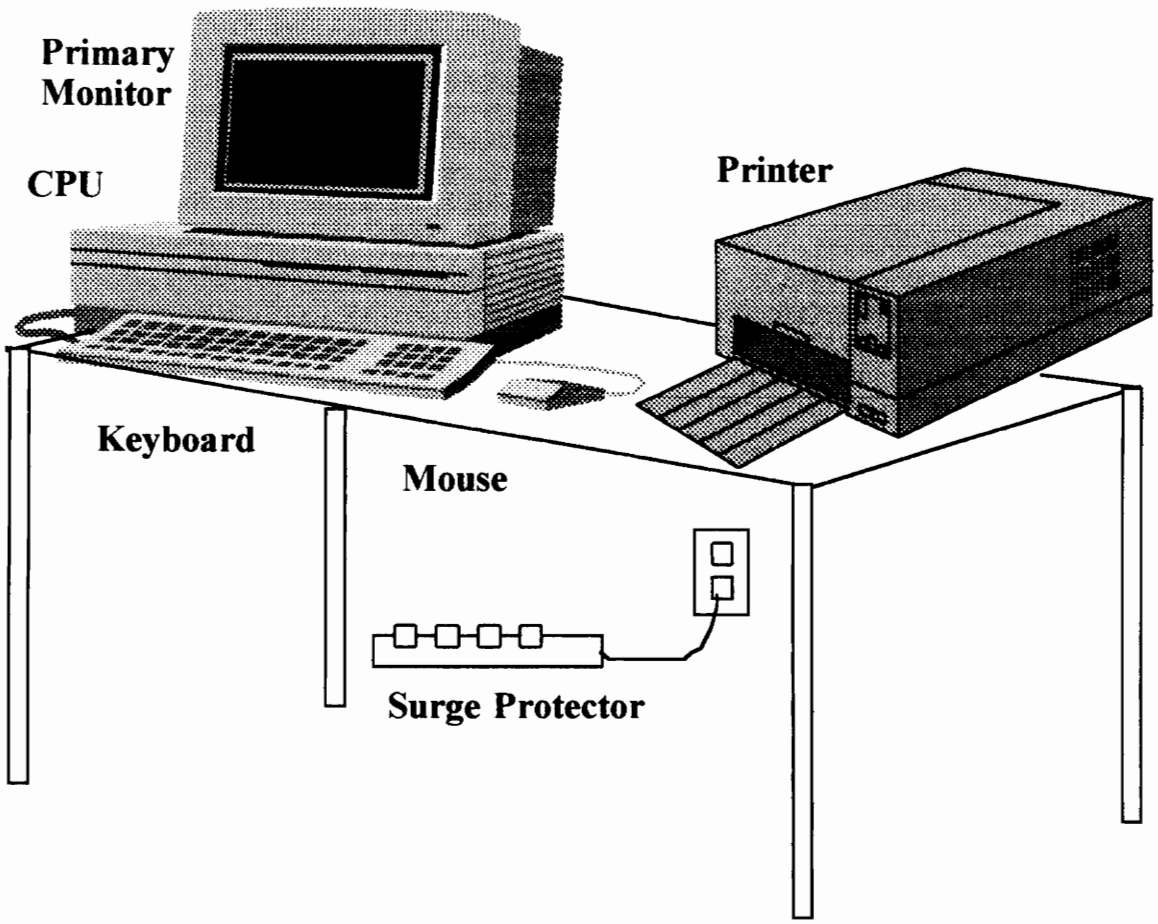


FIGURE 22. PROPOSED SYSTEM HARDWARE CONFIGURATION

including Intergraph Microstation PC Version 5 can be configured easily to a two monitor operating scenario.

5.1.1 Hardware Operating Environment

The system will be placed on an existing computer table in AER's office and shall be powered and protected from power surges by an existing urge protector. The computer table will reside in an office controlled to typical household comfort standards of 70 degrees in the winter and 78 degrees in the summer. Humidity is controlled by both a dehumidifier and a humidifier. New windows in the office were recently installed to minimize drafts and the potential for water damage. Venetian blinds control the amount of light accessing the office. The office windows face north, so very little direct sun will strike the venetian blinds.

5.1.2 Benchmark Hardware System

The requirements for performance and physical parameters of the ideal system, or the benchmark, have been determined by the latest trends in the computer industry, with an emphasis on quality, not quantity. The benchmark hardware provides the basis for the evaluation of candidate hardware components. The performance of the assembled system is a critical requirement or the advanced capabilities of the software will be non-functional. Defining the performance characteristics will require additional knowledge into computer architecture, and thorough

understanding of the current capabilities offered by the industry. Specifying the performance requirements is outside the scope of this paper. The hardware system benchmark requirements are detailed in the next few pages.

Both of the "preferred" CAD software programs require a hardware system of these specifications to achieve the vendor and manufacturer specified performance capabilities. Decreasing any of the capacities is likely to have a negative effect on the CAD system's performance.

System Benchmark Specifications

Primary Monitor	17" flat screen
	256 colors
	non-interlaced
	resolution up to 1,024 x 768 pixels, or greater
	tilt and swivel base
	front control panel
Secondary Monitor	11" screen
	black and white
486 DX2/66 MHz CPU	16 MB standard RAM minimum
	1 MB VRAM
	upgradeable to the Pentium Processor
System Hard Drive	248 MB minimum
High or dual density Disk Drive(s)	
	3.5"
	5.25"
Option Slot	3 EISA slots
Mouse	2 button
Keyboard	Standard

5.1.3 Hardware Life Cycle Cost Analysis

A detailed cost analysis on the candidate hardware systems should be performed to determine if the project is feasible within the $ 8,000 budget, or if more money is required. The software cost analysis showed a present worth cost of $ 5,015 leaving less than $ 3,000 for a computer hardware system.

If the budget is expanded following a dramatic increase in productivity from AER Architects, and a resulting increase in cash flow, then additional hardware may be considered for purchase, to enhance the current CAD system operations. The Principal Architect has generated a "wish list" of expensive hardware options for further evaluation. The additional hardware to be evaluated, per discussions with the Principal Architect include:

Plotter

D or E size

Black and White

Scanner

Color

CD ROM

5.2 Networking

Only one hardware system is required at this time, although the capability to network the PC to another in the event of expansion at AER should also be considered in future studies. Networking requires the installation of a Network Interface Card or NIC. NICs are designed to be compatible with the PC by installing the NIC in an Extended Internal Systems Architecture (EISA) slot located in the back of the CPU.

Additional hardware will be required if the Principal Architect wishes to achieve compatibility over the telephone lines in order to facilitate the exchange of files and data with clients, consultants, contractors, and vendors. A high speed modem for data transmission is required to perform this type of activity. Studies must be made into required transmission data rates, modem characteristics, performance data, and costs. Comparisons of this information will indicate which modem will satisfy the requirement.

5.3 Productivity Measurement

In order to fully determine and evaluate the impact of the CAD system on the productivity of AER Architects, a future study must be completed. This activity can be done using the procedures defined by Liggett and Foster in A CAD Productivity Study. The procedures they devised require compiling complete records of the time taken to design, draft, and revise architectural drawings both before and after the implementation of the CAD system in the design process. Calculations based on the times will enable the architecture firm or their Systems Engineer Consultant to measure the productivity improvement ratios. Similar efforts to improve productivity of an architectural firm's design and drafting capabilities by installing CAD systems have resulted in significant gains.

CHAPTER SIX

CONCLUSIONS

6.1 Summary of the Application of the Systems Engineering Process

The systems engineering life cycle process appears to work very well in this application to the evaluation and selection of a computer aided design system for AER Architects. The Conceptual Design Phase specified the operational concept and maintenance requirements through interactive discussions between the Principal Architect and the systems engineer. The multiple meetings with the Principal Architect were an application of a Quality Function Deployment approach which aimed to capture and address all customer attributes in the system design process. The Preliminary Design Phase activities consisted of a functional analysis of the CAD system software and hardware capabilities, which resulted in a series of functional requirements flow diagrams that helped isolate the desired CAD system capabilities from the Principal Architect's point of view.

A market study, industry surveys and interviews with Principal Architects from other Washington D. C. area architecture firms resulted in a list of ten CAD software packages that formed the slate of candidates for the first application of a decision technique. Each package was evaluated on a small selection of criteria designed to identify the best CAD software packages to satisfy several of AER Architects' system level requirements.

Once all the CAD software capabilities were defined, additional requirements including compatibility, cost, maintainability, training, and vendor were documented. Each major category of requirements was identified as CAD system "attributes", and the specific requirements supporting each attribute were referred to as "subattributes." Each of the attributes and subattributes was ranked and weighted in the application of the Analytic Hierarchy Process (AHP), a multiattribute decision making tool. The weights were input into Automan, a computer software program that performs all the calculations required by AHP. Automan calculated the optimal CAD software package from two "preferred packages."

AutoCAD Release 12 for Windows offered significantly fewer of the requirements specified by AER Architects. As a result, Intergraph's MicroStation PC Version 5 was selected by a wide margin as the optimal CAD software package for AER Architects.

The recommended next steps of the system engineering process are to move into the Detailed Design Phase and complete a study of the hardware required to run MicroStation Version 5.

The systems engineering process provided a logical and systematic approach to perform the evaluation and selection of a CAD software package based on the specific requirements of AER Architects.

APPENDIX A

SUMMARY OF CAD PACKAGES EVALUATED

Name of Software Package	Manufacturer
Design CAD 2D	American Small Business Computers
AutoCAD R12 for Windows	Autodesk
Generic CADD	Autodesk Retail
DataCAD	Cadkey Inc.
Drawbase	CADworks Inc.
Claris CAD	Claris Corp.
VersaCAD	Computervision
PowerDraw	Engineered Software
MicroStation PC V.5	Intergraph Corp.
Cadvance	Isicad Inc.

Alternative Evaluated		**DesignCAD 2D**	
Attribute	Normalized Attribute Weight	Evaluation Rating	Weighted Evaluation
Runs on a PC with Microsoft Windows	30	5	15
Compatibility with other Vendors	27	7.5	20.25
3-D Rendering	24	0	0
User Defined Line Styles	19	5	9.5
		Score:	44.75

Alternative Evaluated		**AutoCAD R12**	
Attribute	Normalized Attribute Weight	Evaluation Rating	Weighted Evaluation
Runs on a PC with Microsoft Windows	30	10	30
Compatibility with other Vendors	27	10	27
3-D Rendering	24	7.5	18
User Defined Line Styles	19	5	9.5
		Score:	84.5

Alternative Evaluated		**Generic CADD**	
Attribute	Normalized Attribute Weight	Evaluation Rating	Weighted Evaluation
Runs on a PC with Microsoft Windows	30	5	15
Compatibility with other Vendors	27	7.5	20.25
3-D Rendering	24	0	0
User Defined Line Styles	19	5	9.5
		Score:	44.75

Alternative Evaluated		**DataCAD**	
Attribute	Normalized Attribute Weight	Evaluation Rating	Weighted Evaluation
Runs on a PC with Microsoft Windows	30	5	15
Compatibility with other Vendors	27	5	13.5
3-D Rendering	24	7.5	18
User Defined Line Styles	19	5	9.5
		Score:	56

Alternative Evaluated		**Drawbase**	
Attribute	Normalized Attribute Weight	Evaluation Rating	Weighted Evaluation
Runs on a PC with Microsoft Windows	30	5	15
Compatibility with other Vendors	27	5	13.5
3-D Rendering	24	2.5	6
User Defined Line Styles	19	5	9.5
		Score:	44

Alternative Evaluated		**Claris CAD**	
Attribute	Normalized Attribute Weight	Evaluation Rating	Weighted Evaluation
Runs on a PC with Microsoft Windows	30	0	0
Compatibility with other Vendors	27	5	13.5
3-D Rendering	24	0	0
User Defined Line Styles	19	5	9.5
		Score:	23

Alternative Evaluated		**VersaCAD**	
Attribute	Normalized Attribute Weight	Evaluation Rating	Weighted Evaluation
Runs on a PC with Microsoft Windows	30	5	15
Compatibility with other Vendors	27	5	13.5
3-D Rendering	24	0	0
User Defined Line Styles	19	5	9.5
		Score:	38

