3-10-2010

Using Decision Analysis to Select Facility Maintenance Management Information Systems

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USING DECISION ANALYSIS TO SELECT FACILITY MAINTENANCE MANAGEMENT INFORMATION SYSTEMS

THESIS

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AFIT/GEM/ENV/10-M04

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AFIT/GEM/ENV/10-M04

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THESIS

Presented to the Faculty

Department of Systems and Engineering Management

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Engineering Management

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March 2010

AFIT/GEM/ENV/10-M04

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AFIT/GEM/ENV/10-M04

Abstract

Maintenance organizations, charged with preserving the built environment, are receiving a shrinking portion of an organization's operational budget to do its job. It has been demonstrated through various studies that efficiencies can be gained by implementing a maintenance management information system (MMIS). However, with so many choices available, maintenance organizations often select the wrong system.

This research effort used value-focused thinking decision analysis to create a model based on values from the Air Force Civil Engineer career field. Data for values and weights were collected from official documents and interviews. The resulting model is highly flexible, allowing the ultimate decision-maker to easily modify weights and value functions related to MMISs. The values and evaluation measures were used to score systems that were selected as alternatives. Sensitivity analyses were conducted to study the influence of evaluation measure weights on the final alternative rankings. The sensitivity analyses displayed alterations in rankings for each alternative based on changes in value weighing. Results indicate that commercially available systems may not be appropriate for Air Force use. The resulting model provides a readily modifiable decision model for the Air Force, as well as other maintenance organizations, to use when selecting a MMIS.

Acknowledgments

I would like to thank several people for their support and guidance throughout the completion of my thesis. First, I want to thank the members of the "proxy decision-making body" who contributed their valuable time and experience. Secondly, I want to thank the members of my thesis committee. Dr. Thal, thank you for your expertise and patience, while I molded my many ideas into a presentable proposal. Dr. Strouble and Major Feng, thank you for the support you provided in transforming my original thoughts into a worthwhile project.

Most importantly, I want to thank my family. To my beautiful wife, your support throughout this entire endeavor has been great. I owe everything to you. To my lovely daughter, you brighten up my day, every day. To my son, you make everything better. To my extended family, thank you for your ongoing support. I love you and thank you all.

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USING DECISION ANALYSIS TO SELECT FACILITY MAINTENANCE MANAGEMENT INFORMATION SYSTEMS

Chapter 1. Introduction

Facility maintenance management can be defined as the orderly control of activities required to keep a facility in an as-built condition, while continuing to maintain its original productive capacity (Korka, Oloufa, & Thomas, 1997). To achieve this goal, facility maintenance managers are confronted with the task of allocating limited resources to correct numerous infrastructure failures. As the age of facilities and hence the maintenance requirements constantly increase, the resources, personnel, time, and funding dedicated to accomplish this critical task are limited by the economic climate. Therefore, to maintain the functionality of constantly degrading facilities, maintenance management personnel have to employ their resources in the most efficient way possible. Many of today's maintenance managers thus apply computerized tools that come in the form of information systems that assist in creating and completing work orders; tracking preventive maintenance; and practicing asset management, inventory control, and safety. The use of these tools results in efficiencies in both resource allocation and facility functionality (Bagadia, 2006; Garg & Deshmukh, 2006; Korka & Oloufa, 1997).

One of the most prevalent tools is a computerized maintenance management system (CMMS), which is a data management instrument that assists maintenance managers in maintaining constant and efficient operations of physical plants. By enabling maintenance managers to accurately control operations and maintenance functions, a CMMS helps maintenance departments responsibly execute day-to-day operations in accordance with their budgetary constraints. These constraints include manpower, equipment replacement, equipment efficiency, facility replacement, and facility repairs. CMMSs have been implemented by private corporations, municipalities, colleges and universities, and manufacturing plants throughout the world to reduce operations and maintenance costs (Bagadia, 2006). However, selecting the most appropriate system is a demanding task. With hundreds of products on the market, organizations often fail at successfully implementing the correct system and achieving the promised benefits (Braglia, Gionata, Frosolini, & Grassi, 2006). To overcome this problem, each organization must develop its own values incorporate its goals when determining if a system should be procured, and establish the specifications for the required system.

In this research effort, the capabilities of various maintenance management information systems on the market were explored, and a methodology to select the best maintenance management information system for facility and infrastructure maintenance applications was developed. In the end, a model to aid any organization in selecting the most appropriate system was created. The purpose of this research effort was to demonstrate a methodology that any possessor of physical plant or infrastructure inventory can apply to effectively select a maintenance management information system that enables them to meet the needs of their customers.

1.2 Background

Maintenance is an unavoidable task of life as demonstrated by the following examples. In order to survive and prevent illnesses, leaf cutting ant colonies maintain their nests by allocating eleven percent of their workforce to removing waste (Hart & Ratnieks, 2002). Moreno, Bustamante, and Vinuela (1995) concluded that chinstrap penguins perform nest maintenance by collecting stones from the ground and stealing stones from other penguins to improve nest quality and thus enhance reproductive success. When humans first began creating permanent settlements, proper dwelling maintenance was vital to the survival of the facilities and civilizations. Maintenance of clean water sources was especially important at the dawn of civilization because the life and health of entire populations depended on it. In ancient Athens, well maintainers, known as supervisors of the fountains, were elected to four-year terms by citizens, while other public works posts were assigned by lot (Wilson, 2006). In ancient Assyria, road maintenance was left to the public, while the maintenance of national highways, which were important for moving armies and supplies, was the responsibility of the monarchy and its army (Bienkowski & Millard, 2000).

In the modern world, everything requires maintenance. Examples include physical assets such as homes and vehicles, as well as intangible objects such as relationships and minds. In most modern societies, a maintenance department is charged with the task of carrying out this basic, yet vital operation. Wireman (1994) asserts that the primary functions of maintenance departments are to maintain existing equipment, perform equipment inspections and service, install new equipment, maintain efficient material control, and perform craft administration. He also suggests that in order to be effective, maintenance departments must develop realistic objectives. These objectives should generally include keeping maintenance costs as low as possible, maintaining quality requirements, maintaining critical infrastructure to insure availability, providing and maintaining adequate facilities for operations, and providing qualified supervision. In an attempt to effectively integrate these functions and objectives, computer aided facility management (CAFM) systems have been developed.

Owners of large municipal infrastructure assets throughout the world, faced with reduced resources and increased maintenance requirements, are seeking ways to improve operations and maintenance efficiency. For this reason, the development and usage of CAFM systems designed to administer and control maintenance operations has increased (Garg & Deshmukh, 2006). According to Teicholz and Ikeda (1995), the support for technology-based maintenance systems began during the recession of the early 1990s. During this time, companies downsized their white-collar workforce performing daily operation and maintenance functions and began exploring new technologies to both replace and supplement their facility maintenance staffs. The need for stricter accountability in cost centers also drove the development of technology-based maintenance systems. Therefore, the capability of these systems to automatically track maintenance and staff costs, calculate assets, allocate manpower for jobs, and perform scheduling appealed to organizations with reduced operational budgets. These systems, known as CMMSs, have evolved into readily available and modifiable software packages that automate most of the logistical functions performed by maintenance personnel.

Bagadia (2006) defines a CMMS as a computer software program designed to assist the planning, management, and administrative functions required for effective maintenance. The modern CMMS not only helps control maintenance, it also contributes to the high quality of both maintenance condition and output. The use of a CMMS is thus applicable to organizations in which equipment and assets are subject to wear and subsequent repairs are done to them. Such industries include manufacturing, facilities, utilities, and fleet operations. Some of the basic functions typically included in a CMMS are the generation, planning, and reporting of work orders; the development of traceable history; and the recording of parts transactions. Additionally, management features include equipment management, preventive maintenance, labor tracking, work order processing, job planning and scheduling, inventory control, and purchasing (Bagadia, 2006). CMMS programs have the ability to interface with existing energy management and control systems and geospatial information systems, as well as property management systems. The coupling of these systems increases the decision-making capabilities of maintenance management personnel by supplying both the best information available and a complete picture of maintenance operations.

The efficiencies gained through the implementation of a CMMS have been documented in several studies. Gabbar, Yamashita, Suzuki, and Shimida (2003) observed a reduction in maintenance costs and downtime at a nuclear power plant, while O'Donoghue and Prendergast (2004) observed greater inventory control and increased productivity at a textile manufacturing plant. Sullivan, Pugh, Melendez, and Hunt (2004) reported positive results from a survey of 558 companies that had implemented a CMMS. On the other hand, the use of a CMMS is not without its challenges. Bagadia (2006) is one of many scholars who have reported on the pitfalls associated with the use of a CMMS. Some of the reasons cited are employee turnover, nonexistent support from management, employee resistance, and most importantly, the wrong CMMS was selected. To address the last reason, a decision model to help organizations select the most appropriate CMMS would be helpful.

To explore this topic, the organization used in this study was the United States Air Force. With bases around the world, the United States Air Force possesses a vast number and range of facilities and infrastructure. The operations and maintenance tasks for these assets are the responsibility of the Civil Engineer (CE) community. This entails the use of information systems to manage, control, plan, schedule, and program work requirements by the most efficient means available. The current automated systems used by the CE community include the Interim Work Information Management System (IWIMS) and the Automated Civil Engineer System (ACES), with IWIMS being specifically used to manage maintenance operations. In addition to providing CE managers with real-time data input and information output necessary for effective resource allocation, the IWIMS is also intended to facilitate the submission of reports to higher echelons of command, including the Department of Defense and the Congress of the United States.

The task of allocating limited resources for facility operations and maintenance that embody the CE community is similar to the problems of other large organizations. Therefore, organizations that perform facility maintenance on a variety of facilities will be able to generalize the results of this research effort and apply its concepts to their own operations and maintenance strategies. This evaluation of the maintenance management information systems available today will address the need to improve both the efficiency of maintenance operations and modernize information systems in today's high tech world. The economic climate of today demands that organizations seek out and act upon opportunities to improve their operations.

1.3 Problem Statement

Infrastructure maintenance is an unrelenting task that must be accomplished to preserve the built environment. However, resources allocated to this vital job have been reduced over the years. Funding has been disproportionately distributed to new projects, thereby neglecting existing infrastructure (Heintz, Pollin, & Garret-Peltier, 2009). Maintenance departments can help themselves by implementing an information system to help better manage personnel, activities, and budgets (Pitt, Goyal, & Sapri, 2006). One of the biggest problems associated with CMMSs is their selection. With a large number of systems on the market, maintenance departments often fall victim to selecting the wrong system (Bagadia, 2006). Developing a decision model to help evaluate and select a system based on a maintenance organization's goals can help organizations realize the results from implementing these systems.

1.4 Research Questions

The overarching research question for this study was: "How can the selection of an appropriate maintenance management information system be enhanced through the development and use of a decision model?" The answer to this question was determined by incorporating answers to the following seven investigative questions into a decision model.

1. What is maintenance management and why is it needed?
2. What are the predominant maintenance strategies and how are they applied?

3. How are information systems used in maintenance management, what are the capabilities of those systems, and what improvements have been documented from implementation?

4. What methodologies are available to aid organizations in evaluating and selecting from a field of alternatives?

5. What are the attributes of a maintenance management information system that the Air Force values and how do variances in these attributes impact the outcome of the selection process?

6. What capabilities are desired in a system that the Air Force values?

7. How are appropriate alternatives screened and selected from the vast field of systems?

The first and second questions establish a baseline for the maintenance management profession and prescribe the underlying theories that allow CMMSs to be effective. The third question aids in the creation of selection criteria for the model. The findings from the fourth question help determine the most appropriate model to use. The answers to these four questions were coupled with the answers to the last three questions to meet the research objective, create the framework of a selection model, and provide insight into factors affecting CMMS selection decision-making for the Air Force.

1.5 Methodology

The value-focused thinking (VFT) methodology was used to create a selection model to address the overarching research question. The VFT methodology is described as clearly defining and structuring an organization's fundamental values in terms of objectives and using those objectives to guide decision-making (Kenney, 1994). VFT is designed to channel the decision-maker's focus on the essential activities that must occur prior to solving a decision problem, thereby helping to uncover hidden objectives and leading to more productive information collection. In the end, VFT facilitates the development of better alternatives for any decision problem and identifies decision situations that are more appealing than the ones that typically confront an organization (Kenney, 1994). The VFT methodology prescribes a 10-step process to develop a decision model which includes measures and weights quantifying the maintenance management information system features that the Air Force values. Information gathered from a proxy decision-maker and relevant published materials was used to create the value hierarchy for the model. The final model was developed using the Air Force as the case study; however, the methodology can be applied to multiple organizations.

1.6 Assumptions

There were two assumptions associated with this study. The first assumption was that all maintenance management software systems, to include theories and practices, collected from literature are suitable for Air Force application. The second assumption was that although there are a variety of Air Force bases, the functions of a CMMS are applicable to all locations.

1.7 Limitations

There are several limitations associated with this study. The first one is the absence of a definitive decision-making body. With the use of the VFT methodology, an ultimate decision-maker or Delphi panel must be available to verify the value hierarchy, determine the associated weights, and define the performance measures. The inclusion of inputs from actual maintenance workers, their supervisors, and company management should be included to create the best value hierarchy. This is not included in this research because of the geographically dislocated nature of these assets. The study was also limited by the amount and quality of data available to evaluate alternatives. Several groupings of similar CMMSs had to be developed. Most of the data for this study was found in trade articles and their associated websites; therefore, a complete and accurate list of capabilities covering the entire gamut of CMMSs was not available. However, these limitations do not diminish the significance of the study as a decision-making body can be gathered by other organizations and new CMMSs can be evaluated as they come on the market using the resulting model.

1.8 Significance of Study

The academic body of knowledge concerning maintenance management information systems is limited. Studies illustrating the success or failure of implementing such systems are rare. There are many articles in trade magazines covering this subject, but very few of academic merit. To fill this gap, this thesis provides a model for determining the appropriate criteria when selecting maintenance management information systems to implement. The public works community will be able to examine different attributes and their application to large-scale maintenance operations. For the Air Force, the conclusions of this thesis form the groundwork for selecting a maintenance management information system and improving the efficiency of facility and infrastructure maintenance activities.

1.9 Organization of Remaining Chapters

The introductory chapter is followed by four additional chapters in this thesis. In the second chapter, a literature review of contemporary topics relevant to maintenance management information systems will be discussed. The third chapter details steps 1-6 of the VFT methodology used in this study, which entails the development of the decision model. Steps 7-10 are presented in Chapter 4, which includes an analysis of the model's results and sensitivity. In the final chapter, conclusions of the study and limitations of the model are presented; the chapter further provides recommendations for future research and model modification.

Chapter 2. Literature Review

The purpose of this literature review is to identify facility and infrastructure maintenance challenges and the strategies devised to overcome them, understand the role of information management systems in maintenance, discover the capabilities of current systems, and highlight realized results from implementation. This chapter provides a summary of the relevant academic literature explored in this study and is organized into four broad sections. The definition, history, and importance of maintenance management are established in the first section to provide a frame of reference for this study. Additionally, modern maintenance challenges are highlighted in the first section to demonstrate the challenges faced by maintenance management personnel. The first section culminates by defining the predominant maintenance strategies that can provide solutions to these challenges and underlie the operations of CMMSs. In the second section, a review of the development of maintenance management information systems and the capabilities of current systems is presented. In the third section, the benefits of maintenance management information system implementation are investigated; the section also covers the common pitfalls associated with CMMS implementation. Finally, in the fourth section, the value-focused thinking process is introduced to provide background on the methodology used for this thesis.

2.1 Introduction to Maintenance Management

The current science, techniques, and technologies involved with maintenance operations have evolved over time. Maintenance management aims to incorporate the aspects of maintenance operations into a streamlined, economically sound process. Mishra and Pathak (2002) suggest that the most important objective of maintenance is to maximize the availability of equipment or facilities, while maintaining a safe environment for customers and workers, to promote progression toward the goals of the parent organization. Effective facility maintenance is essential to retain the level and quality of the modern built environment.

2.1.1 Maintenance Management

Maintenance management is the application of planning, organizing, staffing, program execution, and control processes to maintenance activity (Blanchard, Verma, & Peterson, 1995). Korka et al. (1997) define maintenance management as managing the systematic control of activities required to preserve a facility in an as-built state, while continuing to sustain its original capabilities. Allen (1993) describes maintenance management as using a specific strategy and process to effectively and efficiently utilize resources to ensure that facilities remain at an operable standard required by users. Facility maintenance management thus pertains to the management of sustaining support and maintenance activities that ensure effective and efficient utilization of the built environment throughout its programmed life cycle. Some specific maintenance management responsibilities are the scheduling and development of cost projections, description and dissemination of specific tasks, development of work breakdown structures, and reporting requirements (Blanchard et al., 1995). In summary, maintenance management is the direction of functions that must be accomplished in order to uphold organizational productivity.

Prior to the Industrial Revolution, maintenance activities for facilities and equipment were accomplished by craftsmen, such as smiths, masons, carpenters, and wheelwrights to either replace or repair a part that failed. Because of the time and effort needed to fashion replacement parts, repairs were more prevalent than replacement. In the case of buildings, stone or wooden components that failed were often replaced with stronger materials, which were then incorporated into the construction of the next facility (Sherwin, 2000). During and after the Industrial Revolution, maintenance was largely regarded as repair work. Maintenance functions were reactive in nature and were completed when production was not impacted. Facilities and equipment were operated until they failed because there were no methods to predict breakdowns (Korka & Oloufa, 1997).

The first scientific approach to maintenance management was created in the 1950s and 1960s. Preventive maintenance was advocated as a method to reduce failures and unscheduled downtime (Dekker, 1996). In the 1950s, reliability engineering was developed and led to an emphasis on the concept of preventive maintenance in which time-based maintenance was the preferred method of maintenance. The frequency of activity in time-based maintenance was based on a bathtub curve which represented the increase of failures over specific periods of operations. When the operational life of facilities and equipment are able to be estimated precisely, time-based maintenance is the best policy. However, various other factors such as operational and environmental conditions were often disregarded with this approach. Because this maintenance strategy was based only on the operational period, this method was quite unreliable.

With the development of machine diagnostic techniques in the 1970s, the concept of condition-based maintenance was introduced to replace the flawed time-based maintenance method. In condition-based maintenance, repair actions are completed when failure symptoms are recognized through diagnosis. Condition-based maintenance thus relies on diagnostics that allow organizations to take proper actions at the right time to prevent stoppages. However, due to the constant breakdown of non-critical components in facilities and equipment, this method was not very time or cost effective.

Consequently, maintenance management began to be emphasized in the 1980s as organizations were faced with selecting the appropriate maintenance strategy for their facilities and equipment (Takata et al., 2004). Crippled by budgets negatively impacted by the recession, maintenance management was developed by large corporations to reduce extraordinary operating costs. Reliability-centered maintenance and risk-based maintenance are two of the most well known strategies developed during this era. These two strategies focus maintenance activities only on the failure modes of a piece of equipment or facility, while allowing non-critical components to run until failure and thereby conserving limited maintenance resources (Takata et al., 2004).

Poor maintenance management has resulted in deficient public works and has caused some public pain and suffering in recent years. In 2002, Severe Acute Respiratory Syndrome (SARS) appeared in a Hong Kong housing complex. There were 1,800 cases reported and over 200 deaths from the outbreak. The illness was found to be spread throughout the housing complex from dried toilet U-traps and venting stacks that were not maintained (Pitt et al., 2006). In 2005, Hurricane Katrina devastated the Gulf coast killing nearly 3,500 people and displacing 770,000 more (Townsend, 2006). Poor levee maintenance, combined with the catastrophic nature of the storm, caused the city to be inundated with storm surge (Litman, 2006). In 2006, a bridge in Minneapolis collapsed due to excessive loads being placed on the deck. Although the deck was undergoing repair at the time, the gusset plates that held the bridge together were in severe disrepair. As early as 2003, the Minnesota Department of Transportation knew that the gusset plates were corroding, buckling, and failing, yet they neglected to correct the problem, resulting in the death of 13 and injury of over 100 people (Astaneh-Asl, 2008). As demonstrated through these examples, maintenance of facilities and equipment is critical to preserve the safety of populations residing in the built environment of today.

2.1.2 Maintenance Challenges

All organizations possessing physical assets face similar issues, regardless of its size or function. Manufacturing plants, oil refineries, shopping malls, and housing complexes all face familiar maintenance difficulties. Two of the most compelling challenges are an aging infrastructure and a negative infrastructure investment trend. An understanding of these challenges is important because it provides insight into the complex issues that have shaped the field of maintenance management.

A country's public works infrastructure systems are the foundation on which economic activities and, ultimately, economic growth are dependent (Rioja, 2003). Without schools to teach children, clean water to drink, electricity to power manufacturing facilities, or roads to transport goods and workers, economic prosperity falters. In today's globally competitive marketplace and budget constrained municipalities, organizations are pushed to continuously upgrade their capabilities to create quality products and services for their customers and to advance the cost-effectiveness of their operations. In organizations that depend on extensive physical assets for production, maintenance has a very important role in the mission of the organization. Physical asset availability and reliability are critical to capital intensive business operations; therefore, maintenance effectiveness influences the cost, volume, and quality of production, availability of facilities, and the safety of operations (Pitt et al., 2006). The challenges that make effective, efficient maintenance difficult to obtain are complex, yet common.

One of the most prevalent challenges to maintenance is the advanced age and associated deterioration of infrastructure throughout the country. Infrastructure includes transportation, energy, and water systems, as well as environmental and building systems that house, protect, and sustain critical societal systems such as health, telecommunications, finance, manufacturing, and government (Aktan, Chase, Inman, & Pines, 2001). A majority of the public works facilities in the United State were designed and constructed before World War II with techniques developed in earlier times. With the replacement of parts and upgrades, some of these facilities remain in service today, well past their engineered lifespan. The infrastructure has been degraded by the normal ravages of time, increased population and thus usage, and complex new utilizations that were never intended by the original engineers (Connery, 2008). In the wake of recent events, such as the steam pipe explosion in Manhattan, Connery (2008) suggests that the United States' aging infrastructure must be managed using a new maintenance strategy crafted from a holistic viewpoint to preserve the integrity of vital public works systems. Facilities and their coupled equipment are expected to last longer than they were intended and are being used to provide services for which they were not designed, thereby stressing the built environment and placing great demands on maintenance management personnel (Lewis, 1999).

Wastewater collection systems are a prime example of the aging and deteriorating infrastructure in the United States. Many of the existing systems were designed and constructed in the early 1900s. Maintenance activities over the past 100 years have resulted in pieced-together systems that incorporate technologies from different eras and exacerbate maintenance issues. The rate of deterioration of these systems is impacted by topography, climate, geology, and maintenance and operations conditions and procedures. Maintaining these old deteriorating systems requires enormous capital in time, personnel, and funds from maintenance management entities (Tafuri & Selvakumar, 2002). The American Society of Civil Engineers (ASCE) (2009) reported that aging, inadequately maintained systems seep billions of gallons of raw wastewater into surface waters annually. ASCE also suggests that this problem results from the difficulty of maintaining the aging and deteriorated wastewater systems. The advanced age and resulting conservation demands of vast infrastructure systems present an ongoing challenge for maintenance management entities.

Another broad challenge to maintenance is the negative infrastructure investment trend throughout the United States in the last 40 years. Infrastructure investment includes the activities to repair, replace, and maintain existing facilities. In 2007, the Department of Commerce estimated the value of all non-defense public fixed assets at $8.2 trillion, more than half of the $15.5 trillion total for all public and private assets. Despite the magnitude of capital invested in infrastructure, the rate of public investment has declined steadily since peaking in the late 1960s. From 1950 to 1979, infrastructure investment grew 4 percent per year but decreased to 2.3 percent per year from 1980 to 2007. This negative trend has created an infrastructure investment gap that has increased the pressure on maintenance management professionals (Heintz et al., 2009).

There are numerous examples of underinvestment in the nation's infrastructure systems. The Department of Transportation estimated that an investment of $78.8 billion per year is needed to maintain the existing roads in the United States, but only $70.3 billion was allocated for the task in 2007(Heintz et al., 2009). The Federal Transit Administration estimates its annual public transit operational budget at $15.8 billion, while federal outlays for the mission totaled only $9.8 billion in 2008 (The ASCE, 2009). The nation's airport infrastructure is experiencing an investment shortfall of between $1 and $3.2 billion per year, while the water infrastructure including drinking water, wastewater, and dams is experiencing a shortage of $16.2 billion per year (Heintz et al., 2009). The public parks and recreation infrastructure currently has a $7 billion maintenance backlog after suffering severe, continual budget cuts over the last 50 years (The ASCE, 2009). The insufficient rate of past and present investment in critical infrastructure systems poses a huge challenge for maintenance management experts.

