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A Decision Model for Selecting Energy Efficient Technologies for Low -Sloping Roof Tops Using Value-Focused Thinking

Michael J. McCourt

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THESIS

Michael J. McCourt, Captain, USAF

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DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

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Michael J. McCourt, BS

Captain, USAF

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Michael J. McCourt, BS
Captain, USAF

Approved:

Jeffery D. Weir, Lt Col, USAF (Chairman)	date
Dr. Charles A. Bleckmann (Member)	date
Brian J. Ballweg, Capt, USAF (Member)	date

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Abstract

The Air Force has a large inventory of low-sloping built up roofs (BURs) and millions of dollars are spent each year retrofitting these systems. The DOD has been directed to reduce non-renewable energy consumption by using energy-efficient technologies. These two details present a great opportunity to use the open roof space to install energy-efficient roofing technologies.

The purpose of this research is to provide Air Force decision makers with a tool to assist them in deciding what roofing technologies should be installed on facilities. Value Focused-Thinking is the methodology used to construct the model, in which values were used, instead of alternatives, to create the model. Data was collected from three different Air Force bases and values from three different Air Force Base Civil Engineers were used to evaluate the alternatives. The results show that based on current technologies these decision makers would be best served to retrofit BURs with standing seam metal roofs with some energy-efficient technologies added.

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I. Introduction

1.1 Background

In the United States, there is an estimated 1,400 square miles, an area larger than Rhode Island, of low-sloping roofs on the nation's 4.8 million commercial buildings (US Department of Energy [DOE], 2001). Low-sloping roofs are also prevalent in the Department of Defense (DOD). The Air Force Civil Engineering Support Agency (AFCESA) reports that sixty percent of the total Air Force roofing inventory is low-sloping built-up roofs (BUR) (2006). The majority of this roof area is open and not used for any function or benefit to the government. In addition, each year millions of dollars are spent repairing or replacing low-sloping Air Force roofs with the exact same roofing systems. Today, 75 percent of roofing activity is re-roofing older facilities (DOD, 2005). The current trend to replace roofs in the military is to convert the low-sloping roofs to pitched roofs to reduce maintenance, repair cost, and to lengthen the life of the roof. While this has been proven to save money over time, the Air Force is still missing a great opportunity to save even more money and improve the environment by installing more modern energy efficient roofing technologies.

The Federal Government has over 500,000 facilities in its inventory (Clinton, 1999) and is the largest energy consumer in the United States, consuming over 316 trillion British Thermal Units (BTUs) of energy at a cost of $3.7 billion in 2002. To battle poor energy management practices, President Clinton signed Executive Order (EO) 13123, "Greening the Government Through Efficient Energy Management." This EO promotes energy efficient products and renewable energy resources “in order to save taxpayer dollars and reduce emissions that contribute to air pollution and global climate change” (Clinton, 1999). More recently, President George Bush issued EO 13423, Strengthening Federal Environmental, Energy, and Transportation Management, which states, “It is the policy of the United States that Federal agencies conduct their environmental, transportation, and energy related activities under the law in support of their respective missions in an environmentally, economically and fiscally sound, integrated, continuously improving, efficient, and sustainable manner” (Bush, 2007). Using new roofing technologies will help the Federal Government meet energy objectives mandated in EO 13123 and EO 13423.

The DOD is beginning to use energy efficient products and materials, but many technologies cannot be used without a large open area. Space on military installations is becoming less available due to expanding missions, airfield regulations, and environmental issues. Roof space is an excellent area for the use of energy efficient technology. The DOD document, Commentary on Roofing Systems, UFC 3-330-02A (2005), even states that roofs provide a great opportunity to conserve energy because the ratio of roof area to wall area on commercial buildings is relatively high. An example of government commitment to this concept is the Million Solar Roofs initiative. This directs all organizations to use solar technologies on roofs of government facilities to reduce non-renewable energy consumption. President Clinton set a goal of installing over 2,000 solar energy systems by the end of year 2000 and 20,000 systems by the year 2010 (Clinton, 1999).

Using solar energy and taking advantage of the other technologies that utilize or mitigate climate conditions are smart concepts. Roof areas are ideal spaces for installing new energy-efficient systems because of the extreme conditions encountered. Roofs are exposed to constant changing climates, such as heavy precipitation, strong winds, fluctuating temperatures, and ultraviolet sunlight. Some of these elements can be converted into usable energy or moderated to reduce energy consumption through modern technologies. The initial capital costs of installing the technologies are typically high, but the Air Force can save money through the life cycle of the materials and equipment. EO 13123 also directs government agencies to spend money on energy saving projects, stating, “Agencies shall implement in district energy systems, and other highly efficient systems, in new construction or retrofit projects when life-cycle cost-effective” (Clinton, 1999). EO 13423 has a similar policy and calls on Federal agencies to “… implement renewable energy generation projects on agency property for agency use” to improve energy efficiency (Bush, 2007).

1.2 Problem Statement

Currently there are no specific guidelines to incorporate energy efficient technologies on roofs. The common trend in roof construction is to install high-pitched roofing systems to reduce water damage and prolong the life of the roof. In Air Force Instruction (AFI) 32-1051, Roof Systems Management, civil and roof engineers are instructed on how to develop a database to evaluate roof conditions. Roofs are categorized as red, yellow, or green based on visual maintenance inspections and recorded in the database with other values, such as building age, roof type, area, slope, and building purpose. This information is then used to prioritize the roofs for future replacement and repairs. Throughout the process the engineers are directed to “determine the most technically feasible and economical repair alternatives (recover, slope conversion, or replacement)” (Department of the Air Force, 1994). There is extensive information on roof slope conversion, but very little reference to energy-efficient technologies. Ultimately, cost is the determining factor for repairing or replacing the roofs (Department of the Air Force, 1994).

Energy management regulations in the DOD direct agencies to use new technologies in new projects, but the guidelines are still for general applications. The Air Force Energy Program Procedural Memorandum (AFEPPM) 96-1 focuses on meeting or exceeding energy resource standards to reduce costs because financial resources are decreasing. The regulation states, “Money is a key factor in the implementation of energy conservation programs. The financial resources available to the Air Force in the 1990s will be considerably less than those of the 1980s” (Department of the Air Force, 1996). The Unified Facilities Criteria (UFC) 3-400-01, Energy Conservation, is similar in philosophy to AFEPPM 96-1, but is more directive in construction practices. This document establishes minimum standards for energy conservation in new construction and renovation of existing facilities. It also states environmentally preferable products should also be used in the planning, design, and construction of all projects (DOD, 2002). The document states what should be done, but does not state what technologies should be implemented to accomplish the energy saving goals.

There are many regulations that support new roofing technologies, but military leadership, engineers, and energy managers have no tools to assist them to find the most technically feasible, cost effective, and environmentally responsible innovations for roof space. Therefore, the objective of this research is to develop a model that will assist Air Force decision makers in choosing the best energy efficient roofing technologies to obtain energy objectives. The model can be used at any DOD facility regardless of the environmental conditions.

1.3 Research Objectives and Questions

The purpose of this thesis is to develop a decision support model to assist Air Force decision makers in evaluating energy efficient roofing technologies to be used in retrofitting existing facilities or construction of new facilities. The research will answer the following questions:

1. What energy efficient roofing technologies exist and are they successful?
2. How much energy and money can be saved by using these roofing technologies?
3. What do decision makers in the Air Force value in roofing technologies?

1.4 Research Approach

The primary objective of this research is to develop a multi-objective decision analysis model to evaluate energy efficient technologies to use on low-pitched roofs. Value-Focused Thinking (VFT) is the methodology used to develop this model, which focuses on values, rather than alternatives, when searching for the best solution(s). Some examples of those values include: cost, energy savings, aesthetics, maintenance, and installation. In this technique, the decision maker is able to strategically identify alternatives and may even identify alternatives and objectives not previously considered. Ralph Keeney, in an article discussing VFT, states that "…values guide not only the creation of better alternatives but the identification of better decision situations" (1996).

In developing a VFT model, the researcher must obtain information from the decision maker through interviews and brainstorming sessions. Based on these sessions, the decision maker and the researcher will develop a hierarchy of explicit values. Weights and measures will also be entered in the model based on the decision maker's preferences. After the model is fully developed, the alternatives will be entered into the value hierarchy and, after a few calculations, the alternatives will be scored. This process will present the decision maker with a rank-ordered list to assist in a final determination of which roofing technologies should be used.

1.5 Scope

This research will compare multiple roofing technologies for low-sloping roofs at three different Air Force locations. Low-slope BURs were selected because of the abundance of this roofing system, short life cycle, and high maintenance costs. The bases are real but not identified. The purpose of using real bases is to get an accurate portrayal of how the model works. The installations are located in the northeast, southeast and west continental United States, which were selected by the three regions of Model Building Codes. Building Officials and Code Administrators (BOCA) primarily holds jurisdiction in the northeastern United States and focuses on snow loads. The Uniform Building Code (UBC) has jurisdiction west of the Mississippi River and focuses on seismic and lateral loading. Finally, the Southern Building Code (SBC) focuses on wind and lateral loading (Ballweg, 2006).

Within the VFT model, there are a few limiting factors. First, the values solicited from the decision makers are subjective. Key Air Force decision makers at various locations are asked questions on what they feel are important in roofing technologies. These individuals are very knowledgeable in the subject area and their values are based on personal opinions and experiences. The three models have the same values, but vary in the weights and single dimension value functions. Next, the data collected for evaluation is based upon past performance from various locations and computer simulation. This performance can be greater or smaller due to variables beyond the scope of this research. However, even with these limitations, this model will still aid Air Force leaders in deciding what technologies to use in the open roof area.

1.6 Significance

The significance of the research is the construction of a model to be used at any Air Force installation that will evaluate roofing technologies for open roof area. The model demonstrates what is important to decision makers in terms of new energy-efficient technologies. The goal is that Air Force leaders will utilize the model to aide in deciding what technologies can be installed on facilities to save taxpayer dollars and improve the environment.

1.7 Summary

As organizations on DOD installations continue to expand and consolidate, more space is needed. This space is a valuable commodity and all area should be used to maximize space efficiency. There are vast amounts of low-sloped roofs in the inventory that have open and unused roof area. This, coupled with the Federal Government's policies to improve energy management practices, creates a great opportunity to use energy efficient technologies in roofing systems. The following research will create a repeatable model to assist Air Force decision makers in choosing these technologies. The next chapter is a literature review of energy efficient technologies and current roofing practices of the Air Force. This chapter also includes a review of decision analysis and why VFT is the best method for this research. Chapter three describes the method of VFT in choosing energy efficient roofing technologies, which will also include the construction of the value hierarchy. Chapter four documents the results of the model and evaluates the sensitivity analysis. Finally, chapter five will conclude the research, emphasizing the benefits, explaining the gaps in the model, and recommending areas for future research.

II. Literature Review

2.1 Introduction

This chapter will cover several background and literature topics. In the first few sections current energy and roofing practices will be discussed, followed with brief summaries of modern roofing technologies. These sections will include advantages and disadvantages of the new systems. Since the purpose of the research is to develop a decision tool, the latter sections will discuss decision analysis and the specific methodology selected, VFT.

2.2 Building Energy Use

Commercial buildings use a great deal of energy to conduct daily business and this consumption is increasing exponentially as industries grow. According to Mark Levine, in an article discussing building energy use, buildings consume more than one-third of the total energy used in the world (1999). Most of the energy is used to condition the interior environment in either heating or cooling the facility. Total building energy use can be reduced by one of two ways: either by reducing energy loss or by creating energy with the available space. This research will focus on installing roofing technologies that reduce energy loss, create energy, or both. Levine also points out, "the choice of fuel and technology are important, as are the efficiency of the technology and the saturation of equipment that provides energy services."

As stated in chapter one, the federal government pays more than three billion dollars in energy bills each year to power its 500,000 facilities. In order to reduce this enormous bill and growing energy use, President Bush directed federal agencies to reduce the energy use level by 30 percent. This will reduce the bill by one billion dollars per year, although an initial five billion dollar investment in energy projects is needed to get to the desired goal. In order to achieve this goal and future energy goals, the DOD will have to look to the private sector for these investments. Energy Savings Performance Contracts (ESPCs) are a great example of this, as they are a congressionally-approved method for funding capital improvements. As stated in a Department of Energy document to finance solar energy systems, “Congress explicitly authorizes and encourages agencies to use this purchasing and financing vehicle to retrofit aging facilities with energy saving, environmentally beneficial improvements and to acquire related maintenance services” (US DOE, 2001). Since roofs have large areas of available space and constantly need maintenance they are good candidates for energy saving, environmentally beneficial projects.

2.3 Roofing Basics

The function of a roof is to protect the facility and the occupants from extreme environmental conditions. Roofs are grouped by roof slope in two major categories; low-sloping (flat) and high-pitched roofs. The Air Force categorizes a low-slope roof as having an incline of less than three inches per foot of slope (14 degrees) and a pitched roof as having three inches or more per foot (DOD, 2006). Low-sloping roofs are commonly seen in commercial facilities due to the large areas to be covered and the low cost of installation. Types of low-sloped roofing systems include bituminous built-up, modified bitumen roofing, single-ply, and sprayed-in-place polyurethane foam. High-pitched roofs are usually observed on houses and smaller facilities, although they are becoming more popular in commercial applications due to the benefits of high-pitched roofs. These structures usually consist of asphalt shingles, slate, tile, and metal roofing (DOD, 2006). Both roofing systems have to be able to withstand extreme environmental conditions. To prevent leaking two different systems are employed: waterproofing and watershedding. Low-sloped systems use a waterproofing method to resist leaking because the water pools in low lying areas. They use a waterproofing membrane, usually bitumen or tar, to seal the roof. High-pitched roofs use a watershedding method, in which water is washed off the roof before it can penetrate the facility (DOD, 2005). The roofing systems not only have to combat rain and snow, but also have to withstand extreme temperature shifts. Depending on the geographical location, roofs can experience temperature differentials up to 150 degrees (Akbari, 2003). In the U.S. 90 percent of low-sloped and high-pitched roofs are dark colored (U.S. Environmental Protection Agency, 2006), which absorb more heat and can reach 150-190 degrees Fahrenheit (F) (Akbari, 2003). This extreme heat not only increases the interior temperature of the building, but increases the heat gain of the surrounding area. This effect is known as the heat island effect and is caused by the removal of heat mitigating vegetation and constructing facilities with heat conducting materials (Kennedy, 2002). All roofs must be built to manage the forces exerted on the roof, such as snow and wind loads. Climatic conditions vary in the continental U.S., which requires contractors to build to the local specifications.

2.4 Built-Up Roofs

The most common roof in the Air Force building industry is the low-slope built-up roof (BUR). These systems do not perform as well as other modern roofing systems, but they remain attractive to developers due to low initial costs for construction. These types of roofs still have practical applications and are not disappearing in the near future. The National Roofing Contractors Association (NRCA) estimates that over eighteen billion dollars were spent constructing and repairing BUR in the USA, and 79.1% were low-sloping (Lounis, 1998b). These roofs are still prevalent in facility construction and this is a major reason why they were selected for this research.

The modern low-slope BUR has a slight grade of 1/8 to 1/2 inches per foot and is constructed of layering roofing materials to protect the building. Most BUR have five basic elements: waterproofing membrane, thermal insulation, flashings, structural deck, and vapor or air barrier (Lounis, 1998a). The waterproofing membrane is the most essential element to the success of a BUR. It is manufactured by adhering three or more felt plies with hot bitumen and then reinforced with organic, asbestos, or glass-fiber felts. The roof life increases with the number and strength of the felt plies. The insulation is another important layer in a BUR and is becoming more important due to rising energy costs. The materials for insulation vary and can range from glass fiber board to foam or wood. If any moisture infiltrates this layer the thermal performance is greatly compromised (Griffin, 1982). Flashings are used to cover and seal vertical joints, such as vents or chimneys, but still are the most common source of leaks. The flashings are metal strips that are attached to the vertical element and the flat roof with fasteners and adhesives. The metal roof deck provides structural stability to sustain loads and to transmit the loads to the framing. The vapor barrier prevents the condensation within the roof system and an air barrier minimizes air leakage (Lounis, 1998b). Many facilities do ballast the final layer with small stones, or aggregate, to assist in the protection against environmental elements. The typical Air Force facility is constructed of three inches of 4-ply polyisocyanurate insulation, steel deck material, and is ballasted with stone (AFSECA, 2006). A typical cross-section of an Air Force BUR is seen in Figure 2.1.

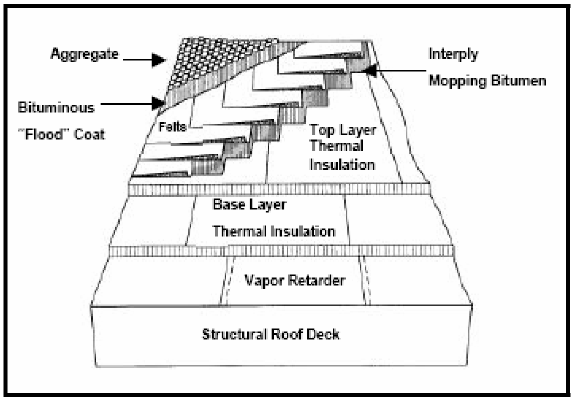

Figure 2.1. Typical Air Force BUR (DOD, 2005).

Since the BUR is a multi-component system, it is vulnerable to multiple failure modes. All roofs will fail, so proper installation and maintenance is key to the longevity of the roof life. Some recurring material failures are caused by water ponding, untested new materials, membrane splitting, water vapor condensations, membrane blistering, and leakage or destruction of the insulation due to vapor barrier use. Water penetration can cause a great amount of damage to the roof and to the interior systems of the building. For this reason water proofing membranes have been the focus for preventing roof failures. According to Lounis et al (1998a) in a paper discussing performance predictions of roofing systems, roofing membranes have less than a 50% probability of lasting 20 years. The performance of a roof deteriorates with time due to the aging effects of the components from aggressive environmental factors, excessive loads, poor workmanship and lack of maintenance (Lounis, 1998a).

Many organizations, including the Air Force, use Roof Management Systems (RMSs) to combat aging effects and reduce repair and replacement costs. RMSs may prolong the life of a roof, but they require a continuing allocation of substantial manpower and capital resources, which are frequently not available. They are dependent on extensive databases that include an inventory of roof condition data, corrective maintenance activities, and cost data. RMSs can provide decision makers with strategies to maintain roofs, but resources are limited. The Air Force needs to find a better avenue to prolong roof lives and to save maintenance costs (Department of the Air Force, 1994).