Alternative Evaluated		**PowerDraw**	
Attribute	Normalized Attribute Weight	Evaluation Rating	Weighted Evaluation
Runs on a PC with Microsoft Windows	30	0	0
Compatibility with other Vendors	27	2.5	6.75
3-D Rendering	24	2.5	6
User Defined Line Styles	19	5	9.5
		Score:	22.25

Alternative Evaluated		**MicroStation V.5**	
Attribute	Normalized Attribute Weight	Evaluation Rating	Weighted Evaluation
Runs on a PC with Microsoft Windows	30	10	30
Compatibility with other Vendors	27	7.5	20.25
3-D Rendering	24	10	24
User Defined Line Styles	19	10	19
		Score:	93.25

Alternative Evaluated		**Cadvance**	
Attribute	Normalized Attribute Weight	Evaluation Rating	Weighted Evaluation
Runs on a PC with Microsoft Windows	30	10	30
Compatibility with other Vendors	27	5	13.5
3-D Rendering	24	5	12
User Defined Line Styles	19	5	9.5
		Score:	65

APPENDIX B

SUMMARY OF OUTPUT FROM AUTOMAN

Model: AERJ--Expanded Evaluation of CAD S/W Packages 11/01/93 Pg 1

Table 1. Ranking of Alternatives by Overall Rating

RANK	ALTERNATIVE	RATING	
=>1	MicroSta	0.713	
2	AutoCAD	0.287	

Table 2. Model Structure, Weights, Shares, and Inconsistency Ratios

CATEGORY	CRITERION	WEIGHT	SHARE	RATING INCONSISTENCY
CAPABILY	ReqAddOn	0.362	0.171	0.000
	MultiRef	0.222	0.105	0.000
Weight = 0.471	3DRendrg	0.170	0.080	0.000
Inconsistency = 0.009	Presenta	0.139	0.065	0.000
	UserDLS	0.064	0.030	0.000
	MultiLin	0.044	0.021	0.000
COMPATIB	R/WFiles	0.604	0.147	0.000
	3rdParty	0.298	0.072	0.000
Weight = 0.243	DBMacros	0.098	0.024	0.000
Inconsistency = 0.038				
COST	PresWrth	1.000	0.120	0.000
Weight = 0.120				
Inconsistency = 0.000				
MAINTBLY	Upgrades	0.644	0.050	0.000
	UpCompat	0.242	0.019	0.000
Weight = 0.078	Warranty	0.114	0.009	0.000
Inconsistency = 0.013				
TRAINING	Availaby	0.540	0.031	0.000
	Effectiv	0.232	0.013	0.000
Weight = 0.057	Convenie	0.128	0.007	0.000
Inconsistency = 0.016	Variety	0.100	0.006	0.000
VENDOR	TechStaf	0.441	0.013	0.000
	InstalSp	0.247	0.007	0.000
Weight = 0.030	Hot-Line	0.150	0.005	0.000
Inconsistency = 0.007	UserComm	0.091	0.003	0.000
	Maturity	0.071	0.002	0.000

[Inconsistency of pairwise comparisons between categories = 0.031]

*Pairwise comparisons with inconsistency values > 0.1 should be redone.

Table 3. Ratings by Criterion and Overall Ratings of Alternatives

CATEGORY: CRITERION	RATINGS AutoCAD	MicroSta
1: ReqAddOn	0.200	0.800
1: MultiRef	0.059	0.941
1: 3DRendrg	0.125	0.875
1: Presenta	0.100	0.900
1: UserDLS	0.333	0.667
1: MultiLin	0.200	0.800
2: R/WFiles	0.111	0.889
2: 3rdParty	0.667	0.333
2: DBMacros	0.091	0.909
3: PresWrth	0.516	0.484
4: Upgrades	0.545	0.455
4: UpCompat	0.444	0.556
4: Warranty	0.333	0.667
5: Availaby	0.667	0.333
5: Effectiv	0.375	0.625
5: Convenie	0.750	0.250
5: Variety	0.600	0.400
6: TechStaf	0.413	0.588
6: InstalSp	0.545	0.455
6: Hot-Line	0.556	0.444
6: UserComm	0.667	0.333
6: Maturity	0.111	0.889
OVERALL RATING	0.287	0.713

Table 4. Pairwise Comparison Data for Weighting Categories and Criteria and for Rating Alternatives

Comparisons between Categories

	Capably	Compatib	Cost	Maintbly	Training	Vendor
Capably		3.000	4.500	6.000	7.500	9.250
Compatib			2.500	4.000	5.000	6.750
Cost				2.000	2.500	4.000
Maintbly					1.750	3.500
Training						3.000
Vendor						

Comparisons between Criteria within Category: Capably

	ReqAddOn	MultiRef	3DRendrg	Presenta	UserDLS	MultiLin
ReqAddOn		1.500	2.250	3.500	5.000	7.000
MultiRef			1.000	1.500	3.750	6.000
3DRendrg				1.000	2.500	4.000
Presenta					2.000	3.500
UserDLS						1.250
MultiLin						

Comparisons between Criteria within Category: Compatib

	R/WFiles	3rdParty	DBMacros
R/WFiles		2.500	5.000
3rdParty			3.750
DBMacros			

Comparisons between Criteria within Category: Cost

	PresWrth
PresWrth	

Comparisons between Criteria within Category: Maintbly

	Upgrades	UpCompat	Warranty
Upgrades		3.000	5.000
UpCompat			2.400
Warranty			

Comparisons between Criteria within Category: Training

	Availaby	Effectiv	Convenie	Variety
Availaby		2.500	4.000	5.500
Effectiv			1.500	3.000
Convenie				1.000
Variety				

Comparisons between Criteria within Category: Vendor

	TechStaf	InstalSp	Hot-Line	UserComm	Maturity
TechStaf		2.000	3.000	4.500	6.000
InstalSp			1.750	2.500	4.000
Hot-Line				1.500	2.500
UserComm					1.000
Maturity					

Table 4. Pairwise Comparison Data for Weighting Categories and Criteria and for Rating Alternatives

Comparisons between Alternatives rated by Criterion: ReqAddOn

	AutoCAD	MicroSta
AutoCAD		0.250
MicroSta		

Comparisons between Alternatives rated by Criterion: MultiRef

[See Table 5 for Performance Data]

Comparisons between Alternatives rated by Criterion: 3DRendrg

	AutoCAD	MicroSta
AutoCAD		0.143
MicroSta		

Comparisons between Alternatives rated by Criterion: Presenta

	AutoCAD	MicroSta
AutoCAD		0.111
MicroSta		

Comparisons between Alternatives rated by Criterion: UserDLS

	AutoCAD	MicroSta
AutoCAD		0.500
MicroSta		

Comparisons between Alternatives rated by Criterion: MultiLin

[See Table 5 for Performance Data]

Comparisons between Alternatives rated by Criterion: R/WFiles

	AutoCAD	MicroSta
AutoCAD		0.125
MicroSta		

Comparisons between Alternatives rated by Criterion: 3rdParty

	AutoCAD	MicroSta
AutoCAD		2.000
MicroSta		

Comparisons between Alternatives rated by Criterion: DBMacros

	AutoCAD	MicroSta
AutoCAD		0.100
MicroSta		

Comparisons between Alternatives rated by Criterion: PresWrth

[See Table 5 for Performance Data]

Table 4. Pairwise Comparison Data for Weighting Categories and Criteria and for Rating Alternatives

Comparisons between Alternatives rated by Criterion: Upgrades

	AutoCAD	MicroSta
AutoCAD		1.200
MicroSta		

Comparisons between Alternatives rated by Criterion: UpCompat

	AutoCAD	MicroSta
AutoCAD		0.800
MicroSta		

Comparisons between Alternatives rated by Criterion: Warranty

[See Table 5 for Performance Data]

Comparisons between Alternatives rated by Criterion: Availaby

	AutoCAD	MicroSta
AutoCAD		2.000
MicroSta		

Comparisons between Alternatives rated by Criterion: Effectiv

	AutoCAD	MicroSta
AutoCAD		0.600
MicroSta		

Comparisons between Alternatives rated by Criterion: Convenie

	AutoCAD	MicroSta
AutoCAD		3.000
MicroSta		

Comparisons between Alternatives rated by Criterion: Variety

	AutoCAD	MicroSta
AutoCAD		1.500
MicroSta		

Comparisons between Alternatives rated by Criterion: TechStaf

[See Table 5 for Performance Data]

Comparisons between Alternatives rated by Criterion: InstalSp

	AutoCAD	MicroSta
AutoCAD		1.200
MicroSta		

Comparisons between Alternatives rated by Criterion: Hot-Line

	AutoCAD	MicroSta
AutoCAD		1.250
MicroSta		

Table 4. Pairwise Comparison Data for Weighting Categories and Criteria and for Rating Alternatives

Comparisons between Alternatives rated by Criterion: UserComm

	AutoCAD	MicroSta
AutoCAD		2.000
MicroSta		

Comparisons between Alternatives rated by Criterion: Maturity

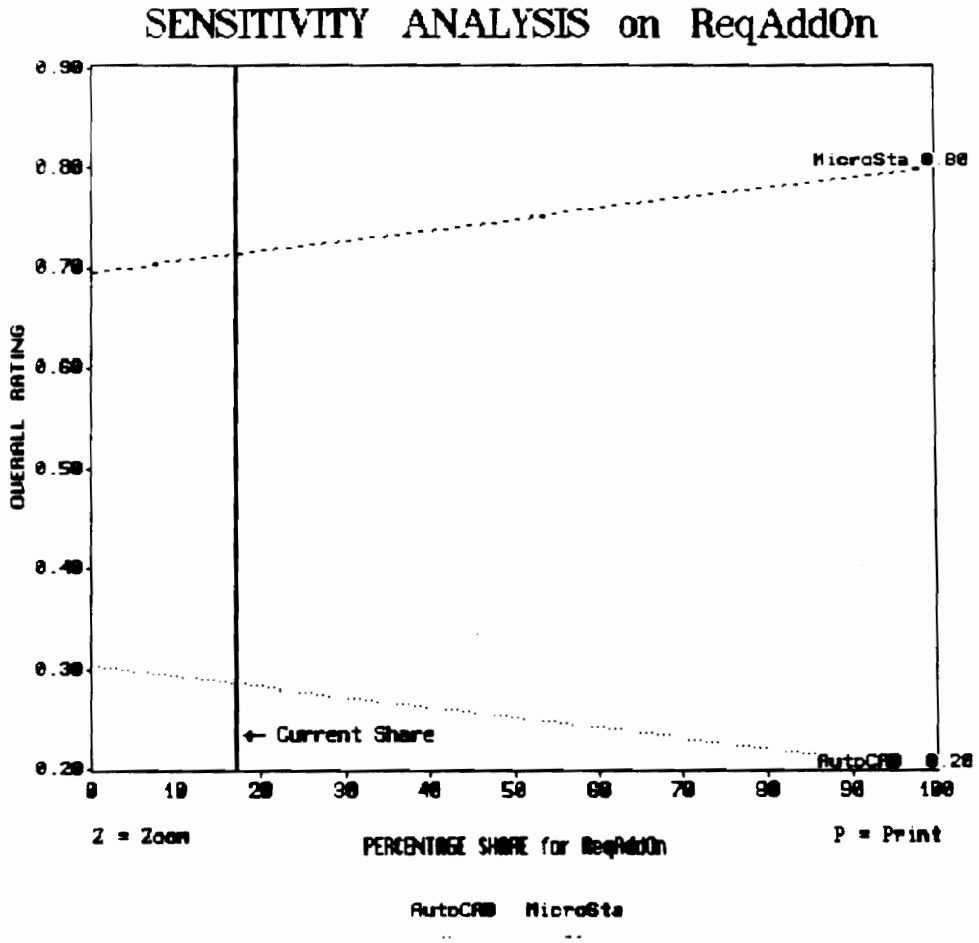
	AutoCAD	MicroSta
AutoCAD		0.125
MicroSta		