Both areas of concern are displayed in the ASCE's recently released 2009 Report Card for America's Infrastructure. Four general infrastructure areas, Water and Environment, Transportation, Public Facilities, and Energy, encompassing the entire breadth of public infrastructure systems present in the country, were evaluated in the report. An advisory council of 28 engineers, with expertise within each area, analyzed the current conditions of each system and consulted with additional experts to make assessments. The report concluded that the overall grade for the condition of infrastructure in the United States was a D. The conclusion of the study was similar to the 2005 assessment, in which a majority of the deficiencies resulted from delayed maintenance, underfunding, and a lack of modernization. Advanced age and degradation, combined with sub-par funding, impacted the grade of dams, drinking water, levees, wastewater, and inland waterways. The average age of the 85,000 dams in the country is 51 years. Of those, 4,100 were found to be deficient due to age, deterioration, and a lack of maintenance; they require an additional $12 billion over the next 10 years to make improvements. The nation's drinking water infrastructure faces an annual funding deficit of $11 billion needed to maintain, repair, and replace the current facilities that are reaching the end of their useful life and no longer able to maintain the required drinking water standards. Many of the country's wastewater treatment facilities have reached the end of their design lives and are plagued by chronic overflows from inadequately maintained, under designed, and aging systems that discharge 850 billion gallons of raw sewage per year. According to the Congressional Budget Office, the gap between actual spending and needs for wastewater systems was between $23 and $37 billion per year (The ASCE, 2009). These examples highlight the complexity that maintenance entities encounter when faced with the advanced age of existing facilities and a deficit of funding.

2.1.3 Maintenance Management Strategies

Establishing an effective maintenance management strategy is the foundation of any organization's goal of providing highly reliable and productive facilities. Maintenance management strategies provide guidelines to direct organizations toward maintenance success. Maintenance management strategies must be selected based upon the optimal approach to reducing financial expenditures and total life-cycle costs. The objective of maintenance management is to conduct maintenance only when required to ensure safe, continual, and cost-effective use of the facilities at acceptable levels of operation or when there is the opportunity of extending the useful life of the elements of the facility (Horner, El-Haram, & Munns, 1997). Several maintenance management strategies have been developed to achieve this objective. This study will examine reactive, preventive, predictive, and reliability-centered maintenance strategies to highlight the full spectrum of approaches available to managers today.

2.1.3.1 Reactive Maintenance

The most basic approach to maintenance is to rely on reactive maintenance, which is also known by other names such as frequency-based, breakdown, or corrective maintenance. This strategy has also been described as the fire-fighter approach to maintenance (Swanson, 2001). In reactive maintenance, facilities and their associated equipment are allowed to operate until they fail. Repairs are only completed when the desired operational level of the facility cannot be met. No planning activities are taken to detect the onset of impending failures or to prevent frequent failures. No maintenance activities are taken to preserve the asset as the manufacturer or builder intended to ensure that the full life-cycle of the equipment or facility is met. Under this strategy, temporary repairs are often made to return facilities to operation as quickly as possible and permanent repairs are deferred (Swanson, 2001). The main objective of reactive maintenance is to keep facilities operating as long as possible to maximize the availability of production capabilities (Sharma, Kumar, & Kumar, 2005).

Reactive maintenance is effective for organizations that need to minimize the maintenance manpower and financial resources expended to keep the facility operational (Swanson, 2001). It is also effective for small management departments that do not possess the quantity and quality of manpower to conduct routine maintenance (Sullivan et al., 2004). This strategy is also used when the customer demand for services or products from a facility exceed the supply and the profit margin is extremely high. Reactive maintenance is also effective when equipment and facilities are relatively new and are unlikely to fail. This approach to maintenance solves production problems when they are critical to facility operations (Sharma et al., 2005).

There are quite a few disadvantages to reactive maintenance. Reactive maintenance results in unpredictable and fluctuating production capacity, high levels of out-of-tolerance and scrap output for manufacturing, and increased overall maintenance costs to repair catastrophic failures (Swanson, 2001). Failure to prevent frequently recurring disruptions adds to the maintenance costs. The tempo and level of maintenance operations causes resource-deprived maintenance organizations to reduce their capabilities and only conduct temporary expedient repairs. This leads to more unreliable systems and more failures (Turner, 2002). The life-cycle of equipment and facilities are reduced because no life-extending, periodic maintenance is performed. Failures of primary systems often lead to the subsequent failures of secondary systems. Since the equipment associated with facilities is meant to run until failure, an extensive inventory of repair parts must be kept on hand (Sullivan et al., 2004). Reactive maintenance saves maintenance and capital costs in the short-term, but it is an inefficient use of resources and has been shown to have more expensive long-term costs than other maintenance strategies (Sullivan et al., 2004).

2.1.3.2 Preventive Maintenance

The preventive maintenance strategy prescribes maintenance activities conducted on a time and or machine-run-based schedule that detects and mitigates the degradation of facilities and equipment. This strategy is aimed at sustaining or extending the useful life of equipment and facilities by controlling the level of degradation (Sullivan et al., 2004). Sharma et al. (2005) suggest that the main objective of preventive maintenance is to decrease frequent, sudden, and sporadic failures by performing maintenance activities at a specified predetermined interval. While reactive maintenance is performed when a system fails, preventive maintenance actions are performed on an established schedule. Maintenance activities are performed after a specified period of time or amount of usage and are based on the estimated probability that the equipment or facility will fail within that specified period or amount of usage. The maintenance work includes parts and components replacement, cleaning, adjustment, and lubrication, as well as inspection for signs of deterioration (Swanson, 2001).

The preventive maintenance strategy offers various advantages. Extended equipment and facility life-cycles and a reduction of unpredicted breakdowns are two of the most noted advantages (Mobley, 2002; Sharma et al., 2005; Sullivan et al., 2004; Swanson, 2001). Energy savings are also achieved through this strategy because equipment and facilities operate more efficiently when maintained on a regular schedule. Horner et al. (1997) note that with preventive maintenance, downtime associated with maintenance activities can be scheduled to not interfere with facility operations. Other advantages include facility management control of scheduling and overtime, adequate spare parts inventories, standardized maintenance procedures, and flexible maintenance scheduling (Sullivan et al., 2004; Mobley, 2002).

Despite the advantages of a preventive maintenance strategy, its disadvantages reduce its utility. Sullivan et al. (2004) state that although preventive maintenance decreases the number of frequently recurring failures, it does not prevent catastrophic system failures. Swanson (2001) cites the need to disrupt production to perform maintenance work as a disadvantage. This becomes an issue when production is at a high rate and preventive maintenance must be performed to maintain the required level of production. Mobley (2002) notes the costs associated with the frequency of maintenance actions and use of a large amount of spare parts as disadvantages. Sullivan et al. (2004) also highlight the performance of unneeded maintenance, incidental damage to secondary systems while performing unneeded maintenance, and the labor-intensive nature of preventive maintenance as disadvantages. Regardless of its disadvantages, preventive maintenance has advantages over reactive maintenance in long-term performance.

2.1.3.3 Predictive Maintenance

Predictive maintenance is described as a strategy that uses the actual operating conditions of plant equipment and systems to optimize the operation of the entire plant (Petrescu & Duta, 2008). Also known as condition-based maintenance, Sullivan et al. (2004) describe this strategy as a process of directing maintenance actions based on measurements that detect the onset of degradation. This approach allows causal stressors in equipment and facilities to be eliminated or controlled prior to failure; it also allows managers to know the current and future functional capabilities of their assets. With predictive maintenance, diagnostic equipment is used to measure and record the physical condition of facility components. The information recorded and analyzed includes equipment temperature, noise, lubrication, vibration, and corrosion. If these measurements fall outside a specified range, maintenance activities are taken to restore the equipment or system to its proper condition. This strategy ensures that facilities and equipment are only taken off-line when direct evidence is present indicating that degradation exists (Swanson, 2001; Sharma et al., 2005). Some activities associated with this strategy include monitoring the vibration of rotating machinery, the infrared image of electrical equipment, thermal image of different components, lubricating oil analysis, process efficiency, and visual inspection (Petrescu & Duta, 2008).

According to Sullivan et al. (2004), there are numerous advantages to predictive maintenance. For instance, activities can be scheduled in advance to eliminate overtime costs, minimize inventory, and order required parts ahead of time. An increase in equipment and facility reliability, energy savings, and optimization of operations are also cited as advantages. The universal advantage of this strategy from the literature is that maintenance is only conducted when the need is imminent and not after some pre-determined time period (Swanson, 2001; Sharma et al., 2005; Sullivan et al., 2004).

On the other hand, there are also some disadvantages with the predictive maintenance strategy. Initial startup for a predictive maintenance strategy is costly. Purchasing diagnostic equipment for each facility's components is expensive. Additionally, training maintenance workers to use the diagnostic equipment also requires resources (Sullivan et al., 2004). Sharma et al. (2005) also indicated that although vibration techniques are the preferred method to monitor rotating and reciprocating machines, limitations and deficiency in data quality and quantity reduce the accuracy and efficiency of diagnostic monitoring.

2.1.3.4 Reliability-Centered Maintenance

Sharma et al. (2005) described reliability-centered maintenance (RCM) as a systematic approach used to optimize predictive and preventive maintenance strategies to increase facility and equipment efficiency, uptime, performance, and quality while aiming to minimize maintenance costs. By recognizing that all components of a facility are not of equal importance, that different components have different failure rates, and that maintenance managers do not have unlimited workers or funds, RCM is able to focus on maintaining system operation rather than restoring equipment to ideal condition, thereby resulting in a high level of facility reliability and cost-effectiveness (Sullivan et al., 2004).

RCM allows maintenance managers to systematically view system functions, failures of those functions, causes and effects of those failures, and the infrastructure impacted by those failures. Once the failures are determined, the consequences of those failures are classified into one of four categories: safety and environmental, operational, non-operational, and hidden failure consequences. These categories are used as a strategic framework for maintenance decision-making. The decision-making process, running the classification of consequences through a logic decision tree, is used to determine the most pressing task that must be completed to maintain the facility. This approach provides maintenance managers an understanding of how infrastructure is interconnected, what their staff can achieve, and the causes of failures (Carretero et al., 2003).

RCM is based on three major goals (Carretero et al., 2003). The first one is to enhance the safety and reliability of facilities by focusing on the most important functions required to maintain the desired operational level of a facility. The second goal is to prevent or mitigate the consequences of failures by protecting the entire facility instead of fixing every insignificant failure. The third goal is to shrink maintenance costs by eliminating unnecessary maintenance actions.

Compared to the previously mentioned maintenance strategies, RCM possesses the most advantages. This strategy combines elements of the reactive, preventive, and predictive maintenance strategies in an effort to capitalize on the advantages of each. To provide world-class maintenance, the continually top-performing organizations use the following mix of strategies: <10% reactive, 25-25% preventive, and 45-55% predictive (Sullivan et al., 2004). According to Sullivan et al. (2004), RCM is usually the most efficient strategy. Maintenance costs are reduced by eliminating unnecessary activities and overhauls, reducing the frequency of needed overhauls, and minimizing the need for maintenance worker overtime. Because maintenance actions are mainly focused on critical components, the probability of sudden, catastrophic failures is greatly reduced.

RCM is heavily reliant on predictive maintenance technologies and its disadvantages reflect this. Sullivan et al. (2004) suggest that the main disadvantage of RCM is the significant amount of resources required to initiate the strategy. These resources include capital for equipment, training, time, and energy needed to install and monitor diagnostic equipment on every facility in the maintenance manager's portfolio. This notion is echoed by Carretero et al. (2003), who lists an additional disadvantage as the time it takes to implement a robust RCM strategy. Usually a company's top financial managers pursue the long-term goal of reduced maintenance costs with short term goals of quarterly profits. If results are not seen soon after implementation, support for the strategy wanes, thereby reducing its effectiveness.

2.2 Information Systems for Maintenance

Information technology systems have been shown in recent research to have a positive correlation on the profitability and competiveness of organizations (Kans, 2007). These systems have been in use by organizations for over 40 years and today are a common tool in the workplace. In nearly every sphere of organizational activity, data capture and interpretation have contributed to dramatic improvements in the effectiveness and efficiency of operations. Similarly, CMMSs have assisted with maintenance activities for several decades. With the rapid evolution of information technology, the role of CMMSs has changed from simple planning of maintenance activities to facilitating a more deliberate, information-based approach to asset management (Labib, 2004). In an effort to emphasize the importance of modern information technology on maintenance operations, this section will detail some historical points and highlight the need of the CMMS.

2.2.1 Maintenance Information System Development

Zhang, Li, and Hou (2006) assert that the aim of maintenance strategies is to reduce maintenance costs while improving maintenance operation, help maintenance managers make the right decisions at the right time, manage all associated activities, and control the failure and degradation of facilities. They suggest that it is impossible to manually manage the information needed to attain those aims. The information is vital to justify budgets, maintenance decisions, and spare parts purchases. Labib (2004) also claims that information technology is needed to aid maintenance management. He suggests that there are several factors driving this need. The first one is the amount of information that needs to be processed to facilitate educated decision-making. Second is the requirement of real-time data about facilities and equipment to determine actual maintenance requirements. This is needed to reduce the waste associated with manufacturer suggested maintenance schedules. The third factor is the speed with which decisions need to be made. Hipkin (1997) also identified the need for information systems in maintenance management. He cited the need for organizations to become more efficient and cut costs, perform maintenance at the optimal time, and identify and base maintenance decisions on the health of critical systems. Information technology is thus needed to assist maintenance managers with assessing the complexity and vastness of their assets.

2.2.1.1 History

As computers and information technology proliferated throughout the latter part of the 20th century, so did its application to maintenance activities (Kans, 2007). Before 1960, there was no computerized maintenance support available. In the 1970s, maintenance planning systems were available, but companies usually possessed only one mainframe. As a result, computation time was shared between the organization's departments, with higher priority being given to more important activities such as finance and logistics. Additionally, the only task that could be performed by the planning system was the scheduling of preventive actions. During this period, maintenance management activities were almost exclusively conducted manually.

As microcomputers became available in the 1980s, systems dedicated to maintenance activities became more prevalent. Maintenance managers were able to systemize, plan, and account for maintenance activities. Close to 60 CMMSs were available by 1985, and they included the basic maintenance functions of plant inventory, scheduling, cost and budgeting, stock control, and maintenance history. There were also some maintenance information system innovations in the 1980s. For instance, the U.S. Navy attempted to digitize and integrate many different sources of maintenance data to create a historical database. The U.S. Air Force used the first handheld computer to integrate failure data with both historical data and manuals to diagnose failure causes (Kans, 2007). Throughout the 1980s, CMMSs became better and more widely adopted to assist maintenance managers.

In the early 1990s, efficiency and cost reduction became themes in CMMS literature. As the technology improved, user interfaces and the integration of maintenance with quality and energy management became the emphasis of CMMS development. The main focus of CMMSs in the early 1990s was the management of preventive maintenance used for policy making, planning and scheduling, and fault diagnosis. A small number of CMMSs supported predictive maintenance. Those systems provided condition monitoring, maintenance communication, and vibration monitoring. Over 200 CMMSs were available to customers at that time. In the late 1990s, economic aspects drove the development of CMMSs and the focus shifted to cost reduction and cost-effectiveness. As a result, CMMSs were linked to asset management strategies in which costs, production quality, efficiency, and facility condition were all taken into account to make a decision (Kans, 2007).

In recent years, the focus of CMMS development has been on integrating systems with predictive and proactive maintenance strategies to achieve even greater efficiencies. The related literature has been centered on the financial aspects of maintenance and its connection to organizations' bottom lines (Kans, 2007). Kans (2007) concludes that the use of CMMSs has shifted from a maintenance function to business integration, from reactive maintenance to predictive maintenance, and from an operational view of maintenance to a strategic one. As CMMS utility has increased over the years, organizations and scholars have noted the importance of the systems through the proliferation of their use and associated research.

2.2.1.2 CMMS Characteristics

The capacity of modern CMMSs to store and process vast quantities of data purposefully and rapidly has produced great efficiencies for maintenance managers (Labib, 2004). The advantages of a CMMS over manual operations are obvious, and the analytical power and storage capacity are major drivers. CMMSs give maintenance managers the ability to produce optimal schedules, issue precise work orders, conduct equipment monitoring, and create a knowledge base of equipment and facility history (Korka et al., 1997). Zhang et al. (2006) point to the ability to store and query data as needed, quality reports, automatic generation of work orders, the ability to manage inventories, and the ability to integrate the system with modern maintenance strategies as advantages.

Modern CMMSs have evolved into robust systems with a large number of capabilities. CMMSs assist maintenance managers in handling a wide range of information regarding their workforce, repair schedules, equipment histories, and spare parts inventories. The systems enable preventive maintenance activities, inventory control, and materials purchasing to be automated. They also allow managers to plan and schedule work orders in a way that most efficiently balances the workload. CMMSs also have utility in coordinating and communicating scheduled availability, downtime, and rapid response with the production function of the organization (Zhang et al., 2006).

Labib (2004) posits the utility of the CMMS is further demonstrated by the support it provides the various levels of organizational hierarchy. Modern CMMSs can order and track the movement of spare parts from their manufacturer to their disposal. They can also perform condition-based monitoring on equipment and facilities. The systems reduce equipment or facility failure response time. They offer accountants information on equipment and facilities that enables informed decisions regarding capital expenditures. One of the most important aspects of the CMMS is that it provides senior management insight into the state of asset health.

By providing a platform for decision analysis and acting as a guide to management, a CMMS is an avenue to achieve world-class maintenance for an organization. Management is provided with statistics and reports that detail performance in key areas and highlight problematic issues, thereby opening maintenance practices up to scrutiny. This scrutiny helps managers determine which strategies work, what equipment is deficient, and most importantly, where the money is going (Labib, 2004). CMMSs assist the maintenance functions in managing the ever increasing complexity and varied nature of facilities and equipment that appear in today's built environment (Zhang et al., 2006). The information provided by CMMSs can create great efficiencies for organizations.

2.2.2 Current Systems

There is not much peer reviewed literature exploring the historical development of CMMS functions. The capabilities and functions of these systems continually change as new companies and their systems emerge every day. Therefore, this section will review information provided from industry as it relates to the selection of commercially available software packages.

Currently, there is a plethora of CMMSs on the market today, with estimates ranging from 100 (Berger, 2009) to more than 1700 (People and Processes Inc., 2008). Berger (2009) has conducted an annual review of CMMS/Enterprise Asset Management (EAM) software on the market since 1987. According to him, CMMS packages range in price from $1000 for simple applications up to multimillion dollar solutions designed for complex enterprises. The systems are priced with flexibility in mind. Users can pay up-front, by the month, by metered activity, or by performance. Most packages are designed to be robust enough to allow for easy configuration for any use.

Weir (2009) compiled a list of functions that CMMSs are capable of performing. Although the functions are not all inclusive, they demonstrate the power of the modern systems. These functions include the following.

- Registering the company's list of assets
- Accounting for assets, purchase prices and depreciation rates
- Planning, documenting, and scheduling preventive maintenance activities
- Tracking planned and unplanned work
- Providing management of shift work schedules
- Facilitating condition monitoring and process results
- Controlling inventory

- Assisting with project management
- Monitoring and tracking transportation and fleet status
- Incorporating safety aspects
- Providing maintenance budget information

Sullivan et al. (2004) investigated the benefits of implementing a CMMS specifically for facility maintenance. Many of the CMMSs on the market today are able to interface with existing energy management and control systems as well as property management systems. They also provide the following list of capabilities.

- Work order generation, prioritization, and tracking by equipment/component
- Historical tracking of all work orders generated which become sortable by equipment, date, person responding, etc.
- Tracking of scheduled and unscheduled maintenance activities
- Storing of maintenance procedures as well as all warranty information by component
- Storing of all technical documentation or procedures by component
- Real-time reports of ongoing work activity
- Calendar- or run-time-based preventive maintenance work order generation
- Capital and labor cost tracking by component as well as shortest, median, and longest times to close a work order by component
- Complete parts and materials inventory control with automated reorder capability
- PDA interface to streamline input and work order generation
- Outside service call/dispatch capabilities

2.3 CMMS Implementation

In the academic literature, there has not been much reported regarding the benefits achieved from implementing CMMSs, nor has there been much reported about failed implementation attempts. However, there are a few good case studies that document the successful implementations of CMMSs in power plants and the manufacturing industry. There is also literature that acknowledges the challenges associated with CMMS implementation.

2.3.1 Benefits of Implementing a CMMS

One case study examined the implementation of a CMMS in a medium-sized Irish textile manufacturing company (Gabbar et al., 2003). The company had 110 employees, including nine maintenance technicians and one maintenance manager. A preventive maintenance strategy was in existence at the time of the CMMS implementation. The maintenance staff used a manual documentation system and was only concerned with ensuring preventive maintenance activities were completed on time to minimize machine breakdown and maximize production quality. The maintenance manager was tasked with planning and scheduling maintenance, supervising the maintenance staff, ordering and inventorying spare parts, working as a liaison with equipment manufacturers, commissioning new equipment, troubleshooting defaulting equipment, and upgrading the facility without the assistance of any software system (Gabbar et al., 2003).

Seven months after the implementation of the CMMS, an analysis and evaluation of the maintenance operations was performed. The maintenance function achieved very positive results. The cost of spares was reduced, facility uptime and equipment availability improved, lead times were reduced, organizational morale increased, unscheduled maintenance was reduced, and work order schedules were streamlined. The improved maintenance activities resulted in savings totaling 267,000 U.K. pounds sterling. The implementation of the system cost 122,000 U.K. pounds sterling; using a return on investment analysis, the payback was found to be 6 months. Other benefits were made in production capacity as the output of seamed threads almost doubled going from 380 to 650 per hour. These results indicate some of the efficiencies that can be gained by implementing a CMMS (Gabbar et al., 2003).

Another study that was conducted to demonstrate the effectiveness of a CMMS was in a nuclear power plant (O'Donoghue & Prendergast, 2004). In this study, a CMMS was used to determine the optimum strategy for maintaining the water supply tanks and associated equipment used to store and pump water into the steam generators. Before the implementation, a reactive maintenance strategy existed. The CMMS was implemented to include only one of the numerous tanks. The CMMS provided the framework for and aided the execution of a predictive maintenance strategy for the tank and netted some cost and production benefits. The annual maintenance costs for the tank were reduced from $121,000 to $100,000, and the downtime was reduced from 660 to 250 hours, increasing the production capability of the power plant. This case study demonstrated some of the powerful attributes of CMMSs when successfully implemented (O'Donoghue & Prendergast, 2004).

2.3.2 Common Implementation Pitfalls

The use of a CMMS in maintenance operations has led to the optimal use of resources, but potential implementation problems also exist. Details of implementation problems have been noted by several researchers. Hipkin (1997) suggests that organizational management is a determining factor in successful adoption of a CMMS. If management is not supportive of a new system, or if decision-makers do not consider the data generated by the system, the effort will be fruitless. He also suggests that resistance to change will always be a part of new technology adoption. This sentiment is echoed by

Korka et al. (1997) and Bagadia (2006). Korka et al. (1997) conclude that the reliability of electronically connected equipment and personnel training serve as inhibiters of CMMS adoption. Bagadia (2006) includes a lack of feedback on system utilization, poor technical support, unrealistic goals, and employee turnover among reasons for failure. One of most widely noted reasons for failure in the studies is the process used to select a system.

As noted by Bragalia et al. (2006), there are many systems, with varying characteristics and prices, available to maintenance entities. Bagadia (2006) advises that there is no "best" CMMS. Instead, each individual organization must select a system based on their unique requirements. Hipkin (1997) postulates that the organization selecting a system must know and understand how the infrastructure system has operated in the past and have precise knowledge of essential processes. Bragalia et al. (2006) claim that organizations that selected their system without considering their specific requirements reported that the CMMS did not provide the advertised benefits and the results were below their expectations. Even Wireman (1994), in the early days of CMMS usage, suggested that failure to match the system's specifications with the using organization's goals and requirements would doom implementation to failure. To avoid the waste of valuable resources, the process used for CMMS selection should be formalized.

2.4 Methodology

To achieve desired results, the selection of a CMMS should involve a thorough process to determine an organization's goals and evaluate relevant alternatives. As discussed earlier, the selection process for many organizations in the past has failed to deliver promised results; therefore, there is a need to provide a structured approach to the selection process. Decision analysis, and more specifically value-focused thinking, is a tool that can supplement the selection process.

2.4.1 Decision Analysis

Decision analysis is a discipline that incorporates all available information to systematically evaluate and select from a complex set of alternatives (Clement & Reilly, 2001). The difficulties in making decisions arise from the complexity, uncertainty, sensitivity of the best choice, and tradeoffs between objectives that surround any selection process. Decision analysis provides structure and guidance through procedures, methodologies, and analytical tools to identify, represent, and assess the important aspects of a decision. Applying decision analysis results in the identification of the best possible course of action; it also provides a systematic model of the decision problem that represents the issue at hand and provides insight for the decision-makers. Decision analysis can be applied to simple decisions within a certain environment and complex decisions within uncertain environments, as well as problems with single, multiple, conflicting, or hierarchical objectives. In summary, decision analysis can provide an effective tool for maintenance managers to evaluate and select maintenance management information systems.