2.5 Current Roofing Technologies

Although BURs are very common in construction and design practices, many other energy efficient roofing technologies exist and are operating at sufficient energy saving levels. This section will give a brief overview of the technologies, as well as some pros and cons for each. This research will concentrate only on technologies that can be used on rooftops.

2.5.1 Standing Seam metal roofs

As mentioned in chapter one, the Air Force converts many low-sloping roofs into standing seam metal roofs (SSMRs) to avoid many problems of the low-slope roofs. SSMRs are high pitched roofs that are constructed of roll-formed steel or aluminum. The metal panels are then joined by standing steams, also known as double lock seams.

SSMRs have many benefits when correctly installed on a facility. First, a steep-sloped roof can greatly enhance the aesthetics of a building and make a strong visual statement. Along with aesthetics, the functionality of the roof is also improved. This type of metal roof system employs the watershedding method to prevent water penetration and does not allow water to pond. The metal materials, usually steel or aluminum, also give the roof desirable features. Metal roofs do not deteriorate overtime due to ultraviolet ray exposure. This enables the system to function for a long period of time with few failures. Another advantageous quality of metal is a high resistance to accidental holes or punctures, due to the high strength. Furthermore, after its useful life the metal roof can be recycled and made into other products. Finally the SSMRs are more cost effective compared to BUR because they have a longer life span and require less maintenance.

Although there are many positive advantages to SSMRs, there are some disadvantages, too. When constructing or retrofitting a roof, the geometrical design will increase construction cost and time. SSMRs need extra structural support to achieve a high pitch and to hold the heavy metal. An additional cost driver may be complex geometries involved in covering a facility, such as multiple planes and valleys. Another disadvantage is that metals are great conductors of heat. This can increase energy bills and can increase the temperature in the surrounding environment. If the roofs are painted a dark color, as most Air Force roofs are for appearance purposes, they increase in heat conductivity and add to the heat island effect (DOD, 2006).

2.5.2 Cool Roofs

A technology that reduces the effect of a dark roof is to simply coat the roof with a light colored, highly reflective material, which is known as a cool roof. As mentioned earlier, dark colored roofs can reach temperatures of 150-190 degrees Fahrenheit (F) during the summer months. Dark roofs absorb heat and, in turn, increase building cooling loads. Cool roof technology can reduce the roof temperature by as much as 70 degrees, saving energy and decreasing bills. Akbari et al. (2003) reports from a nation-wide study that "metropolitan-wide annual savings from the application of cool roofs on residential and commercial buildings were as much as $37M for Phoenix and $35M in Los Angeles and as low as $3M in the heating-dominated climate of Philadelphia" (Akbari, 2003).

Figure 2.2. Cool Roof Reduces Temperatures in Phoenix, AZ (Arizona Foam and Spray, 2007).

The technology for cool roofs is relatively simple compared to other energy-efficient technologies. The roofs only need a "cooling" surface which can be attained by lightly colored durable paints. The most common cool roofs are acrylic coatings, polyurethane foam or lightly colored ceramic tiles. They have two beneficial properties that make them cool, high reflectance and emittance. The Environmental Protection Agency (EPA) defines solar reflectance, or albedo, as "…the percentage of solar radiation that is reflected by a surface." Emittance is defined as "…the percentage of energy a material can radiate away after it is absorbed" (2006). The Solar Reflectance Index (SRI) is the combined value of the reflectance and emittance, or the roof's ability to reject heat. A white shingle has an SRI of 100, while a black shingle has an SRI of zero (EPA, 2006).

The properties defined above enable cool roofs to provide many benefits to the facility and also to the environment. Not only do cool roofs reduce air conditioning loads, they reduce peak cooling during the hottest temperatures of the day, which reduces the strain on the power grid. In a study by Akbari et al. comparing potential energy savings in two identical portable classrooms in Sacrament, CA, a cool roof had a 46% reduction in energy use and peak power savings of 20% versus the dark roof (Akbari, 2003). Two military installations with cool roofs, Edwards AFB and San Diego Naval Base Marine Barracks, reported a 35% reduction in peak roof temperatures. Cool roofs also decrease air pollution and smog because they diminish the heat island effect. Another benefit is that cool roof technology extends the life of the roof. The reflecting surfaces reduce the solar energy absorption, decrease ultraviolet radiation damage, and lessen daily contractions and expansions of roofing material (U.S. Environmental Protection Agency, 2006). Finally, by becoming more energy efficient, the demand for non-renewable energy decreases.

Although cool roofs have many benefits, they also have concerns with performance over the lifetime. Due to aging, dirt, and microbial accumulation, the initial reflectance may diminish (US DOE, 2006a). Washing and recoating must be performed on a regular basis, which increases maintenance man-hours and costs.

2.5.3 Green Roofs

Green roofs today are one of the fastest growing environmentally friendly technologies in the world. They are simply a protective vegetative cover that is constructed on top of the roof deck. Even though vegetative roofs are popular they are not a new concept. The earliest example of a green roof was recorded in 600 B.C. by the Greeks when they documented The Hanging Gardens of Babylon (Wong, 2003).

Figure 2.3. 22,000 Square-Foot Rooftop Garden on Chicago City Hall (US DOE, 2007).

There are two types of green roofs, intensive and extensive. Intensive roofs are designed to be accessible to the public. They are frequently used as parks or building amenities and incorporate sidewalks and recreational areas. A variety of plants, flowers, and even trees can be integrated into the design. In 2001, the city of Chicago constructed an intensive green roof to diminish the heat island effect which is seen in Figure 2.3 (US DOE, 2007). Extensive roofs, on the other hand, are developed for ecological benefits and minimal human interaction. The vegetation consists of native drought-tolerant grasses or prairie vegetation to keep maintenance low (US DOE, 2001). Both types, however, are constructed in the same fashion. The vegetative layer is planted in a growth medium on top of drainage layer. Underneath the drainage layer is a root barrier, and then a waterproof membrane to prevent any penetration and leakage. The bottom layers consist of insulation and a structural roof deck. An example of these different layers can be viewed in Figure 2.4.

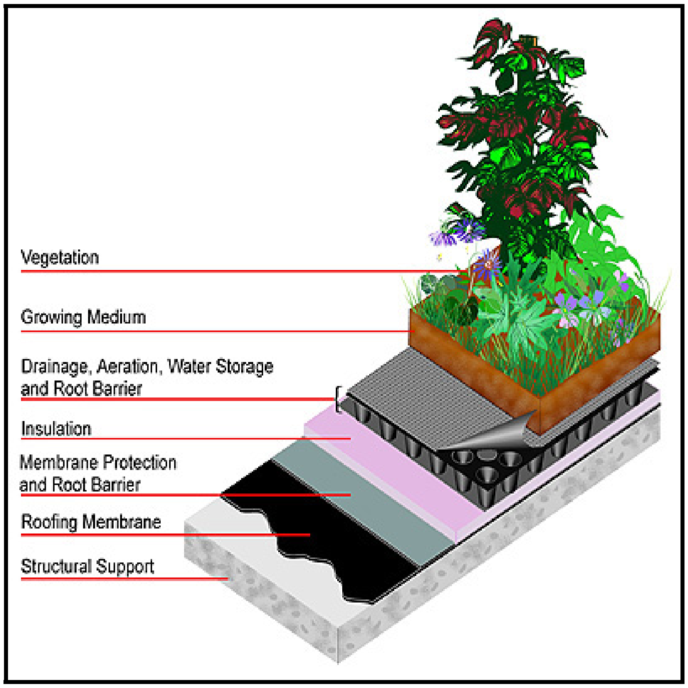

Figure 2.4. Components of a Typical Green Roof (US DOE, 2005).

Green roofs are growing in popularity because of the numerous benefits they provide. Green roofs, like cool roofs, reduce the energy consumption. Wong et al. conducted a simulation that showed a green roof reduced the energy consumption of a building and achieved a net savings of 14.6% (Wong, 2003). The growth medium layer is an added layer of insulation, which reduces energy loss and mitigates the heat island effect. The vegetative layer absorbs the sunlight and uses it for biological functions. In an in-depth analysis of green roofs in Singapore, it is reported that the plant layer can shield 87% of solar radiation, where as a bare roof receives 100%. Unlike cool roofs, green roofs continue to prevent energy loss in the winter and fall seasons. Another benefit to green roofs is the improved stormwater management of the surrounding area due to delays of water entering the sewage system. A high percentage of rain does not even reach the drainage systems because it is stored in the growth medium, used by the plants, and then returns to the atmosphere through evaporation. In general, green roofs also have longer life spans than conventional roofing systems. The added layers help protect the membrane and deck from harmful ultraviolet radiation, hail, and other extreme environmental conditions (Liu, 2003). Wong et al. state that "…several papers in the literature have made claims that the life of green roof is almost double that of average flat roofs. And the life expectancy of waterproofing membrane can be increased to more than 40 years" (Wong, 2003). Green roofs not only improve the functionality of the building but also improve the health conditions for the occupants. The air quality is improved by the vegetation removing airborne pollutants. This, coupled with the sight of extra greenery, can improve the health condition of the buildings occupants. Health conditions for the local wildlife are improved, too. A large fraction of the footprint of the facility is recaptured for wildlife habitats. The greenery attracts wildlife and can provide homes for birds. The last benefit is the added social benefit an intensive roof would provide. It allows the occupants to gather outside and use the roof space in a functional matter.

Green roofs do have multiple advantages, but they also have some disadvantages. One disadvantage is the high initial costs of construction which holds back many developers in the design phase. This is largely attributed to the added structural loading capacity. The structural cost of roof deck with roof garden is approximately 50% more than that of a roof deck without a roof garden. Many studies, although, have shown green roofs outperform conventional roofs over a lifetime and are actually less expensive.

Also, extensive roofs have a relatively low weight demand (50–150 kg/m2) and can be used safely on existing structures (Wong, 2003). Another disadvantage is the increased maintenance green roofs require. An intensive roof would require a part-time or full-time gardener to water, prune, and fertilize plants. The extensive roof would not require as much attention, but would require a gardener to water and replace patches on an as-needed basis.

2.5.4 Solar Thermal Systems

Solar thermal systems are emerging technologies that convert sunlight into useable heat energy. These systems come in any size, can be used in any climate, and use a free fuel. Solar collector systems can reduce the total energy consumed in a single-family home by 20 to 30 percent (Hug, 2006).

Most solar thermal systems have a simple design. The solar heating system consists of a heat collector, a heat transfer circuit that includes the fluid and the means to circulate it, and a storage system including a heat exchanger. The solar collector, usually installed on the roof, consists of a dark colored heat absorber, a clear cover to let in solar energy and to create a greenhouse effect, vents or pipes that transfer heated air or liquid to where it is used, and insulation to prevent heat loss (US DOE, 1999). After the liquid is warmed it is either directly stored or used (opened-loop system), or it is transferred to a heat exchanger (closed-loop system) to warm another tank of water. There are two types of systems, active and passive. An active system uses pumps and fans to transport the liquid, and a passive system uses design features and natural ventilation to move the liquid (US DOE, 1999). An example of an active, closed loop system can be seen in Figure 2.5.

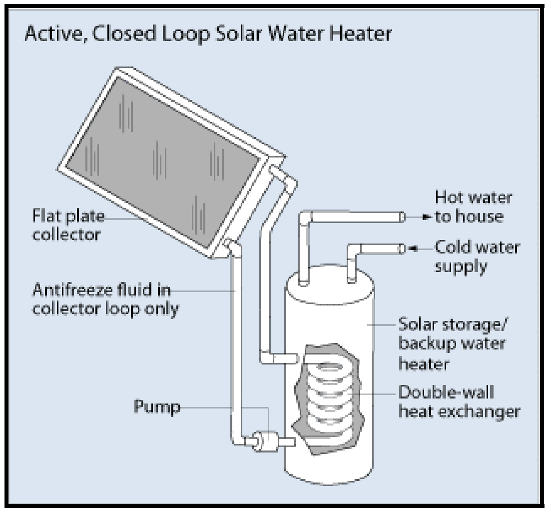

Figure 2.5. Example of a Solar Thermal System (US DOE, 2006d).

Using the sun's energy has many advantages for the building owner and the environment. The solar thermal systems can produce a large part of the needed energy to heat potable water. Heating water for pools, showers, and laundry areas are excellent cost effective examples that reap the benefits of solar collectors (US DOE, 1999). The solar thermal systems are also very efficient in producing energy. Even small solar heaters can reach an efficiency of 65%, which is significantly higher than all non-renewable energy resources (Hug, 2006). This technology can extend the life of a roof as well. The collectors absorb the ultraviolet rays and the heat, not the roofing materials. Finally, this system produces silent energy that is pollution-free and does not contribute to greenhouse gas emissions and global warming.

Solar systems do have limitations, but they can be remedied with thought into location and design. Solar systems work excellent in warmer seasons and climates, but the energy production decreases with cold temperatures. A solar heating system can deliver enough heat for bathing, showering, and washing machines from May to August in northern U.S. homes, but electricity sources are needed to heat the liquid in the cooler months (Hug, 2006). Not only does local climate affect production, but so does the design, equipment, and materials. For instance, insulated storage tank size and high performance heat exchangers are highly important aspects in the efficiency of a system. Another area of concern is the equipment will require roof penetrations to install the collectors and pipes. Proper installation is critical in minimizing roof damage.

2.5.5 Photovoltaic Systems

A photovoltaic system, like a solar thermal system, is another technology for transforming sunlight into useable energy. Photovoltaic systems, or commonly called solar cells, convert the sunlight into electricity rather than heat. The photovoltaic effect was first observed in 1877, but the true value of the photovoltaic effect was not realized until the 1950s when the space age was booming. At this point, solar cells were developed to power satellites. Today photovoltaic systems power every satellite in space and have become the leading renewable energy source for many commercial buildings and residential homes (US DOE, 1999).

Photovoltaic systems produce electricity when sunlight shines on the semiconductor material in a photovoltaic cell, creating an electric current. The most common semiconductor material is silicon, which includes these types: mono-crystalline or single crystal silicon, multi-crystalline silicon, polycrystalline silicon, and amorphous silicon (Keeney, 1988). There are also a number of different types of photovoltaic panels that can be used on roofs to generate electricity; fixed horizontal plate, fixed-tilt, horizontal north/south tracking, horizontal east/west tracking and two-axis tracking. The fixed horizontal plate is stationary and lays flat with no orientation to the time of day, year, or latitude. Fixed-tilt panels are static, but are tilted, based on latitude of the site, to receive a higher irradiance from the sun. In Figure 2.6, the panels are tilted to receive the most sunlight. These panels can be adjusted throughout the year. The north/south and east/west horizontal tracking systems rotate on one axis to maximize output. The two axis tracking system rotates on two axes to receive the highest irradiance in any direction. All tracking systems use computer controls to achieve the maximum amount of irradiance. A new photovoltaic technology is the Building Integrated Photovoltaic system (BIPV). The BIPV uses thin film technology which layers semiconductor materials only a few micrometers thick. This state-of-the-art technology can be built directly into the building structure, such as a roof shingle or a sheet of glazing (US DOE, 2006b).

Figure 2.6. An Example of Fixed Position Solar Panels (H2-PV, 2007).

The technological advances will continue to improve photovoltaic systems because of the established benefits that they demonstrate. This technology produces clean energy all year that does not consume fossil fuels nor does it generate air pollutants.

Photovoltaic panels also prolong the life of the roof, due to reduced exposure to sunlight. BIPVs are very appealing because they can be built into the facility and are not as prominent as other energy efficient technologies. They also serve a dual purpose of creating electricity and protecting the building.

Photovoltaic systems have great benefits, but they have some problems, too. The panel equipment installed on roofs does require roof penetration and added structural support. The new BIPV does require roof penetration for wiring and structure, but does not require additional support. There is a tradeoff between panels and BIPV; panels have higher efficiency, but BIPV are more accommodating in design and construction. All photovoltaic systems have high initial costs, especially BIPV, but prices continue to decrease with improving technology (US DOE, 2005). The panel systems frequently pay for themselves over the lifetime of the roof due to production of the electricity and the extended life. The U.S. Postal Service installed a 127 Kilowatt solar array at the Marina Processing and Distribution Center in southern California and it is expected to save $25,000-$28,000 per year in energy costs (US DOE, 2006b).

2.6 Decision Analysis

In today's high-paced world, decisions are expected to be made more quickly, more precisely, and without error. Simple decisions can be made with little thought to the problem, such as where to eat lunch or what shirt to wear. Complex problems, on the other hand, require in-depth analysis in order to make informed decisions. Due to the information age, more facts and data are available to assist a decision maker, but it also can confuse and overwhelm the decision maker. John Hammond and Ralph Keeney, in an article on making smart choices state "…the pace of change is accelerating, so yesterday's assumptions, facts and considerations may not be appropriate today. Technology is changing at incredible rates causing complete paradigm shifts" (Hammond, 1999). All this added information and technology can make it difficult to make smart decisions on a routine basis.

David Skinner, in his book Introduction to Decision Analysis, defines decision analysis (DA) as "…a methodology and set of frameworks for facilitating high quality, logical discussions, illuminating difficult decisions, and leading to a clear and compelling action by the decision maker" (Skinner, 2001). Theories on DA are broken into two categories, normative and descriptive. Normative theory describes how people should make decisions, and descriptive theory tries to explain how people make decisions. In studying how people function, scientists have revealed that individuals use unconscious routines, or heuristics, to deal with the complex decisions (Hammond, 2001). These heuristics work well in most situations, but the human mind can only sort so much information and may need a decision tool or methodology to assist in making better decisions.

In the decision analysis literature, there are many methodologies to help one make logical decisions. In most methodologies, there is a recurring theme of breaking down or decomposing the problem to better understand the situation and to simplify the problem. Each process includes some form of the following steps; define problem, identify objectives, develop alternatives, evaluate consequences, and evaluate tradeoffs. The problem is the challenge that must be solved, the objectives are the desired goals for achievement, the alternatives are possible solutions, the consequences are undesirable side effects of alternatives, and tradeoffs are values that can be exchanged. Models are developed in various stages in the processes, frequently involving numerical expressions to allow experts to acknowledge what is known and not known.