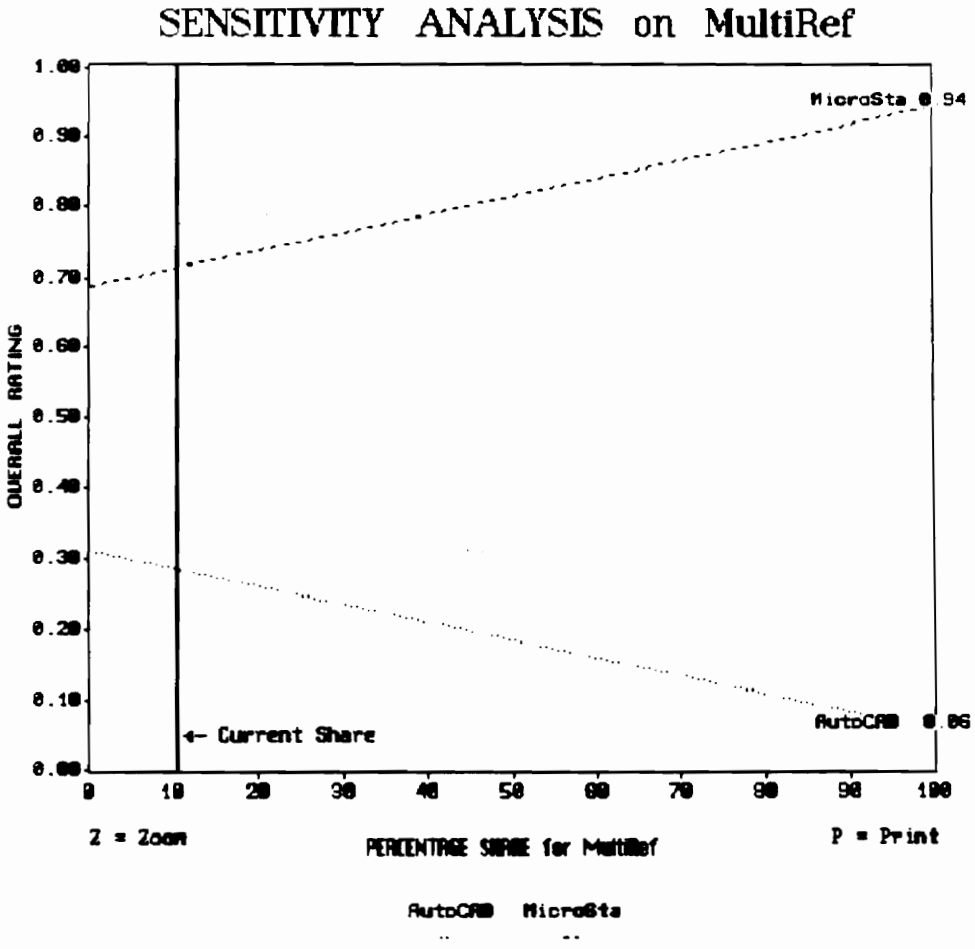
Table 5. Performance Data for Rating Alternatives

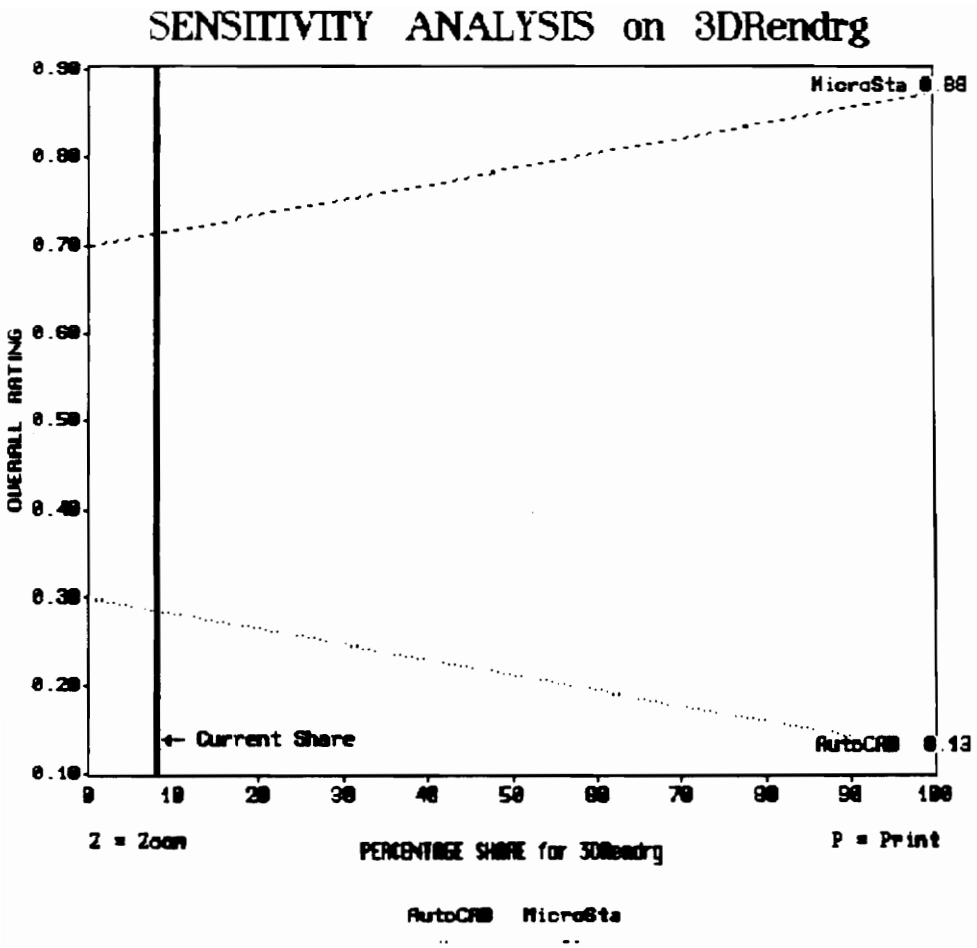
CRITERIA	ALTERNATIVES		IS HIGHER BETTER?
	AutoCAD	MicroSta	
ReqAddOn	[See Table 4 for Pairwise Comparison Data]		
MultiRef	2	32	Yes
3DRendrg	[See Table 4 for Pairwise Comparison Data]		
Presenta	[See Table 4 for Pairwise Comparison Data]		
UserDLS	[See Table 4 for Pairwise Comparison Data]		
MultiLin	4	16	Yes
R/WFiles	[See Table 4 for Pairwise Comparison Data]		
3rdParty	[See Table 4 for Pairwise Comparison Data]		
DBMacros	[See Table 4 for Pairwise Comparison Data]		
PresWrth	5015	5336	No
Upgrades	[See Table 4 for Pairwise Comparison Data]		
UpCompat	[See Table 4 for Pairwise Comparison Data]		
Warranty	1	2	Yes
Availaby	[See Table 4 for Pairwise Comparison Data]		
Effectiv	[See Table 4 for Pairwise Comparison Data]		
Convenie	[See Table 4 for Pairwise Comparison Data]		
Variety	[See Table 4 for Pairwise Comparison Data]		
TechStaf	33	47	Yes
InstalSp	[See Table 4 for Pairwise Comparison Data]		
Hot-Line	[See Table 4 for Pairwise Comparison Data]		
UserComm	[See Table 4 for Pairwise Comparison Data]		
Maturity	[See Table 4 for Pairwise Comparison Data]		