2.4.2 Value-Focused Thinking vs. Alternative-Focused Thinking

Decision analysis prescribes one of two approaches for making a decision. Before the 1990s, the traditional method used to develop decision criteria was through the study of alternatives. In this approach, the potential alternatives of a decision are identified and evaluated based on the objectives and criteria of the decision. This method of decision analysis is known as alternative-focused thinking. Keeney (1992) suggested that this technique limits the focus of decisions only to the available alternatives, thus failing to reach maximum effectiveness. This approach excludes criteria that demonstrate the important values of the decision-maker. These values should guide the decision-maker, help determine the objectives and criteria, and promote the search for alternatives that satisfy the objectives and criteria (Leon, 1999). This method is known as value-focused thinking. The fundamental difference between the paradigms is that the alternatives are defined before the values in alternative-focused thinking, while value-focused thinking establishes the values soon after a problem has been identified (Leon, 1999; Keeney, 1992). Alternative-focused thinking helps a decision-maker choose between existing alternatives that may or may not solve the problem at hand. On the other hand, value-focused thinking identifies values that are important to the decision and develops alternatives from them.

2.4.3 Value-Focused Thinking

Value-focused thinking (VFT) focuses on the decision-maker's values. Leon (1999) defined values as the end state at which the decision-maker desires to arrive through the decision. Value-focused thinking promotes the creation of alternatives that are tailored to the values of the decision context, not on pre-existing alternatives. Through this approach, the evaluation and selection of the best alternative is rooted in the established values of the decision-maker. Keeney (1992) published the following advantages to using the value-focused thinking approach.

- Identifying decision opportunities
- Guiding strategic thinking

- Interconnecting decisions
- Guiding information collection
- Facilitating involvement
- Improving communication
- Evaluating alternatives
- Uncovering hidden objectives
- Creating alternatives

Keeney (1992) posits that the benefits of VFT are a direct result of making decisions based on values. He also suggests that this methodology is not only suited to solve present problems, but can provide insight into problems that may exist in the future (Keeney, 1992).

2.4.4 Value-Focused Thinking 10-Step Process

To provide a systematic process to exploit the value-focused thinking methodology, Shoviak (2001) incorporated the principles of value-focused thinking advocates and developed the 10-step process shown in Figure 1. This process is not the only prescribed method of executing a value-focused thinking analysis, but it provides a solid framework to gather and organize a decision-maker's values and to evaluate alternatives (Weir, 2010). The first seven steps are conducted to create the value model and score all available alternatives, while the last three steps offers insight into the decision analysis.

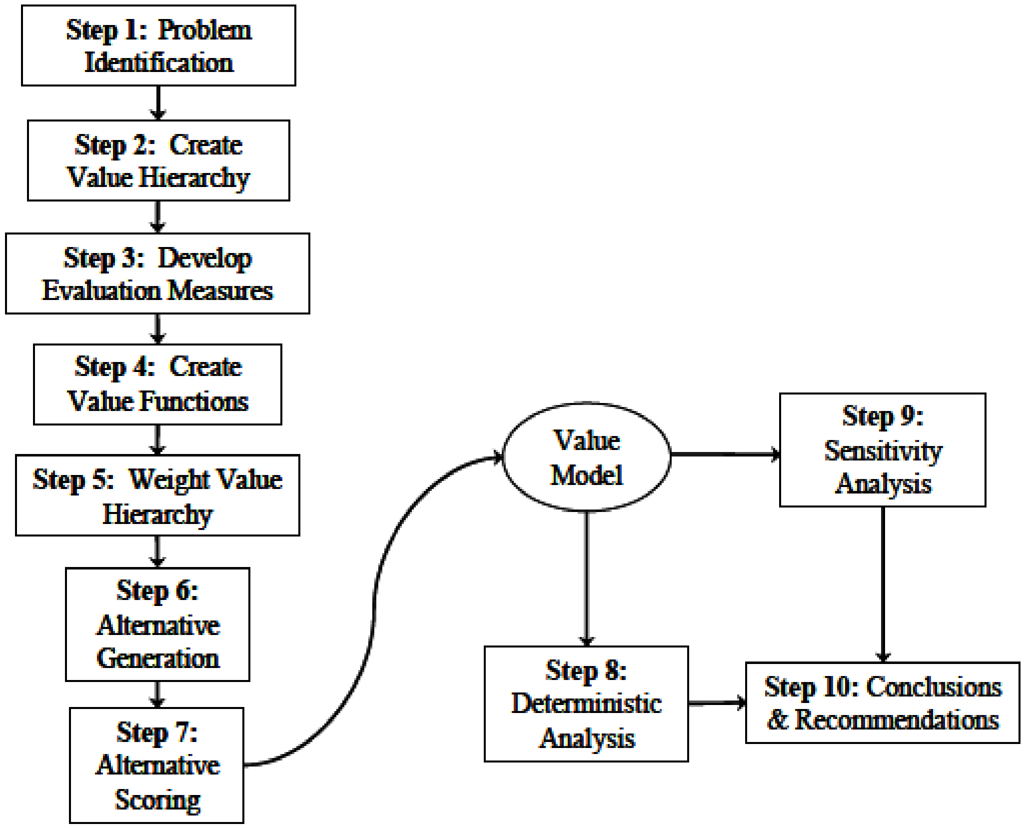


Figure 1. Value-Focused Thinking 10-Step Process (Shoviak, 2001)

2.4.4.1 Step 1 - Problem Identification

Identifying the problem is the first and one of the most important steps in the decision-making process. Alternatives are often suggested and considered before the problem is properly defined. Therefore, decision-makers often fail to completely understand their decision-making objectives, which results in wasted resources and a less useful model. To prevent such a failure, the decision-maker must commit enough time and effort to properly identify the problem (Braziel, 2004; Jurk, 2005; Moon, 2004).

2.4.4.2 Step 2 – Create Value Hierarchy

After the problem is clearly defined, the value hierarchy is then constructed. The value hierarchy is a graphical representation of the values associated with a problem that the decision-maker considers important. This hierarchy allows the decision-maker to visualize the problem, identify values relevant to the problem, and then determine how the values impact the decision-making process. At the top of the hierarchy is the clearly defined problem statement. Below the problem statement is the first tier of values. Each value equidistant from the problem statement constitutes a tier. These values define the important aspects of the decision problem. Below that tier are more values that further define the values of their parent tier. Once the values can no longer be further defined, the hierarchy is considered complete (Braziel, 2004; Jurk, 2005).

Kirkwood (1997) suggested that value hierarchies should possess five properties: completeness (collectively exhaustive), non-redundancy (mutually exclusive), independence, operability, and a small size. Completeness refers to the fact that all concerns necessary to assess the objective of the decision analysis are adequately covered in each layer. Non-redundancy refers to the requirement that the values do not overlap tiers. Independence requires that the preference level for an evaluation measure not depend on the level of any other evaluation measure. Operability requires the resulting hierarchy to be understandable to any stakeholder who may use the model. Finally, the small size requirement helps ensure the hierarchy is easy to communicate and defend, while being practical. Adhering to these principles will help make the decision analysis effective and transparent (Braziel, 2004; Jurk, 2005; Moon, 2004).

2.4.4.3 Step 3 – Develop Evaluation Measures

When values can no longer be sub-divided into more specific values, the decision-maker must develop the specific measures that can adequately represent each value. Some values may require multiple measures for full representation. The evaluation measures enable the decision-maker to quantify the level of attainment of a particular value achieved by an alternative. The measures are associated with the values in the last tier of each branch (Braziel, 2004; Jurk, 2005).

The evaluation measures contain attribute levels or scores using scales that are both natural or constructed and direct or proxy. A natural scale is one that can be easily interpreted by anyone. An example of a natural scale would be the number of dollars that a particular maintenance management information system costs. A constructed scale is one that is developed for specific decision problems; these scales are used when no natural scale exists. An example of a constructed scale would be using good, better, or best to describe a maintenance management information system's user interface. A direct scale is one that directly measures the level of attainment of an evaluation measure. An example of a direct scale would be the average number of times out of 100 that a maintenance management information system fails to launch. A proxy scale indirectly measures the level of attainment of a value through an associated measure. An example of a proxy scale would be to use the number of false reports to measure the accuracy of a maintenance management information system (Braziel, 2004; Jurk, 2005).

Keeney (1992) suggests that there are three desired properties of evaluation measure scales that decision-makers should consider: measurability, operationality, and understandability. The property of measurability ensures that the decision-maker's value is appropriately measured. The property of operationality ensures that the decision-maker's relative preferences for varying levels of a value are indicated by attribute levels associated with each measure. Finally, understandability ensures that ambiguity when depicting and interpreting consequences in terms of attributes is minimized. The values are clarified and the value-focused thinking process is facilitated when these three properties are incorporated into the value hierarchy of a decision problem (Keeney, 1992).

2.4.4.4 Step 4 – Create Value Functions

A value function has to be created to convert the differing units of each of the measure scales into a common scale. The Single-Dimension Value Function aids this process by converting the evaluation measures with different units into value units that measure the level of value attainment for each alternative. When using the Single-Dimension Value Function, the evaluation measures are converted into value units ranging from zero to one. The least preferred scores are fixed with a value of zero, while the most preferred scores are fixed with a value of one. Graphically, the Single-Dimension Value Function has an *x* and *y* axis. The *x* axis represents the score of a particular measure, while the *y* axis represents the converted value for the measure. The function is created using the decision-maker's judgment and allows them to consistently measure the aggregate value of each alternative (Keeney, 1992; Braziel, 2004; Jurk, 2005).

Although there are numerous types of value functions, piecewise linear and exponential are the predominate ones. The piecewise linear function consists of segments of straight lines joined together to form a continuous line, while the exponential function uses an exponential equation to convert the differing units of each measure into value units. With these functions, the least desired score is fitted to zero, while the most desired score is fitted to one. Both functions usually take on monotonically increasing or decreasing shapes (Braziel, 2004; Jurk, 2005) as shown in Figures 2 and 3.

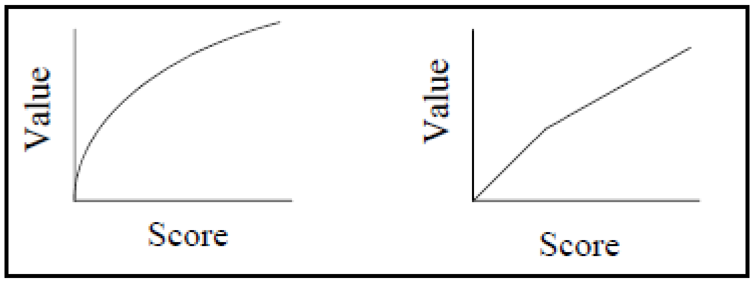


Figure 2. Monotonically Increasing Exponential (left) and Piecewise Linear (right) Value Functions (Braziel, 2004)

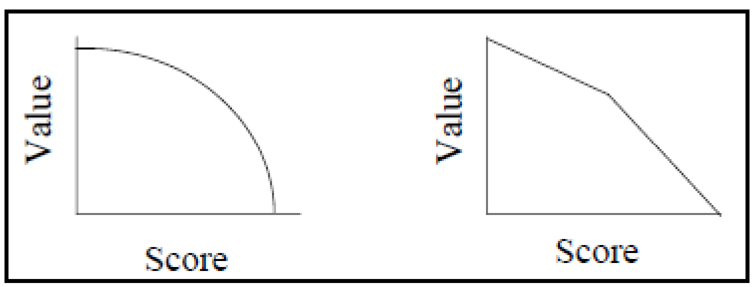


Figure 3. Monotonically Decreasing Exponential (left) and Piecewise Linear (right) Value Functions (Braziel, 2004)

2.4.4.5 Step 5 – Weight Value Hierarchy

The decision-maker must designate the level of importance associated with each value and measure. This is accomplished by assigning weights to each value and measure in the hierarchy using value judgments from the decision-maker. Initially, each value and measure is given a local weight, which measures the relative importance of each value and measure on each tier within each branch of the hierarchy. The summation of the local weights within a tier of a branch must equal one. After the local weights are determined, the global weights can be calculated. The global weights are computed by multiplying the local weight by all the weights above it. The summation of the global weights must also equal one. The local weights indicate the decision-maker's preference for the values and measures within a tier, while the global weights indicate the decision-maker's preference for the values and measures overall (Braziel, 2004; Jurk, 2005; Moon, 2004).

2.4.4.6 Step 6 – Alternative Generation

The range of alternatives that are usually generated in decision situations is often narrow, consisting of those used in previous applications and those readily available (Keeney, 1992). Value-focused thinking promotes the use of values to develop creative alternatives. There are different techniques for generating alternatives; however, this process is not necessary if the alternatives come from an outside source (Keeney, 1992). If too many or too few alternatives are generated, the value hierarchy created in step two can be used to reduce the field or identify gaps in the values (Braziel, 2004; Jurk, 2005; Moon, 2004).

2.4.4.7 Step 7 – Alternative Scoring

To score the alternatives, data concerning the aspects of the measures for each alternative must be collected. This step is often a time-consuming process because it requires locating the data, verifying it, and applying it to the model. The data must be properly documented to support the validity of the results. The decision-maker considers each measure of each alternative at the same time to maintain transparency for each measure definition and their associated categories, ensuring the consistency of each score. If the decision-maker consists of multiple personnel, a consensus should be formed for each score (Braziel, 2004; Jurk, 2005; Shoviak, 2001).

2.4.4.8 Step 8 – Perform Deterministic Analysis

The deterministic analysis is the mathematical process of combining the Single-Dimension Value Function determined in step four and the associated weights determined in step five of each measure for each alternative. This process creates a weighted sum score for each alternative by combining multiple evaluation measures into a single measure. The resulting weighted sum score allows the alternatives to be rank ordered (Braziel, 2004; Jurk, 2005).

There are two value function types that are used in value-focused thinking, additive and multiplicative. The additive value function is simplistic and is the one most commonly used. It also enables the decision-maker to easily generate a detailed sensitivity analysis. To use this mathematical technique, several conditions must be met. The first condition is that each evaluation measure is required to have a Single-Dimension Value Function and an assigned weight. The next condition is that each Single-Dimension Value Function is required to have a range from 0 for the worst evaluation measure score to 1 for the best. Finally, the summation of weights for each alternative must equal one. Once these conditions are met, a value function that allows each alternative to be rank-ordered is developed (Braziel, 2004; Jurk, 2005; Shoviak, 2001).

2.4.4.9 Step 9 – Perform Sensitivity Analysis

The sensitivity analysis is performed after the deterministic analysis. The sensitivity analysis permits the decision-maker to examine the impact of model weights on the final alternative rankings. The model weights located in the higher tiers of the hierarchy are manipulated because the changes tend to result in greater impacts on the final rankings. The sensitivity analysis is a great tool because it can demonstrate the impact of differing opinions on the assigned weights and thus the resulting ranking of alternatives. In conclusion, the sensitivity analysis highlights the range in the values of the weights before the final ranking of alternatives is changed (Braziel, 2004; Jurk, 2005).

2.4.4.10 Step 10 – Conclusions and Recommendations

Following the completion of both the deterministic and sensitivity analysis, the results are presented to the decision-maker. The results are a mere guide to the decision-maker. The analysis allows the decision-maker to examine the changes in the results and make inferences when adjustments are made to the model. The value-focused thinking model does not result in a solution, but rather a decision aid based on the values initially identified (Braziel, 2004; Jurk, 2005; Moon, 2004).

2.5 Summary

This literature review provided an assessment of relevant information pertaining to the selection of a maintenance management information system. Seven topics were discussed to provide a background on maintenance issues: maintenance management, maintenance challenges, maintenance strategies, information systems for maintenance management, current systems, benefits and pitfalls of implementation, and decision analysis concepts, specifically, value-focused thinking. A deep understanding of the details presented in this chapter serves as a foundation from which to develop a model to properly select a maintenance management information system.

Chapter 3. Methodology

This chapter details the creation of a value-focused thinking model to improve the selection process maintenance organizations use to select maintenance management information systems. This research evaluated several commercially available systems to rank order the systems the Air Force Civil Engineer community should consider selecting to support maintenance activities. Value-focused thinking was chosen as the best decision analysis tool to aid this endeavor. This methodology allows the decision-maker to evaluate the available systems according to their values. The goal of this research effort was to develop a computerized maintenance management system selection decision model based on values and measures that can be easily modified for further use by other maintenance organizations. By detailing every step of the model developent process, valuable insight about important aspects of this decision-making exercise can be gained. A 10-step process to build a value-focused thinking model was developed by Shoviak (2001) and the first six steps will be covered in this chapter. Chapter 4 will include steps seven through nine. Chapter 5 will conclude both the 10-step process and the research.

3.1 Step 1 – Problem Identification

This step provides the reason for the development of the decision model. The utilization of a maintenance management information system has been demonstrated to produce efficiencies in maintenance operations. As the economic downturn has reduced the resources allocated to accomplish this task, proper stewarship of the remaining resources can be aided by a maintenance management information system. The problem is that, with such a large number of systems with varying capabilities and costs available, a large number of implementation attempts fail to provide anticipated benefits Braglia et al., 2006). Therefore, this research was designed to assist maintenance management decision-makers in evaluating and ultimately selecting the system that best suits their organization. The problem statement for the decision model was thus stated as follows: "What is the best maintenance management information system for the United States Air Force?"

3.2 Step 2 – Create Value Hierarchy

The value hierarchy is a graphic illustration of the important values used to help solve a decision problem. This diagram can only be created after the problem has been clearly defined. Kirkwood (1997) suggests two ways to develop the hierarchy, top-down or bottom-up. The top-down method first solicits the decision-maker's values in a broad sense. An example would be using cost and capabilities as broad values when evaluating information systems. The broad values are usually the first-tier values that appear in the hierarchy. The first-tier values are further dissected into more specific components that help define the broad values. In the end, a series of specific values that completely define the decision-maker's values are located in the last tier of the hierarchy. The specific values located below a broad value should align with and encompass the full spectrum of that broad value. On the other hand, the bottom-up approach first solicits specific values from the decision-maker. These values are then grouped using a technique like affinity diagraming to develop the hierarchy. An example would be to use initial cost, operations and maintenance cost, and training cost to develop the broad value of cost. After reviewing previous research using the VFT methodology, the top-down approach is often the most preferred. The resulting hierarchy allows the decision-maker to assess the worthiness of the values and corresponding sub-values.

The final hierarchy is determined by the decision-maker, usually an assorted panel of experts and stakeholders concerned with the decision. Because of the exhaustive time demands imposed on members of such a panel, assembly was difficult. Therefore, a proxy decision-making body consisting of instructors at the Civil Engineer school was assembled. The combined experience of the proxy decision-makers totalled nearly 28 years. To expedite the process of constructing the value hierarchy, the “gold standard” method was used. This method, used when the ultimate decision-maker is not available (Weir, 2010), uses strategic objectives, visions, or plans from published documents to deduce the measures and values of the decision-maker. This allows the decision analyst to present a preliminary hierarchy to the decision-maker as a “strawman” to which changes can be made. For this model, Air Force Instruction 32-1001 was used to create the initial hierarchy; Table 1 shows the themes that were extracted from the document. Other maintenance organizations should use their own published goals and objectives to drive the initial development of the hierarchy; consultation with maintenance workers, supervisors, financial management, and upper management should be used to verify the values that the organization espouses.

Table 1. Value Themes from AFI 32-1001

Maintenance Management Information System Themes		
Timely Operations	Economic Operations	Emergency Response
Reliable, Cost Effective Utilities	Quality Standards	Operations Performance Assessment
Work Order Generation and Execution	Effective Allocation of Resources	Effective Logistics Support
Facility Management	Energy Management	Service Contract Management
Electronic Submission of Workorders	Automated Coordination	Recurring Work Program
Work Order Closeout	Capitilization of Work Performed	Higher Headquarters Communications

Figure 4 displays the "strawman" hierarchy developed from the analysis of Air Force Instruction 32-1001. The purpose of the "strawman" hierarchy was to expedite the process and assist the proxy decision-making body in generating values. Affinity grouping was used to organized the themes and identify commonalities. These groupings were further assembled in accordance with themes from the literature concerning implementation failures. The *Ancillary* value encompassed the themes of Emergency Response, Quality Standards, Operations Performance Assessment, Automated Coordination, and Higher Headquarters Communication. The *Asset Management* value covered the themes of Timely Operations, Effective Allocation of Resources, Facility Management, and Capitalization of Work Performed. The *Integration* value dealt with Energy Management, while the *Inventory* value included Effective Logistics Support. The *Service Contracts* and *Utilities* values engrossed Service Contract Management and Reliable, Cost Effective Utilities, respectively. The *Work Order Features* value enveloped the themes of Electronic Submission of Workorders, Recurring Work

Program, and Workorder Closeout. Finally, the Economic Operations theme was covered within the *Cost* value. The resulting groupings formed the values and sub-values of the "strawman" hierarchy.

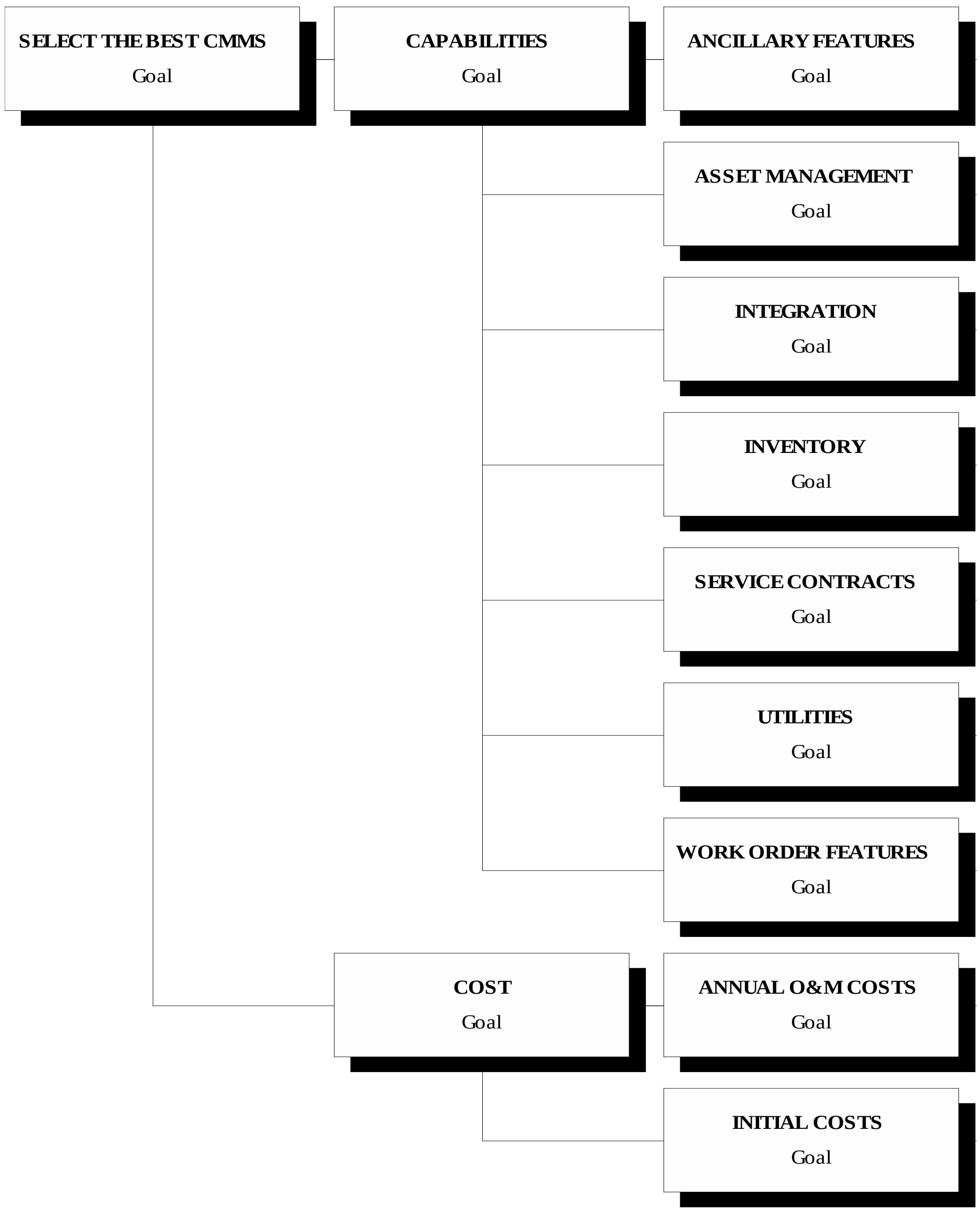


Figure 4. "Strawman" Hierarchy

Cost and *Capabilitie*s were selected as the top-tier values because they encompassed the general themes from the document and conveyed the most basic concerns of maintenance managers. *Capabilities* was chosen because maintenance managers must first determine what aspects of maintenance management systems their organization can utilize to gain efficiencies. Braglia et al. (2006) noted that on average, only 10 percent of system functions are ever adequately exploited. Braglia et al. (2006) also suggested that most implementation failures result from users not knowing the capabilities of the systems that they are selecting. *Cost* was chosen because maintenance managers must make a case to upper management for the purchase of a new system. The utilization of a maintenance management information system requires a long-term investment and an accurate representation of that commitment will help solidify their position.