2.6.1 Alternative-Focused Thinking versus Value-Focused Thinking

In the decision analysis arena there are two types of thought processes; Alternative-Focused Thinking (AFT) and Value-Focused Thinking (VFT). In AFT the decision maker thinks of the alternatives first and then the criteria to evaluate the alternatives (Keeney, 1996). This is typical of most decision making. For example, when one is deciding on where to eat, the individual will think about which restaurants are available. This type of decision making limits the focus to the alternatives available. The other thought process, VFT, does not concentrate on only the alternatives, but first concentrates on values and objectives that are important in the decision. In the restaurant example, the decision maker would think about values, such as food quality, waiting time, and service, before thinking about the alternatives. In any decision, values are fundamentally important because they guide the decision making process. Alternatives are important because they are means to achieve your values (Keeney, 1996).

VFT is used over AFT for this research for a variety of reasons. VFT allows the decision maker to be proactive rather than reactive. Instead of choosing between alternatives the decision maker focuses on the values and objectives which create alternatives that may not have been considered in the beginning. Another reason why VFT is preferred is that a great deal of time and effort is directed towards making the values explicit. This forces the decision maker to really think about what is important in the decision. The identification of values is the first activity in the process and then the explicit values are used to develop opportunities and to create alternatives. When using VFT, the range of alternatives is expanded and consequences are more thoroughly analyzed (Leon, 1999).

2.6.2 Value-Focused Thinking

VFT is the methodology used in this research for the challenge of choosing the best roofing technology for the Air Force. The process involves several steps to build a model to analyze alternatives. In the beginning steps, the problem is defined and a brainstorming session is conducted to discuss objectives, goals, and measures. These elements are then used to create a value structure, or value hierarchy, to encompass all the evaluation considerations for the alternatives. Several structures may be appropriate for the same problem in VFT due to the nature of building process. The models will capture values of importance in the decision context and may not capture every value of each alternative. Each structure has tradeoffs between completeness and conciseness.

It is important that decision makers understand the differences in the following elements of the VFT methodology and model; objectives and goals, fundamental and mean objectives, branches and tiers, and evaluation measures and value functions. In a decision a person or group is trying to achieve certain objectives and frequently sets goals for each objective. Craig Kirkwood defines an objective as “the preferred direction of movement with respect to an evaluation consideration,” and a goal as “a threshold of achievement with respect to an evaluation consideration which is either attained or not by any alternative that is being evaluated” (1997). An objective in the restaurant example is to wait the least amount of time for food and a goal is to wait less than fifteen minutes. It is also important to understand the difference between a fundamental objective and a means objective. Fundamental objectives concern the ends that the decision makers value in a particular decision situation, and means objectives are ways to achieve those ends. The fundamental objective in the restaurant example is to have a fine dining experience, whereas the means objectives may be to wait for a short period, with great food quality, and prompt table service. In VFT, the objectives or values are used to create the model and eventually measure the alternatives. The values of the decision will be configured into branches and tiers to fully represent the decision challenge. The objectives are divided into separate means objectives or branches, and tiers that consist of "evaluation considerations at the same distance from the top of a value hierarchy," showing levels of importance (Kirkwood, 1997). The last elements the decision maker should comprehend are the evaluation measures and single dimension value functions that are used to evaluate and score the alternatives. The evaluation measures are developed as a measuring scale for the degree of attainment of an objective. Minutes would be the evaluation measure for the time to wait for a table in a restaurant. The evaluation measures are then converted into a value between zero and one through a single dimension value function in order to score and compare the alternatives (Kirkwood, 1997).

This research will follow the ten step VFT process developed by an AFIT student in 2001 (Shoviak, 2001). The VFT methodology will be discussed in greater detail in chapters three and four. The following is list of the steps taken in the process:

1. Problem Identification
2. Create Value Hierarchy
3. Develop Evaluation Measures
4. Create Value Functions
5. Weight Value Hierarchy
6. Alternative Generation
7. Alternative Scoring
8. Deterministic Analysis
9. Sensitivity Analysis
10. Conclusions and Recommendations

2.7 Summary

Chapter two summarized a brief background on building energy use, BUR basics, and modern roofing technologies. The roofing sections also covered the positive and negative features that each option had to offer. Finally, the chapter covered a decision analysis background and the VFT method that is used in this research.

III. Methodology

3.1 Introduction

This chapter will describe the model building process to analyze the decision of choosing the best energy efficient roofing technology. It is a ten step process that was previously developed in an AFIT thesis by Mark Shoviak (2001). As in many decision situations, especially in the Air Force, cost is a major value and frequently is the only value considered in a decision. The model developed in this chapter will look at values other than money to choose a roofing technology, and a cost benefit analysis will be performed in chapter four to show the best value the Air Force can achieve per dollar.

3.2 Step 1: Problem Identification.

The first step in the process is to clearly identify the problem to be evaluated. This is critical to ensure all resources are used to solve the correct problem. A defined challenge enables the decision maker to identify values and objectives to be inserted into the decision model and, hopefully, accomplished by the final resolution.

As stated in chapter one, there are thousands of acres of open space on Air Force facilities and the U.S. government is trying to improve its energy use by installing green energy systems. In this research the problem is how to effectively choose an energy efficient technology to be installed in this open roof area. A model is built to allow Air Force decision makers to choose the best technology for a given geographical location. The model also is built in a step-by-step method so it can be recreated and changed to suit newer technologies in the future.

3.3 Step 2: Create Value Hierarchy

After determining the problem to be addressed, a value hierarchy is constructed. The VFT model is a treelike structure that decomposes into smaller values and objectives that are more easily examined. The process of decomposing the problem has several benefits in the analysis to include, guiding the gathering of pertinent information, helping in alternative identification, opening communications, and evaluating alternatives (Kirkwood, 1997).

To properly evaluate the decision, the value hierarchy should have the following characteristics; completeness, non-redundancy, independence, operability, and small size. First, the model should be complete in covering all the concerns in evaluating the ultimate objective of the decision. Second, the hierarchy should not be redundant, or no two evaluation considerations should cover the same objective or value (Kirkwood, 1997). This will eliminate one value having additional weight. All values should also be independent, or one value should not influence another. Next, the hierarchy should be operable, or easily understood. Finally, in keeping with operability, the hierarchy should be as small as possible, while still encompassing all values and objectives of the problem (Kirkwood, 1997).

The two standard approaches to constructing a value hierarchy are bottom-up and top-down. The bottom-up approach is an alternative driven method in which the alternatives are examined before values and objectives are established. Differences between the alternatives are then used to develop the evaluation measures and values. These values are then grouped into layers and tiers. The bottom layer is created first and then the top tiers are constructed on top, hence the bottom-up approach. The top-down approach does not focus on the alternatives in the development of the hierarchy. In the initial stage of the process, a brainstorming session is held and the decision maker is asked what they value in order to determine the goals and objectives. The broad categories are then divided into smaller components to further define and examine the category. The resulting model has a series of smaller values and measures that can be quantified. The smaller components represent the higher tier categories (Kirkwood, 1997). In the top-down approach it is important to focus on the values in the model rather than the alternatives. This approach is often used when alternatives are not well specified.

This research used the top-down approach. After discussing the challenge and providing background information, as in chapter one and two, a brainstorming session was conducted with each decision maker. The following generalized questions were asked to initiate the brainstorming and to determine what was valued in energy efficient roofing technologies:

> What do you value/want in roofing technologies?
> What is your ultimate objective?
> What would you like to achieve in this situation?
> What are your values that are absolutely fundamental?
> What objectives do you have for your customers?
> What environmental, social, economic, or health and safety objectives are important?

The brainstorming session yielded many ideas and values. After the session, the values were constructed into the value hierarchy seen in Figure 3.1. The top-tier of the hierarchy is the fundamental objective that is to be accomplished in the decision, which is selecting the best roofing technologies for Air Force facilities. The next tier presents the broad categories the decision maker deems important in energy efficient roofing technologies; environmental, operational, and political.   Each value is further defined in the following sections.

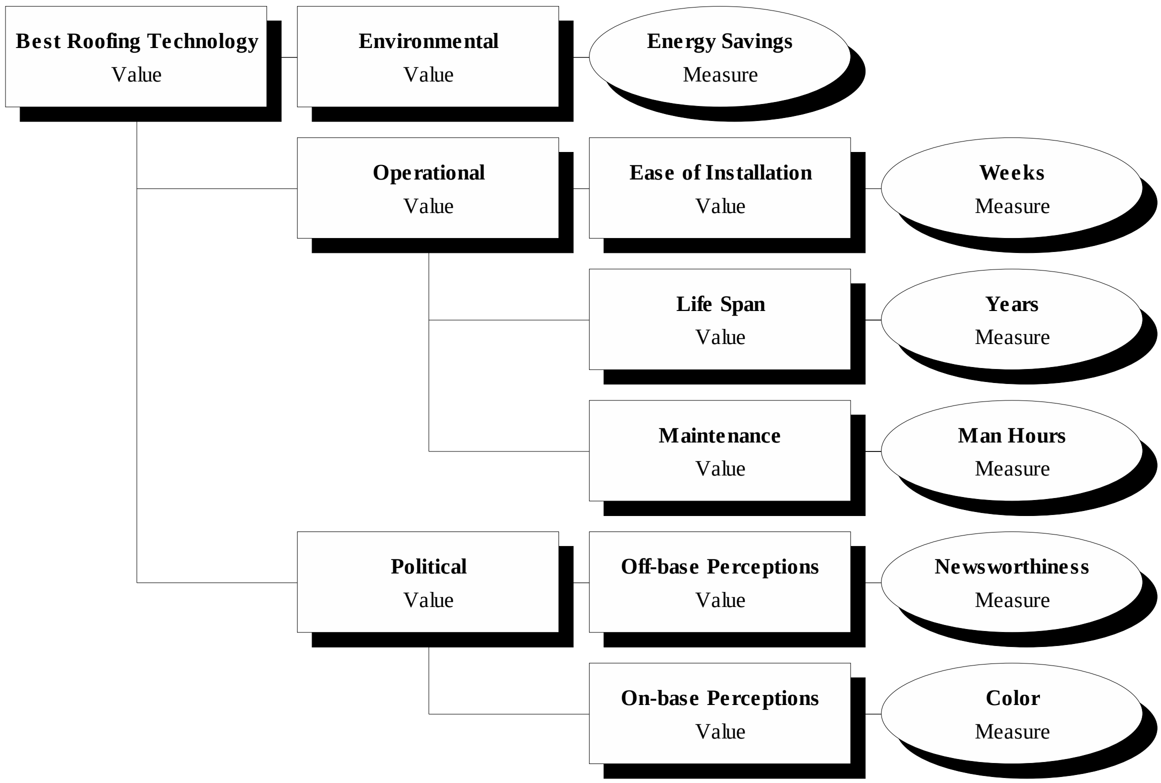

Figure 3.1. Value Hierarchy for Selecting Energy Efficient Roofing Technologies.

3.3.1 Environmental Value

All the decision makers want to be better stewards to the environment and wish to install new technologies that do just that. As energy prices continue to rise and the global climate worsens there is more pressure on the U.S. government to start producing projects that are less stressful to the environment.

3.3.2 Operational Value

The next top-tier value is the operational value. The decision makers want a roof that functions properly and diminishes the burden on the civil engineering squadron. This tier was broken down into further values; ease of installation, life span, and maintenance.

3.3.3 Ease of Installation

The Air Force has numerous missions and any delays can prove to be disastrous. Construction can include many disturbances, such as loud noises, fumes, and building access detours. To minimize delays, Air Force base civil engineers want technologies that are easily installed and can be constructed in a minimal amount of time.

3.3.4 Life Span

Base civil engineers are responsible for constructing facilities that are safe and clean. Leaks in roofing systems cause various problems, for example mold growth, and can jeopardize the safety and health of the building occupants. The new technologies should last as long as possible to prevent failures and keep customers comfortable.

3.3.5 Maintenance

Most civil engineers believe that manpower is stretched thin in the squadron. This will only worsen with the downsizing of the Air Force. Each decision maker indicated they do not have personnel to do the required roof maintenance at the present time. Usually the maintenance is reactive, or administered when a failure occurs. There are numerous facilities at each Air Force base and not enough people to do the necessary maintenance. The decision makers value technologies that require little maintenance so their personnel can focus on other important mission functions.

3.3.6 Political Value

Not only do Air Force decision makers worry about functionality of facilities, but they have to think about public perception. The base is under heavy scrutiny to look professional. This last top-tier value was divided into off-base and on-base perceptions.

3.3.7 Off-base Perceptions

The military wants to maintain good public relations by providing services that are perceived as good choices for the nation and its people. Any projects that can be advertised as well-spent tax dollars by the government will only improve public opinion.

3.3.8 On-base Perceptions

Military bases employ thousands of individuals and even house thousands of families. Each base has hundreds of visitors each day, many times distinguished visitors from other foreign nations. The decision makers want facilities that are pleasing to the eye. All bases have architectural compatibility standards which require most facilities to follow similar design schemes for appearance purposes, such as using similar materials, layouts, and colors.

3.4 Step 3: Develop Evaluation Measures

The next step in the Shoviak process applies evaluation measures to the lowest value in each tier. In developing a hierarchy, values are broken down until they can be measured. Each measure will be either on a natural or constructed scale. A natural scale is considered to be known by everyone and is in general use. A good example of a natural scale is profit. A constructed scale is developed to measure the level of attainment of an object or element, such as test grading. The measures will also fall under two other categories, direct or proxy. A direct scale measures the level of accomplishment of an objective, while a proxy scale reflects the level of achievement of its associated objective (Kirkwood, 1997). Examples of each type of measure are shown in Table 3.1.

	Natural	Constructed
Direct	Net Present Value Time to Remediate Cost to Remediate System Reliability Bandwidth per sec Revisit time	Olympic Diving Scoring Weather Prediction Categories Project Funding Categories R&D Project Categories
Proxy	Gross National Product (Economic growth) Site Cleanup (Time to Remediate) Number of Subsystems (System Reliability)	Performance Evaluation Categories (Promotion Potential) Instructor Evaluation Scales (Instructor Quality) Student Grades (Student Learning)

Table 3.1. Evaluation Measure Examples (Weir, 2006)

In this research there are six measures that will evaluate the alternatives for roofing technologies. They are seen in the value hierarchy in Figure 3.1 and are as follows; energy use of the facility, degree of difficulty for installation, years for life span, man hours in maintenance, newsworthiness for off-base perceptions, and color for aesthetics.

3.4.1 Energy Use (Environmental Value)

This is a natural, proxy measure. This will measure the potential savings compared to a typical generic Air Force facility. The generic facility used for this research is a two story, 25,000 square foot office building. It has a 3-ply built-up roof with a steel deck (AFCESA, 2006). Any reduction in energy use in a facility will decrease the use for electricity from non-renewable energy sources, thus helping the environment.

3.4.2 Weeks (Ease of Installation Value)

This measurement is categorized as natural and direct. It will measure the time it takes to install the roofing technology in weeks. Longer installations result in more delays and frustrations for the building occupants and possible mission delays. Construction that will take least amount of time to complete and is barely noticeable is the most preferred rating.

3.4.3 Years (Life Span Value)

The years evaluation measure is natural and direct. A longer life is preferred in order to avoid leaks and potential health and safety hazards for the building occupants.

3.4.4 Man Hours (Maintenance Value)

This is a constructed, proxy measure and is divided into three categories; low (less than 2 hours per year), medium (2-10 hours per year), and high (greater than 10 hours per year). Civil engineering manpower is limited to perform all maintenance and inspections on every building on an installation. A technology that requires little to no man hours to maintain is desirable.

3.4.5 Newsworthiness (Off-base Perceptions Value)

Newsworthiness is a constructed, proxy measure. Any project that is considered a good use of tax funds is desirable by the Air Force. This measure is grouped into three discrete categories; not newsworthy, newsworthy with text, and newsworthy with text and photo. These measures were constructed by reviewing Air Force historical data and interviews in the Public Affairs (PA) office. PA decides whether or not information is newsworthy based on several factors, including technological advancement and uniqueness. Technologies that help the environment are inclined to get more press coverage. Any positive advertisement to the public is preferred.

3.4.6 Color (On-base Perceptions Value)

The final measure in the model is a constructed, proxy measure. Base appearance is very important to base commanders. Any color that follows the base architectural compatibility standards, usually dark brown, is more preferred. This will be a categorical measure with brown, green, black, silver/grey, white, tan, and other as the categories.