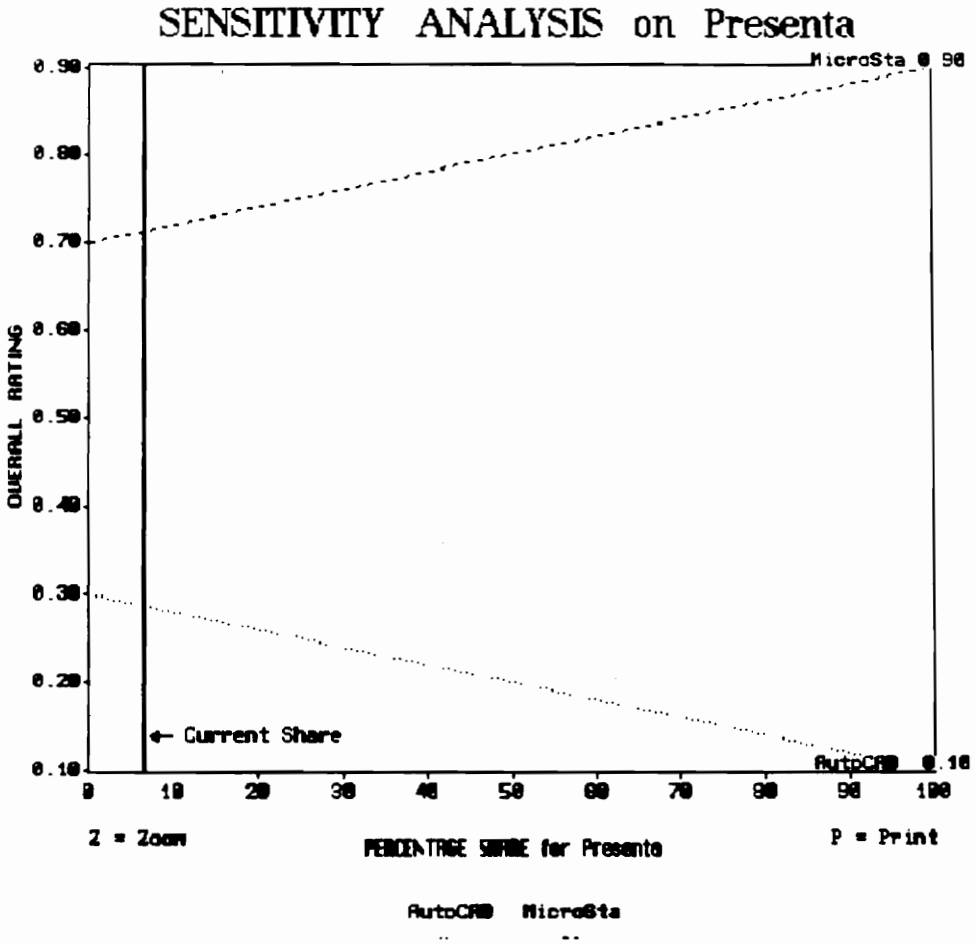
APPENDIX C

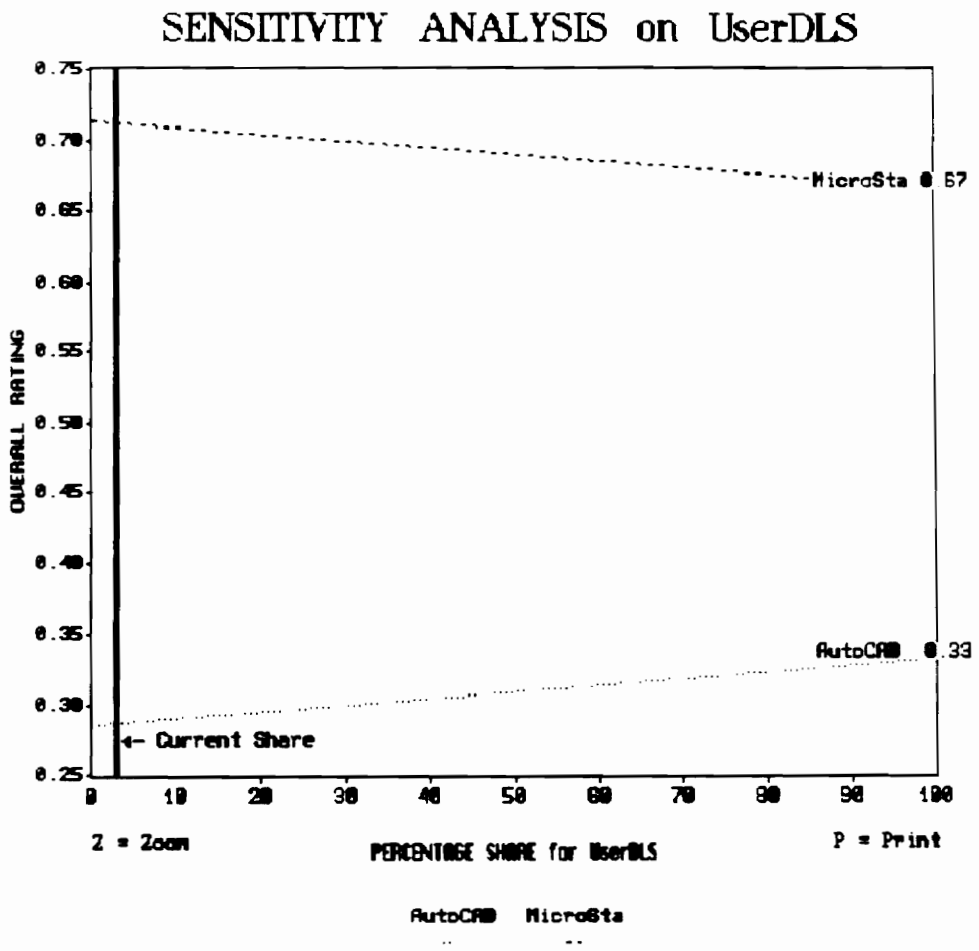
AUTOMAN SENSITIVITY ANALYSIS

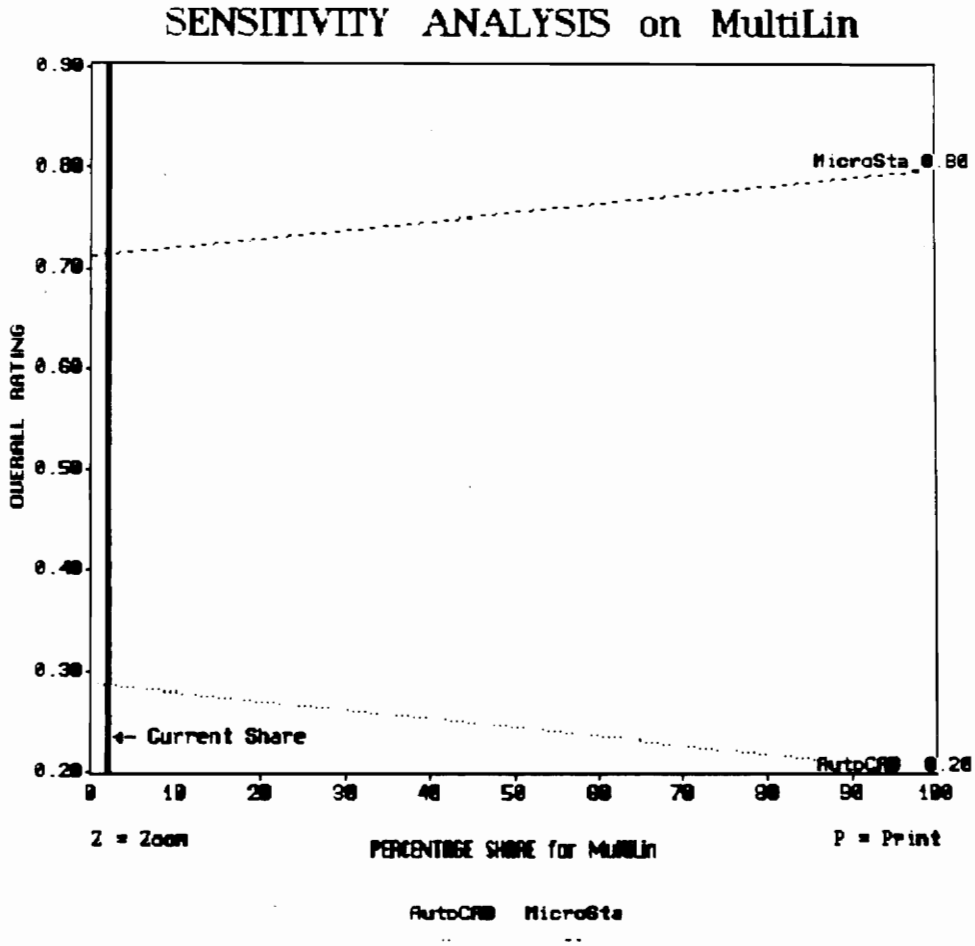

SENSITIVITY ANALYSIS on ReqAddOn
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
OVERALL RATING
MicroSta 0.80
← Current Share
AutoCAD 0.28
0
10
20
30
40
50
60
70
80
90
100
Z = Zoom
PERCENTAGE SHARE for ReqAddOn
P = Print
AutoCAD
MicroSta

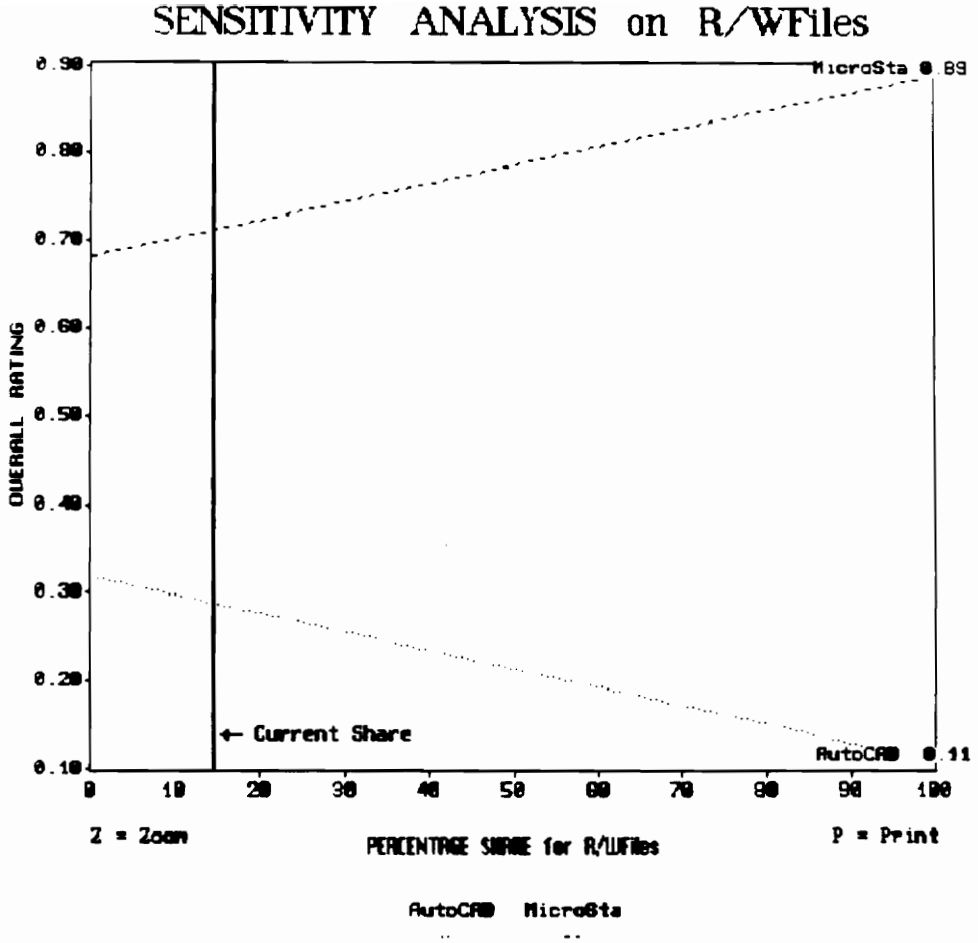

SENSITIVITY ANALYSIS on MultiRef
OVERALL RATING
MicroSta 0.94
AutoCAD 0.06
← Current Share
Z = Zoom
P = Print
AutoCAD MicroSta

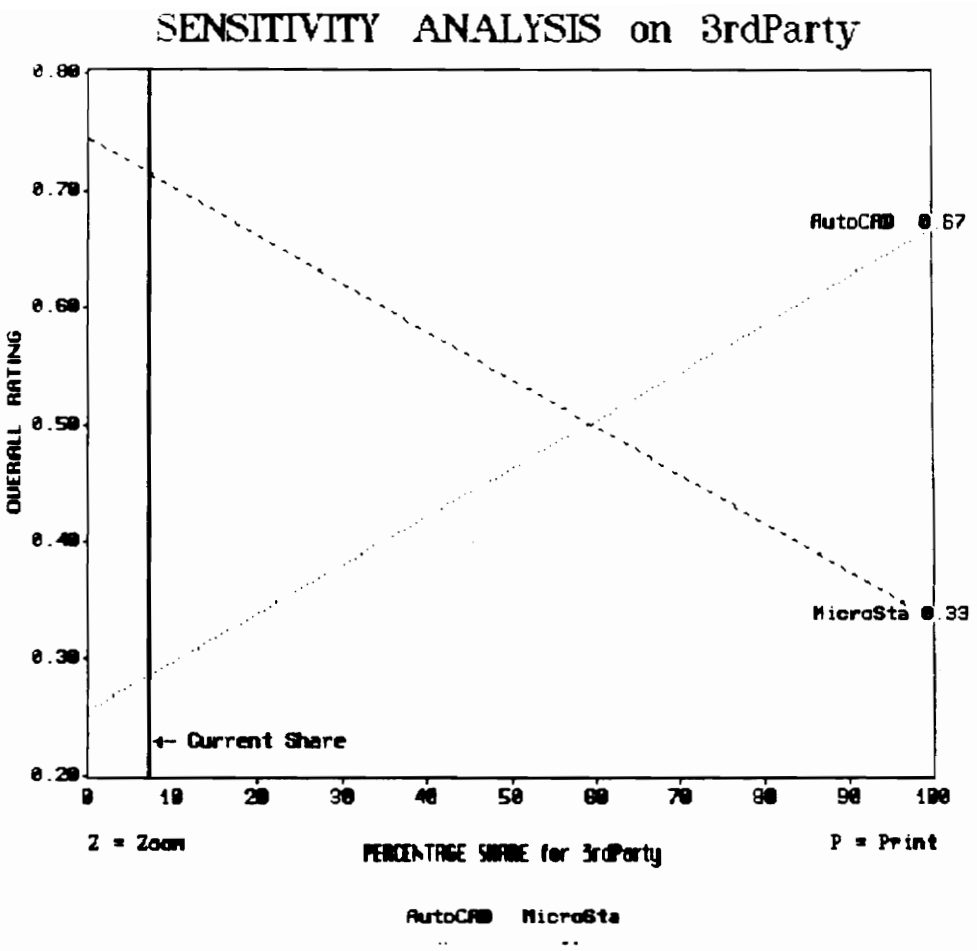

SENSITIVITY ANALYSIS on 3DRendrg
OVERALL RATING
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
MicroSta 0.88
← Current Share
AutoCAD 0.13
0
10
20
30
40
50
60
70
80
90
100
Z = Zoom
PERCENTAGE SHARE for 3DRendrg
P = Print
AutoCAD MicroSta