After the first meeting with the proxy decision-making body, the "strawman" hierarchy was reconfigured to incorporate their inputs. Beginning with the top tier, the proxy decision-making body considered whether the proposed hierarchy reflected their values. The top-tier values remained unchanged; however, the second-tier values were changed to provide more definition to the values. Each branch of the hierarchy will be discussed further in the following sub-sections.

3.2.1 *Cost*

The *Cost* value was defined as all the costs associated with the procurement of a system. To capture the complete financial investment associated with the procurement of a maintenance management information system, both the initial and annual operating and maintenance costs were considered. The *Initial Cost* is the number of dollars required to obtain the software package, initial training, and a license for each of the organization's users. This was important because the decision-making body knew the up-front cost of utilizing the system.

Additionally, *Annual Operating and Maintenance Costs* were used to further define the *Cost* value. The two annual costs include hosting and infrastructure and maintenance. "Hosting Cost" covers system monitoring, backup, reporting, and security for organizations without the infrastructure to maintain their own system, while the "Maintenance Cost" covers annual upgrades, integration, and testing on the system each year. These measures are important to the proxy decision-making body because they are informed of the level of commitment required to keep the system operating in top condition throughout the year. The intent of these measures was to ensure that the organization realizes the long-term cost required to continue operating the system. The *Cost* branch did not change from the "strawman" hierarchy to the final hierarchy.

3.2.2 *Capabilities*

The *Capabilities* value was defined as all of the functions of a maintenance management information system that were desired by a maintenance organization. Four broad sub-values were created to further define the important capabilities that were valued by the proxy decision-maker. A large number of changes were subsequently made to the "strawman" to arrive at the final hierarchy.

The *Integration* sub-value, simple, yet important, gives the maintenance manager an indication of the system's ability to be integrated with Geographic Information Systems, Energy Management Control Systems, Personal Digital Assistants, and other third party software. Initially, the *Integration* value was only concerned with the Energy Management and Control Systems but was expanded to include additional systems. The proxy decision-making body indicated that it values the benefits derived from using the aforementioned information systems and the ability to readily transfer existing data. Incorporating these systems into the overall asset management strategy, combined with a fast, seamless transfer of existing facility data was greatly valued by the decision-maker.

The *Asset Management* sub-value allows the maintenance manager to determine how well the system complements the responsible allocation of resources. The sub-value encompasses capitalization, human resources, inventory control, real property, service contracts, and utilities. These sub-values help further quantify what exactly Asset Management should include. Capitalization allows maintenance managers to track work performed on and changes made to an asset, while real property deals with tracking all assets and critical components. Human resources include features such as job performance, payroll, education levels, and certifications. The level of control exerted over inventory, service contracts, and utilities are also valuable to maintenance managers. Because many of its resources are limited, this wide range of functions was important to the proxy decision-making body.

The sub-value of *Workorder Management* is usually the most widely used and highly regarded aspect of maintenance management systems (Braglia et al., 2006). This value gauges the system's ability to aid preventive maintenance practices as well as work planning. The proxy decision-making body emphasized the importance of the Recurring Work Program, Preventive Maintenance, and Workorder Management to the Air Force

Civil Engineer mission. Preventive maintenance activities such as documenting procedures, producing schedules, overriding incorrect schedules, automatically resetting maintenance triggers, and the routing of maintenance workers for preventive maintenance were some of the functions evaluated. Work planning aspects such as the assignment of qualified workers for specific jobs, indication of parts availability, tracking of workorders, repair history reports, and the retrieval of appropriate drawings were also evaluated. These functions were highly valued by the proxy decision-making body, as the bulk of their activities include preventive maintenance and workorders submitted by their customers.

The *Ancillary* sub-value was further divided into three values, *Fleet Management*, *Information Technology Features*, and *Safety*. *Fleet Management* and *Safety* were two important values not included in the "strawman" hierarchy that were emphasized by the proxy decision-making body. *Fleet Management* includes the ability for the maintenance manager to track both the current status and the maintenance history of their fleet. *Information Technology Features* includes security, system backup, user permissions, and operating system. *Safety* aspects that were evaluated were the inclusion of hazard information associated with different jobs, material handling, and specialized work. The proxy decision-making body acknowledged that these features are often overlooked because they are inherent to maintenance jobs, but they are highly valued and need to be included in a complete system. The resulting final hierarchy of values is displayed in Figure 5.

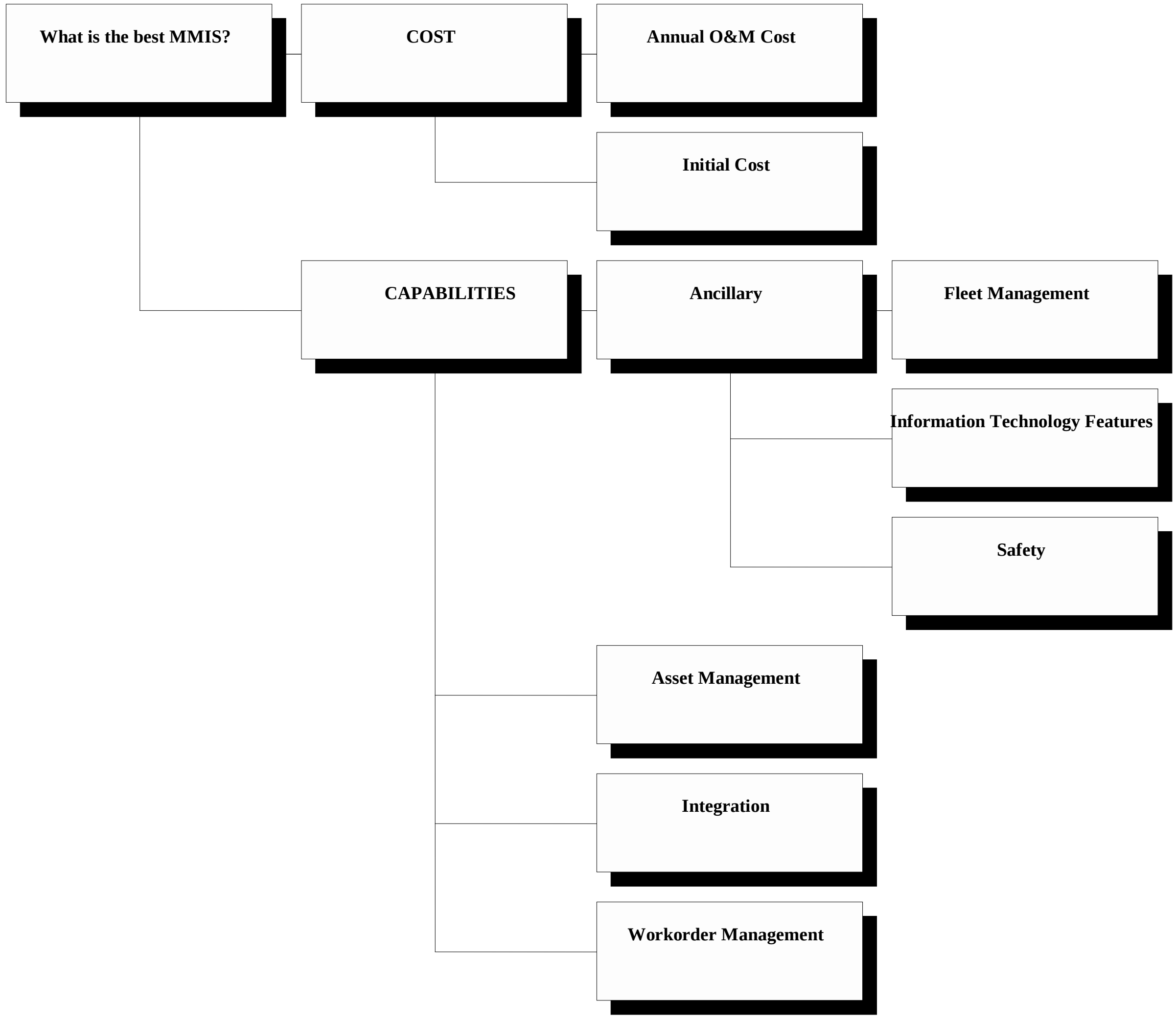


Figure 5. Final Value Hierarchy

3.3 Step 3 – Develop Evaluation Measures

Once the value hierarchy was constructed, the next step was to develop evaluation measures. Each measure had a combination of two of the four scale descriptors, natural or constructed and direct or proxy. Each measure had an upper and lower bound. The upper bound represents the most preferred level of a measure, while the lower bound represents the least preferred level.

To promote ease of use and understanding, the decision analyst should maximize the number of natural, direct scales as much as possible, while creating as few constructed, proxy scales as possible. The measures that defined the *Cost* bottom-tier values were able to achieve this standard. However, each one of the measures used to define the *Capability* bottom-tier values was a constructed, proxy scale due to the varying levels of features that a maintenance management information system can possess. In total, there were 3 natural, direct measures and 21 constructed, proxy measures. The decision-maker determined the final measures, their scale type, and their upper and lower bounds. A complete summary of all the measures is displayed in Table 2. Detailed defintions for each measure are located in Appendix A.

Table 2. Summary of Measures

1st Tier Value	2nd Tier Value	3rd Tier Value	Measure	Measure Type	Lower Bound	Upper Bound	Units
Cost	Initial Cost	N/A	First Cost	Natural Direct	0	6000	Dollars per User
	Annual O&M Cost	N/A	Maintenance Cost	Natural Direct	0	30	Percentage of Initial Cost
		N/A	Hosting Cost	Natural Direct	0	15000	Dollars per Year
Capabilities	Ancillary	Fleet Management	Vehicle History	Constructed Proxy	No	Yes	Categorical
			Vehicle Status	Constructed Proxy	No	Yes	Categorical
		Information Technology Features	Archive	Constructed Proxy	Poor	Exceptional	Categorical
			Electronic Signing	Constructed Proxy	No	Yes	Categorical
			Login Security	Constructed Proxy	No	Yes	Categorical
			Operating System	Constructed Proxy	None	All	Categorical
			Permissions	Constructed Proxy	No	Yes	Categorical
			Smart Reporting	Constructed Proxy	Poor	Exceptional	Categorical
		Safety	Hazards	Constructed Proxy	No	Yes	Categorical
	Asset Management	N/A	Capitalization	Constructed Proxy	No	Yes	Categorical
		N/A	Human Relations	Constructed Proxy	No	Yes	Categorical
		N/A	Inventory Control	Constructed Proxy	Poor	Exceptional	Categorical
		N/A	Real Property	Constructed Proxy	Poor	Best	Categorical
		N/A	Service Contracts	Constructed Proxy	No	Yes	Categorical
		N/A	Utilities	Constructed Proxy	Poor	Best	Categorical
	Integration	N/A	EMCS	Constructed Proxy	No	Yes	Categorical
		N/A	GIS	Constructed Proxy	No	Yes	Categorical
		N/A	PDA	Constructed Proxy	No	Yes	Categorical
		N/A	Third Party Software	Constructed Proxy	No	Yes	Categorical
	Workorder Management	N/A	Preventive Maintenance	Constructed Proxy	Poor	Exceptional	Categorical
		N/A	Work Planning	Constructed Proxy	Poor	Exceptional	Categorical

3.4 Step 4 – Single Dimension Value Function

Once the evaluation measures have been determined, the next step was to develop single dimension value functions (SDVFs). The SDVFs are used to convert the data inputs for each measure of the hierarchy into a corresponding value that embodies the preference of the decision-maker. The conversion of different units and scales of measurement into a common scale helps to effectively and impartially score and rank alternatives. The SDVF is an *x*-*y* graph of the decision-maker's preference versus the upper and lower bounds that each measurement can assume. The *x*-axis corresponds to the upper and lower bounds of the measure, while the y-axis ranges from 0 to 1 to reflect the decision-maker's preference. The value of 0 represents the least preferred level of a measure, while the value of 1 represents the most preferred. This step was difficult, as each SDVF could take any number of shapes. This step was also necessary to quantify the subjective and categorical nature of data resulting from the evaluation process.

When a measure can assume only a small range of specific scores, a discrete SDVF is recommended, otherwise a continuouse SDVF is warranted. The decision-maker decided that the three cost measures should be represented by exponential SDVFs that were monotonically decreasing as shown in Figure 6. The remainder of the measures were determined to be represented by discrete SDVFs as shown in Figure 7. The SDVFs for all 24 measures are located at Appendix A.

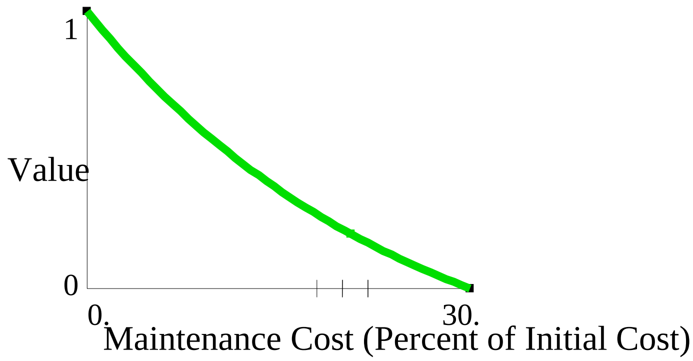


Figure 6. Monotonically Decreasing SDVF for Maintenance Cost

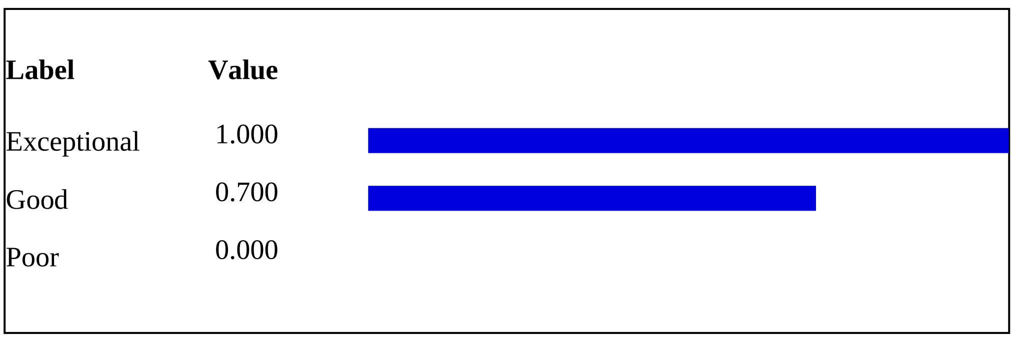


Figure 7. Discrete SDVF for Archive

3.5 Step 5 – Value Hierarchy Weighting

After the identification of evaluation measures and development of their SDVFs, the next step was to weight the values and measures throughout the hierarchy. Applying weights to each component of the hierarchy allows the decision-maker to establish the level of importance of each value. The values and measures can be prioritized through the application of local or global weights. When applying local weights, only the values in the same branch within the same tier are evaluated and their sums must total one. The application of global weights requires the evaluation of all values from all branches across the same tier with the weights summing to one. The global weights ultimately determine the level of importance to the decision problem for each value and measure. The decision-maker determined the local weights using a direct measure approach. Starting at the top of the hiearchy, portions of one point were spread across each value or measure in that tier. The decision-making body debated and finally consented upon the distribution of that one point. This process was repeated down to the bottom-tier of the hiearchy. The local weights were then used to calculate the global weights. Table 3 displays the local and global weights for the measures in decreasing order of their global weights, allowing the decision-maker to easily discern the importance of each measure.

3.6 Step 6 – Alternative Generation

After the value hiearchy was completed with single dimension value functions and weighting, the next step was to generate alternatives. The alternatives were generated using the U.S. Air Force Civil Engineer community as the end-user. The Air Force expressed a desire to acquire a commercially available system that is readily available (Byers, 2010). Because the Air Force is a possessor of vast, multifaceted facilities, only five of the top commercially available enterprise systems were evaluated. The criteria for the selection of alternatives included annual sales and number of customers as displayed in Table 4, which shows the resulting top ten systems.

Table 3. Cumulative Chart of Measure Weights

Measure	Local Weight	Global Weight	Cumulative Global Weight
Preventive Maintenance	0.670	0.171	0.171
Third Party Software	0.500	0.170	0.341
Work Planning	0.330	0.084	0.425
Maintenance Cost	0.800	0.080	0.505
EMCS	0.200	0.068	0.573
GIS	0.200	0.068	0.641
Human Relations	0.300	0.051	0.692
First Cost	1.000	0.050	0.742
Real Property	0.200	0.034	0.776
PDA	0.100	0.034	0.810
Inventory Control	0.150	0.026	0.836
Utilities	0.150	0.026	0.862
Vehicle Status	0.670	0.023	0.885
Hosting Cost	0.200	0.020	0.905
Capitilization	0.100	0.017	0.922
Service Contracts	0.100	0.017	0.939
Vehicle History	0.330	0.011	0.950
Smart Reporting	0.250	0.011	0.961
Login Security	0.208	0.009	0.970
Hazards	1.000	0.009	0.979
Archive	0.167	0.007	0.986
Permissions	0.167	0.007	0.993
Electronic Signing	0.125	0.005	0.998
Operating System	0.083	0.002	1.000

Table 4. Selection Criteria for Alternatives

Computerized Maintenance Management System	Total Sales	Number of Customers
Oracle Utilities Work and Asset Management 1.7.15.2™	$18 Billion	20,000
IBM Maximo Asset Management 7.1™	$200 Million	10,000
Infor EAM 8.4™, IFS Applications 7™	$120 Million	15,000
IFS Applications 7™	$200 Million	2500
Mincom Ellipse 6.3™	$150 Million	650
Invensys Avantis.PRO 4.1™	$35 Million	720
Lawson Enterprise Asset Management™	$41 Million	250
Maintenance Connection Onsite/Online™	$25 Million	500
Assetpoint Tabware EFX00™	$25 Million	123
Invara SuprEAM™	$16 Million	60

The use of the decision model in this application incorporates computerized maintenance management systems that can be easily procured and implemented. The alternatives were also chosen because they could provide the best options that can approach the values of the Air Force. The alternatives were Oracle Utilities Work and Asset Management 1.7.15.2™, IBM Maximo Asset Management 7.1™, Infor EAM 8.4™, IFS Applications 7™, and Mincom Ellipse 6.3™. Customized systems that could be developed specifically for the Air Force were not considered; however, the systems chosen will provide the decision-maker with valuable insight to develop a customized system if none of the alternatives are considered acceptable.

3.7 Summary

This chapter provided an explanation of how the values and measures were derived to form the hierarchy. The first six steps of the 10-step VFT methodology were discussed. The methodology was applied to the problem of selecting a maintenance management information system, and the basic framework of the decision model was presented. The extensive detail provided in this chapter should allow different decision-makers to apply the model to their particular scenario by changing measures, values, and weights. The deterministic and sensitivity analyses are discussed in the next chapter.

Chapter 4. Results and Analysis

This chapter discusses the results from the application of the model and provides an analysis of the model for further insight. Steps seven, eight, and nine of the value-focused thinking (VFT) process are covered in this chapter. In step seven, actual data pertaining to the five alternatives were entered into the model and the results of the alternate scoring are presented. In step eight, a deterministic analysis of the value scores is presented. Finally, in step nine, sensitivity analysis of the model is performed to analyze the impact of altering the evaluation weights on the final rankings of the alternatives.

4.1 Step 7 – Alternative Scoring

After generating the alternatives, they must be scored. Each alternative was scored for each measure using the weights and single dimension value functions generated earlier. The alternatives were scored one measure at a time to convey an unbiased and objective view of the data. Data used to score each alternative was obtained from published literature pertaining to each system as well as the Plant Services' 2009 annual review of maintenance management information systems. Appendix B presents the scores of each alternative for each measure. The alternatives' scores will be analyzed to provide further insight for the decision-maker.

4.2 Step 8 – Deterministic Analysis

After the alternatives have been scored, the next step is to provide a deterministic analysis to create a rank order of the alternatives. The final rank order is based on each alternative's total value, which indicates its ability to achieve the overall objective of the model. The additive value function mentioned in Chapter 2 was used to generate each alternative's total value to be used for ranking. The additive value function produces total values from the product of the global weight and the value resulting from the single dimension value function for each measure. The additive value is demonstrated by the following formula,

$$v(x) = \sum_{i=1}^{n} \lambda_i v_i(x_i)$$

where $v(x)$ is the total for the alternative, n is the total number of measures, λ_i is the global weight for the measure, and $v_i(x_i)$ is the value for the measure determined using the SDVF.

In the end, each alternative received a total value score ranging from 0 to 1 that reflected its overall achievement of the decision-maker's objective. The total value for the alternatives in this research ranged from 0.826 for Infor EAM 8.4™ to 0.684 for IFS Applications™. A bar graph of the deterministic analysis results is presented in Figure 8. The alternatives are clearly differentiated, with no close scores. Based on the total values derived from the deterministic analysis, Infor EAM 8.4™ appears to be the best alternative.

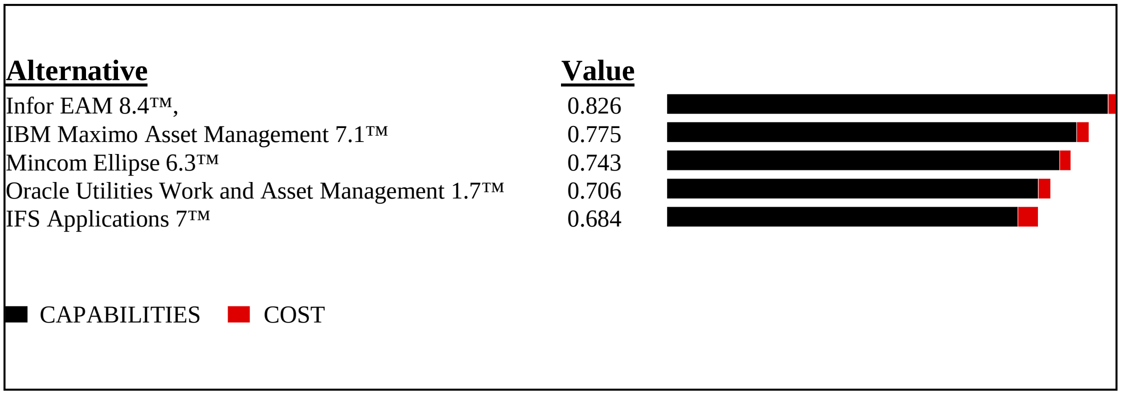


Figure 8. Deterministic Analysis Results by 1st Tier Value

Figure 8 demonstrates the model's utility in rank ordering the value each maintenance management information system provides to the Air Force. The compartmentalized bars in Figure 8 demonstrate the amount of value allocated to each first-tier value. The compartments provide the decision-maker a clear, unambiguous display of how *Cost* and *Capabilities* impact the overall ranking of each system. Figure 8 can be used to guide the decision-maker's investigation into why the Maximo system that has worked for the Navy does not rank highest for the Air Force. The decision-maker can clearly see that the Air Force places a large amount of value on the capabilities of a system and not the cost.

Figure 9 provides further insight into the decision model by presenting a breakout of the top 14 measures, which account for 90.5% of the model's total value. The remaining 10 measures are also shown as a lump sum within the "Other" category. As would be expected, the top two highest weighted measures, Preventive Maintenance and Third Party Software, have the most influence on the final rankings of the alternatives. It is interesting to note that the Oracle system scores well in the two highest weighted measures, but scores poorly with Work Planning and Human Relations. This fact reflects the balance of the model and highlights the trade-offs inherent within the decision model.