3.5 Step 4: Create Single Dimension Value Functions

After evaluation measures are determined for the low-tier values, single dimension value functions (SDVF) are created for these measures. This converts each measurement into a value between one and zero for scoring the alternatives. There are two types of SDVF; discrete and continuous. Discrete SDVFs are categorical and are created by determining the value increments between each of the possible evaluation scores and then this data is used to specify the value function. The discrete value function does not have value between categories so the categories must be collectively exhaustive. The on-base perception evaluation measure will have a discrete SDVF with six color categories. If an evaluation measure has an infinite amount of scoring levels a continuous SDVF is used. An example of a discrete and a continuous SDVF is seen in Figure 3.2 and 3.3. Continuous SDVFs are divided into three groups; piecewise linear,

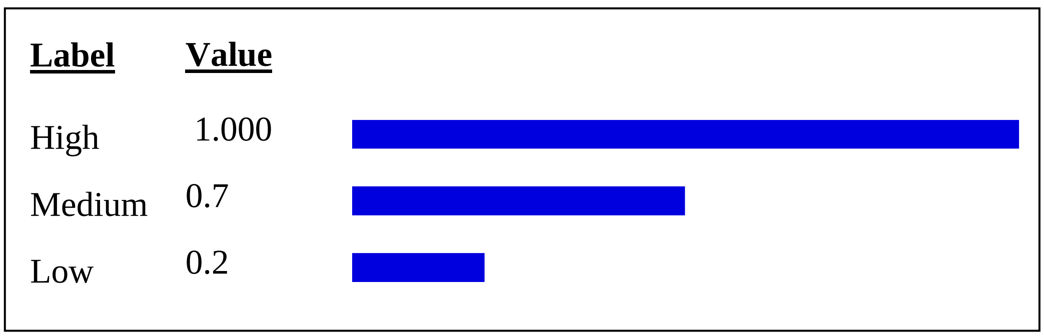

Figure 3.2. Example of a Discrete (Categorical) SDVF

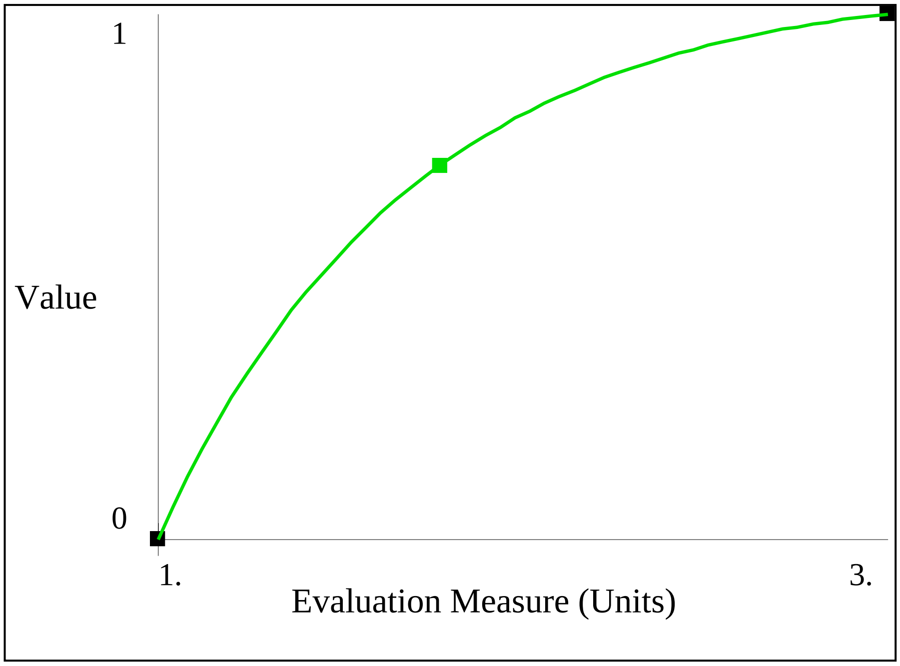

Figure 3.2. Example of a Continuous (Exponential) SDVF

linear, or exponential. Piecewise linear is similar to discrete functions and is used when the evaluation measure has as a small number of different scoring levels (Kirkwood, 1997). The SDVF is determined in the same manner as a discrete SDVF and has values at every evaluation score. That is, a line is drawn between the values at the different scoring levels to allow for a finer distinction between alternatives (Kirkwood, 1997). The exponential and linear value functions have specific equations and can be seen in equations 3.1 and 3.2. The SDVF is dependent on the range of the evaluation and the exponential constant, the Greek letter ρ. The curve of the value function depends on ρ, in which a larger value straightens out the curve and a smaller ρ has more of a curve. If ρ is infinity the equation becomes linear and is seen in the lower half of each equation. The software used for this research, Logical Decisions ® for Windows™ version 5.114 (2000), lets the DM establish a mid-value point on the curve and the software determines the function. The function is monotonically increasing (Eq. 3.1) if higher amounts or levels are desired, and monotonically decreasing (Eq. 3.2) when lower amounts are preferred (Kirkwood, 65). Each SDVF is specified so that the least preferred level is equal to zero and the most preferred level is equal to one (Kirkwood, 68). The SDVF for each evaluation measure can be seen in Appendix A.

$$v(x) = \begin{cases} \dfrac{1-\exp[-(x-Low)/\rho]}{1-\exp\{-(High-Low)/\rho]}, \rho \neq Infinity \\ \dfrac{x-Low}{High-Low}, otherwise \end{cases} \qquad \text{Eq. 3.1}$$

$$v(x) = \begin{cases} \dfrac{1-\exp[-(High-x)/\rho]}{1-\exp\{-(High-Low)/\rho]}, \rho \neq Infinity \\ \dfrac{High-x}{High-Low}, otherwise \end{cases} \qquad \text{Eq. 3.2}$$

where:

v(x)	=	the exponential value function
High	=	the upper bound of the evaluation measure
Low	=	the lower bound of the evaluation measure
ρ	=	the exponential constant of the value function
exp	=	the exponential function (e^x, or 2.7182^x)

3.6 Step 5: Weight the Value Hierarchy

The next step in the process is to weight the hierarchy. This allows the decision maker to compare the values to show importance. Kirkwood defines the weight for an evaluation measure as "the increment in value that is received from moving the score on that evaluation measure from its least preferred level to its most preferred level" (1997). There are various procedures to weight the hierarchy and the weights are assigned either globally or locally. Global weighting calculates weights for the values across the entire hierarchy, and all the values in a given tier sum to one. Local weights on values sum to one as well, but only in a specific branch and tier. For instance, all the weighted values under the operational value in Figure 3.1 will add to one. One method to determine local weights is called swing weighting. The multiplicative values for the weights are based on what the decision maker believes the value of swinging from the least preferred end of the range to the most preferred end. The method is executed by using the lowest value in a branch and using it to scale the other value increments. Take for example a tier with three values. The lowest value would have the value x. If the second value had a weighting that is 1.5 times greater than the first value then it would have a weighting of 1.5x. The third value has three times the weighting and would be equal to 3x. Finally the three increments are set to equal one, resulting in the following weights; 0.18, 0.27, and 0.55.   A more simple method is the 100-point method, or 100-poker chip method, in which the decision maker is told he has 100 points or chips to assign importance to each value in a tier. The decision maker can see the size of the piles and then refine the numbers at the end. This was the method used in this research and the results for the three decision makers are shown in Table 3.1.

Measure (Value)	Northeast	Southeast	West
Energy Savings (Environmental)	25.0%	30.0%	10.0%
Weeks (Ease of Installation)	10.0%	10.0%	15.0%
Years (Life Span)	25.0%	20.0%	35.0%
Man Hours (Maintenance)	25.0%	20.0%	25.0%
Newsworthiness (Off-base Perceptions)	5.0%	5.0%	10.0%
Color (On-base Perceptions)	10.0%	15.0%	5.0%

Table 3.2. Global Weights of Measures for Each Decision Maker in the Continental U.S.

3.7 Step 6: Alternative Generation

After the model is built the alternatives can be entered, but the challenge is what alternatives should be entered. Just building the value hierarchy helps identify alternatives that may not have been realized before. The model summarizes the objectives for the decision, so a good alternative must perform well with respect to the values in the hierarchy (Kirkwood, 1997). In many VFT applications, there are too few or too many alternatives. In this research there could be an infinite amount. Focusing on goals and objectives used to build the hierarchy helps identify alternatives that can better achieve the objectives (Keeney, 1996). To reduce the number of alternatives and only compare the pertinent alternatives, screening criteria were established. In this research, the built-up roof is the current most popular roofing technology and the standing seam metal roof is the technology that the Air Force is using to replace most old roofing systems. These two alternatives were evaluated for the purpose of comparison to the new technologies. The other alternatives were limited to known energy saving technologies. The alternatives must be a proven technology and at least three years old. Since there were multiple technologies for each industry (cool roofs, green roofs, photovoltaic, and solar thermal systems, etc.), the leading, most energy efficient technology was selected for each technology. For example, a fixed-plate photovoltaic system was chosen because of the high efficiency and low relative maintenance cost to other systems. The alternatives selected are shown in Table 3.3.

	Alternatives
1.	Built Up Roof (BUR)
2.	BUR w/Cool Roof Coating
3.	BUR w/Solar Panels
4.	BUR w/Solar Thermal System
5.	Green Roof Extensive
6.	Green Roof Extensive w/Solar Panels
7.	Green Roof Extensive w/Solar Thermal System
8.	Green Roof Intensive
9.	Standing Seam Metal Roof (SSMR)
10.	SSMR w/Cool Roof Coating
11.	SSMR w/Solar Panels
12.	SSMR w/Solar Thermal System

Table 3.3. Alternatives for Energy-Efficient Roofing Technology Evaluation.

3.8 Summary

This chapter developed the VFT model to evaluate and analyze the alternatives. The model is different for each location evaluated and a new model can be created to accurately reflect a new decision maker's requirements in the future. The next chapter will analyze the outcomes by inserting the alternatives into the model and performing deterministic and sensitivity analysis.

IV. Analysis

4.1 Introduction

This chapter covers the next three steps in the Shoviak process and includes a cost analysis. Step 7 scores the alternatives that are entered into the model and identifies which alternatives provide the most value. In Step 8 a deterministic analysis is performed to explain why alternatives scored higher or lower than others. Sensitivity analysis is then conducted in Step 9 to determine if alternative rankings change if weights are altered. The last section covers a cost-benefit analysis, which is performed to demonstrate which alternatives provide the best value per dollar. The previously mentioned analysis is conducted at all three geographical locations with the different decision maker preferences.

4.2 Step 7: Alternative Scoring

After the alternatives are selected, data is collected for each evaluation measure developed in the model. The data should be easily researched or accessible in order to provide recommendations to the decision maker in a reasonable time. Logical Decisions ® for Windows™ (2000) was used to build the model and calculate the scores for each alternative. This program used an additive value function to determine the alternative scores. This function is defined on the next page.

$$v(x) = \sum_{i=1}^{n} \lambda_i \cdot v_i(x_i) \qquad \text{Eq. 4.1}$$

where:

$v(x)$	=	total score for alternative (x)
$v_i(x_i)$	=	SDVF for measure *i*
λ_i	=	the weight for measure *i* (the global weight)
n	=	total number of measures
x	=	the score for alternative *x* on measure *i*

(Kirkwood, 1997)

The data for each location was obtained from various sources. Three energy simulation programs and data from literature were used to estimate energy savings for the alternatives. EQuest, an energy simulation program from the DOE, was used to find the energy consumption for a BUR and SSMR on a generic facility. All energy savings estimates were calculated using the BUR EQuest simulation figures as a baseline. A DOE cool roof calculator was used for cool roof energy savings and the photovoltaic figures were developed using a simulator found on the FindSolar website which was endorsed by the DOE (FindSolar.com, 2007). To calculate energy savings, a weighted average was calculated from the simulation figures and figures from the literature review. The time estimates for the Ease of Installation measure were calculated by a weighted average from data found in the literature review and calculations made from using RS Means (2006), a construction cost and time estimating handbook. Life span and maintenance man hour figures were calculated using average time periods stated in the literature review. The data for the next evaluation measure, newsworthiness, was obtained by the literature review, Air Force historical data, and an interview with a public affair official (Hancock, 2007). And finally the color data used was the predominate color of the roofing system technology. An Air Force decision maker could find much of this data from the same websites and references above or through historical data from that base. The base civil engineer would have much data available at the base level, such as energy consumption of specific facility or construction time periods for similar roofing projects. A base civil engineer would also have many engineers to gather data and make estimations.

The data was not only collected for each alternative, but also for each location. Three different continental U.S. locations were selected to demonstrate the validity of the model. Some data was not the same for each alternative and was site specific. The alternatives with solar panels are a good example of this, in which areas with warmer, brighter climates receive greater energy savings.

It should be also noted that no perfect alternative exists or an alternative that has a score of 1. All the alternatives will have scores between 0 and 1. An alternative could hypothetically score a one for each evaluation measure except for Ease of Installation. All alternatives will have an installation time over zero, which will score less than one for that evaluation measure.

4.2.1 Alternative Scoring at Northeast AFB

Northeast AFB experiences a temperate, humid climate and is affected by the nearby Atlantic Ocean. The average temperature is 54.8ºF, with annual precipitation of 43.97 inches (SRCC, 2007). This area also has a solar rating of 0.43 kWh/sq.ft./day. The raw data for Northeast AFB can be seen in Appendix C.

After inserting the raw data into the model in Logical Decisions ® for Windows™ (2000) the alternatives were scored and ranked. Figure 4.1 shows the final results for Northeast AFB. The standing seam metal roof with a solar thermal system is the highest ranked alternative with a score of 0.574. In the Northeast the standing seam metal roof options had the greatest scores. A deterministic analysis is performed in the next step to reveal how the alternatives scored in each measure.

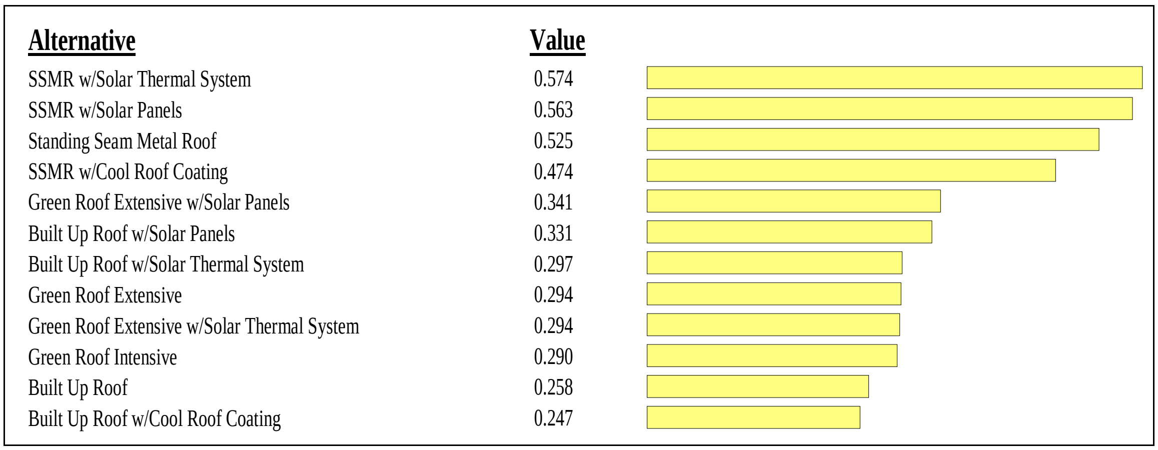

Figure 4.1. Alternative Scoring at Northeast AFB.

4.2.1 Alternative Scoring at Southeast AFB

Southeast AFB has a mild climate that is also affected by the ocean, but has a warmer mean temperature, 72.5 ºF (SRCC, 2000). This installation has an average annual precipitation quantity of 47.17 inches (SRCC, 2000). The sun energy potential is average with a solar rating of 0.46 kWh/sq.ft./day (SolarRating.com). The raw data for Southeast AFB can be seen in Appendix C.

The final scores for Southeast AFB are shown in Figure 4.2. The top alternative is the SSMR with solar panels with a score of 0.692. The top four alternatives have energy generating solar technologies.

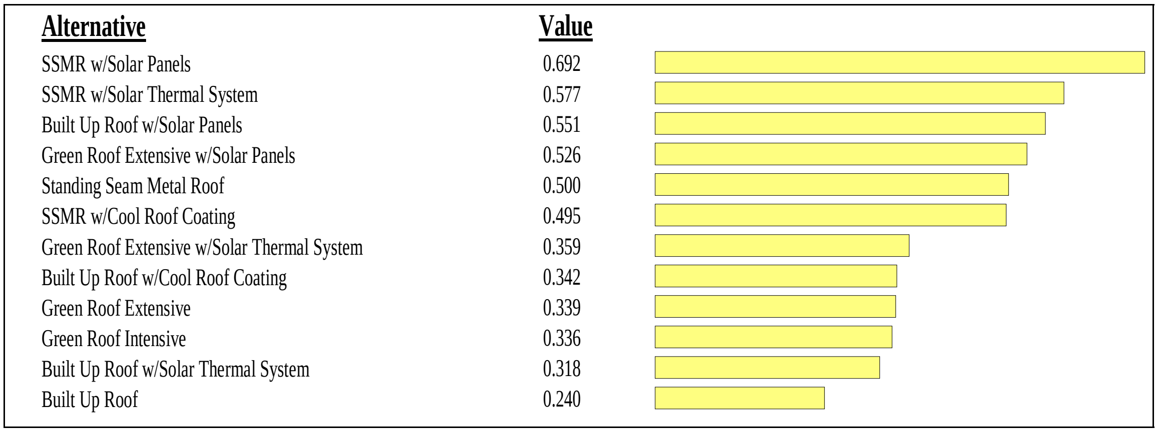

Figure 4.2. Alternative Scoring at Southeast AFB.

4.2.1 Alternative Scoring at West AFB

The last installation evaluated has a climate more extreme than the previous two and is one of the most extreme climates in the continental US. The average temperature is not much higher than Southeast AFB, 72.6ºF, but the area receives higher peak temperatures in the summertime and has over 300 days of sun in the year. This arid region also receives very little precipitation with an average annual total of 7.66 inches (NRCC, 2007). The abundant amount of sunlight gives the area a high solar rating of 0.58 kWh/sq.ft./day.

The alternatives with solar technologies also score well at West AFB. The final scores are shown in Figure 4.3. The SSMR with solar panels is the number one alternative with a score of 0.821.

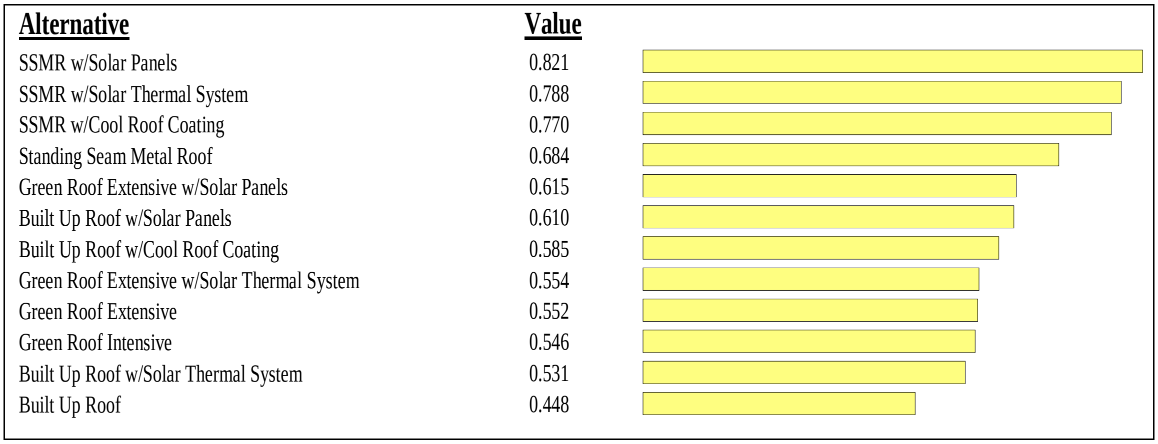

Figure 4.3. Alternative Scoring at West AFB.