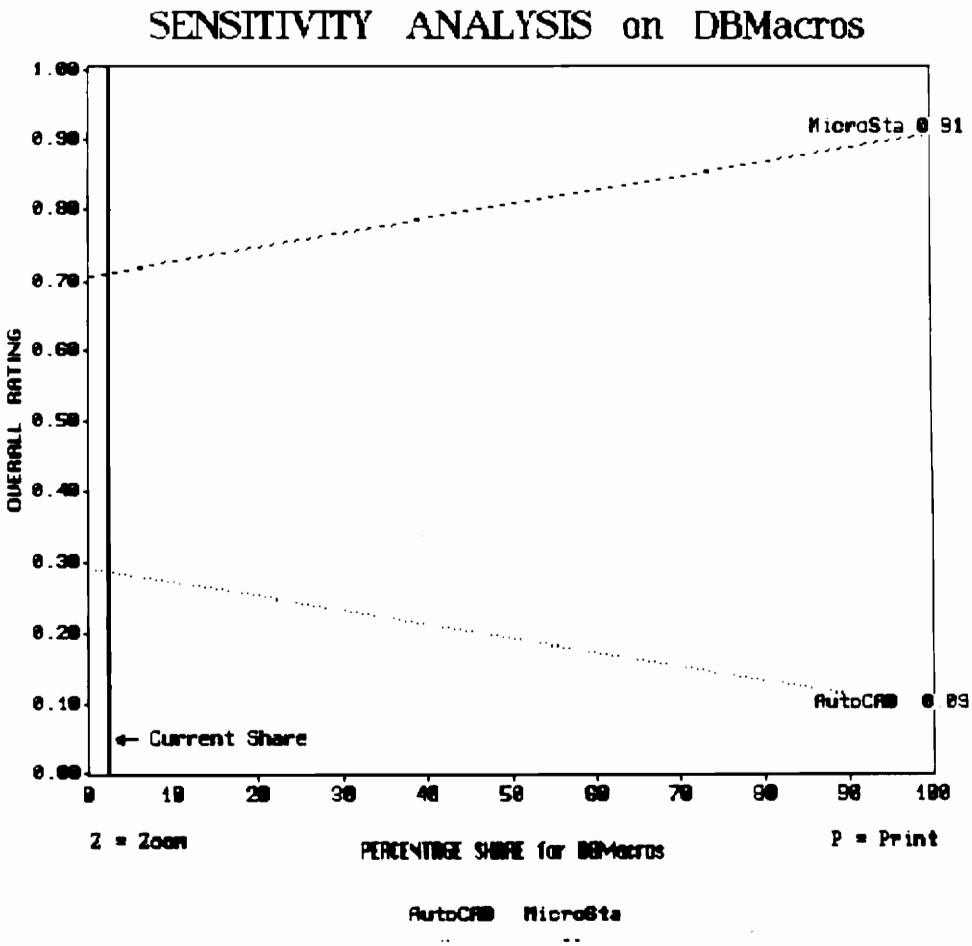

SENSITIVITY ANALYSIS on Presenta
MicroSta @ 90
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
OVERALL RATING
← Current Share
AutoCAD @ 10
0
10
20
30
40
50
60
70
80
90
100
Z = Zoom
PERCENTAGE SHARE for Presenta
P = Print
AutoCAD
MicroSta

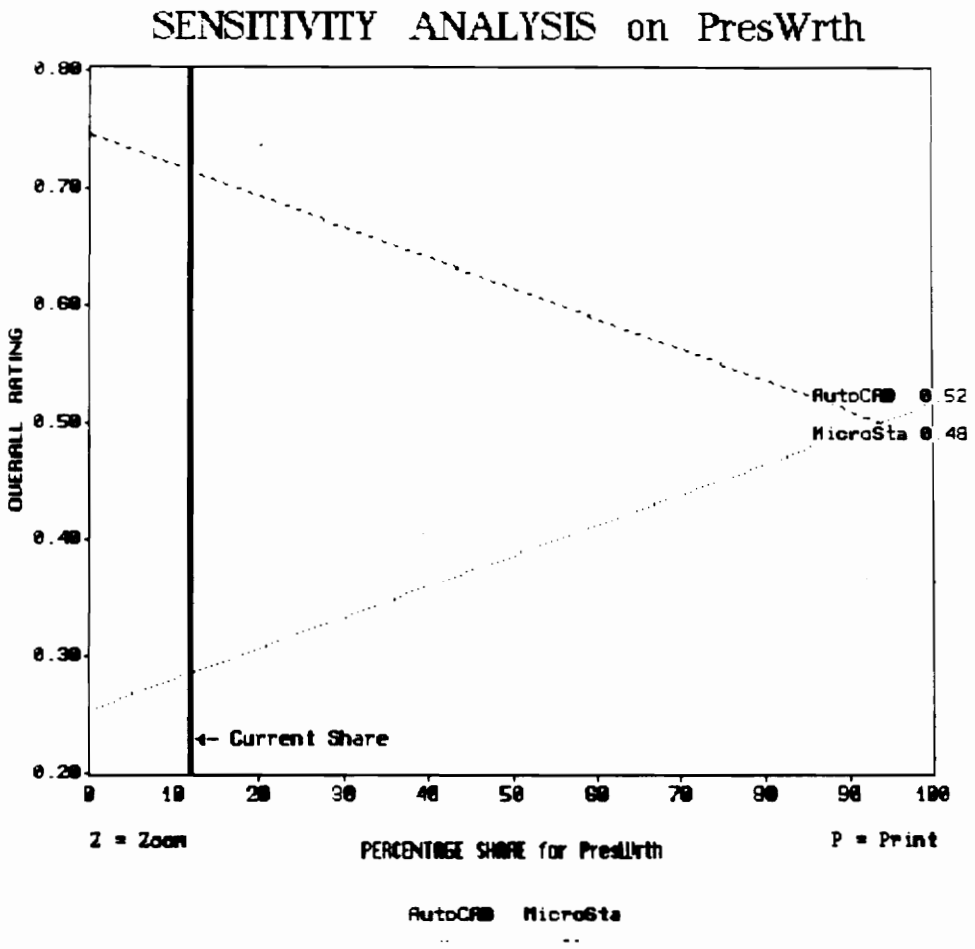

SENSITIVITY ANALYSIS on UserDLS
OVERALL RATING
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
MicroSta 0.67
AutoCAD 0.33
← Current Share
0
10
20
30
40
50
60
70
80
90
100
Z = Zoom
PERCENTAGE SHARE for UserDLS
P = Print
AutoCAD
MicroSta

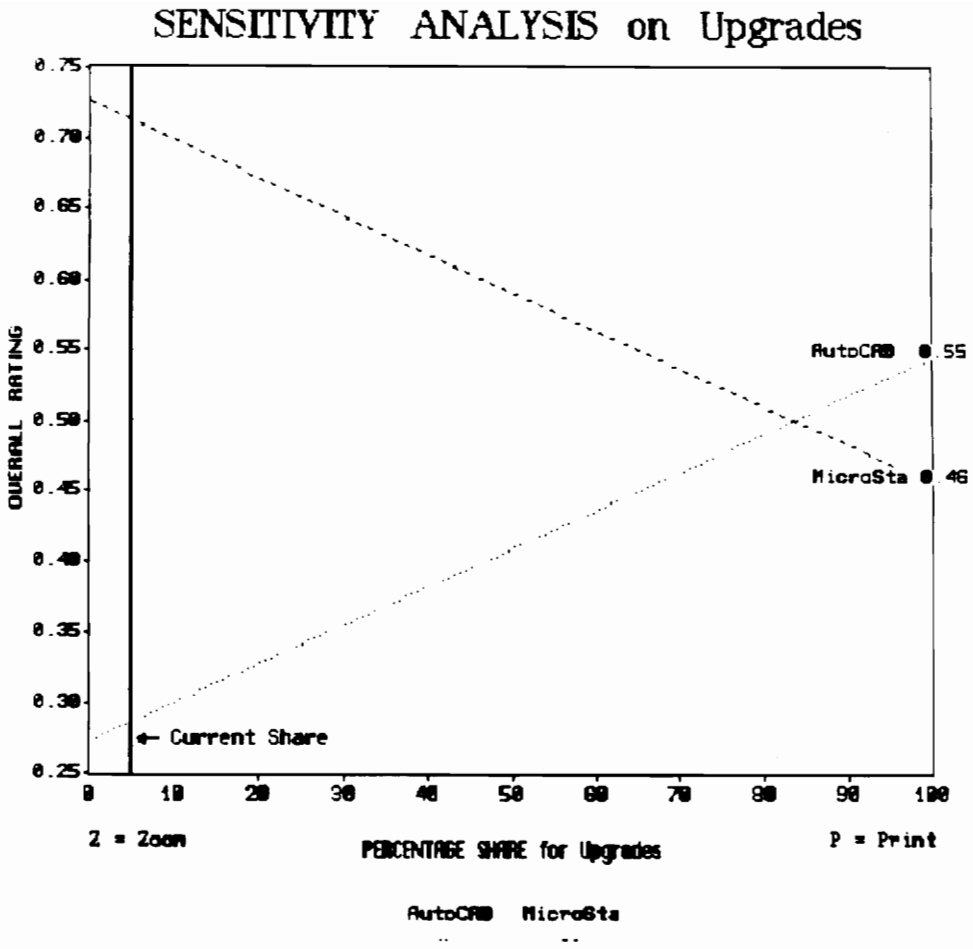

SENSITIVITY ANALYSIS on MultiLin
OVERALL RATING
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
MicroSta 0.80
AutoCAD 0.20
← Current Share
0
10
20
30
40
50
60
70
80
90
100
Z = Zoom
PERCENTAGE SHARE for MultiLin
P = Print
AutoCAD MicroSta

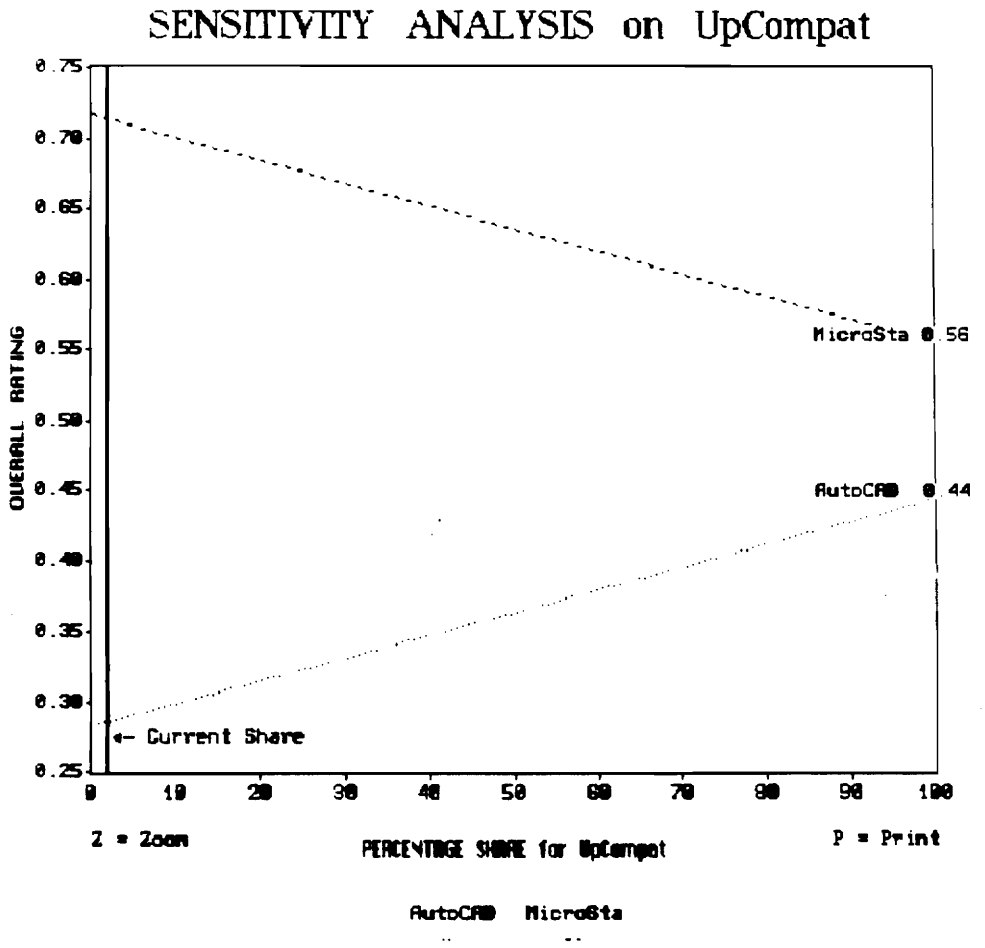

SENSITIVITY ANALYSIS on R/WFiles
MicroSta 0.89
AutoCAD 0.11
← Current Share
OVERALL RATING
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0
10
20
30
40
50
60
70
80
90
100
Z = Zoom
PERCENTAGE SHARE for R/WFiles
P = Print
AutoCAD MicroSta