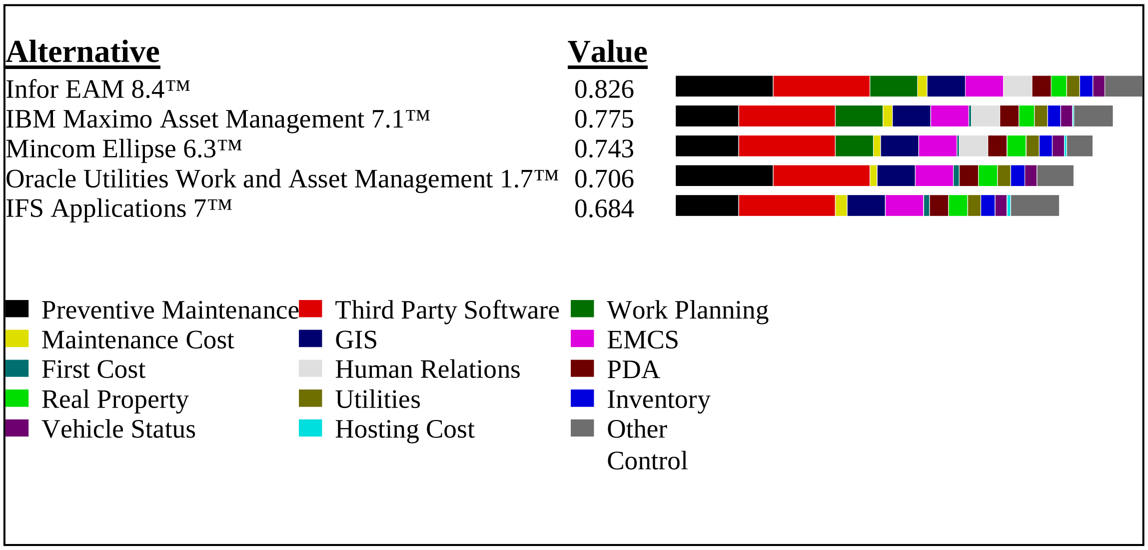


Figure 9. Alternative Score Rankings and Deterministic Analysis by Measure

Additional insight can be gained from examining the deterministic analysis results of the first-tier values of the model. As Figure 10 demonstrates, if pricing alone was the selection basis and allocated the full one point, then IFS Applications 7™, the lowest ranking system, would have been selected. It is also interesting that the highest ranking alternative, Infor EAM 8.4™, scored the least amount of value points within the *Cost* value. This reflects the Air Force's affinity towards *Capabilities* when compared to *Cost*. Figure 11 also supports this fact. Ranking the alternatives based solely on the measures of *Capabilities* results in basically the same rankings as the overall rankings. The Air

Force's devaluation of *Cost*, relative to *Capabilities*, renders the *Cost* value less significant. For organizations with smaller budgets than the Air Force, the *Cost* value may play a more important role within the model.

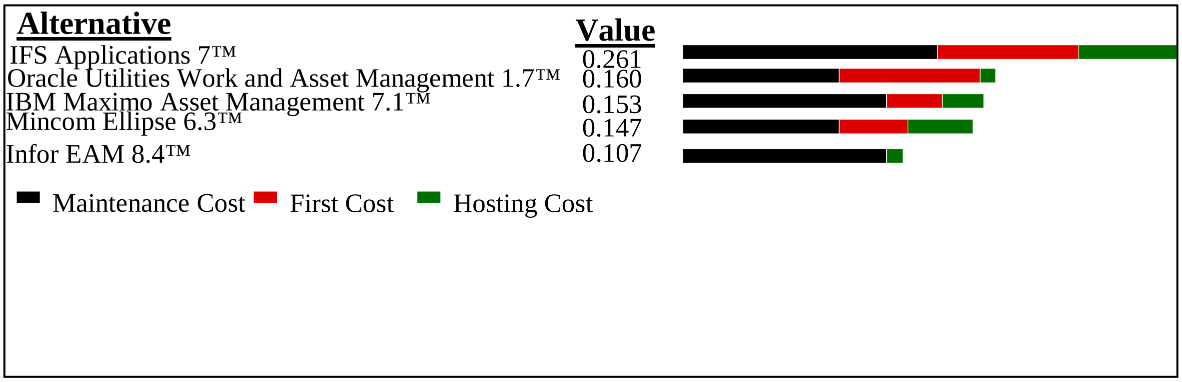


Figure 10. Alternative Score Rankings by Cost

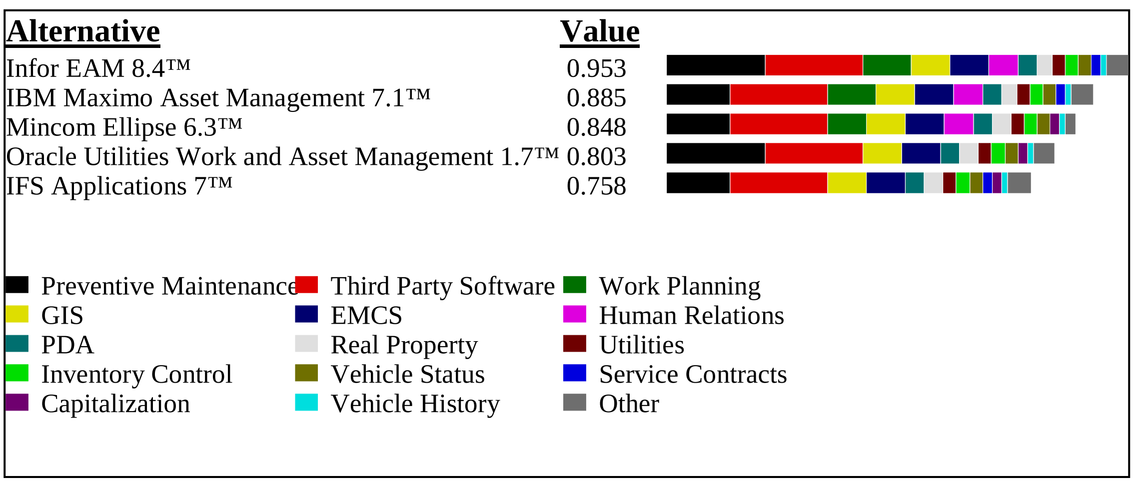


Figure 11. Alternative Score Rankings by Capabilities

4.3 Step 9 – Sensitivity Analysis

After completing the deterministic analysis, the next step was to perform a sensitivity analysis on the model. In addition to the deterministic analysis, the sensitivity analysis can also provide valuable insight to the decision-maker. The sensitivitiy analysis allows the decision-maker to examine how changes in the weights of various goals and measures impact the ranking of the alternatives. This anlysis is especially useful if there were any conflicts concerning the weighting of a goal or measure among the members of the decision-making body. It is also useful if the decision-maker was unsure of the accuracy of the weights that were selected. This analysis also shows the extent to which a weight must change before the final ranking is altered.

The sensitivity analysis is a clear-cut process. The weight of the value or measure of interest is varied from 0 to 1. Weights that are impacted by the change on the same tier and tiers below the value or measure of interest are changed proportionally. The total value for each alternative is recalculated with the new weights and presented on a breakeven chart (Weir, 2010). The decision is considered sensitive if the rankings are altered within the range of realistic weight changes. In other words, if it is realistic for the weight of a value or measure to change enough to vary the rankings, then that component contributes to the sensitivity of the decision model. On the other hand, if changes in the weights of values or measures do not modify the final rankings, then the decision-maker can be confident that their values are accurately reflected within the model (Weir, 2010).

Sensitivity analysis was initially conducted on the first-tier values of the model, *Cost* and *Capabilities*. As displayed in Figure 12, there is not a significant change in the final rankings until *Cost* accounts for more than 56% of the global weight of the model. Since *Cost* currently accounts for 15% of the model's global weight, its weight would have to be almost 4 times greater to alter the outcome. For the Air Force, such a drastic change is not realistic, but for other organizations, such a wide swing might be possible.

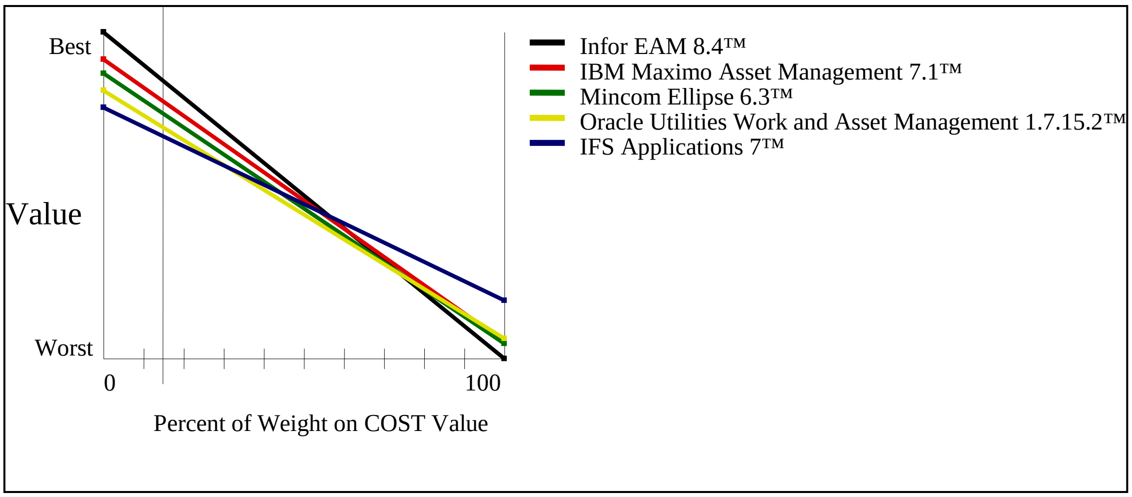


Figure 12. Sensitivity Analysis of 1st Tier Value Cost

The next set of sensitivity analyses to be performed was within the *Cost* branch of the hierarchy. As demonstrated in Figure 13, the measure of Maintenance Cost required substantial weight altering before it impacted the final rankings. The global weight for the measure would have to go from 8% to an unrealistic 75% of the total global weight to change the highest ranking alternative. Figures 14 and 15 also display the need for large changes in global weight distribution before Hosting Cost or First Cost, respectively, altered the final rankings. Hosting Cost requires a change from 2% to 31% of the global weight, while First Cost requires a change from 5% to 39% of the global weight. Varying the weights of values within the *Cost* branch of the hierarchy does not significantly impact the final rankings. Again, these drastic changes are unrealistic for Air Force application, although they may be appropriate for other organizations.

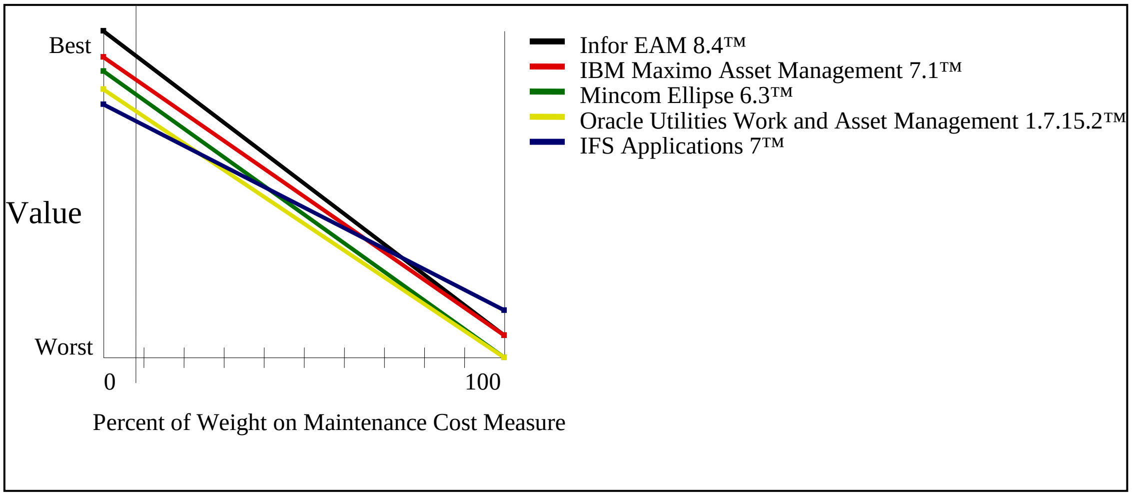


Figure 13. Sensitivity Analysis for Maintenance Cost

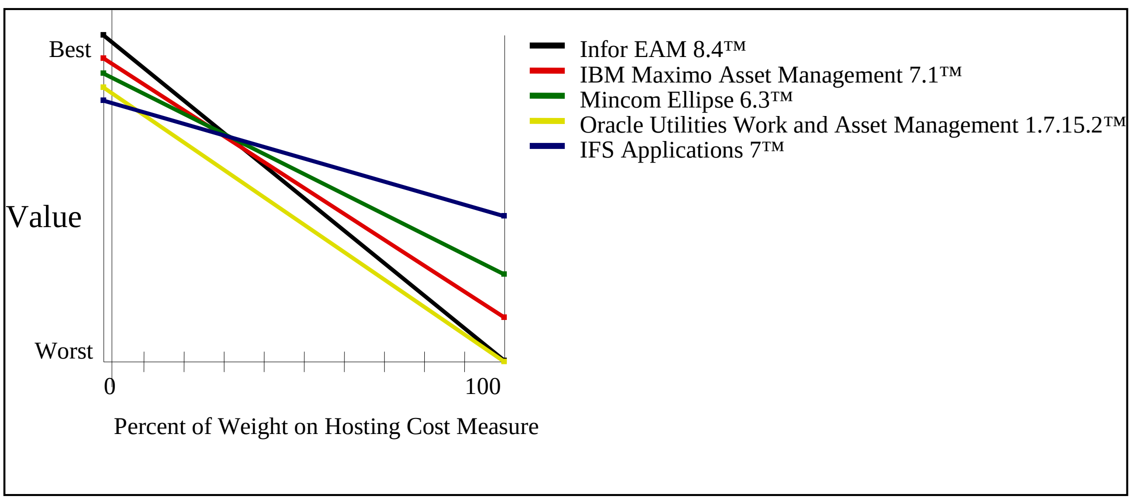


Figure 14. Sensitivity Analysis for Hosting Cost

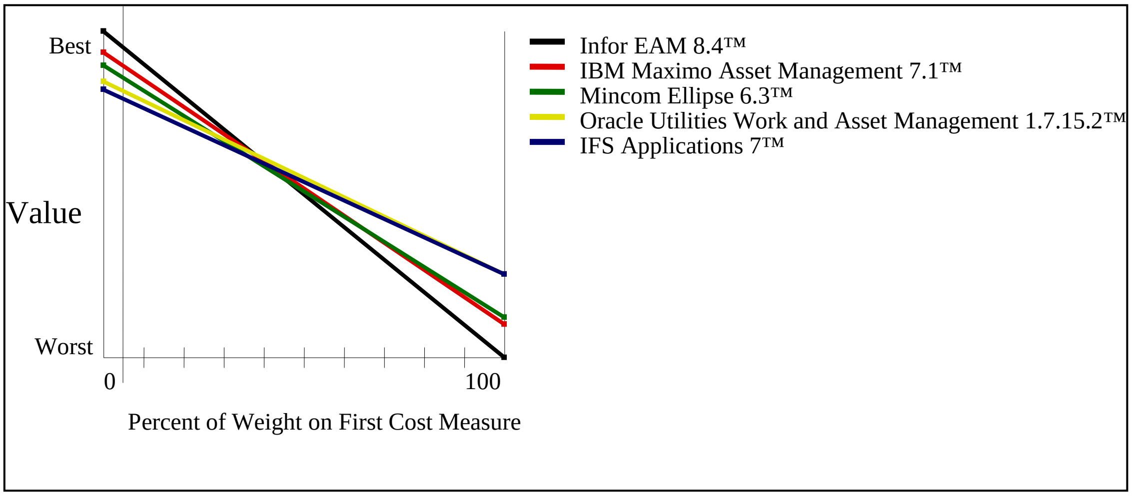


Figure 15. Sensitivity Analysis for First Cost

Next, sensitivity analysis was conducted within the *Capabilities* branch of the hierarchy. The first interesting insight was gained from the *Integration* value displayed in Figure 16. The final rankings were not changed due to any weight changes for this value and its associated measures. Additionally, this remained the case for the following values and measures: *Fleet Management*, Archive, *Information Technology Features*, Electronic Signing, EMCS, GIS, PDA, Human Relations, Login Security, Permissions, Vehicle Status, Vehicle History, Utilities, and Service Contracts. This lack of impact resulted from the fact that the alternatives are able to score consistently well for those values and measures.

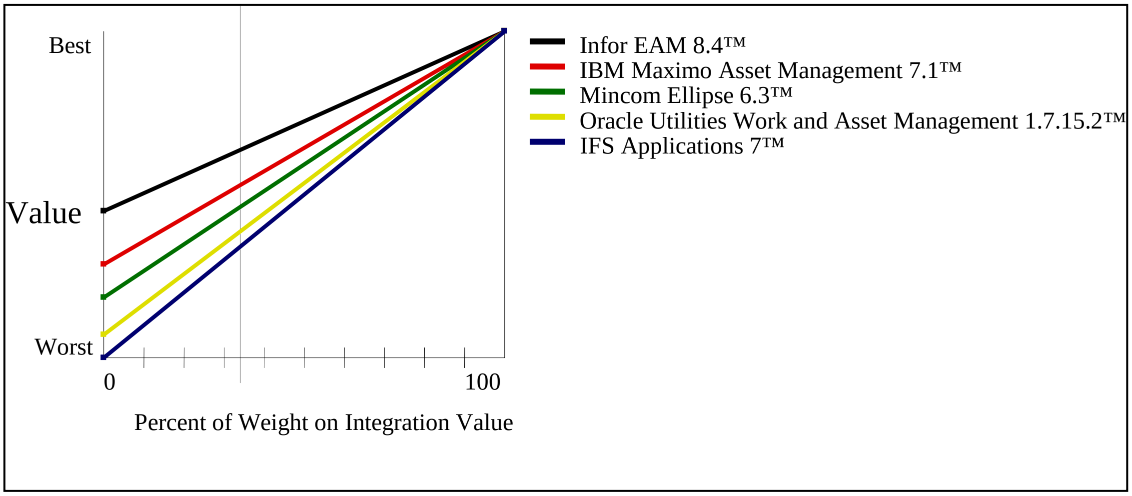


Figure 16. Sensitivity Analysis for Integration Value

The *Ancillary* value was evaluated and the results are shown in Figure 17. The analysis showed that the rankings were not changed by a reduction in the global weight for the value, but are slightly adjusted by large increases in global weight. The global weight for *Ancillary* would have to go from 8.5% to over 77.5% of the global weight to alter the rankings. To discover the measures that contributed to the change in final rankings associated with this value, the subordinate measures that have the potential to change the outcome were evaluated with the results displayed in Figures 18 and 19.

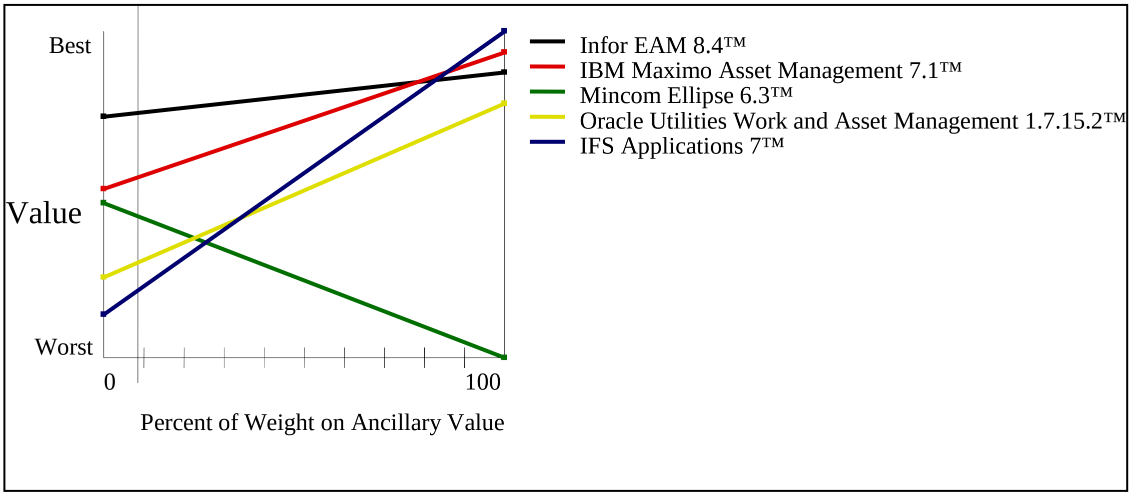


Figure 17. Sensitivity Analysis for Ancillary Value

Figure 18 shows that a substantial increase in the global weight for Smart Reporting, from 1.1% to over 31%, is required to alter the top performing alternative. Conversely, increasing weight of the Hazards measure makes a difference, requiring an increase in global weight of only 4.85% from .99% to 5.75% to alter the ranking of the alternatives. This indicates that the required safety features of the systems should be investigated to provide an explanation of the sensitivity. It also indicates that the top scoring alternative scored very poorly for this measure. Overall, the rankings of the alternatives are not changed by realistic changes in the *Ancillary* value.

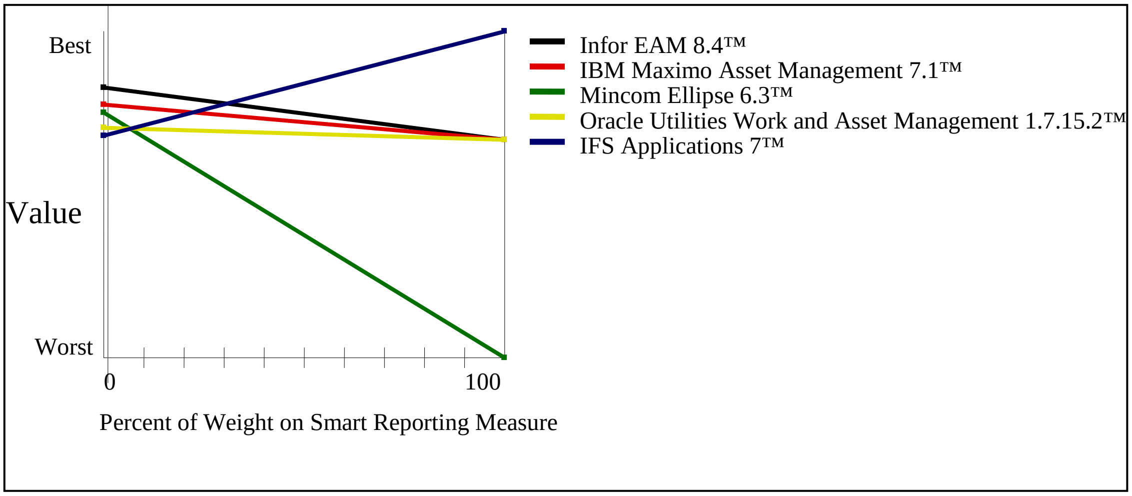


Figure 18. Sensitivity Analysis for Smart Reporting Measure

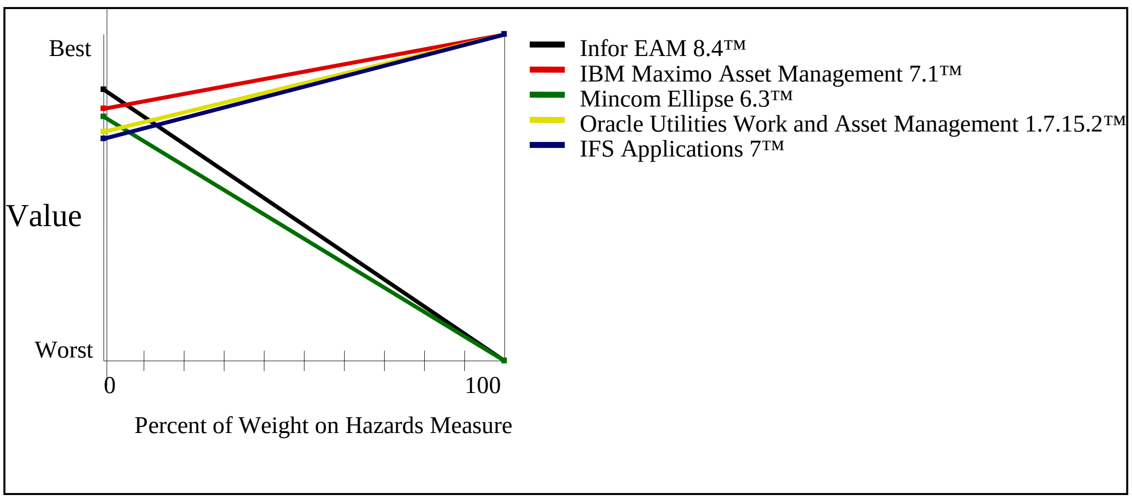


Figure 19. Sensitivity Analysis for Hazards Measure

A sensitivity analysis was performed on the *Asset Management* value and the results are presented in Figure 20. The anlaysis indicates that decreases in the global weight of the value only changes the rankings of the third and fourth best alternatives, while a large increase in global weight can impact the final rankings. Because Minicom scored the best within the *Asset Management* value, large increases in this value's weight give it the edge. The measures of Inventory Control, Real Property, and Capitalization, whose weight changes were observed to impact the results, were all examined to provide further insight. As indicated by Figures 21 and 22, significant altering of the weights of Inventory Control and Real Property is required to change the alternative rankings. Capitilization requires nearly 5 times as much weight, increasing the global weight allocation from 1.7% to 9.5%, to make an impact. Overall, this value does not change the rankings when realistic changes in the global weights are allocated by the decision-maker.