4.3 Step 8: Deterministic Analysis

In this step the alternatives are further analyzed to show how well they scored in each evaluation measure. The horizontal bars visually represent the scores, like the previous section, but are divided into scores from each measure. A deterministic analysis, easily accomplished by Logical Decisions ® for Windows™ (2000), allows the decision maker to see how the each alternative scored by each measure.

4.3.1 Deterministic Analysis at Northeast AFB

The Northeast AFB deterministic analysis bar chart is shown in Figure 4.4. As mentioned in the previous step, the standing seam metal roof alternatives all ranked high. This is now understandable looking at the score received from just the Man Hours measurement, which was weighted relatively high (25% of the total global weighting for one measure out of six). These alternatives each received the highest value for that measure and the other alternatives scored very low or zero. The other measures did contribute to the alternative scores, but were not as significant in the dominance of the SSMR scores.

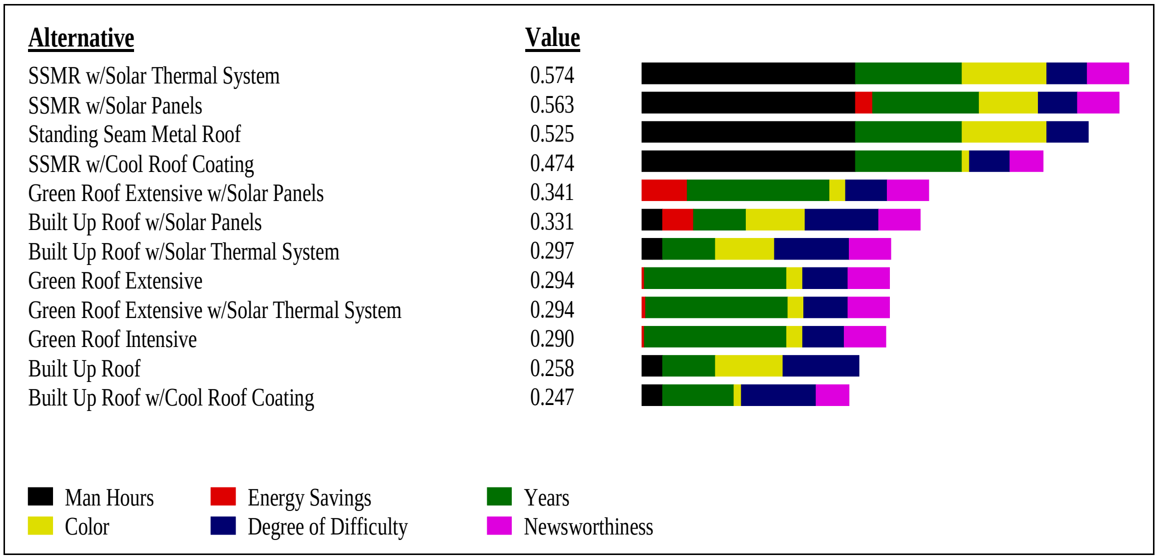

Figure 4.4. Deterministic Alternative Scoring for Northeast AFB.

4.3.2 Deterministic Analysis at Southeast AFB

The Southeast AFB results are similar to Northeast AFB due to similar global weightings by both decision makers. However, the Energy Savings evaluation measure was more influential to the total scores at Southeast AFB. The bar charts are seen in Figure 4.5. At Southeast AFB the energy savings measure was weighted the highest with a weight of 30%, and the Man Hours measurement was weighted at 20%. These two accounted for half of the global weighting of the six evaluation measures, and, as expected, were the most influential in determining final scores. SSMR with solar panels had the greatest score because of the high energy savings and low man hours for maintenance.

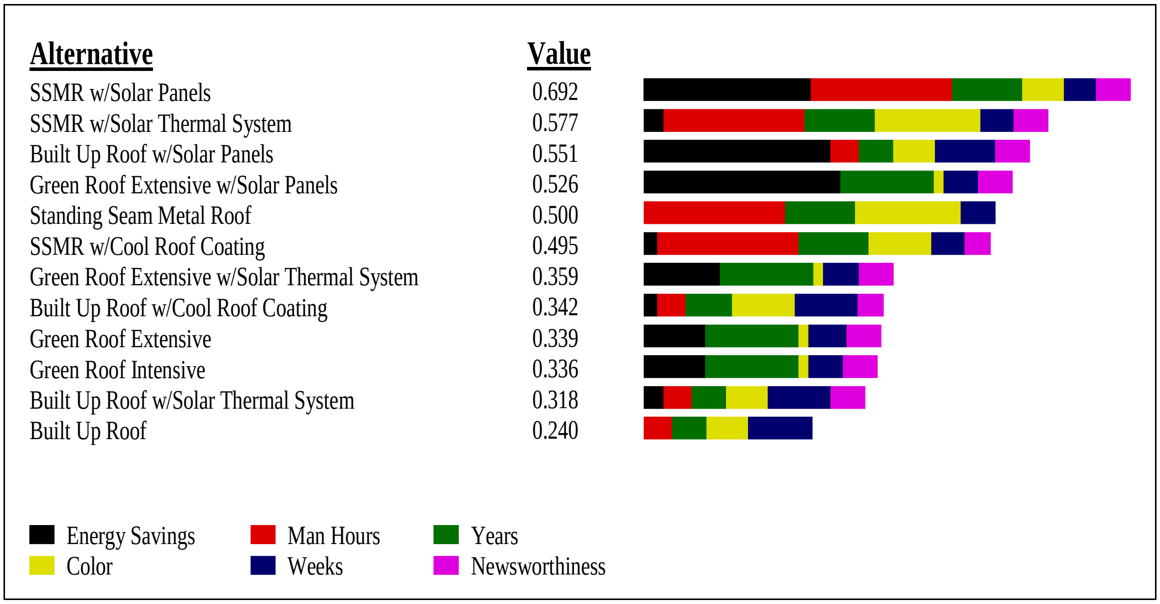

Figure 4.5. Deterministic Alternative scoring for Southeast AFB.

4.3.3 Deterministic Analysis at West AFB

The deterministic analysis at West AFB is shown in Figure 4.6. In this analysis the Years measurement accounts for a large part of each alternative. The Life Span was weighted very high by the decision maker at 35%, but was not a big factor in determining the rankings because all the alternatives received a high score from that evaluation measure. The Man Hours measure was more dominant in the rankings, similar to Northeast AFB. The SSMR alternatives all have low maintenance requirements and, for this reason, have a high ranking at this base. Another interesting observation is that the Energy Savings measure did not play a big role in the final scores. This area of the US has a large potential for solar energy production, but the decision maker weighted this at 10%, which is relatively low.

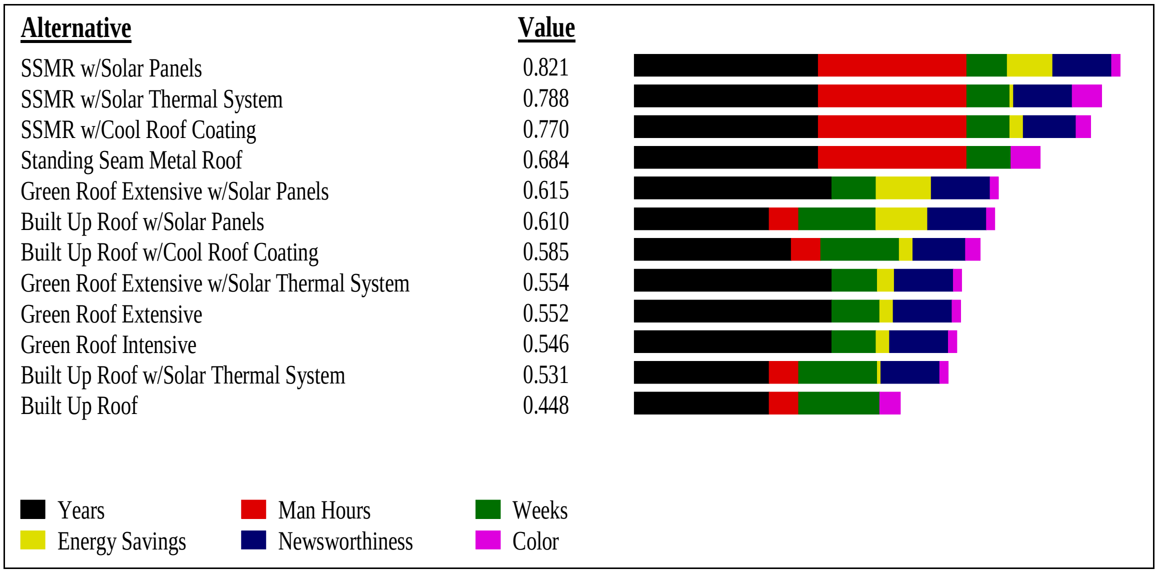

Figure 4.6. Deterministic Alternative Scoring for West AFB.

4.4 Step 9: Sensitivity Analysis

The next step in the VFT process is to "conduct sensitivity analysis to determine the impact on the ranking of alternatives of changes in various model assumptions" (Kirkwood, 1997). The most common area of change is an analysis of the weights in the model. This can be a source of contention with the decision maker and performing a sensitivity analysis on the weights will provide additional insight to the decision maker. Typically, the analysis is performed, and then, only the sensitive values are shown to the decision maker to avoid confusion and manipulation of the model.

The analysis is performed by changing the weight of one value, while keeping the ratio of the remaining values. Equations 4.2 and 4.3 show how the weights will change with respect to the other weights.

$$\lambda_Y = (1-\lambda_X)\left(\frac{\lambda_Y^o}{\lambda_Y^o+\lambda_Z^o}\right) \qquad \text{Eq. 4.2}$$

$$\lambda_Z = (1-\lambda_X)\left(\frac{\lambda_Z^o}{\lambda_Y^o+\lambda_Z^o}\right) \qquad \text{Eq. 4.3}$$

where:

λ_X = new weight of measure X
λ_Y = new weight of measure Y
λ_Z = new weight of measure Z
λ_Y^o = original weight of measure Y
λ_Z^o = original weight of measure Z

(Kirkwood, 1997)

In this research, the sensitivity analysis is only performed on the weights of the evaluation measures because of the small size of the model. The weights can be changed manually, but a function in Logical Decisions ® for Windows™ (2000) allows the decision maker to graph the weight changes and rankings, greatly simplifying the analysis. The following sections will explain the sensitivity analysis on each evaluation measure for each the installations.

4.4.1 Sensitivity Analysis at Northeast AFB

The first sensitivity analysis was performed on the Energy Savings measurement for the Environmental value. The graph is shown in Figure 4.7. If no weight was allocated to this evaluation measure the rankings for the first four alternatives would not change. If the weighting for this measure increased from 25% to 35% the rankings would change, but only switching the top two alternatives. The rankings would also change if this weight was drastically increased to 60% and above, although this is highly unlikely. If the weighting is increased, the overall value or score would decrease because of a decline in the other weightings. The Man Hours measure would be reduced, which earlier was explained as a large reason in the high ranking of the SSMR options.

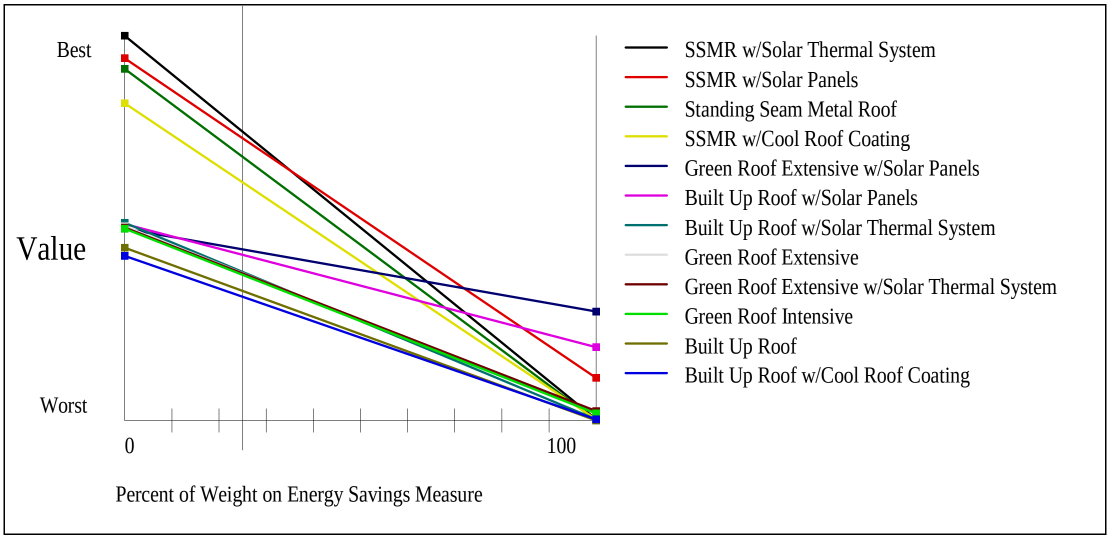

Figure 4.7. Sensitivity Analysis of Environmental Objective at Northeast AFB.

The next analysis on the Weeks measurement, Figure 4.8, is not highly sensitive. The rankings for the top alternatives would not change until a weight of 40-50% was reached.

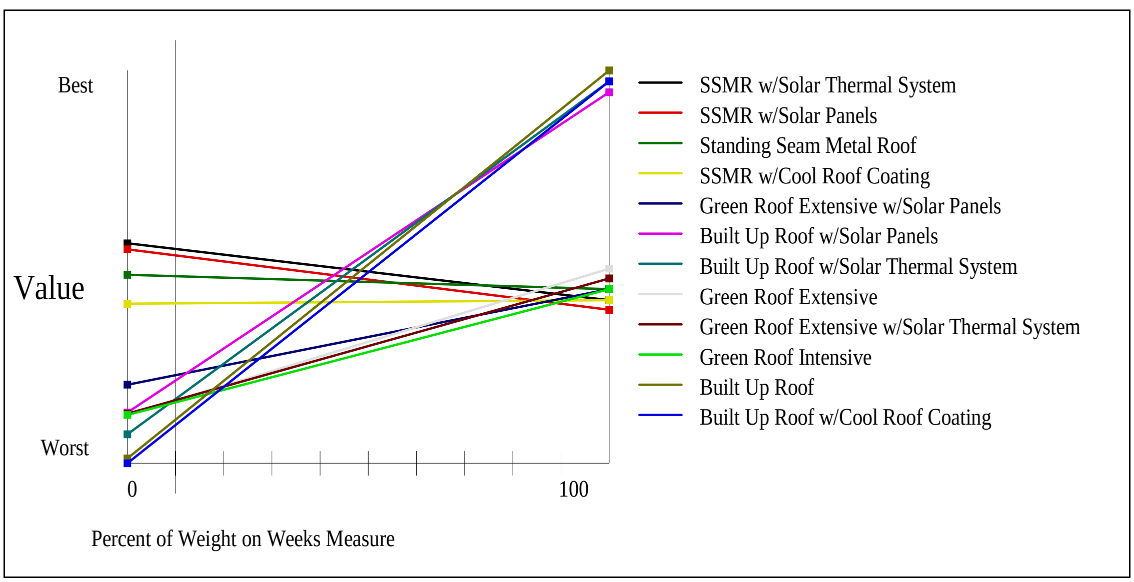

Figure 4.8. Sensitivity Analysis of Ease of Installation Objective at Northeast AFB.

The analysis on the Years measurement for the length of life of the roof is also not extremely sensitive. This is graph is shown in Figure 4.9. The weight on Years would have to greatly increase before the rankings of the top four alternatives would change.

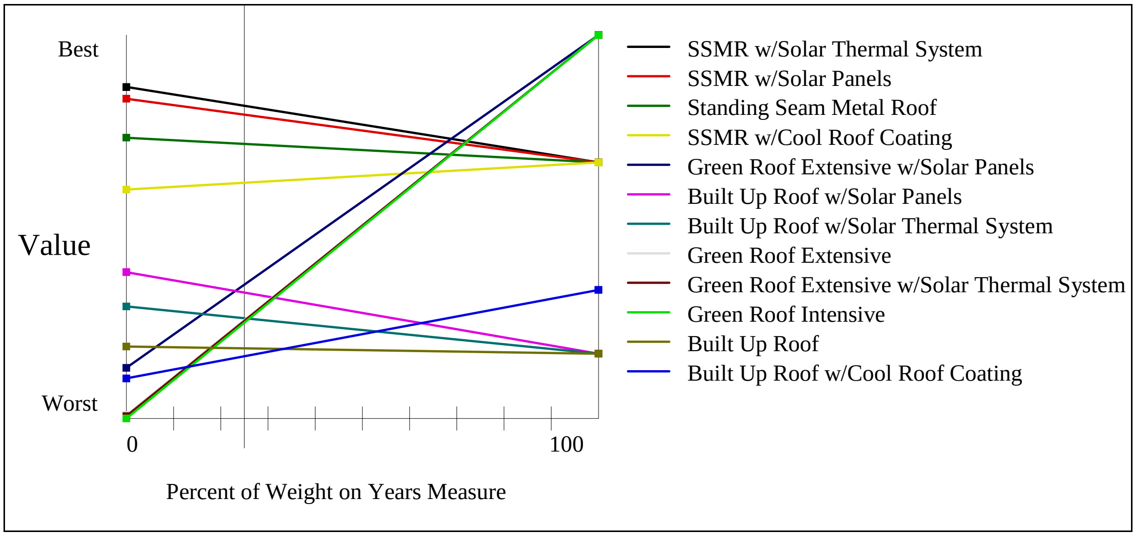

Figure 4.9. Sensitivity Analysis of Life Span Objective at Northeast AFB.

The Man Hours measurement is not sensitive. The SSMR with a solar thermal system will remain the top alternative, unless the weight is reduced to almost zero. This is observed in Figure 4.10. Any increase in weight would increase the overall values of the SSMR alternatives.