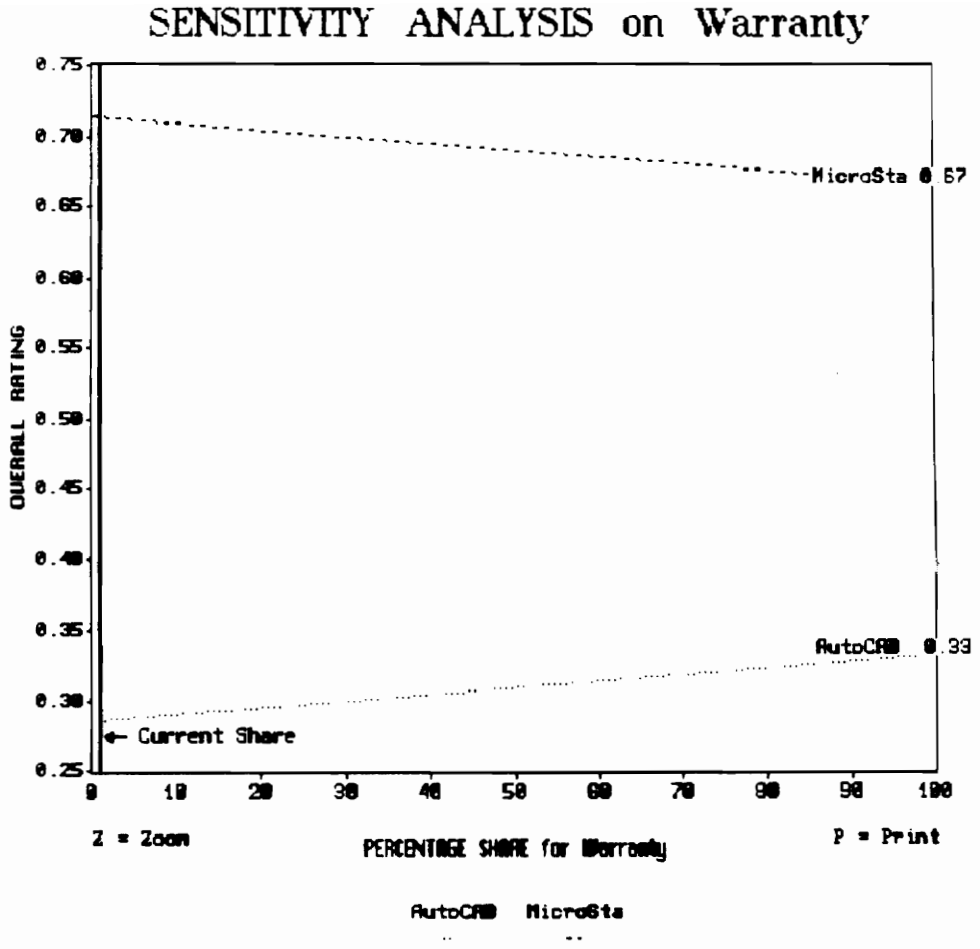

SENSITIVITY ANALYSIS on 3rdParty
OVERALL RATING
0.80
0.70
0.60
0.50
0.40
0.30
0.20
AutoCAD 0.67
MicroSta 0.33
← Current Share
0
10
20
30
40
50
60
70
80
90
100
Z = Zoom
PERCENTAGE SHARE for 3rdParty
P = Print
AutoCAD MicroSta

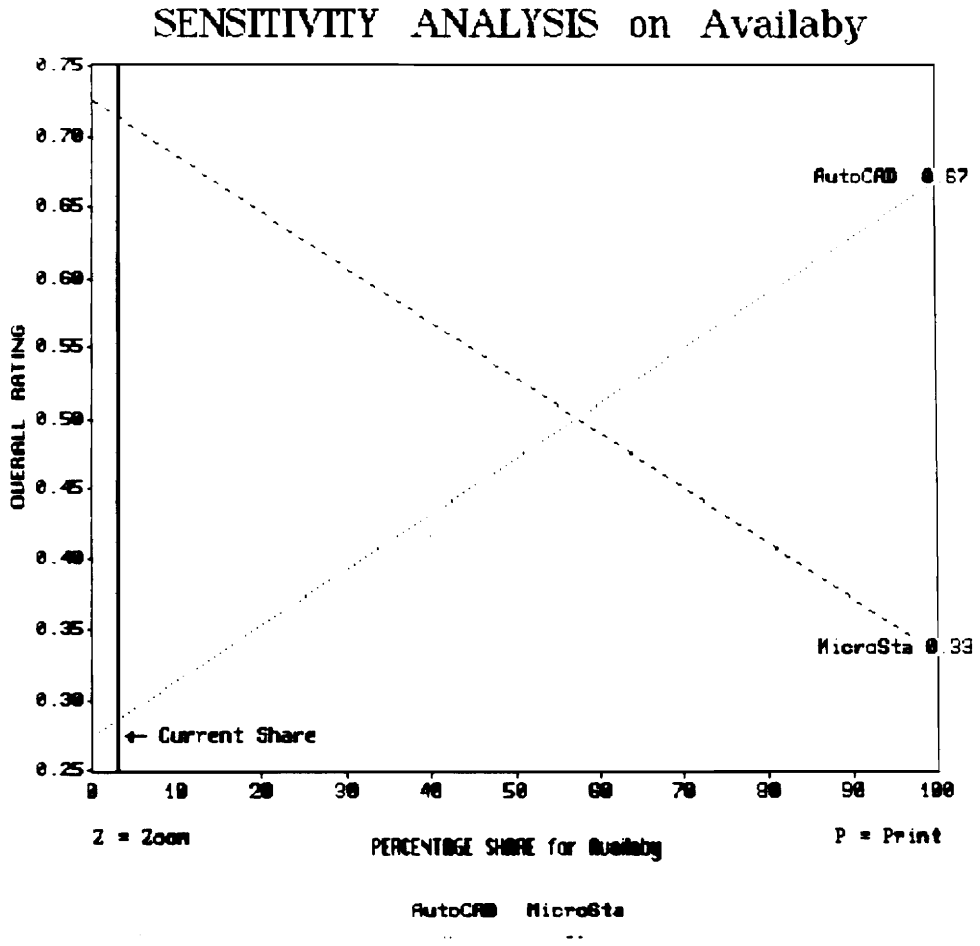

SENSITIVITY ANALYSIS on DBMacros
OVERALL RATING
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
MicroSta 0.91
AutoCAD 0.09
← Current Share
0
10
20
30
40
50
60
70
80
90
100
Z = Zoom
PERCENTAGE SHARE for DBMacros
P = Print
AutoCAD MicroSta

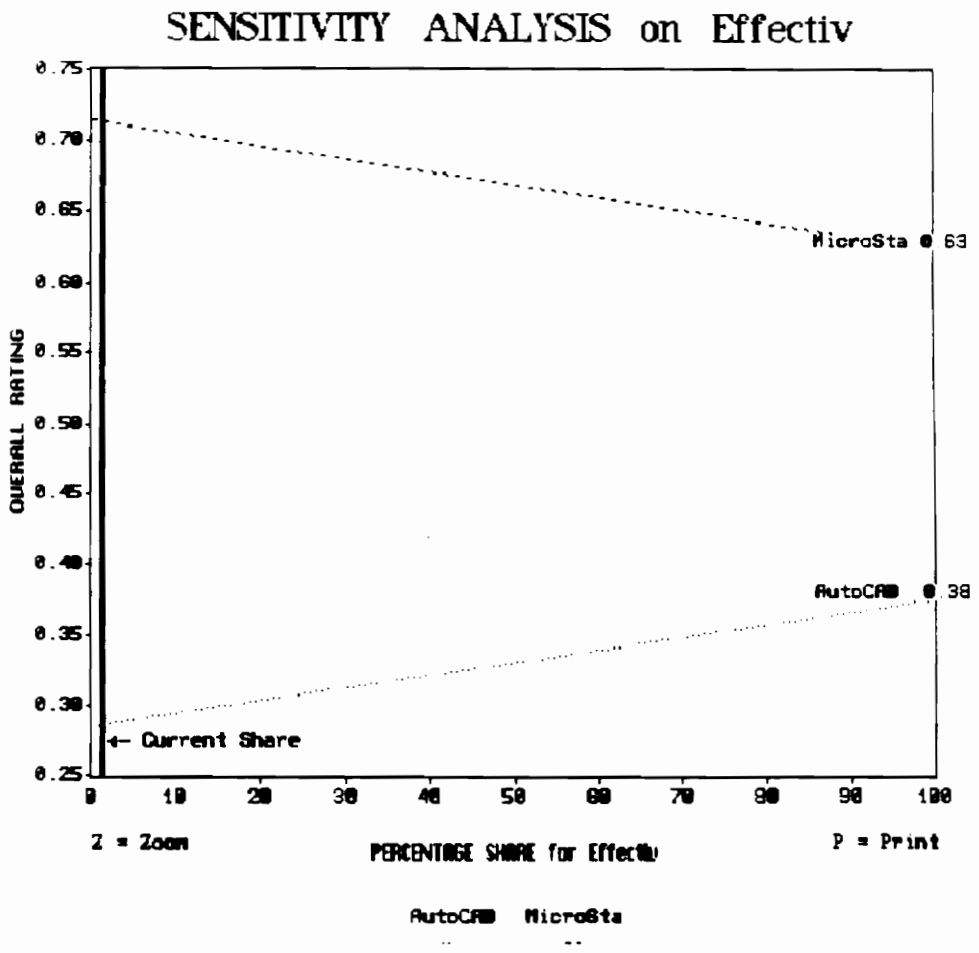

SENSITIVITY ANALYSIS on PresWrth
OVERALL RATING
0.80
0.70
0.60
0.50
0.40
0.30
0.20
AutoCAD 0.52
MicroSta 0.48
← Current Share
0
10
20
30
40
50
60
70
80
90
100
Z = Zoom
PERCENTAGE SHARE for PresWrth
P = Print
AutoCAD MicroSta

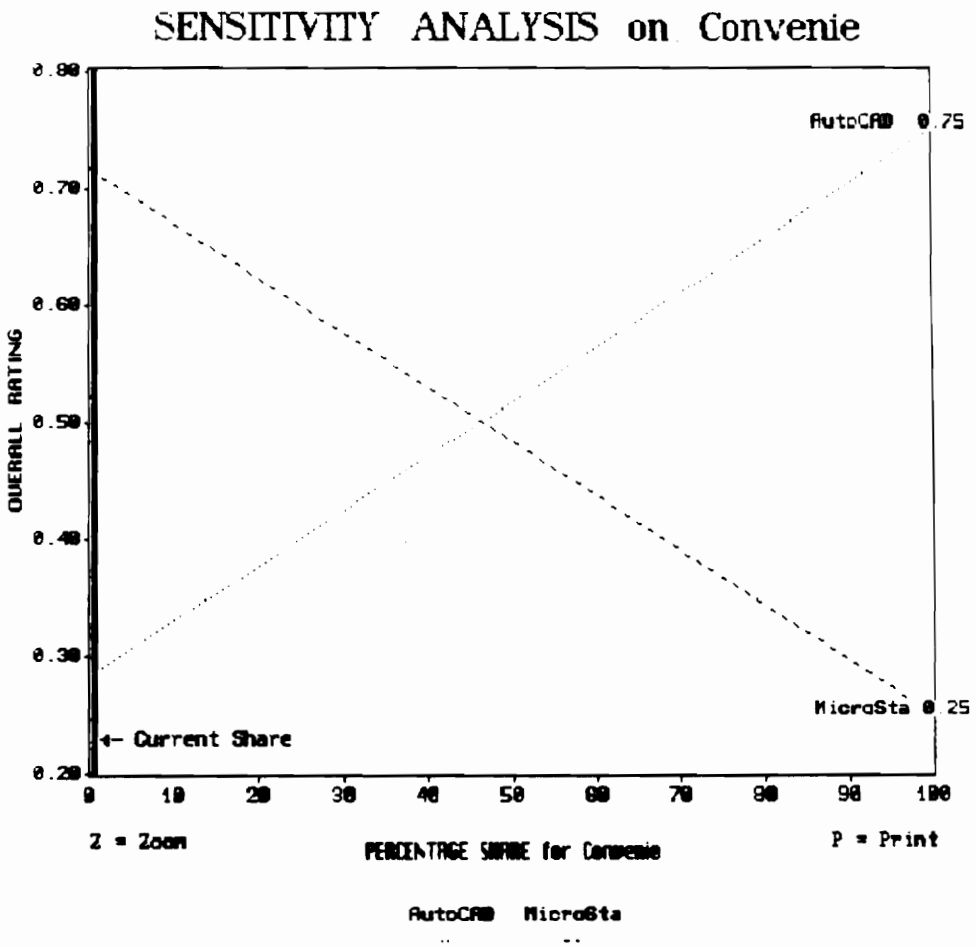

SENSITIVITY ANALYSIS on Upgrades
OVERALL RATING
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
AutoCAD 0.55
MicroSta 0.46
← Current Share
0
10
20
30
40
50
60
70
80
90
100
Z = Zoom
PERCENTAGE SHARE for Upgrades
P = Print
AutoCAD MicroSta