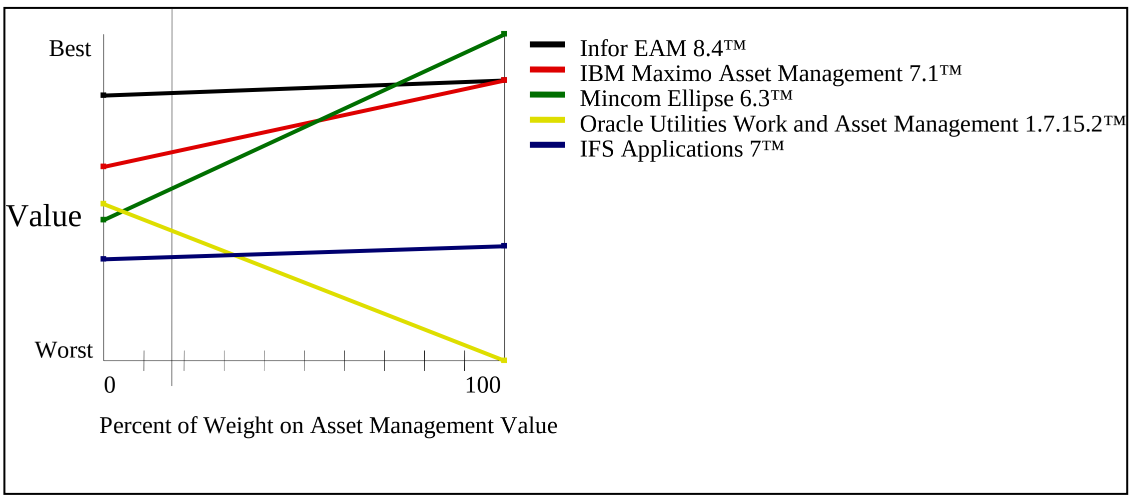


Figure 20. Sensitivity Analysis for Asset Management Value

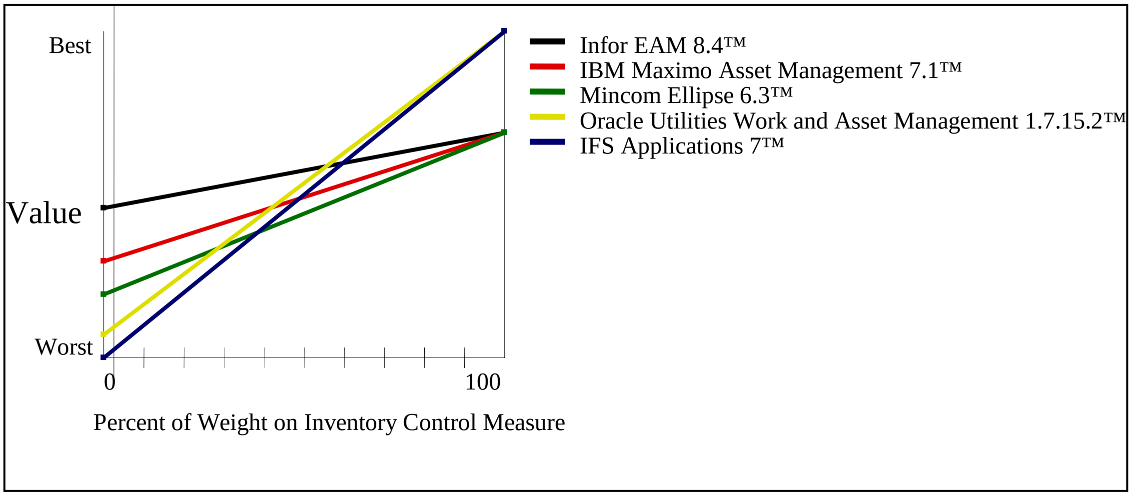


Figure 21. Sensitivity Analysis for Inventory Control

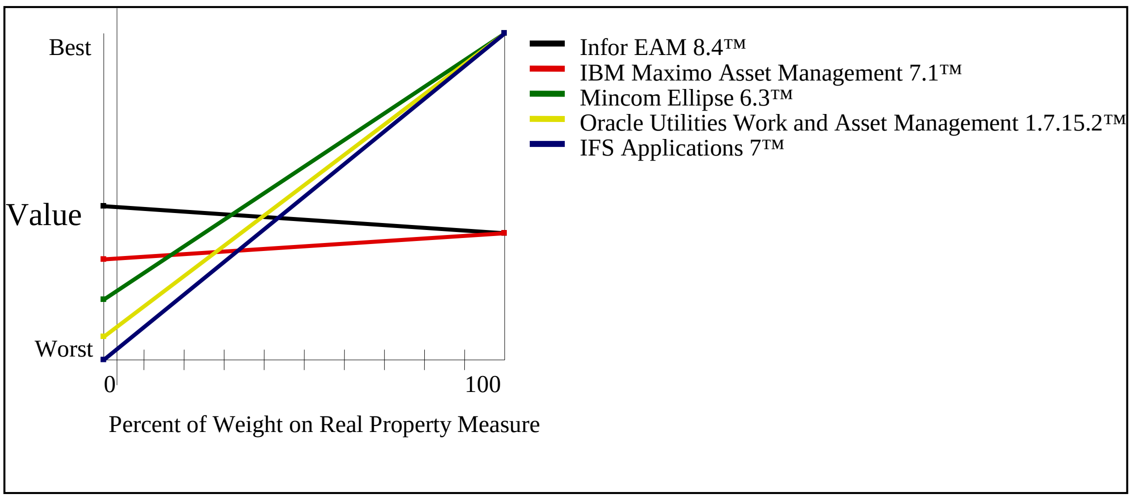


Figure 22. Sensitivity Analysis for Real Property Measure

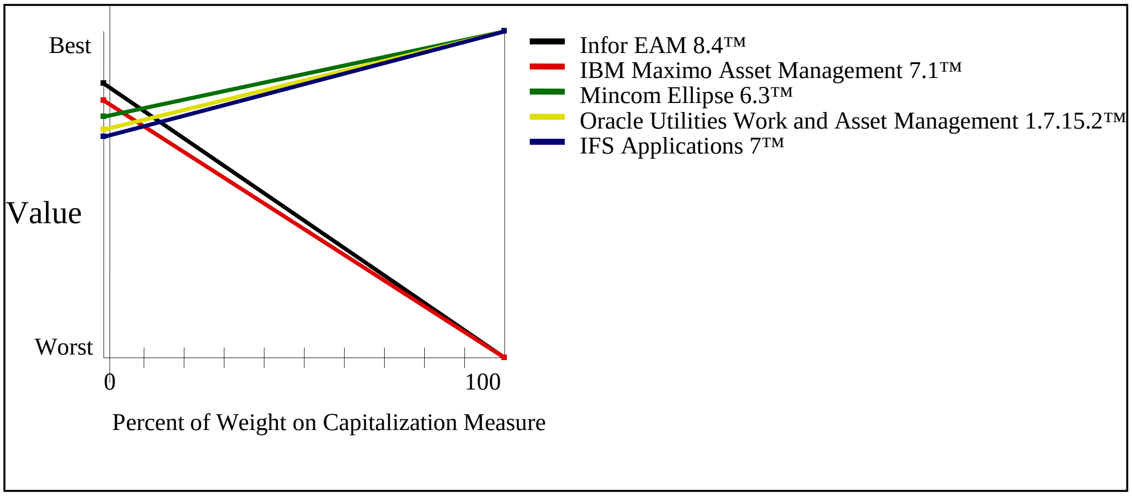


Figure 23. Sensitivity Analysis for Capitalization Measure

Finally, the *Work Order Management* value was examined. Figure 24 shows that the outcome is insensitive to increases in weight for the value, but is sensitive to significant decreases in weight. Both measures that define the value were also examined for further insight. Figure 25 shows that the model is totally insensitive to weight increases of the Work Planning measure. There are a few changes to the results as the weights for Work Planning are decreased. This is due largely to the fact that the Oracle system scored poorly within this measure. Figure 26 shows that both decreases and increases for the Preventive Maintenance measure will alter the final rankings. As the weight associated with this measure increases, the top two scoring alternatives, Infor and Oracle, converge on a perfect score. This is due to the fact that both alternatives scored very well with this measure, while the remaining three did not. If the weights are decreased, then Oracle's poor score in other areas, as well as Infor's average score in other areas distort the rankings. If this measure were excluded from the model, Maximo would be the best alternative. The weight for Preventive Maintenance would have to decrease from 17.1% to 2.75% of the global weight. This alteration is highly unlikely because preventive maintenance features of the systems are highly valued by the decision-maker.

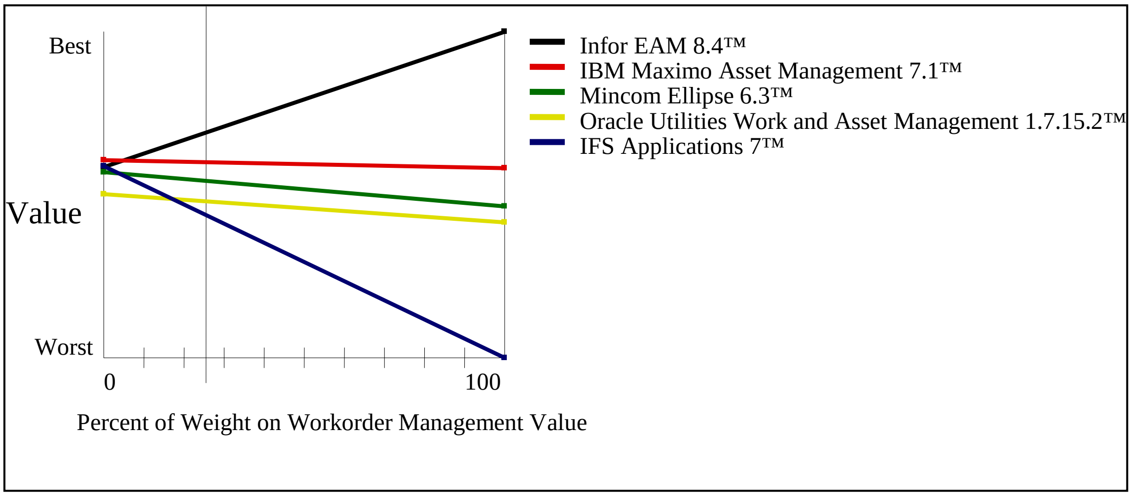


Figure 24. Sensitivity Analysis for Workorder Management Value

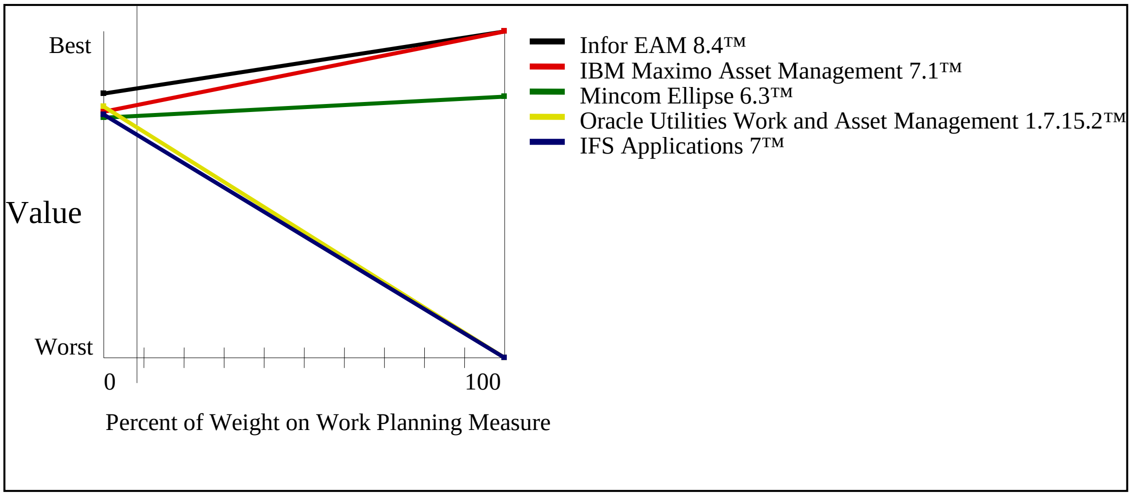


Figure 25. Sensitivity Analysis for Work Planning Measure

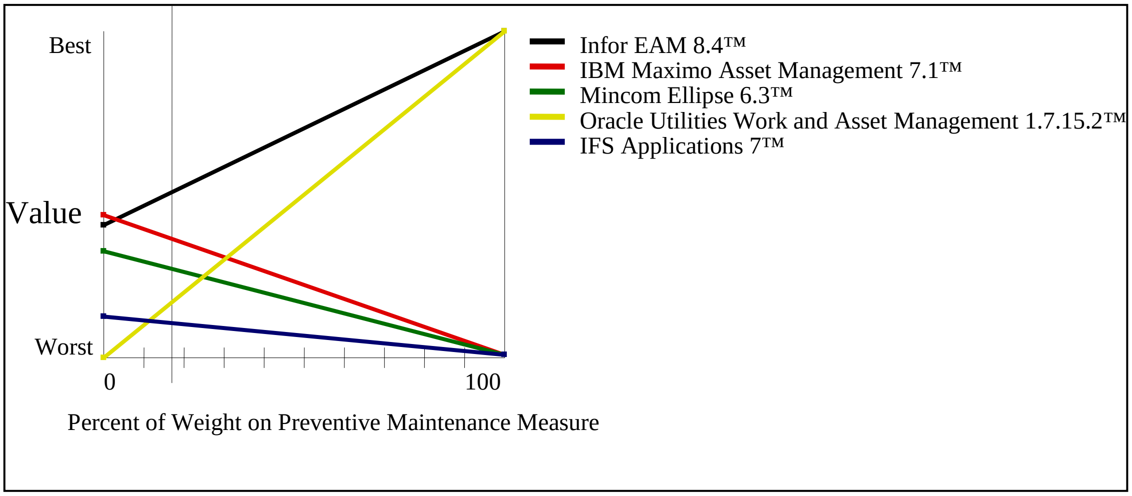


Figure 26. Sensitivity Analysis for Preventive Maintenance Measure

4.4 Summary

This chapter provided an analysis of how well the alternatives met the objective of creating the model. Steps seven, eight, and nine of the 10-step value-focused thinking methodology were discussed. The alternatives were scored using published data in step seven. In step eight, the deterministic analysis rank ordered the alternatives and provided insight into the contribution of each value and measure. Step nine provided further analysis of the decision-making body's assignment of weights throughout the hierarchy. The overall decision was relatively insensitive to alterations of global weights assigned to the values and measures. The conclusions of the research are provided in the next chapter.

Chapter 5. Summary and Conclusions

This chapter provides a brief summary of the research results. A review of the answers to the investigative questions posed in Chapter 1 is provided. This is followed by an evaluation of the model's strengths and limitations. Finally, the conclusions from the research are presented, followed by recommendations for future research in this area.

5.1 Research Summary

The objective of this research effort was to develop a decision model to enhance the selection process associated with the purchase of a commercially available maintenance management information system. Although there are several decision-making methodologies available, the Value-Focused Thinking (VFT) process was selected because of its ability to make subjective requirements objective and channel the organization's values into the decision, while being considered defendable and repeatable. The final model was developed using Shoviak's (2001) 10-step method and was based on Air Force Instruction 32-1001, as well as input from a proxy decision-making body consisting of experienced instructors at the Civil Engineer school. The values and measures developed from published materials, along with expert inputs represent the gold standard approach (Weir, 2010). The resulting answers to the investigative questions guiding this research are summarized below.

1. What is maintenance management and why is it needed?

Maintenance management is the application of planning, organizing, staffing, program execution, and control processes to maintenance activity. It has evolved from a "fix it when it fails" activity during the industrial revolution into a predictable science aimed at preserving operational capacity today. It is needed to efficiently apportion the limited resources, time, money, and manpower allocated to the task.

2. What are the predominant maintenance strategies and how are they applied?

The predominant maintenance strategies are reactive, preventive, predictive, and reliability-centered. They are applied in various situations depending on the requirements of the facilities and its operations. It has been noted that a combination of strategies is needed to provide the best maintenance possible.

3. How are information systems used in maintenance management, what are the capabilities of those systems, and what improvements have been documented from implementation?

Maintenance management utilized the great analytical powers of computers to aid their operations. For instance, information systems keep track of facilities' component repair history, monitor their performance, and indicate the requirement for maintenance. The systems are capable of nearly every aspect of maintenance operations from generating workorders and scheduling workers, to monitoring utilities and paying bills. Although the number of peer-reviewed articles is limited, a few studies citing significant benefits have been authored.

4. What methodologies are available to aid organizations in evaluating and selecting from a field of alternatives?

There are several selection methodologies available. Some include the Analytic Hierarchy Process, Analytic Network Process, Goal Programming, Value Engineering, and Value Analysis. Several methodologies were evaluated and VFT was chosen because it allows the decision-maker to weight their values, handle competing objectives, and produce a highly adaptable model.

5. What are the attributes of a maintenance management information system that the Air Force values and how do variances in these attributes impact the outcome of the selection process?

This question was answered through the development of the model. The values of the Air Force were determined using AFI 32-1001 and the proxy decision-making body. The Air Force primarily values the cost and capabilities of a maintenance management information system. After extensively evaluating the values, measures, and weights determined by the proxy decision-maker, there was not much variance in the outcome of the selection process.

6. What capabilities are desired in a system that the Air Force values?

The four main capabilities that were desired by the Air Force were ancillary features, asset management features, integration features, and work planning features of each alternative. The Air Force strongly desires a system with robust preventive maintenance and integration features, while attributes such as electronic signatures for workorder submission and permission levels for workers were not valued as highly.

7. How are appropriate alternatives screened and selected for evaluation from the vast field of systems?

For this application, the alternatives were screened by their customer base and their annual sales. The top five systems were selected for evaluation. This screening process worked because the system desired by the Air Force needed to be a large, all-encompassing application that could provide a robust set of features. It has been determined through this research that this approach may not be the best to reduce a field of alternatives.

5.2 Value Model Strengths

The final model offers a systematic, defendable, and objective method to evaluate and select maintenance management information systems. These qualities are attributed to the gold standard upon which the initial hierarchy was built. The 10-step methodology developed by Shoviak (2001) presents a simplistic, easy to understand process to create a model. This process reduces the subjectivity that often surrounds unstructured decision processes. The model is defendable because the values espoused by AFI 32-1001 were confirmed through consultation with the proxy decision-making body. The model provides valuable insight through its deterministic and sensitivity analyses, which can spawn further insightful investigation. Although the weights assigned throughout the hierarchy may shift depending on the decision-maker, the values developed for this model represent what is important to the Air Force.

Another strength of this model development methodology is that it is universal enough for implementation, with minor adjustments, by any maintenance organization. The values and measures developed for this model represent the most basic maintenance aspects with which maintenance managers are concerned. They represent a baseline for value and measure development. Obviously, different organizations will adjust weights, values, and measures, but all the components that comprise the basis for system comparison are included in the model.

5.3 Value Model Limitations

The main limitation of this model was the use of non peer-reviewed materials to score each alternative for each measure. The data was obtained from trade magazine evaluations and published literature associated with each alternative. The evaluators can present some bias when evaluating each system, while promotional documents can contain errors. This method could have been complemented by using inputs from existing users of the systems, but time limitations rendered that option unavailable.

Another limitation of this model is the fact that it does not reduce the field of available systems that will be evaluated. For this application, enterprise-type systems were evaluated, but some of the lower grade packages could have ranked higher. If too many alternatives are evaluated, the task of evaluation becomes unmanageable. A method to reduce the number of systems evaluated to a manageable one is needed to increase the utility of this model.

Methodologically, the model is limited by the exclusion of a sensitivity analysis on the single-dimension value functions. The uncertainty associated with the accuracy of the value functions is disregarded. The development of accurate value functions could be hampered by a lack of expertise in other organizations. If the value functions were evaluated for sensitivity, the potential pitfalls associated with the development of accurate value functions could be alleviated.

5.4 Conclusions

This research resulted in both the development of a background within the maintenance management field and creation of a selection model to help maintenance organizations select an appropriate maintenance management information system. The objective was selected because a large number of system implementation failures have been documented (Bragalia et al., 2006), while the systems have been shown to produce benefits (O'Donoghue & Prendergast, 2004). The literature review presented addressed the first purpose, while the second purpose of the research was fulfilled through the development of a value-focused thinking model that included inputs from literature and a proxy decision-making body. This model provides decision-makers with invaluable insight into the evaluation and selection of maintenance management information systems, while simultaneously providing objectivity to the process. The application of this model results in a ranking of alternatives that aids the maintenance management decision-maker in the system selection process.

5.5 Future Research

This research presented a methodology to provide insight and reduce errors when a maintenance management information system is being selected. Upon the completion of this project, several areas for further study were discovered. One future research avenue would be to measure the efficiency of maintenance management operations. This would be performed by evaluating the nature and amount of time used by maintenance personnel for activities not directly related to their duties. The quality of their work should also be evaluated in addition to the cost of the materials that are used. Investigating these three factors can help maintenance managers determine what areas can be targeted to create further efficiencies.

Future research can also strive to develop a more practical method to screen the extensive field of maintenance management information systems. Only the top five systems in terms of sales and customer base were assessed and evaluated in this research effort. With over 400 systems available, the initial field of systems that an organization should evaluate needs to be reduced. Additionally, the actual implementation of a CMMS explicitly in an infrastructure maintenance application is another suggestion for research. Insight into the actual benefits of a system could be gained. Currently, there is a small amount of literature covering system application specifically for infrastructure. The future research advocated above can add to the limited body of literature in the maintenance management the field of research.

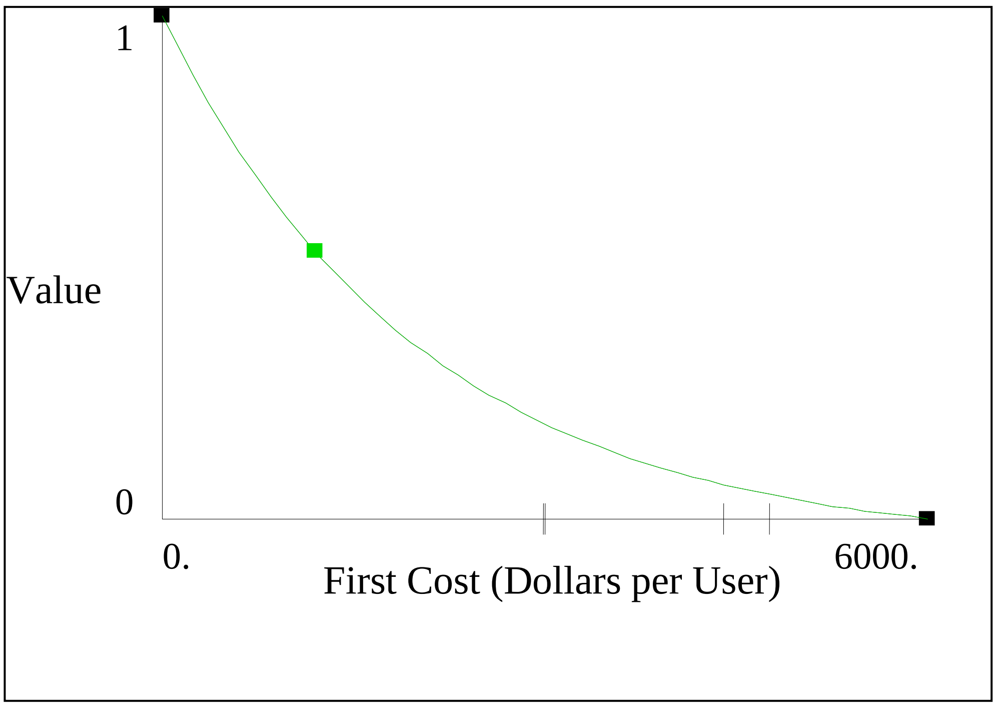
Appendix A: Summary of Measures

Cost Branch

Measure: First Cost

Definition: This is the cost per user to acquire the system, set it up, and train users.