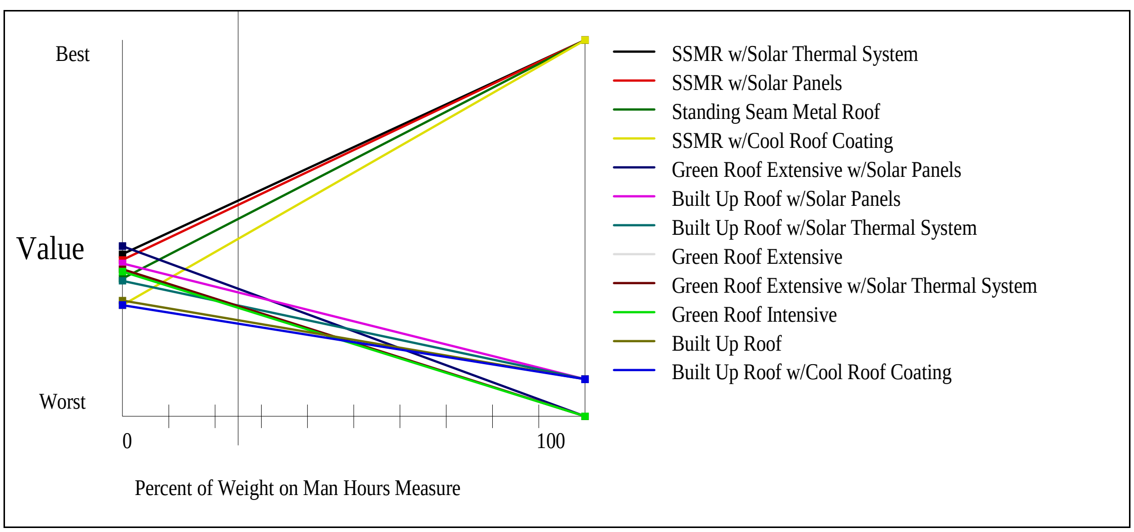

Figure 4.10. Sensitivity Analysis of Maintenance Objective at Northeast AFB.

In the sensitivity analysis for the Newsworthiness measure the SSMR with a solar thermal system is stochastically dominant at all weightings, Figure 4.11.

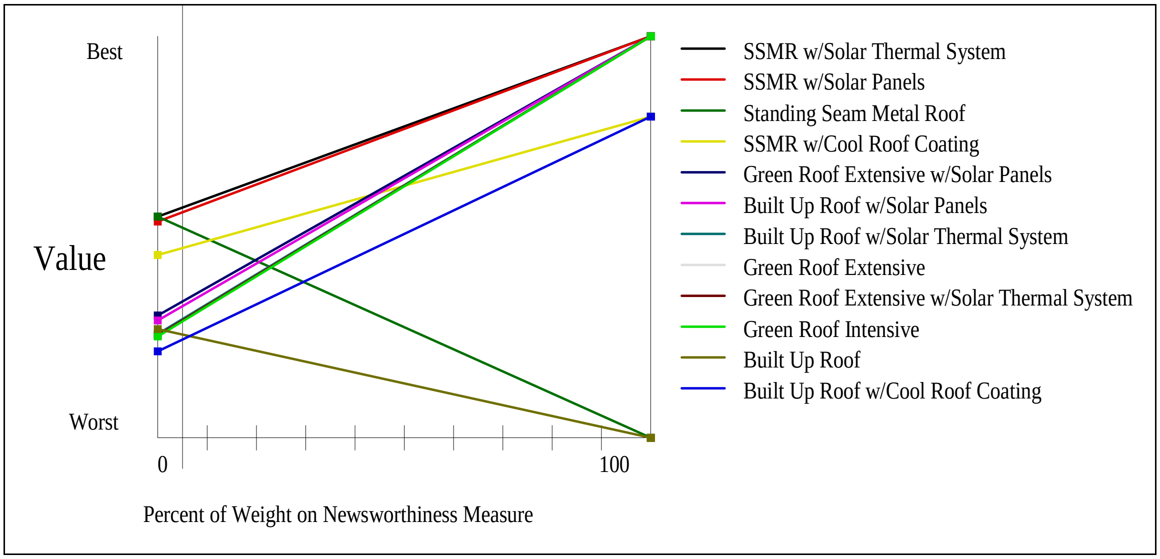

Figure 4.11. Sensitivity Analysis of Off-base Perceptions Objective at Northeast AFB.

The final sensitivity analysis for Northeast AFB was performed on the Color evaluation measure. This is shown in Figure 4.12 and is sensitive to a slight decrease in weight. The top two rankings would switch with a minor drop in weight.

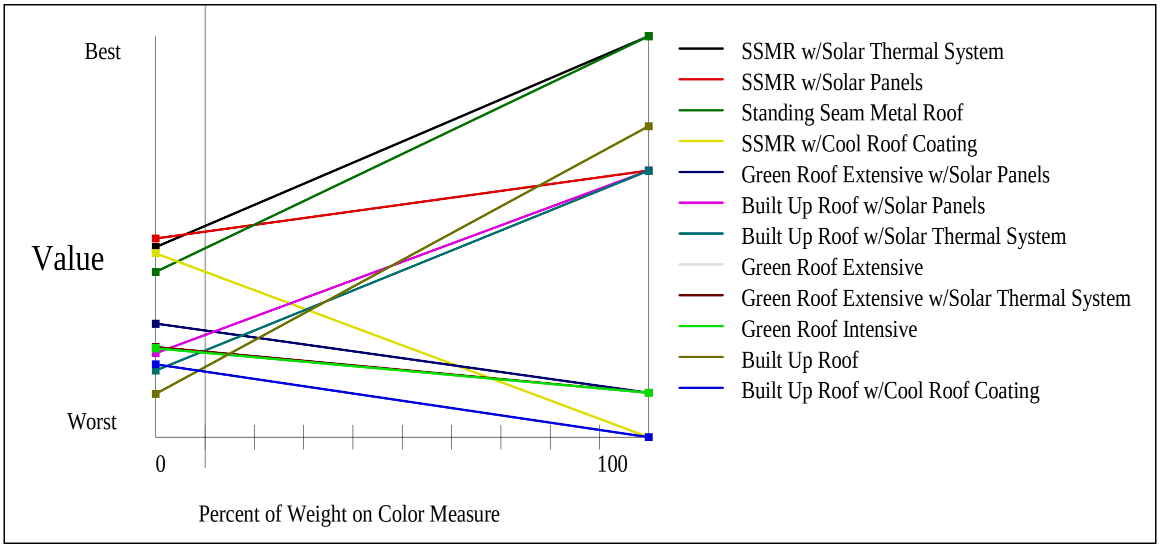

Figure 4.12. Sensitivity Analysis of On-base Perceptions Objective at Northeast AFB.

4.4.2 Sensitivity Analysis at Southeast AFB

The analysis for the Energy Savings measure is not highly sensitive for the first alternative, but is sensitive for the next three. It is probable that the importance for Energy Savings will not drop enough to change the rankings. If the weight is increased from 30% to 35%, the rankings of the alternatives with solar panels will rise due to the high potential of the technologies. In order for the SSMR with solar panels option to fall the weight would have to increase to at least 70%.

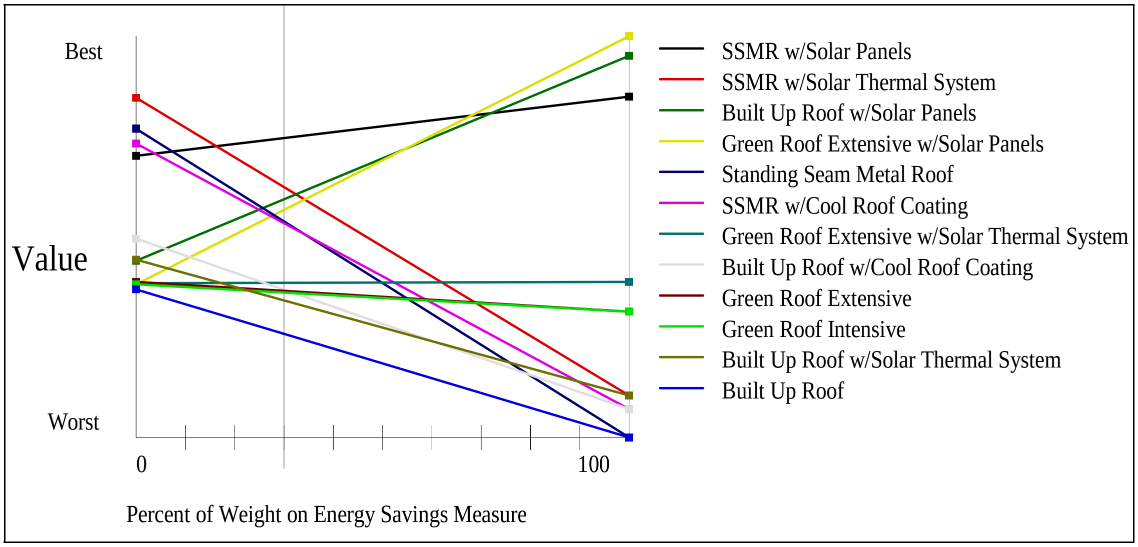

Figure 4.13. Sensitivity Analysis of Environmental Objective at Southeast AFB.

The top ranking will not change until the weight for the Weeks evaluation measure increases to over 30%. This measure is not sensitive to small changes in weight. The graph is shown in Figure 4.14.

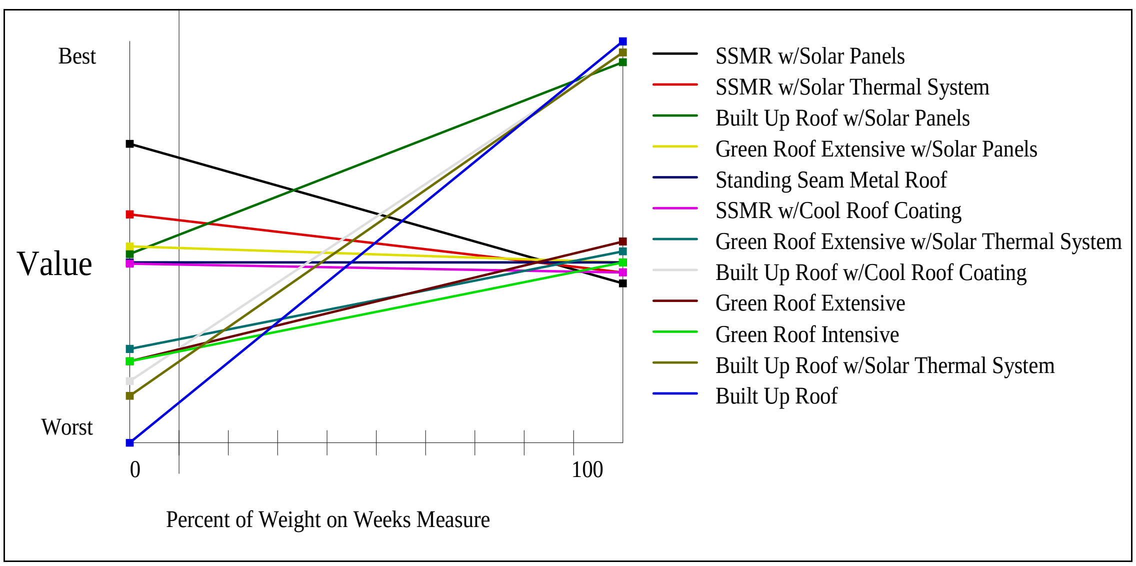

Figure 4.14. Sensitivity Analysis of Ease of Installation Objective at Southeast AFB.

In Figure 4.15, SSMR with solar panels is dominant until the global weight increases to over 60%. The measure for the Life Span value is not sensitive.

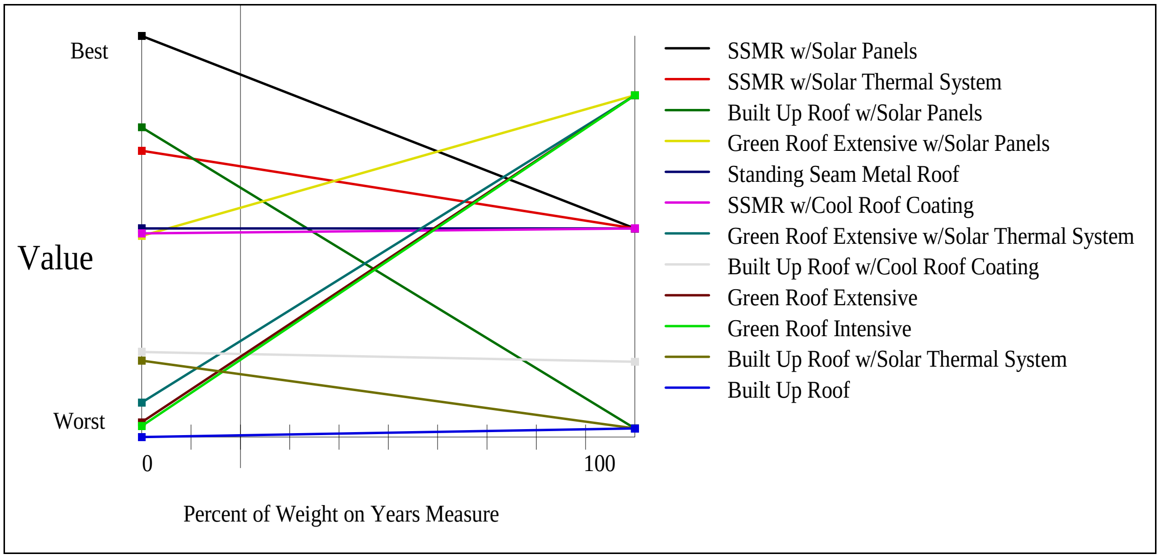

Figure 4.15. Sensitivity Analysis of Life Span Objective at Southeast AFB.

The sensitivity analysis performed on the Man Hours measure for Southeast AFB is not sensitive. Figure 4.16 shows that the SSMR with solar panels is dominant unless there is little to no weighting on the measure.

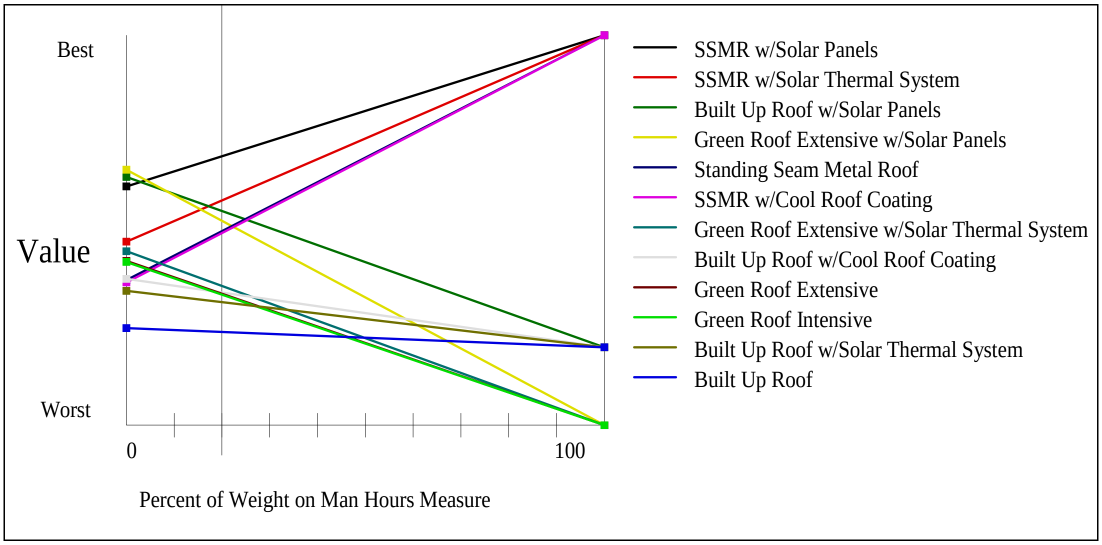

Figure 4.16. Sensitivity Analysis of Maintenance Objective at Southeast AFB.

SSMR with solar panels is stochastically dominant for the Newsworthiness measure shown in Figure 4.17.

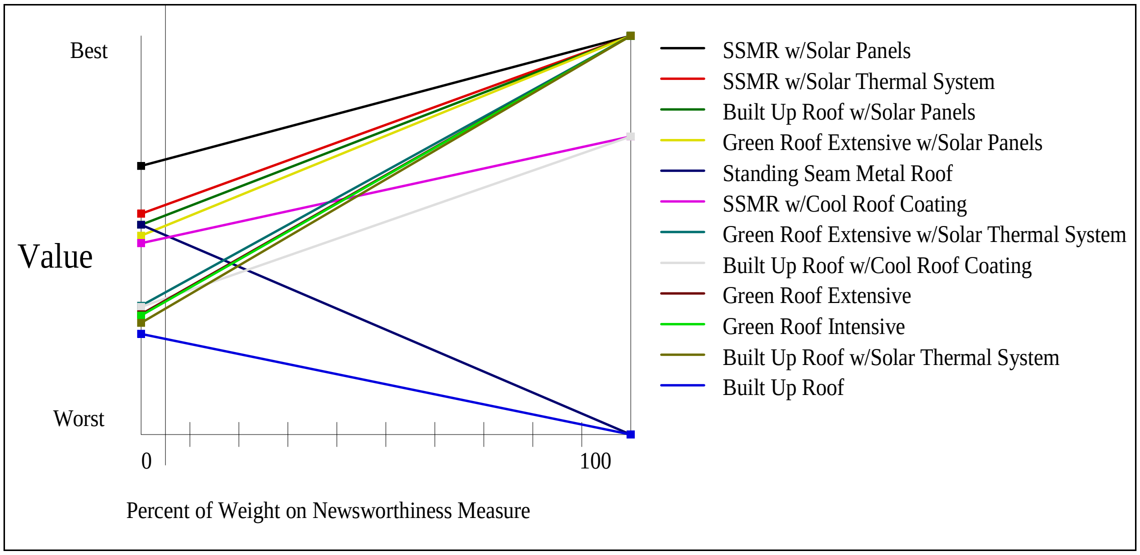

Figure 4.17. Sensitivity Analysis of Off-base Perceptions Objective at Southeast AFB.

The weight for the Color measure at Southeast AFB is slightly sensitive. As shown in Figure 4.18, the rank of the first alternative will change with an increase to approximately 30%. The rankings of the next three ranked alternatives will change with a small decrease in weight.