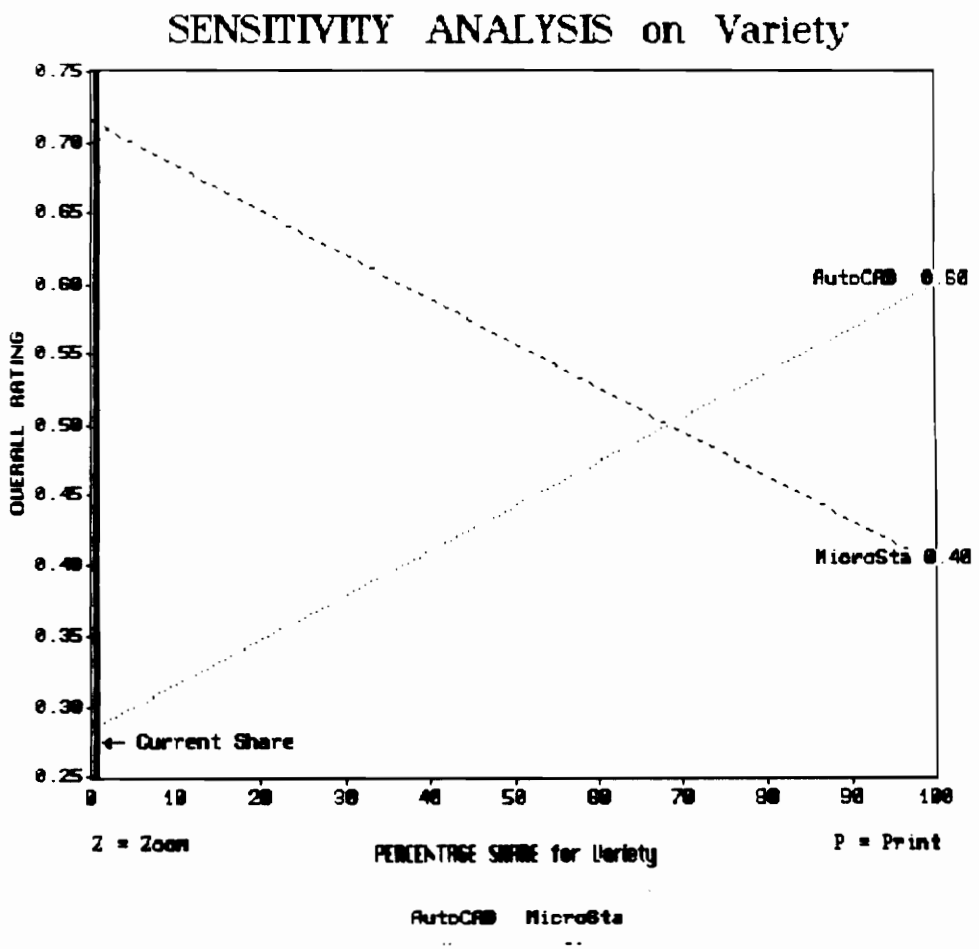

SENSITIVITY ANALYSIS on UpCompat
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
OVERALL RATING
MicroSta 0.56
AutoCAD 0.44
← Current Share
0
10
20
30
40
50
60
70
80
90
100
Z = Zoom
PERCENTAGE SHARE for UpCompat
P = Print
AutoCAD MicroSta

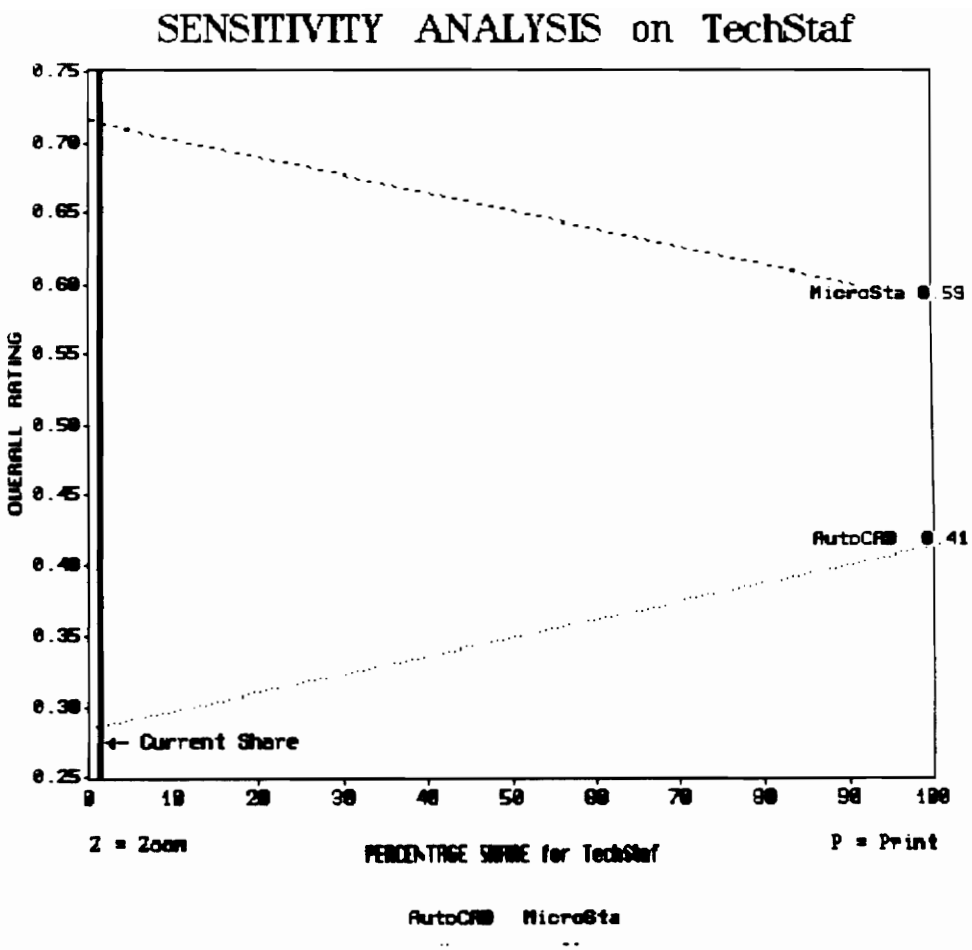

SENSITIVITY ANALYSIS on Warranty
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
OVERALL RATING
MicroSta 0.67
AutoCAD 0.33
← Current Share
0
10
20
30
40
50
60
70
80
90
100
Z = Zoom
PERCENTAGE SHARE for Warranty
P = Print
AutoCAD MicroSta

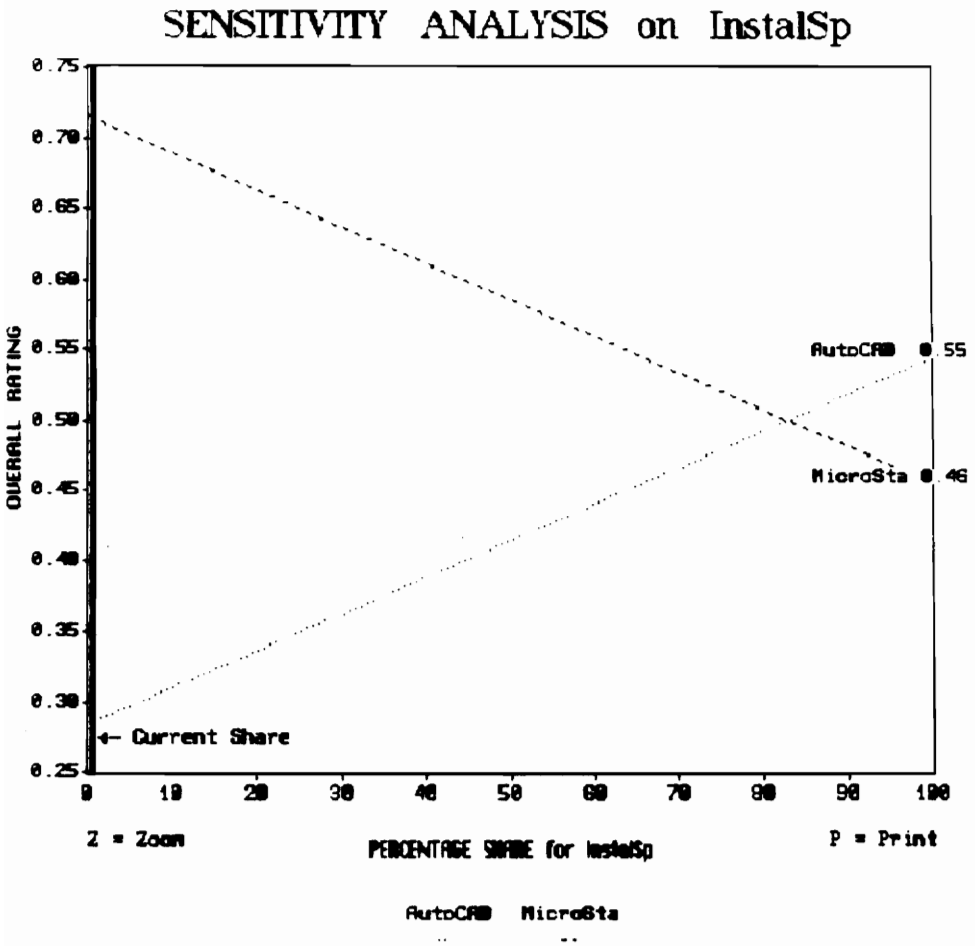

SENSITIVITY ANALYSIS on Availaby
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
OVERALL RATING
AutoCAD 0.67
MicroSta 0.33
← Current Share
0
10
20
30
40
50
60
70
80
90
100
Z = Zoom
PERCENTAGE SHARE for Availaby
P = Print
AutoCAD MicroSta