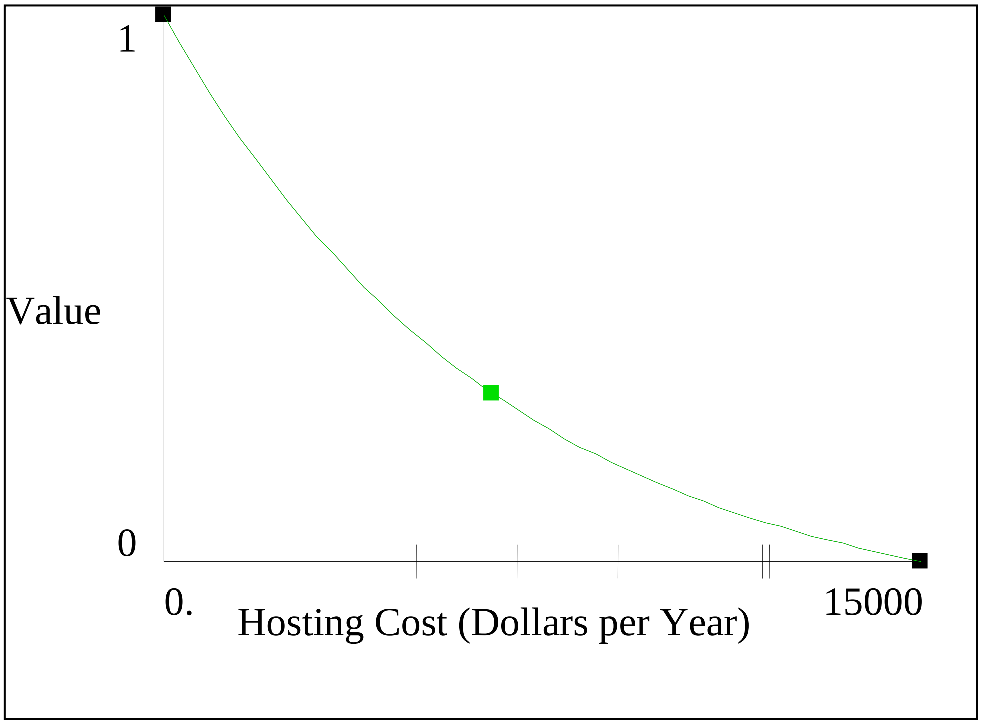
SDVF:



Comments: The upper and lower bounds for this measure were determined from inputs by the researcher and the decision-maker. The researcher suggested a maximum price of $7,500 per user, but the decision-maker suggested $6,000 based on the number of users that will employ the system. The decision-maker decided that $6,000 was the maximum that would be paid to acquire a system and if a system did not meet the minimum, it would not be considered. The monotonically decreasing nature of the function was decided to reflect that a higher price reflects lower value for the decision-maker. The decision-maker placed more value on changes in the lower cost region than in the higher cost region.

Measure: Hosting Cost

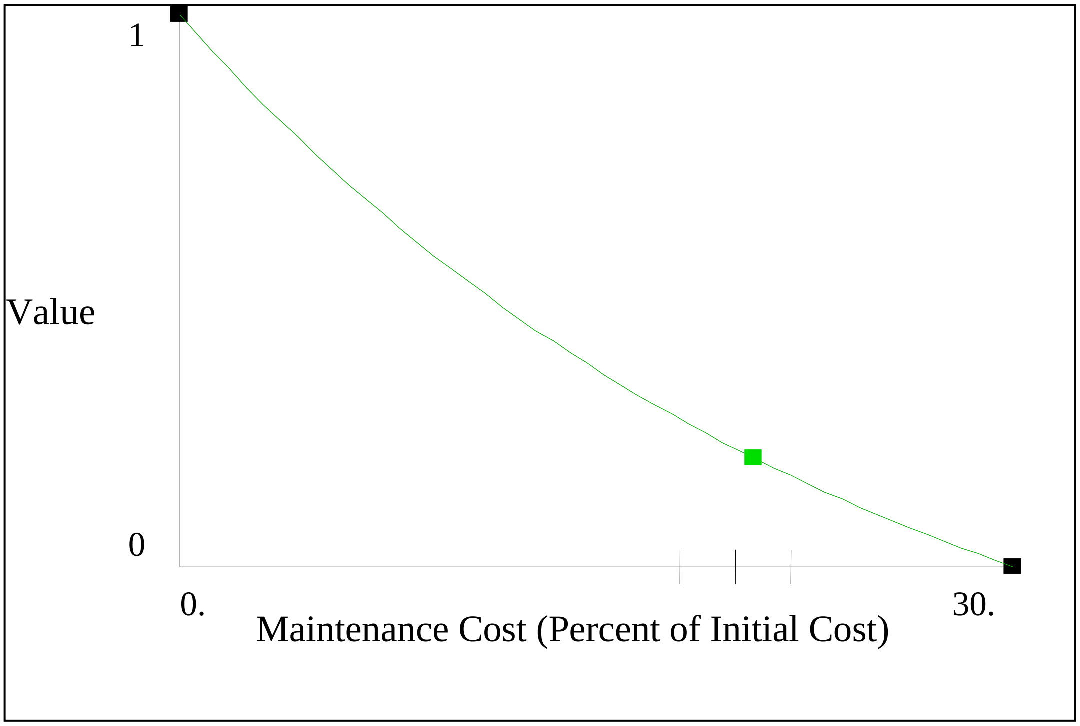
Definition: This is the cost per year to have the system's infrastructure hosted either on site or off site.
SDVF:



Comments: The decision-maker specified the upper and lower bounds of this measure. Usually, for information systems utilized by a large segment of the Air Force, hosting would be performed internally. Accordingly, the decision-maker was not overly concerned about this measure. However, this model is designed to provide universal measures that could be discounted through weighting. The decision-maker valued this measure because of the backup capabilities that could be provided. The decision-makers decided on a maximum of $15,000 a year after probing from the decision analyst.

Measure: Maintenance Cost

Definition: This is the cost to upgrade the system from year to year, as well as provide customer service. The cost is usually reported in percentage of initial cost.
SDVF:



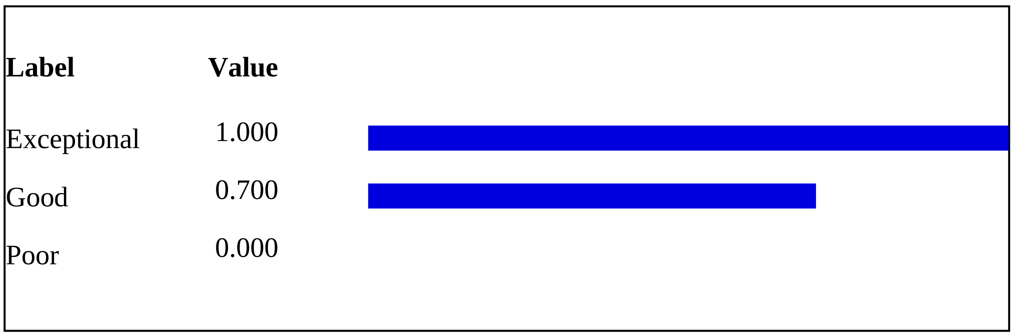
Comments: The decision-maker considered this measure to be one of the most important in procuring a system. It felt that the ability to maintain, upgrade, and provide the latest new features to the system were very important to the mission of maintaining world class installations. A suggestion of 25 percent for the maximum maintenance cost was made by the analyst, but that figure was increased to 30 percent by the decision-maker to reflect the importance of this measure.

Capabilities Branch

Measure: Archive

Definition: What level of archiving is provided by the system?

SDVF:



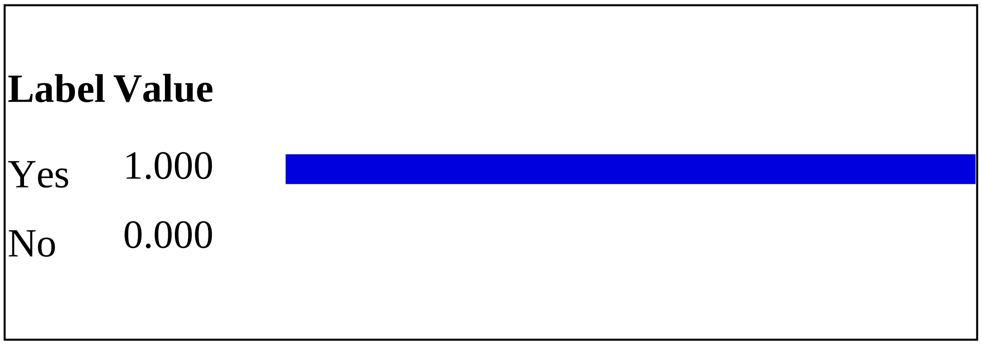
Category Definitions: A rating of Good was received if a system was able automatically archive data. A rating of poor was not received if the system could not perform this task. A rating of Exceptional was received if the system was able to automatically archive data to include changes to all databases.

Comments: The decision-maker valued the ability automatically archive data to prevent total data loss during unexpected power glitches. The analyst suggested the categories and value point assignment and they were accepted by the decision-maker.

Measure: Vehicle History

Definition: Does the system track the service history of vehicles?

SDVF:



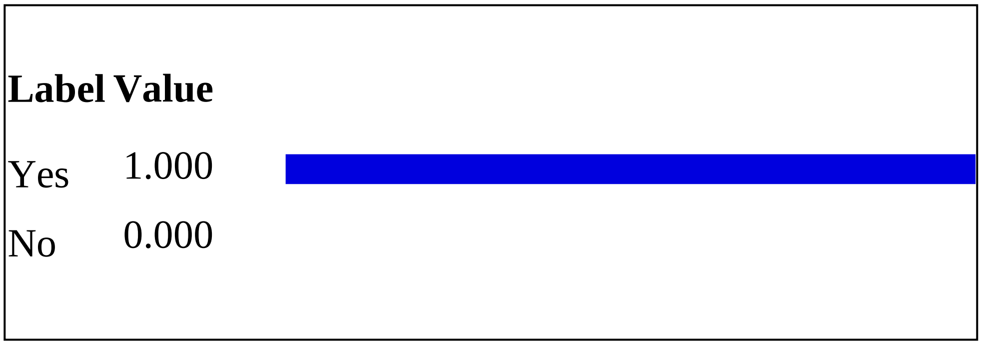
Category Definitions: The maintenance service history is either tracked by the system or not.

Comments: The decision-maker wanted to include this measure along with the Vehicle Status measure so that trends can be identified within its fleet. The decision-maker expressed a desire to review and consider the service history of vehicles when contemplating appropriate replacements. Another concern was the amount of time that each vehicle remained in maintenance and why. Tracking the history of each vehicle is valued by the decision-maker because it helps with replacement considerations.

Measure: Vehicle Status

Definition: Does the system track the status of vehicles?

SDVF:

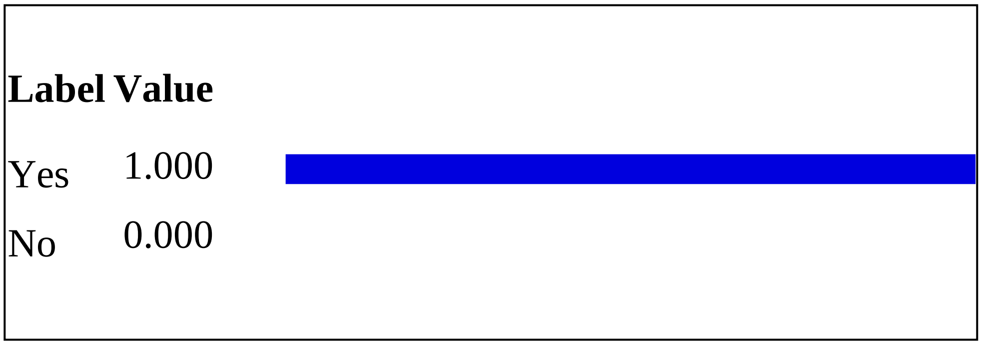


Category Definitions: Is the real-time status of the vehicle fleet tracked?

Comments: The decision-maker decided to make this feature a measure because without their vehicles, maintenance workers' effectiveness is severely reduced. Maintenance workers carry themselves, their tools, and special heavy equipment to their work sites across sprawling installations, therefore the scheduling of jobs has to consider the status of vehicles.

Measure: Electronic Signing

Definition: Does the system require electronic signing to authenticate operations in the system?
SDVF:



Category Definitions: Either the system requires electronic signatures for the submission of workorders, closing out workorders, remotely coordinating on the workorders, or modifying data.

Comments: Electronic signing was not heavily discussed by the decision-maker, but the issue of submitting and coordinating workorders was. The decision-maker valued the ability to ensure that the system was not flooded by multiple facility users reporting the same problem. They also valued not having to waste time driving to multiple facilities with paper copies of workorders to get required signatures and not having workers call in to close out workorders. The decision-maker also valued the ability to track changes to data back to a source.

Measure: Login Security

Definition: Does the system require logins?

SDVF:

Label	Value
Yes	1.000
No	0.000

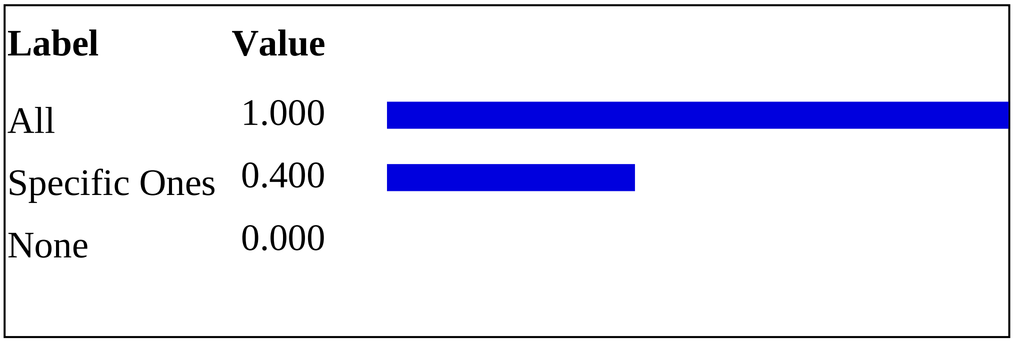
Category Definitions: Either the system requires individual logins and passwords for access or not.

Comments: The security of information technology transactions was discussed briefly by the decision-maker and this security feature was a minimum requirement.

Measure: Operating System

Definition: What operating systems does the system operate on?

SDVF:



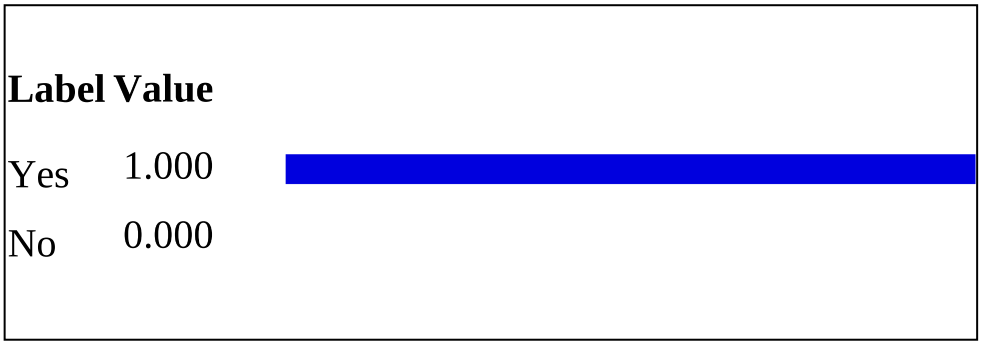
Category Definitions: A rating of None was allocated to systems that required proprietary operating systems and data servers. A rating of Specific Ones was given for systems that only operated on specific systems and data servers. A rating of All was given for systems that were able to be installed on every system available.

Comments: The decision-maker decided on the value points for this measure without any suggestions from the analyst. The decision-maker felt that a commercially available system should be able to work on any system that the organization currently has. The analyst acknowledged that if an organization was overly concerned with security, this categorical scale could be completely different. The decision-maker decided that for its operations, the ability to work on existing equipment was highly valued.

Measure: Permissions

Definition: Can the system be configured to differentiate between the rights of users?

SDVF:



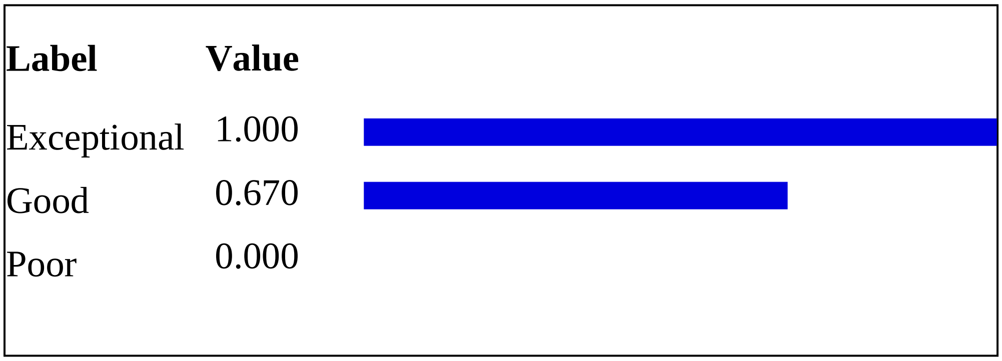
Category Definitions: Does the system allow different users to be allocated different rights within the system.

Comments: The decision-maker simply required this feature in the system. Inadvertant modifications to data were a concern and this measure addressed it.

Measure: Smart Reporting

Definition: What level of analytical reporting does the system provide?

SDVF:



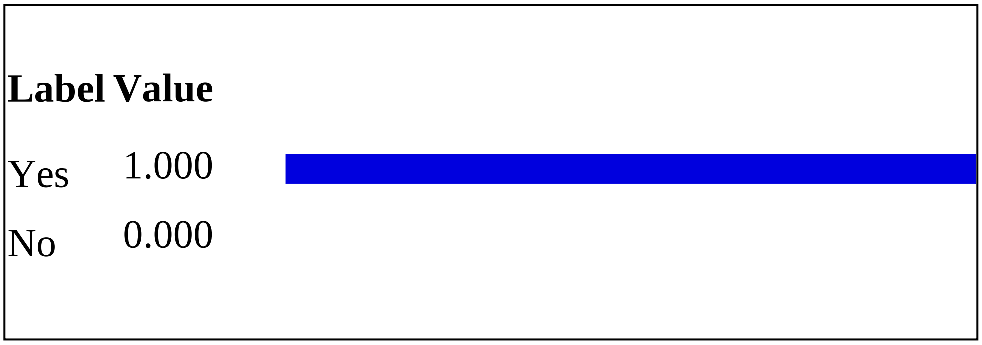
Category Definitions: A rating of Good was administered for systems that were able to simply create analytical reports and graphs from stored data. If the system could not provide this function, it received a rating of Poor. The Exceptional rating was reserved for systems that were able to perform data warehousing and create specific key performance indicators and balanced scorecard reports.

Comments: The decision-maker felt that the metrics that could be captured from a system could vividly describe the state of an installation. Extensive discussion on the creation of charts and graphs to notify superiors of resource allocation and needs indicated a high level of value involved with this measure. Analysis of that data and reports that could be generated by the system helps maintenance mangers adjust strategies to properly allocate resources.

Measure: Hazards

Definition: Does the system provide a minimum level of imbedded saftey features?

SDVF:

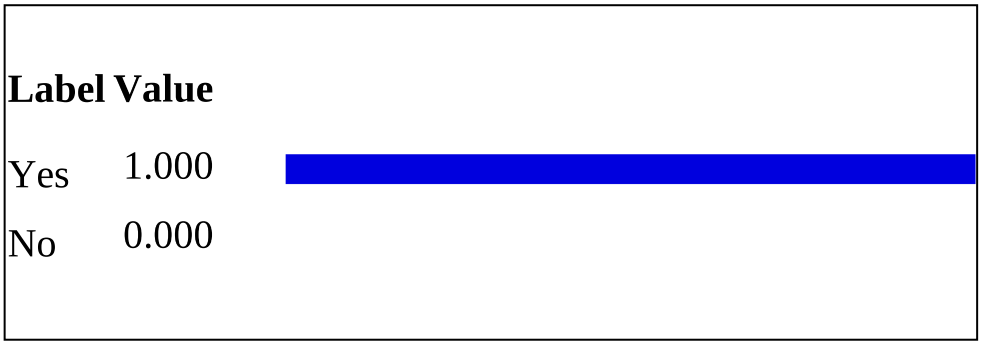


Category Definitions: Either the system has provides its users with a list of job hazards and safety procedures involved with each particular job or not. Features include lockout/tagout procedures, indication of buried utilities, and special certification requirements such as confined space and hazardous materials handling.

Comments: The analyst initially suggested that lockout/tagout and hazards should be separated measures. The decision-maker countered that all hazards, no matter what the source, should be identified by the system. The importance of this measure is reflected in the yes/no nature of its ratings.

Measure: Capitalization

Definition: Does the system track the amount of work that has been performed on facilities?
SDVF:



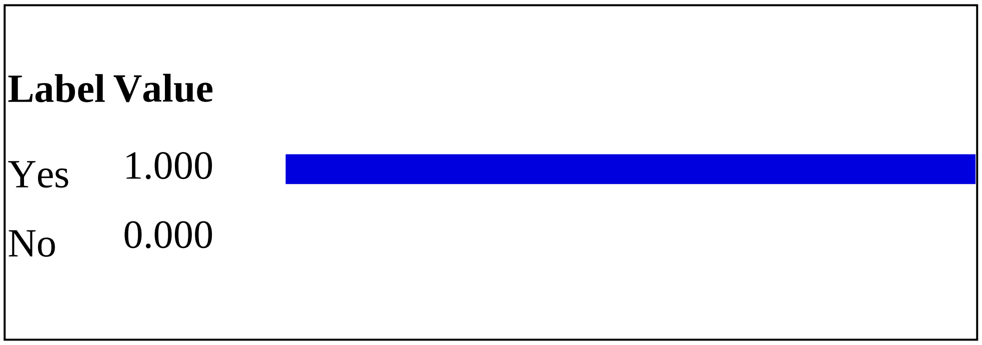
Category Definitions: Either the system is able to track the amount of maintenance and repair work performed on a facility or not.

Comments: This feature will allow maintenance managers to evaluate facilities and equipment with frequent problems and requirements to develop better maintenance strategies. This feature was especially valuable to the decision-makers because its maintenance budget is based on its total assets.

Measure: Human Relations

Definition: Does the system provide a minimum level of Human Relations features?

SDVF:



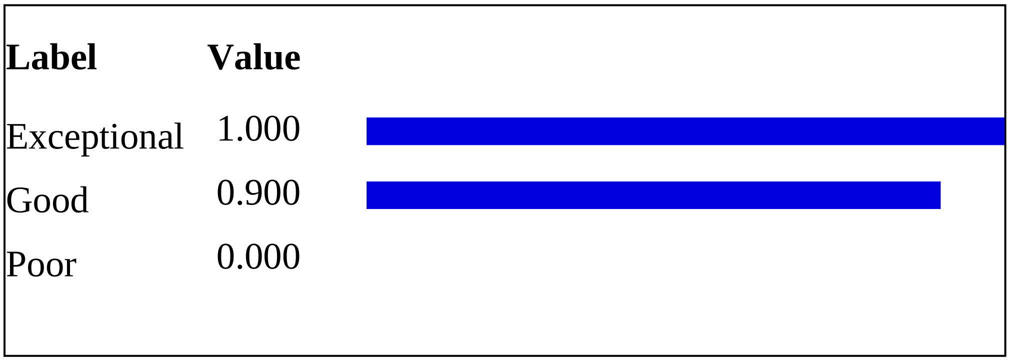
Category Definitions: Either the system is able to track manpower, training records, education, leave scheduling, and job ratings or not.

Comments: The analyst suggested a series of categories to capture varying levels of human relations type features that could be included in a system. The decision-maker completely disagreed with this approach to this important value. The decision-maker felt that a system should meet these minimum standards or be severely marked down. The decision-maker felt that its workers are its most important asset and this feature should be included in any system.

Measure: Inventory Control

Definition: What is the level of inventory control that the system provides?

SDVF:



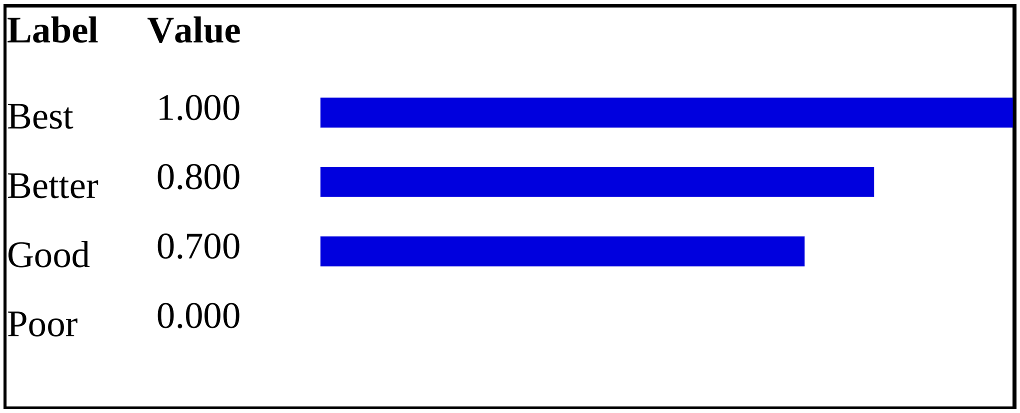
Category Definitions: A rating of Good was given if the system was able to perform lot management, track the status of parts, order additional parts, and pay bills. If these capabilities were absent, then the system received a rating of poor. An Exceptional rating was given if a system could also provide supplier histories and ratings.

Comments: The decision-maker insisted that for the Air Force, the features of a Good rating were most important, but it also wanted to give additional value for providing information concerning suppliers. This information could be used to select suppliers whose products last longer.

Measure: Real Property

Definition: What is the level of Real Property management features that the system provides?