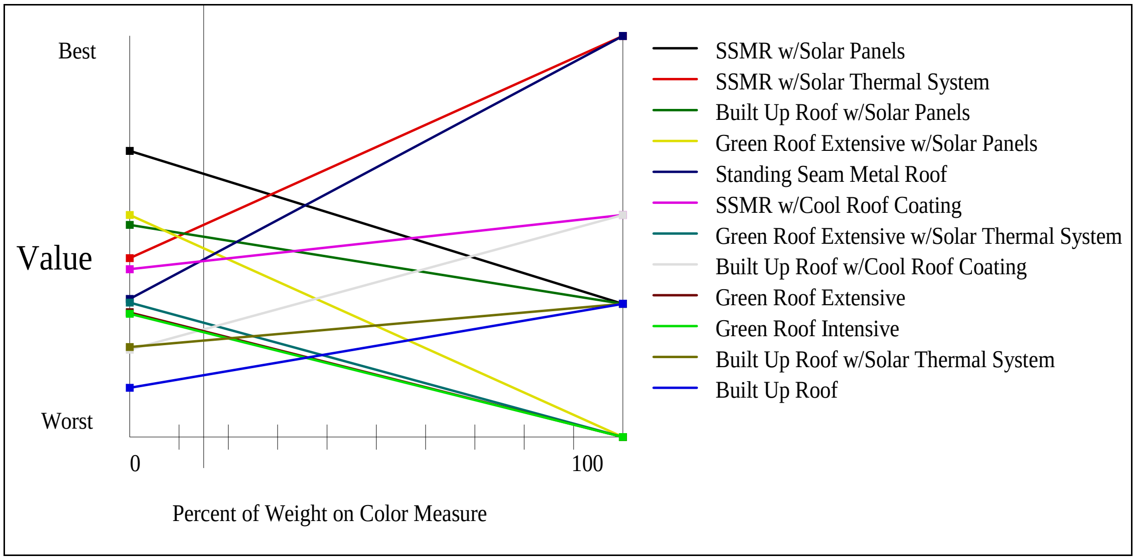

Figure 4.18. Sensitivity Analysis of On-base Perceptions Objective at Southeast AFB.

4.4.3 Sensitivity Analysis at West AFB

The rankings will change with a small decrease in weight for the Energy Savings measurement. Otherwise, the SSMR with solar panels will stay the top alternative until the weight increases to over 60%, which has a low probability. The graph is shown in Figure 4.19.

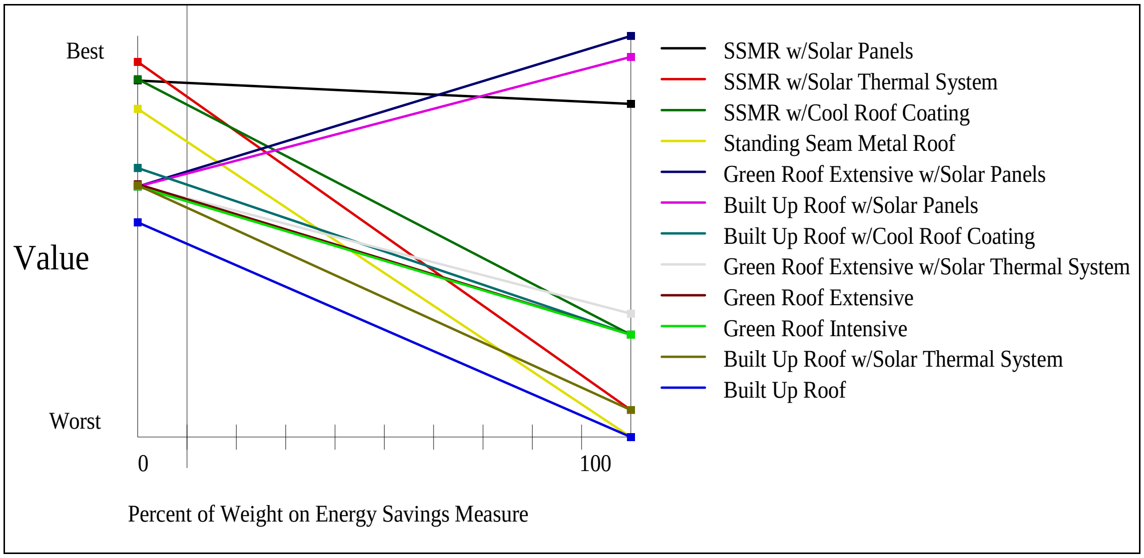

Figure 4.19. Sensitivity Analysis of Environmental Objective at West AFB.

The weight for the Weeks measure is insensitive to small changes. As shown in Figure 4.20, the top alternative will not change until the weight reaches 45%. At this weight the roofing technologies with short installation times take over.

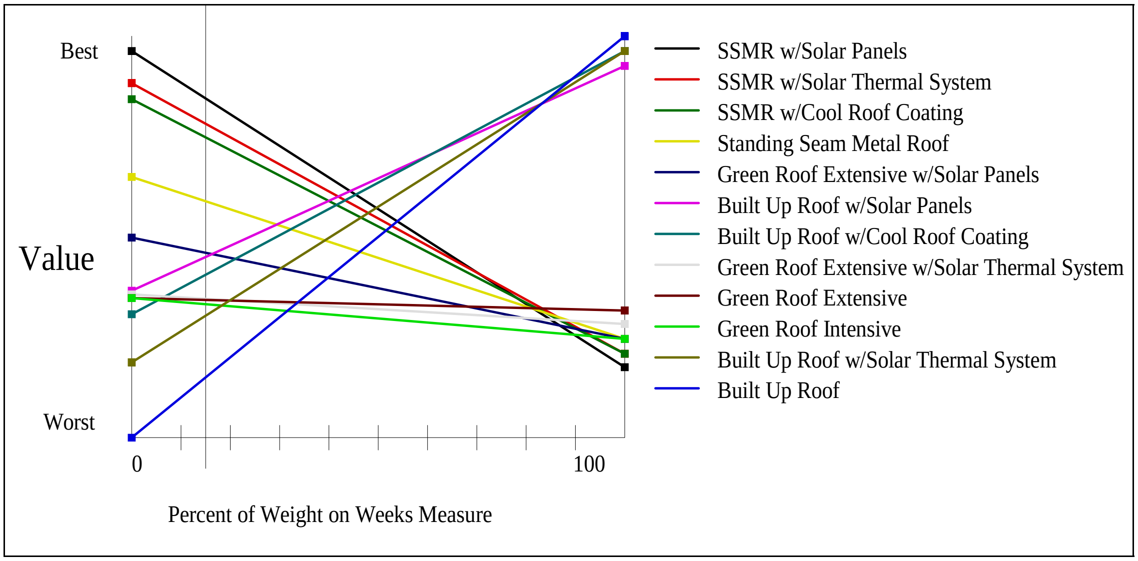

Figure 4.20. Sensitivity Analysis of Ease of Installation Objective at West AFB.

In Figure 4.21, the graph shows the Years measure is not sensitive to small changes in weight. The weight will have to increase to over 80% before the SSMR is dropped from the top rank. The green roof alternatives will be ranked at a weight above 80%.

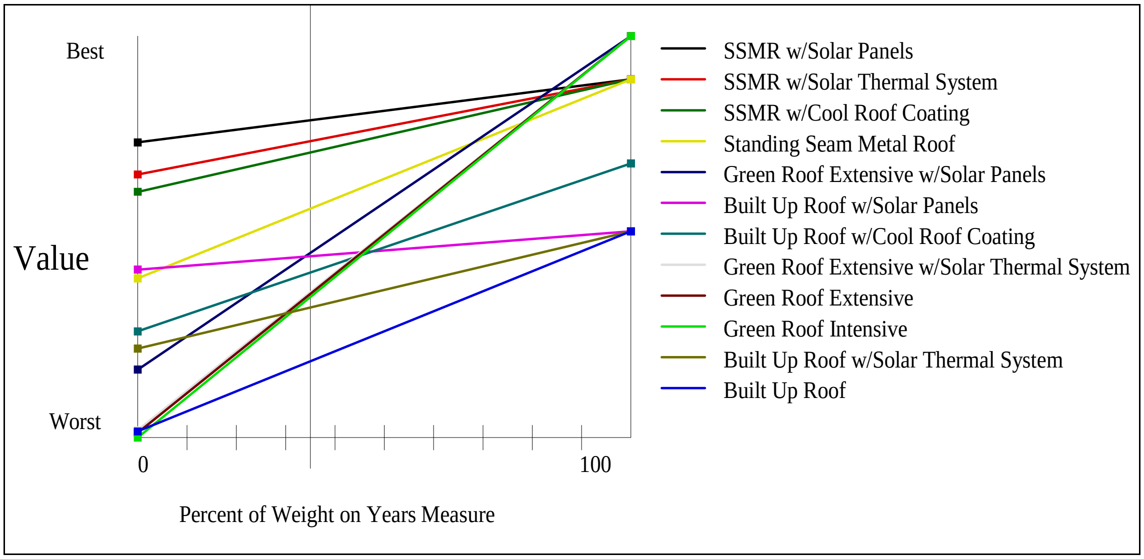

Figure 4.21. Sensitivity Analysis of Life Span Objective at West AFB.

The SSMR with solar panels is dominant in the Man Hours measure. The weight would have to decrease to 5% before it would lose its top ranking. This can be seen in Figure 4.22.

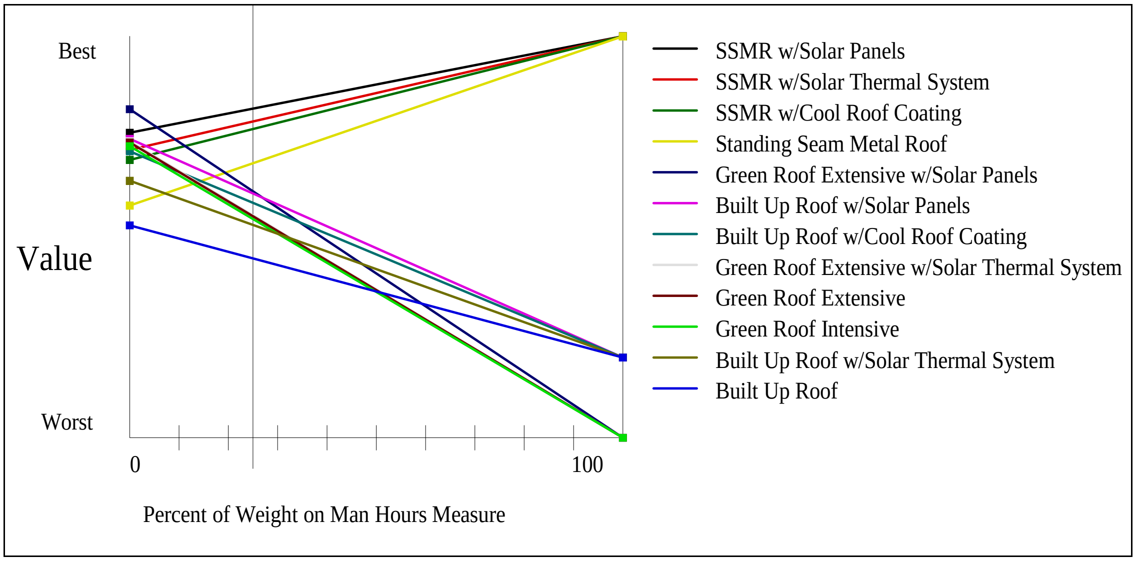

Figure 4.22. Sensitivity Analysis of Maintenance Objective at West AFB.

The SSMR is stochastically dominant between the weights of 0% and 100% of the global weighting of the Newsworthiness measure. This graph is shown in Figure 4.23.

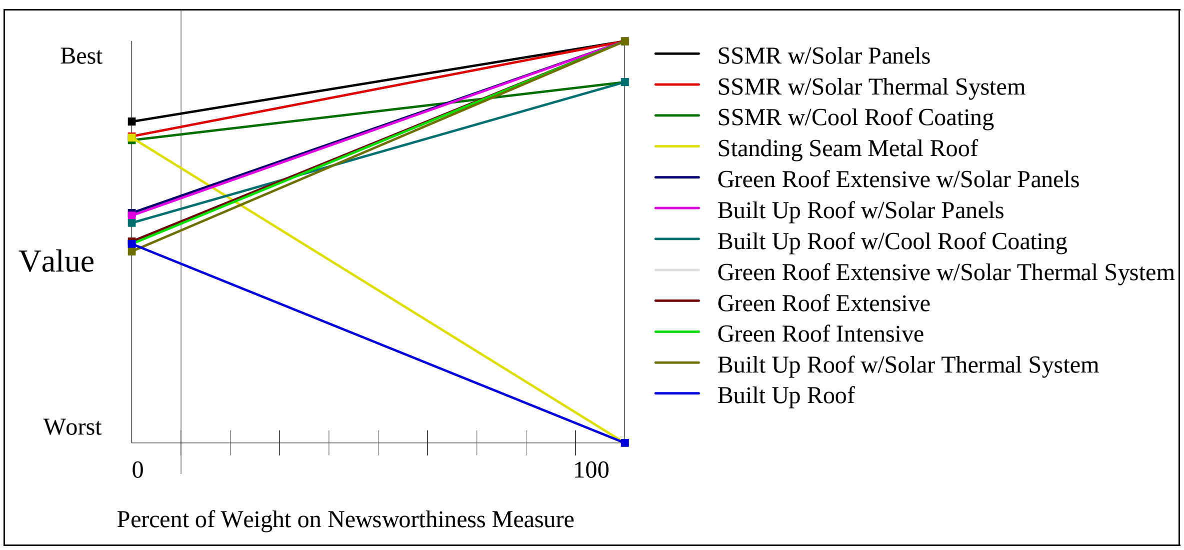

Figure 4.23. Sensitivity Analysis of Off-base Perceptions Objective at West AFB.

The last measure, Color, is sensitive to a small increase of the weight. If it rises to 10% the SSMR with a solar thermal system will become the top alternative, shown in Figure 4.24.

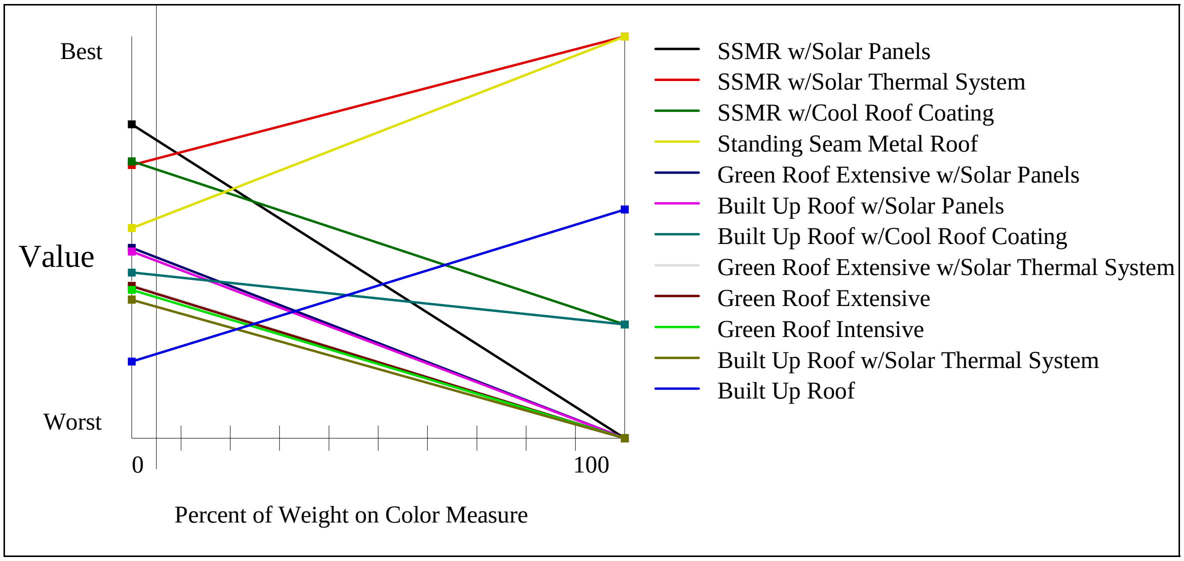

Figure 4.24. Sensitivity Analysis of On-base Perceptions Objective at West AFB.

4.5 Cost Analysis

The cost analysis step in the process was added because cost was purposely left out as a value in the model. This is common in the VFT practice as cost is frequently a deciding factor a decision. The reason for leaving cost out of the model is to evaluate what the decision maker truly values, excluding cost.

The installation costs in this research were calculated from figures obtained from the RS Means cost estimating handbook, literature review, and speaking with local contractors and construction managers. A base civil engineer would estimate the costs in a similar manner, but would also send out a Request For Proposal (RFP) to have contractors bid the project with more cost estimates. A table of cost with location cost factors can be seen in Appendix D. In the evaluation a scaled cost value ratio was calculated to compare the value per cost of the alternatives. It is determined by dividing the VFT score by the installation cost and then multiplying that number by a scaling constant, in this case 100,000. After the cost-value ratio was calculated the values and costs were graphed to visually observe the best options. The cost analysis was separately performed for all three locations due to differences in construction cost and energy savings.

4.5.1 Cost Analysis at Northeast AFB.

Construction cost in the Northeast AFB area is more expensive than the other two installations. The costing data is shown in Table 4.1. The BUR has the highest ratio, due to such a low initial cost, but as one can see, there are no energy savings with a BUR. The other alternatives that had a high cost value ratio were the BUR with a cool roof coating, BUR with a solar thermal system, SSMR, and SSMR with a solar thermal system. All these alternatives had relatively low installation cost which resulted in a greater ratio.

Table 4.1. Costing Data for Northeast AFB.