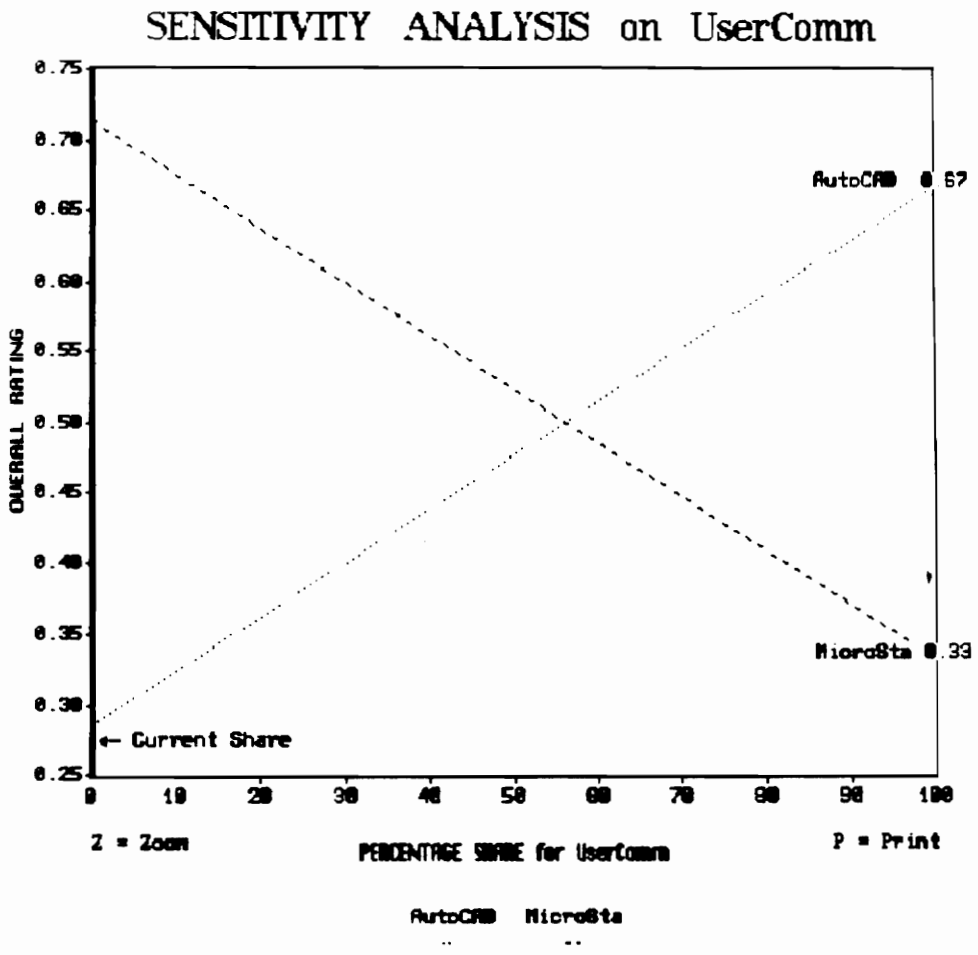

SENSITIVITY ANALYSIS on Effectiv
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
OVERALL RATING
MicroSta 0.63
AutoCAD 0.38
← Current Share
0
10
20
30
40
50
60
70
80
90
100
Z = Zoom
PERCENTAGE SHARE for Effectiv
P = Print
AutoCAD
MicroSta

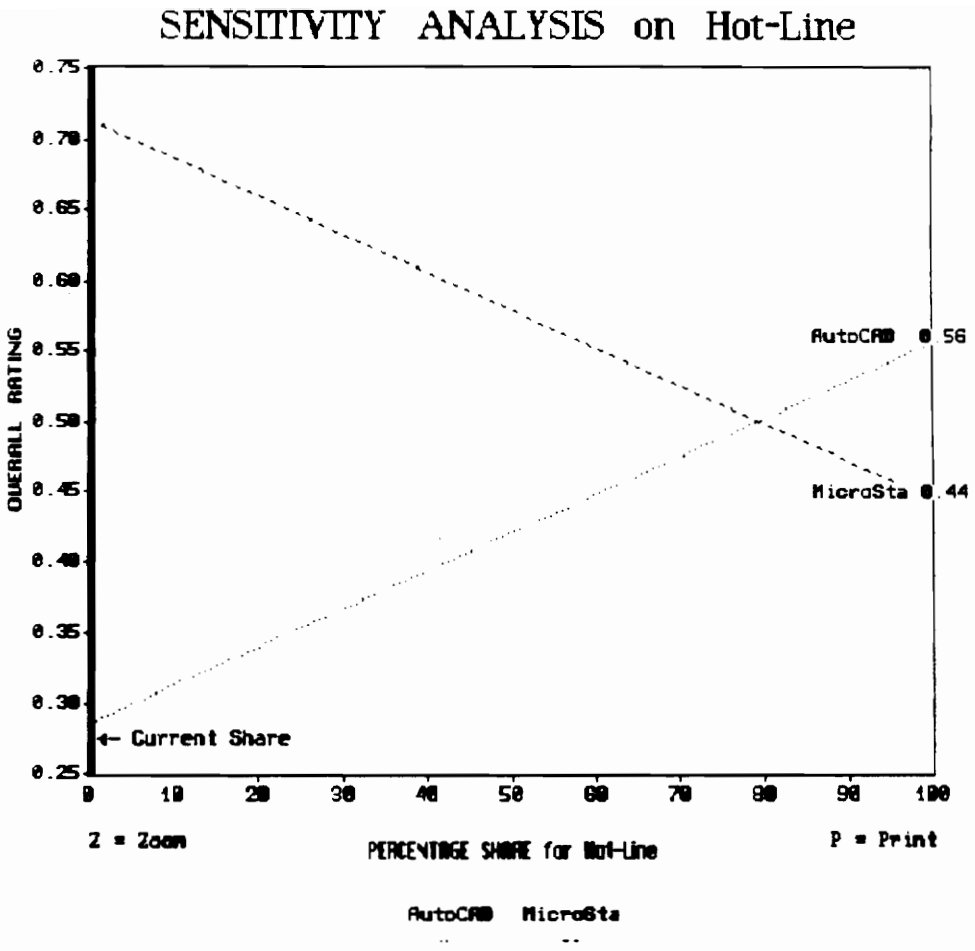

SENSITIVITY ANALYSIS on Convenie
AutoCAD 0.75
MicroSta 0.25
← Current Share
OVERALL RATING
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0
10
20
30
40
50
60
70
80
90
100
Z = Zoom
P = Print
AutoCAD MicroSta


SENSITIVITY ANALYSIS on Variety
OVERALL RATING
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
AutoCAD 0.60
MicroSta 0.40
← Current Share
0
10
20
30
40
50
60
70
80
90
100
Z = Zoom
PERCENTAGE SHARE for Variety
P = Print
AutoCAD MicroSta


SENSITIVITY ANALYSIS on TechStaf
OVERALL RATING
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
MicroSta 0.59
AutoCAD 0.41
← Current Share
0
10
20
30
40
50
60
70
80
90
100
Z = Zoom
PERCENTAGE SHARE for TechStaf
P = Print
AutoCAD MicroSta


SENSITIVITY ANALYSIS on InstalSp
OVERALL RATING
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
AutoCAD 0.55
MicroSta 0.46
← Current Share
0
10
20
30
40
50
60
70
80
90
100
Z = Zoom
PERCENTAGE SHARE for InstalSp
P = Print
AutoCAD MicroSta


SENSITIVITY ANALYSIS on UserComm
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
OVERALL RATING
AutoCAD 0.67
MicroSta 0.33
← Current Share
0
10
20
30
40
50
60
70
80
90
100
Z = Zoom
PERCENTAGE SHARE for UserComm
P = Print
AutoCAD MicroSta


SENSITIVITY ANALYSIS on Hot-Line
OVERALL RATING
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
AutoCAD 0.56
MicroSta 0.44
← Current Share
0
10
20
30
40
50
60
70
80
90
100
Z = Zoom
PERCENTAGE SHARE for Hot-Line
P = Print
AutoCAD MicroSta

FOOTNOTES

(1) Interviews with architects: Matthew Maio 8/24, 9/9/93
Will Johnson 9/17/93
Jeff Elliott 9/22/93

(2) Architectural Record, September 1993, p.54-55.

(3) Liggett and Foster, p.6.

(4) Liggett and Foster, p.7.

(5) Interviews with architects: Matthew Maio 8/24, 9/9/93
Will Johnson 9/17/93
Jeff Elliott 9/22/93

(6) Ibid.

(7) Blanchard and Fabrycky.

(8) Blanchard and Fabrycky.

(9) Blanchard and Fabrycky. p 22.

(10) Blanchard and Fabrycky. p 36.

(11) Hauser and Clausing. p. 63.

(12) Ibid.

(13) Blanchard and Fabrycky. p. 40.

(14) Blanchard and Fabrycky. p. 55-56.

(15) Canada and Sullivan. p. 211.

(16) Blanchard and Fabrycky. p 152.

(17) Blanchard and Fabrycky. p 155.

(18) Canada and Sullivan. p. 467.

REFERENCES

Architectural Record. McGraw Hill: New York. September 1993.

Blanchard, Benjamin S. and Wolter J. Fabrycky. Systems Engineering and Analysis. Prentice Hall: New Jersey. 1990.

Canada, John R. and William G. Sullivan. Economic and Multiattribute Evaluation of Advanced Manufacturing Systems. Prentice Hall: New Jersey. 1989.

Computer-Aided Engineering. May 1993.

Computer Graphics World. June 1993.

Dummer, G.W.A. and R.C. Winton. An Elementary Guide to Reliability. Pergamon Press, Oxford. 1974.

Hauser, John R. and Don Clausing. "The House of Quality." Harvard Business Review. May-June 1988.

Liggett, Hampton R. and Steven R. Foster. CAD Productivity Study. The University of Tennessee Center for Computer Integrated Engineering and Manufacturing: Knoxville, Tennessee. 1986.

Progressive Architecture. Pentin Publishing: Cleveland, Ohio. August 1993.

Sink, D. Scott. Productivity Management: Planning, Measurement and Evaluation, Control and Improvement. John Wiley and Sons: New York. 1985.

Smith, David J. and Alex H. Babb. Maintainability Engineering. John Wiley and Sons, New York. 1973.

Stores. National Retail Federation Inc.: New York. April 1992.

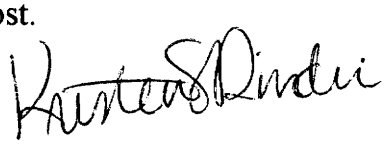
VITA

Kristen Sue Badgley Rindin was born as a small child in Ithaca, New York, in the summer of 1966, while her father, Dr. Robert H. Badgley was studying for his PhD in Nuclear Physics. Kristen's mother, Dorothea A. Steffan, was quite busy at the time supporting Dr. Bob (as we often refer to him) in his post-graduate work at Cornell while working full time as a nurse, raising the first child, Robert Jr., and carrying young Kristen around for nine long months.

Kristen went on to achieve greatness in many arenas as a child, including playing the French Horn for 10 years, performing in church choirs and plays, competing in gymnastics and basketball athletic events, and demonstrating a noticeable lack of talent in both tap and ballet classes. Kristen was an outstanding student through junior high and high school, and graduated second in a class of 532 from South Lakes High School in Reston, Virginia. Her studious nature resulted in her admittance to all colleges to which she submitted applications. She selected Virginia Polytechnic Institute and State University over Carnegie Mellon and Cornell after reviewing the family finances with Dr. Bob. Virginia Tech offered the largest scholarship and had one of the finest and progressive engineering schools in the country.

Four fun-filled years later, in 1988, Kristen graduated with a Bachelors Degree in Mechanical Engineering, and has managed to avoid designing turbomachinery in her jobs with General Electric Aerospace and the Martin Marietta Corporation. Her career has concentrated in the test

and evaluation of large scale mainframe computer systems and software, and the systems integration and installation of a worldwide LAN with Computer Integrated Manufacturing capabilities. Her latest career assignment is as a member of the first Washington area Technical Leadership Development Program for Martin Marietta. Kristen was selected as one of the four members from a selection pool of over two-thousand employees for this prestigious program. The rotational assignments over the next two years will provide Kristen with valuable insight into the division and corporate level activities that propel Martin Marietta to be the largest remaining defense contractor in the United States.

One of Kristen's favorite activities outside of work and graduate school for the last three years has been running. Kristen has been increasing her mileage lately, and spending more time at the George Mason Track working on improving her road and track race times. She won a spot on the Martin Marietta Corporate Track and Field Team this past June, and competed in the "Corporate Olympics" in Seattle in July. She has continued her running, and achieved a milestone on 17 October 1993 by running in the Army Ten Mile as part of the Martin Marietta Women's Team, which placed second in the event.

Kristen is married to Jeffrey A. Rindin, an F-16 pilot with the D.C. Air National Guard, and the architect that inspired this project topic with his repeated requests for his own CAD system. In a calculated effort to minimize the dollars flowing from the joint checkbook, Kristen embarked upon this evaluation to identify the CAD system that provides the most advanced capabilities for the most reasonable cost.