SDVF:



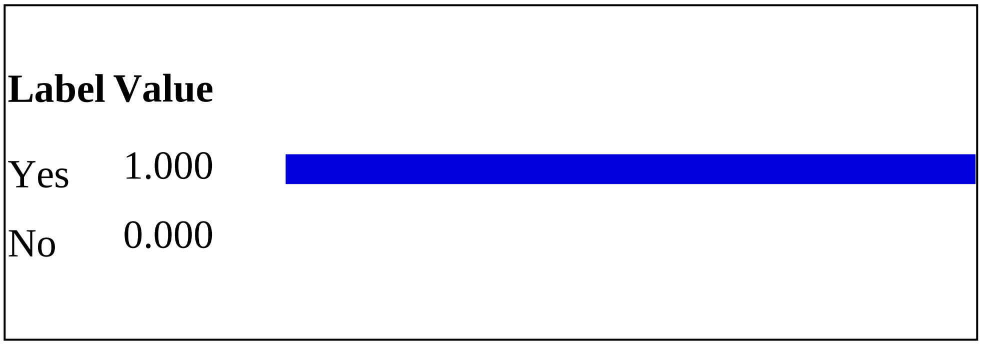
Category Definitions: A rating of Good was given for the system being able to simply catalogue the organization's facilities and equipment, with a Poor rating being given for not meeting this minimum standard. A rating of Better was given if a system could also track linear assets. A rating of Best was given if updates to as-built drawing could be made through the system in addition to meeting the Better rating.

Comments: These ratings were suggested by the analyst and accepted by the decision-maker after extensive conversation concerning the importance of real property features on maintenance operations. The decision-maker finally decided that complete asset management required knowledge of the complete array of an organizations assets.

Measure: Service Contracts

Definition: Does the system track Service Contracts?

SDVF:



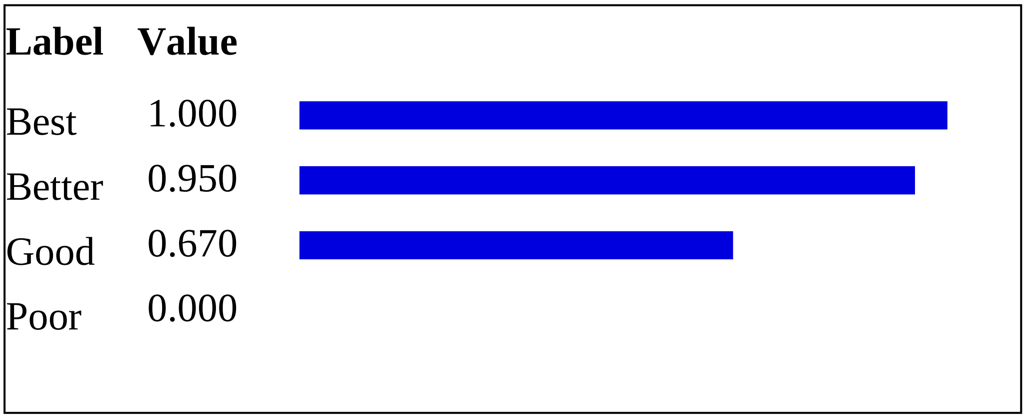
Category Definitions: Either the system is able to track Service Contracts or it cannot.

Comments: The decision-maker felt that this measure was important to its operations and wanted to mark down any system that did not include this feature. Because the Air Force reduced its manpower to create fiscal efficiencies, it uses many service contracts to perform maintenance activities that were once carried out by uniformed personnel. Tracking Service Contracts is valued because it enables maintenance managers to view their operations holistically.

Measure: Utilities

Definition: What is the level of utility features that the system provides?

SDVF:



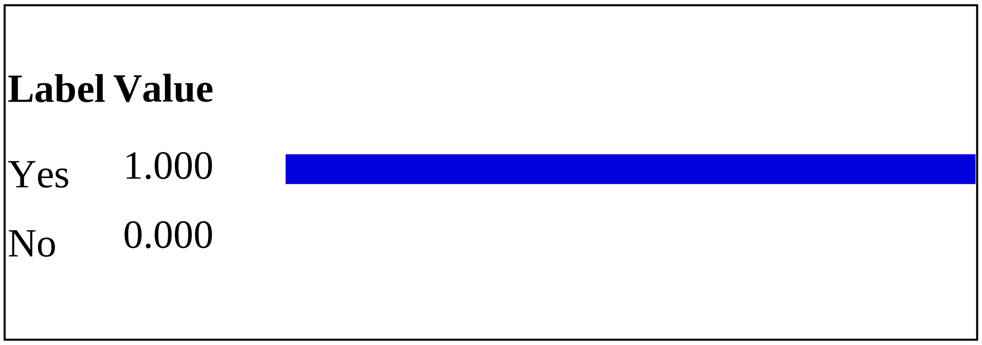
Category Definitions: A rating of Good was received if the system was able to track the total consumption of utilities. A Poor rating was received if the system could not meet this minimal standard. A rating of Better was received if the system was capable of not only tracking total usage, but the source of usage. A rating of Best was received if a system was able to provide real-time usage statistics and bill pay features in addition to meeting the requirements for the lesser ratings.

Comments: The decision-maker completely changed the scores and definitions of each category after suggestions were made by the analyst. The analyst suggested giving .80 value points for the ability to track real-time usage statistics and bill pay, while 1 value point was given for additionally being able to pinpoint the source of usage. The abilities to track real-time usage and to pay bills were not given the importance that the analyst suggested. The decision-maker only wanted a .05 value point increase for tracking real-time usage and bill pay, thus reducing the importance of these features. Tracking the source of usage was valuable to decision-maker because heavy usage can be pinpointed and altered to reduce energy bills.

Measure: EMCS

Definition: Can the system be integrated with Energy Management Control Systems?

SDVF:



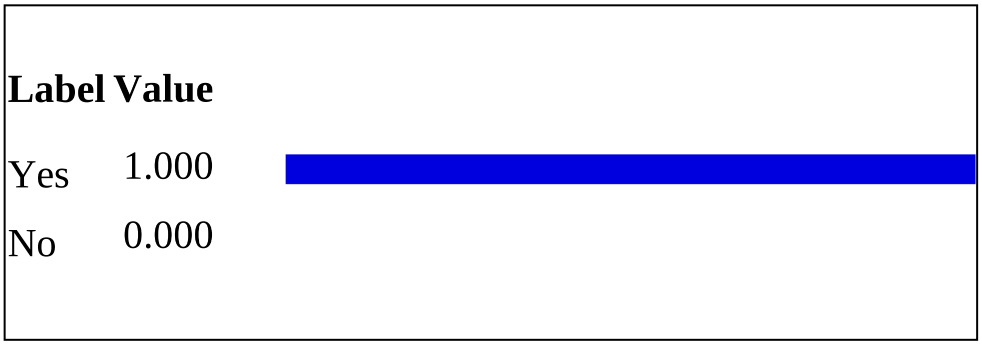
Category Definitions: Either the systems can be integrated or they cannot. The decision-maker did not want categories and considered this a simple yes or no.

Comments: The Air Force uses EMCSs to manage and control the energy that is consumed by an installation. The utilization of this system provides the Air Force with automation that provides centralized control of buildings, their components, and equipment. The integration of this system provides the user with extensive asset management capabilities.

Measure: GIS

Definition: Can the system be integrated with Geospatial Information Systems?

SDVF:



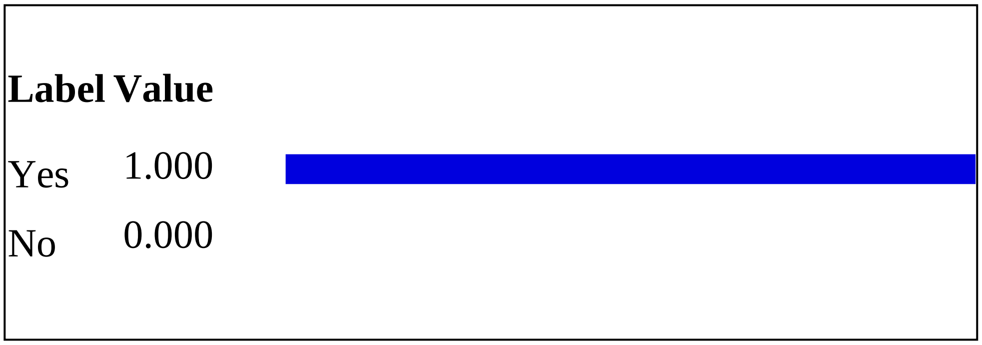
Category Definitions: Either the systems can be integrated or they cannot. The decision-maker did not want categories and considered this a simple yes or no.

Comments: The Air Force uses GIS to provide cartographic data and analysis to assist Air Force missions around the world. The utilization of this system provides the Air Force with up-to-date pictures of what is on the ground to aid installation planning, defense, and orientation. The integration of this system provides the user with a critical to visual access its assets.

Measure: PDA

Definition: Can the system be integrated with Personal Digital Assistants?

SDVF:



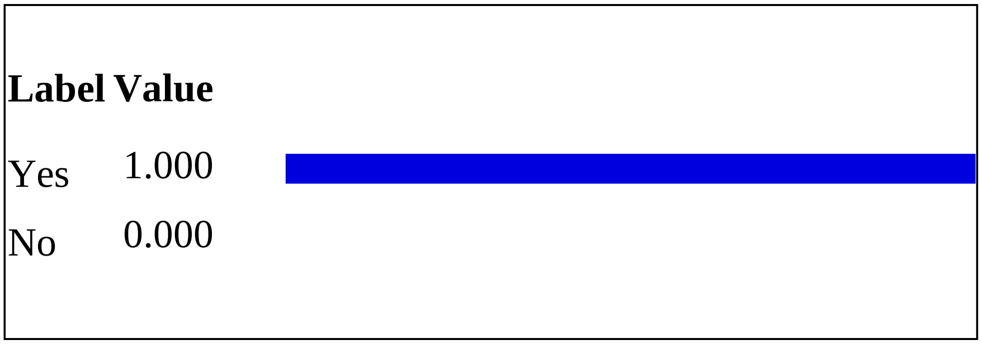
Category Definitions: Either the systems can be integrated or they cannot. The decision-maker did not want categories and considered this a simple yes or no.

Comments: The Air Force does not currently use PDAs, but the decision-maker felt that this technology would play a role in maintenance operations in the near future. The use of PDAs streamlines the completion maintenance work by providing much of the required information that workers often have to search for, such as part numbers, facility drawings, and tool requirements.

Measure: Third Party Software

Definition: Can the system be integrated with information systems besides EMCS, GIS, and PDA that are already in existence?

SDVF:



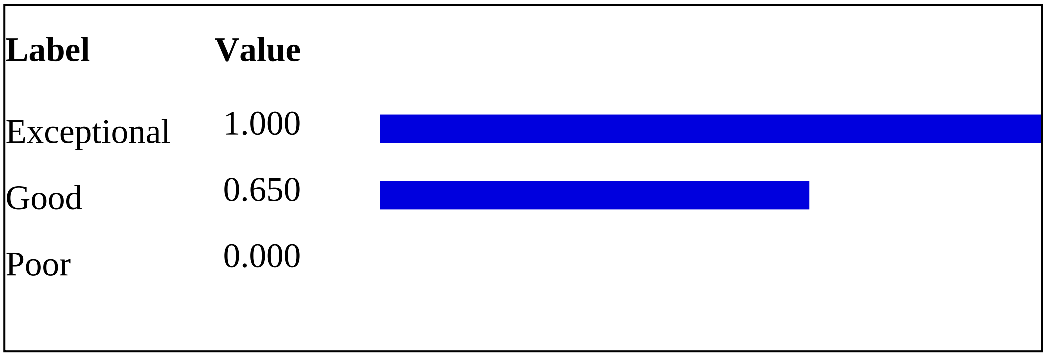
Category Definitions: The decision-maker decided that the ability to transfer existing data the system was very important. The two categories reflect the fact that the system must include this feature or will suffer greatly in the ratings.

Comments: Surprisingly, this was one of the most deeply discussed topics during meetings with the decision-maker. The inability to migrate archived data between different systems has greatly hindered the adoption of a robust system in the past. The ability to communicate with financial management and customer service systems was also discussed by the decision-maker. The decision-maker felt that this feature was highly valuable.

Measure: Preventive Maintenance

Definition: What level of preventive maintenance functions does the system provide?

SDVF:



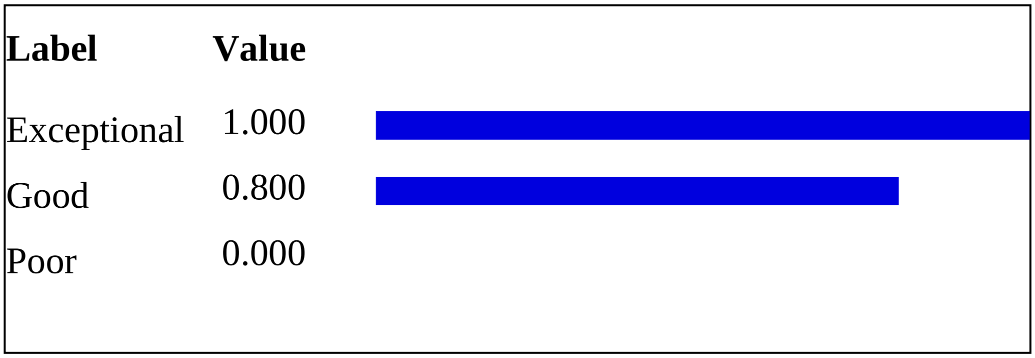
Category Definitions: A rating of Good is received for having preventive maintenance tasks, procedures, and scheduling imbedded into the system. If a system did not meet this standard, it received a rating of Poor. An Exceptional rating is gained by first meeting the Good standard and then having the ability to modify preventive maintenance schedules, tasks, and procedures, automatic trigger reset after work has been completed, and the ability to forecast preventive maintenance schedules.

Comments: The decision-maker determined this measure to be the most important feature for a system. Most of the work done for maintenance operations is of the preventive maintenance nature. The decision-maker emphasized the importance of Direct Scheduled Work and the Recurring Work Programs that demand the most man-hours on Air Force installations.

Measure: Work Planning

Definition: What level of work planning features does the system provide?

SDVF:



Category Definitions: Good is defined as being able to track workorders and the availability of parts and also scheduling workers. If the system did not possess these basic features, then it would receive a rating of Poor. Exceptional is defined as being able to provide history and trend reports and electronic drawings for facilities and equipment in addition to meeting the Good rating.

Appendix B: Alternative Scores

Cost Branch

First Cost

Computerized Maintenance Management System	Score
Oracle Utilities Work and Asset Management 1.7.15.2™	**$2995**
IBM Maximo Asset Management 7.1™	**$4770**
Infor EAM 8.4™, IFS Applications 7™	**$9995**
IFS Applications 7™	**$3000**
Mincom Ellipse 6.3™	**$4400**

Maintenance Cost

Computerized Maintenance Management System	Score
Oracle Utilities Work and Asset Management 1.7.15.2™	**22%**
IBM Maximo Asset Management 7.1™	**20%**
Infor EAM 8.4™, IFS Applications 7™	**20%**
IFS Applications 7™	**18%**
Mincom Ellipse 6.3™	**22%**

Hosting Cost

Computerized Maintenance Management System	Score
Oracle Utilities Work and Asset Management 1.7.15.2™	**$12000**
IBM Maximo Asset Management 7.1™	**$9000**
Infor EAM 8.4™, IFS Applications 7™	**$11880**
IFS Applications 7™	**$5000**
Mincom Ellipse 6.3™	**$7000**

Capabilities Branch

Vehicle History

Computerized Maintenance Management System	Score
Oracle Utilities Work and Asset Management 1.7.15.2™	**Yes**
IBM Maximo Asset Management 7.1™	**Yes**
Infor EAM 8.4™, IFS Applications 7™	**Yes**
IFS Applications 7™	**Yes**
Mincom Ellipse 6.3™	**Yes**

Vehicle Status

Computerized Maintenance Management System	Score
Oracle Utilities Work and Asset Management 1.7.15.2™	**Yes**
IBM Maximo Asset Management 7.1™	**Yes**
Infor EAM 8.4™, IFS Applications 7™	**Yes**
IFS Applications 7™	**Yes**
Mincom Ellipse 6.3™	**Yes**

Archive

Computerized Maintenance Management System	Score
Oracle Utilities Work and Asset Management 1.7.15.2™	**Poor**
IBM Maximo Asset Management 7.1™	**Poor**
Infor EAM 8.4™, IFS Applications 7™	**Exceptional**
IFS Applications 7™	**Poor**
Mincom Ellipse 6.3™	**Poor**

Electronic Signing

Computerized Maintenance Management System	Score
Oracle Utilities Work and Asset Management 1.7.15.2™	**Yes**
IBM Maximo Asset Management 7.1™	**Yes**
Infor EAM 8.4™, IFS Applications 7™	**Yes**
IFS Applications 7™	**Yes**
Mincom Ellipse 6.3™	**No**

Login Security

Computerized Maintenance Management System	Score
Oracle Utilities Work and Asset Management 1.7.15.2™	**Yes**
IBM Maximo Asset Management 7.1™	**Yes**
Infor EAM 8.4™, IFS Applications 7™	**Yes**
IFS Applications 7™	**Yes**
Mincom Ellipse 6.3™	**Yes**

Operating System

Computerized Maintenance Management System	Score
Oracle Utilities Work and Asset Management 1.7.15.2™	**None**
IBM Maximo Asset Management 7.1™	**All**
Infor EAM 8.4™, IFS Applications 7™	**All**
IFS Applications 7™	**Specific Ones**
Mincom Ellipse 6.3™	**All**

Permissions

Computerized Maintenance Management System	Score
Oracle Utilities Work and Asset Management 1.7.15.2™	**Yes**
IBM Maximo Asset Management 7.1™	**Yes**
Infor EAM 8.4™, IFS Applications 7™	**Yes**
IFS Applications 7™	**Yes**
Mincom Ellipse 6.3™	**Yes**

Smart Reporting

Computerized Maintenance Management System	Score
Oracle Utilities Work and Asset Management 1.7.15.2™	**Good**
IBM Maximo Asset Management 7.1™	**Good**
Infor EAM 8.4™, IFS Applications 7™	**Good**
IFS Applications 7™	**Exceptional**
Mincom Ellipse 6.3™	**Poor**

Hazards

Computerized Maintenance Management System	Score
Oracle Utilities Work and Asset Management 1.7.15.2™	**Yes**
IBM Maximo Asset Management 7.1™	**Yes**
Infor EAM 8.4™, IFS Applications 7™	**No**
IFS Applications 7™	**Yes**
Mincom Ellipse 6.3™	**No**

Capitilization

Computerized Maintenance Management System	Score
Oracle Utilities Work and Asset Management 1.7.15.2™	**Yes**
IBM Maximo Asset Management 7.1™	**No**
Infor EAM 8.4™, IFS Applications 7™	**No**
IFS Applications 7™	**Yes**
Mincom Ellipse 6.3™	**Yes**

Human Relations

Computerized Maintenance Management System	Score
Oracle Utilities Work and Asset Management 1.7.15.2™	**No**
IBM Maximo Asset Management 7.1™	**Yes**
Infor EAM 8.4™, IFS Applications 7™	**Yes**
IFS Applications 7™	**No**
Mincom Ellipse 6.3™	**Yes**

Inventory Control

Computerized Maintenance Management System	Score
Oracle Utilities Work and Asset Management 1.7.15.2™	**Exceptional**
IBM Maximo Asset Management 7.1™	**Good**
Infor EAM 8.4™, IFS Applications 7™	**Good**
IFS Applications 7™	**Exceptional**
Mincom Ellipse 6.3™	**Good**

Real Property

Computerized Maintenance Management System	Score
Oracle Utilities Work and Asset Management 1.7.15.2™	**Best**
IBM Maximo Asset Management 7.1™	**Better**
Infor EAM 8.4™, IFS Applications 7™	**Better**
IFS Applications 7™	**Best**
Mincom Ellipse 6.3™	**Best**

Service Contracts

Computerized Maintenance Management System	Score
Oracle Utilities Work and Asset Management 1.7.15.2™	**No**
IBM Maximo Asset Management 7.1™	**Yes**
Infor EAM 8.4™, IFS Applications 7™	**Yes**
IFS Applications 7™	**Yes**
Mincom Ellipse 6.3™	**No**

Utilities

Computerized Maintenance Management System	Score
Oracle Utilities Work and Asset Management 1.7.15.2™	**Better**
IBM Maximo Asset Management 7.1™	**Better**
Infor EAM 8.4™, IFS Applications 7™	**Better**
IFS Applications 7™	**Better**
Mincom Ellipse 6.3™	**Better**

EMCS

Computerized Maintenance Management System	Score
Oracle Utilities Work and Asset Management 1.7.15.2™	**Yes**
IBM Maximo Asset Management 7.1™	**Yes**
Infor EAM 8.4™, IFS Applications 7™	**Yes**
IFS Applications 7™	**Yes**
Mincom Ellipse 6.3™	**Yes**

GIS

Computerized Maintenance Management System	Score
Oracle Utilities Work and Asset Management 1.7.15.2™	**Yes**
IBM Maximo Asset Management 7.1™	**Yes**
Infor EAM 8.4™, IFS Applications 7™	**Yes**
IFS Applications 7™	**Yes**
Mincom Ellipse 6.3™	**Yes**

PDA

Computerized Maintenance Management System	Score
Oracle Utilities Work and Asset Management 1.7.15.2™	**Yes**
IBM Maximo Asset Management 7.1™	**Yes**
Infor EAM 8.4™, IFS Applications 7™	**Yes**
IFS Applications 7™	**Yes**
Mincom Ellipse 6.3™	**Yes**

Third Party Software

Computerized Maintenance Management System	Score
Oracle Utilities Work and Asset Management 1.7.15.2™	**Yes**
IBM Maximo Asset Management 7.1™	**Yes**
Infor EAM 8.4™, IFS Applications 7™	**Yes**
IFS Applications 7™	**Yes**
Mincom Ellipse 6.3™	**Yes**

Preventive Maintenance

Computerized Maintenance Management System	Score
Oracle Utilities Work and Asset Management 1.7.15.2™	**Exceptional**
IBM Maximo Asset Management 7.1™	**Good**
Infor EAM 8.4™, IFS Applications 7™	**Exceptional**
IFS Applications 7™	**Good**
Mincom Ellipse 6.3™	**Good**

Work Planning

Computerized Maintenance Management System	Score
Oracle Utilities Work and Asset Management 1.7.15.2™	**Poor**
IBM Maximo Asset Management 7.1™	**Exceptional**
Infor EAM 8.4™, IFS Applications 7™	**Exceptional**
IFS Applications 7™	**Poor**
Mincom Ellipse 6.3™	**Good**

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 074-0188*

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1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From – To)*
25-03- 2010	**Master's Thesis**	Nov 2009 – Feb 2010

4. TITLE AND SUBTITLE Using Decision Analysis To Select Facility Maintenance Management Information Systems	**5a. CONTRACT NUMBER** **5b. GRANT NUMBER** **5c. PROGRAM ELEMENT NUMBER**
6. AUTHOR(S) Graddy, Marchello, T., Captain, USAF	**5d. PROJECT NUMBER** **5e. TASK NUMBER** **5f. WORK UNIT NUMBER**
7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(S) Air Force Institute of Technology Graduate School of Engineering and Management (AFIT/EN) 2950 Hobson Way WPAFB OH 45433-7765	**8. PERFORMING ORGANIZATION REPORT NUMBER** AFIT/GEM/ENV/10M-04
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A	**10. SPONSOR/MONITOR'S ACRONYM(S)** **11. SPONSOR/MONITOR'S REPORT NUMBER(S)**

12. DISTRIBUTION/AVAILABILITY STATEMENT

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

Maintenance organizations, charged with preserving the built environment, are receiving a shrinking portion of an organization's operational budget to do its job. It has been demonstrated through various studies that efficiencies can be gained by implementing a maintenance management information system (MMIS). However, with so many choices available, maintenance organizations often select the wrong system.

This research effort used value-focused thinking decision analysis to create a model based on values from the Air Force Civil Engineer career field. Data for values and weights were collected from official documents and interviews. The resulting model is highly flexible, allowing the ultimate decision-maker to easily modify weights and value functions related to MMISs. The values and evaluation measures were used to score systems that were selected as alternatives. Sensitivity analyses were conducted to study the influence of evaluation measure weights on the final alternative rankings. The sensitivity analyses displayed alterations in rankings for each alternative based on changes in value weighing. Results indicate that commercially available systems may not be appropriate for Air Force use. The resulting model provides a readily modifiable decision model for the Air Force, as well as other maintenance organizations, to use when selecting a MMIS.

15. SUBJECT TERMS

Decision Analysis, Value-Focused Thinking, VFT, Facility Maintenance Management, Computerized Maintenance Management System

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Alfred E. Thal Jr., PhD, (ENV)
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(Include area code)*
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Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

	Form Approved *OMB No. 074-0188*