Alternatives	Energy Savings ($ Per Year)	Installation Cost ($)	Alternative VFT Score	Cost Value Ratio (Value Per $)
BUR	$0.00	$38,430.00	0.258	0.671
BUR w/Cool Roof Coating	$736.88	$59,017.50	0.247	0.419
BUR w/Solar Panels	$17,464.08	$861,930.00	0.331	0.038
BUR w/Solar Thermal System	$1,105.32	$54,900.00	0.297	0.541
Green Roof Extensive	$3,684.41	$205,875.00	0.294	0.143
Green Roof Extensive w/Solar Panels	$21,148.49	$1,029,375.00	0.341	0.033
Green Roof Extensive w/Solar Thermal System	$4,789.73	$222,345.00	0.294	0.132
Green Roof Intensive	$3,684.41	$368,516.25	0.290	0.079
Standing Seam Metal Roof	$0.00	$109,800.00	0.525	0.478
SSMR w/Cool Roof Coating	$736.88	$130,387.50	0.474	0.364
SSMR w/Solar Panels	$13,079.64	$933,300.00	0.563	0.060
SSMR w/Solar Thermal System	$1,105.32	$126,270.00	0.574	0.455

In Figure 4.25 the value of each alternative is positioned on the x-axis and the cost is graphed on the y-axis. According to this graph the higher points should not be selected. They are dominated by the lower cost and higher benefit points or alternatives. A "best" line was entered on the lower points to show a marginal cost of value relationship. Any alternatives falling above this line should not be selected based on value and cost. The decision maker can use this graph to pick the highest valued alternative based on the amount of money that is available. The dashed line is an assumption that greater values will start to become much more expensive do to high cost of greater technologies. Typically a decision maker only has a certain amount of money that can be spent. The graph allows the decision maker to easily choose the highest valued alternative with a low cost. A decision maker may also observe that even though they have a certain amount of money they may not have to spend the whole amount to get a desired value. For instance, the decision maker may have $400,000 to spend to re-roof an Air Force facility. When looking at the graph the decision maker will notice they can spend $126,000 on the SSMR with a solar thermal system to get the highest value. Then the extra money can be spent elsewhere, either on another project or on the same project, but on other avenues to increase the value of that alternative. They could look at the deterministic analysis and observe the SSMR takes a long time to install and spend the extra money on reducing the installation time.

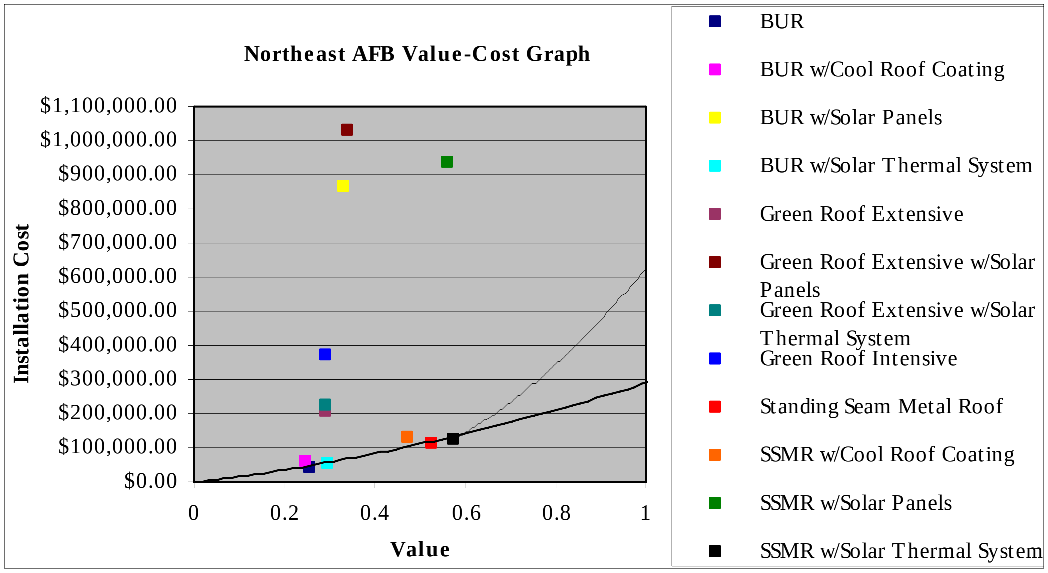

Figure 4.25. Value-Cost Graph for Northeast AFB.

4.5.2 Cost Analysis at Southeast AFB

Southeast AFB typically has lower costing construction compared to the Northeast. As seen in the Table 4.2 the BUR alternative has the top cost-value ratio. The BUR does have a very low installation cost. The BUR with a cool roof coating, BUR with a solar thermal system, and the SSMR alternatives also have high cost-value ratios. These alternatives for the Southeast have low installation cost. The solar panel alternatives have low ratios due to the extremely high cost of installation.

Table 4.2. Costing Data for Southeast AFB.

Alternatives	Energy Savings ($ Per Year)	Installation Cost ($)	Alternative VFT Score	Cost Value Ratio (Value Per $)
BUR	$0.00	$26,250.00	0.240	0.914
BUR w/Cool Roof Coating	$419.94	$40,312.50	0.342	0.848
BUR w/Solar Panels	$12,052.29	$588,750.00	0.551	0.094
BUR w/Solar Thermal System	$629.91	$37,500.00	0.318	0.848
Green Roof Extensive	$2,099.70	$140,625.00	0.339	0.241
Green Roof Extensive w/Solar Panels	$14,151.99	$703,125.00	0.526	0.075
Green Roof Extensive w/Solar Thermal System	$2,729.61	$151,875.00	0.359	0.236
Green Roof Intensive	$2,099.70	$251,718.75	0.336	0.133
Standing Seam Metal Roof	$0.00	$75,000.00	0.500	0.667
SSMR w/Cool Roof Coating	$419.94	$89,062.50	0.495	0.556
SSMR w/Solar Panels	$9,049.72	$637,500.00	0.692	0.109
SSMR w/Solar Thermal System	$629.91	$86,250.00	0.577	0.669

The Southeast AFB value-cost graph, Figure 4.26, looks similar to the Northeast AFB. The same alternatives fall along the best value per cost line. However, there is a point that does have a greater value, SSMR with a solar thermal system, and is not dominated by the points on the best value line. The decision maker has to decide if the added value is worth the added cost.

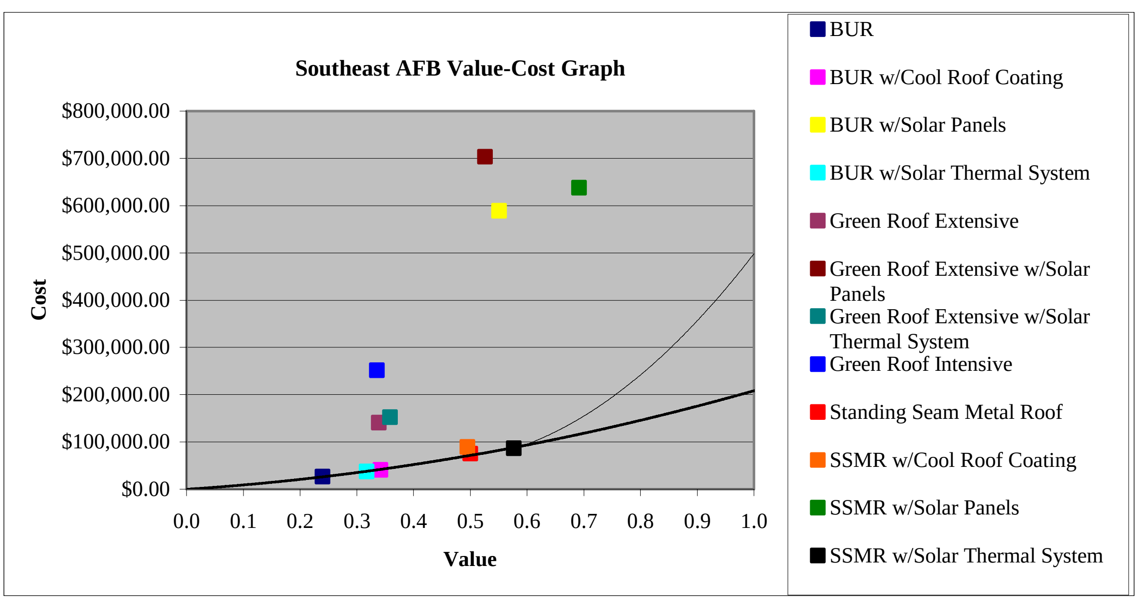

Figure 4.26. Value-Cost Graph for Southeast AFB.

4.5.3 Cost Analysis at West AFB

The construction costs at West AFB are also lower than the Northeast region of the US. The BUR, BUR with cool roof coating, and the BUR with a solar thermal system all had the highest ratio. These alternatives also had the lowest installation costs. The SSMR alternatives, excluding the solar panel option, had the next highest scores.

Table 4.3. Costing Data for West AFB.

Alternatives	Energy Savings ($ Per Year)	Installation Cost ($)	Alternative VFT Score	Cost Value Ratio (Value Per $)
BUR	$0.00	$30,660.00	0.448	1.461
BUR w/Cool Roof Coating	$2,897.30	$47,085.00	0.585	1.242
BUR w/Solar Panels	$19,411.90	$687,660.00	0.610	0.089
BUR w/Solar Thermal System	$724.32	$43,800.00	0.531	1.212
Green Roof Extensive	$2,897.30	$164,250.00	0.552	0.336
Green Roof Extensive w/Solar Panels	$22,309.20	$821,250.00	0.554	0.067
Green Roof Extensive w/Solar Thermal System	$3,621.62	$177,390.00	0.554	0.312
Green Roof Intensive	$2,897.30	$294,007.50	0.546	0.186
Standing Seam Metal Roof	$0.00	$87,600.00	0.684	0.781
SSMR w/Cool Roof Coating	$2,897.30	$104,025.00	0.770	0.740
SSMR w/Solar Panels	$14,544.44	$744,600.00	0.821	0.110
SSMR w/Solar Thermal System	$724.32	$100,740.00	0.788	0.782

The graph in Figure 4.27 also looks similar to the other value-cost graphs. The same alternatives fall along the best value line. These alternatives show the decision maker that a certain level can be achieved with saving large amounts of money.

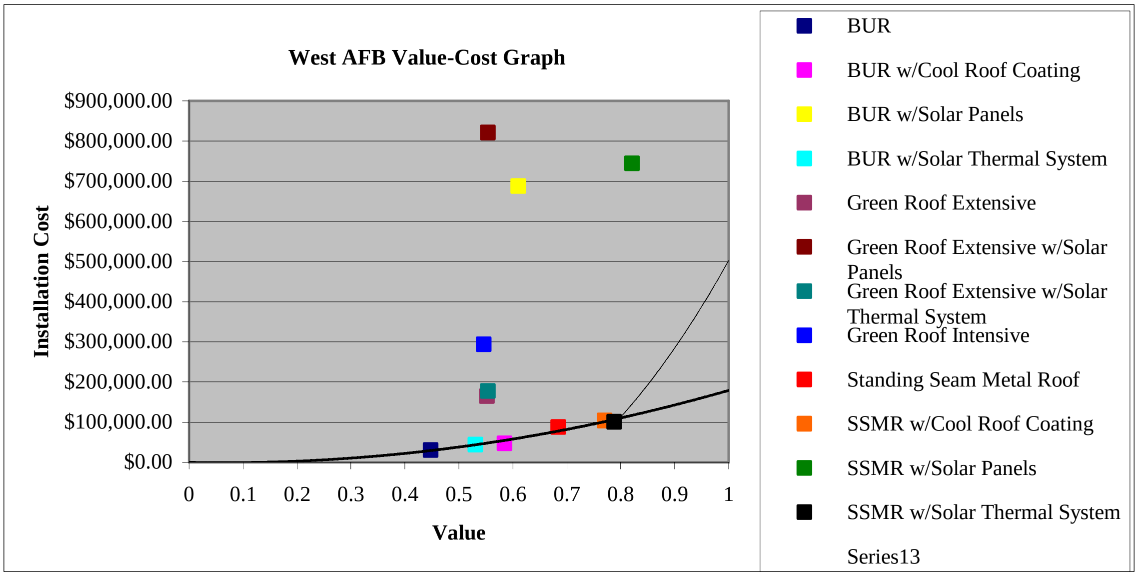

Figure 4.27. Value-Cost Graph for West AFB.

4.6 Summary

This chapter analyzed the alternatives that were entered into the model that was created in chapter three. First, data was gathered from various sources to score the alternatives and then deterministic and sensitivity analysis were performed to further investigate the decision. Finally, a cost analysis was performed to assist the decision maker in choosing the best roofing technology based on a value versus cost.

V. Results and Conclusions

5.1 Introduction

The final chapter covers the last step in the ten-step process. It will begin with a brief summary of the research and then each research question from chapter one will be addressed. The model strengths will be discussed followed by a few limitations of the research. Finally, the chapter will finish with recommendations for further research and a final conclusion.

5.2 Research Summary

The research was conducted to provide Air Force decision makers with a tool to assist them in deciding what roofing technologies should be installed on facilities. VFT is the methodology used to construct the model, in which much effort was expended in determining what values and objectives are important in the decision of selecting rooftop technologies. After researching current technologies, alternatives were selected, entered into the model, scored, and analyzed.

5.3 Research Questions

Three questions were asked in first chapter as the basis for research.

1. What energy efficient roofing technologies exist and are they successful?

Throughout the research, numerous technologies were discovered. This study concentrated on the technologies that were known to have positive energy saving effects. Many technologies were actually found to have been used for decades and sometimes centuries (i.e. green roofs). They have become mainstream in building design because of the global emphasis on decreasing non-renewable energy consumption and lessening negative effects to the environment.

The energy efficient technologies covered in this research were the cool roof, green roofs, photovoltaic, and solar thermal systems. They all have been proven to reduce energy cost, but the efficiency is dependent upon many factors, such as geographical location. All four technologies work well in areas with high solar ratings. Also for each option the technologies must be installed correctly and maintained to maximize the benefits. Cool roofs provide great benefits during warm months, but can have negative effects in cold months. Green roofs are less affected by climate changes compared to the other technologies. Building designers can pick vegetation that grows well in the geographical area and the extra layers provide increased insulation. Photovoltaic systems offer the highest energy savings as a stand alone system and offer even more building energy savings when coupled with a green roof. The solar thermal system can also be combined with a green roof to improve energy savings. Solar thermal savings were low in this research, but can be greatly improved if used at a facility that has high hot water consumption, such as a gymnasium.

2. How much energy and money can be saved by using these roofing technologies?

Each alternative in this research has the potential to save energy. As discussed in the previous question, a photovoltaic array on a green roof can save the most energy in any of the three locations examined for the generic Air Force facility. The highest energy savings calculated in this research was 77% by the generic facility with an extensive green roof with solar panels. West AFB had the greatest potential to save energy for each solar technology option used in the model. Using any of the technologies will save energy, but may not save money over the lifetime of the roofing system. The installation costs are still very high for many of the options and for the size of the facility. With the continuous improvements in efficiency and increased contractor availability for modern technologies, cost savings may be feasible in the foreseeable future. Other facility sizes and types may produce better results, and sometimes worse.

3. What do decision makers in the Air Force value in roofing technologies?

The decision makers, base civil engineers, selected in this research are the individuals who are most likely to make roof retrofitting decisions in the Air Force. A response from one of the decision makers in the initial brainstorming stage was "to install a roof that lasted forever, had no leaks, and required little maintenance." This was a typical response from all the engineers. After further deliberation the following values were determined to be important for roofing technologies; reduction in nonrenewable energy consumption to help the environment, quick installation to minimize mission delays, extended roof life to keep occupants safe and healthy, low maintenance demands to lessen the stress on civil engineering manpower, high off-base perceptions to advertise the Air Force is operating responsibly, and good on-base perceptions to keep the base looking professional.

5.4 Model Strengths

The model established in the research had many strengths to make it a valuable tool to Air Force decision makers. First the VFT methodology identified what the decision makers value in roofing technologies. The decision analysis process allowed the Air Force engineers to focus on the values rather than what can be purchased from the money that is available. Of course the decision makers tried to capitalize on the money they had, but many times values are overshadowed by cost. Another strength of the model is the inherent flexibility it possesses. It can be adapted to any location, climate, or decision maker. Not only does it work for the Air Force in the continental U.S., but it can also be used by any decision maker retrofitting a BUR in any location in the world. The model also allows any roofing alternative to be entered and evaluated. The next asset of the model is that it has a mathematical background which makes the process more objective. A choice can be made with greater confidence and certainty in the outcome. The deterministic analysis and sensitivity analysis also make the model an effective tool, because of the additional insight it provides. Deterministic analysis allows the decision maker to see the strengths and weaknesses of each alternative, while the sensitivity analysis lets the analyzer see any impacts in the rank of the alternatives when changing weights. One more analysis that complements the model is the cost-value examination. This allows the decision maker to get the highest value out of the limited funds that are available to the organization. The final strength the model has is the small size. It is easily understood and defendable to the decision maker. It contains no complex equations or concepts. The model can be created in a short period of time while still providing a thorough decision analysis.

5.5 Research Limitations

The first limitation in this research is that several assumptions were made with respect to the data used. The energy simulations and calculations were based on a generic Air Force facility. Most facilities are more complex with unique designs and systems. The technologies evaluated in the research may perform better or worse with different building configurations, certainly with building size. This limitation will be overcome in the real world as the analysis will be done on an existing facility or the design plan of a new facility. The technologies in the research were also assumed to be installed and maintained correctly in the estimations and calculations. Another feature of the VFT model is the potential for decision maker bias. The individual may insert weights and values into the model based on a particular alternative in mind. In the research the decision makers were told not to think about alternatives when creating the model to avoid skewing the values and SDVFs. Bias can never be completely removed because of personal experience and knowledge, which gives the decision maker values.

5.6 Recommendations for Future Research

In creating this model for roofing technology selection, many thoughts and doors were opened for future endeavors. To begin, other facilities should be evaluated. Other facilities have different energy requirements and configurations that may be more energy and cost effective. Military housing may be good study due to the low energy consumption and high roof area to wall ratio. Another recommendation is to apply the technologies in a real world situation. There are numerous re-roofing construction projects around the Air Force and even on the same installations. Different technologies could be selected by this model and then compared. This also could be applied to other DOD agencies. Other organizations may have completely different value sets. Next, this model should be applied to locations with extreme climates to see possible shifts in weights. Alaska would be a good location due to the extreme cold and limited sun exposure. Finally, a study should be performed on Air Force civil engineering manpower. In this research, one of the dominating values in the decision was a roofing technology that required little to no maintenance. In today's Air Force, civil engineering manpower is limited and unable to perform the necessary maintenance on the current roofs.

5.7 Final Conclusions

The VFT model is an effective tool to assist Air Force decision makers in selecting energy-efficient roofing technologies. According to this research, the Air Force is moving in the right direction of installing standing seam metal roofs, but should add low cost energy efficient technologies, such as a small solar thermal system or a cool roof coating. These alternatives have high value at relatively low cost. These options will help the US reduce energy bills and dependence on foreign energy sources.

Appendix A: SDVFs for All Evaluation Measures

Northeast AFB Evaluation Measures SDVFs

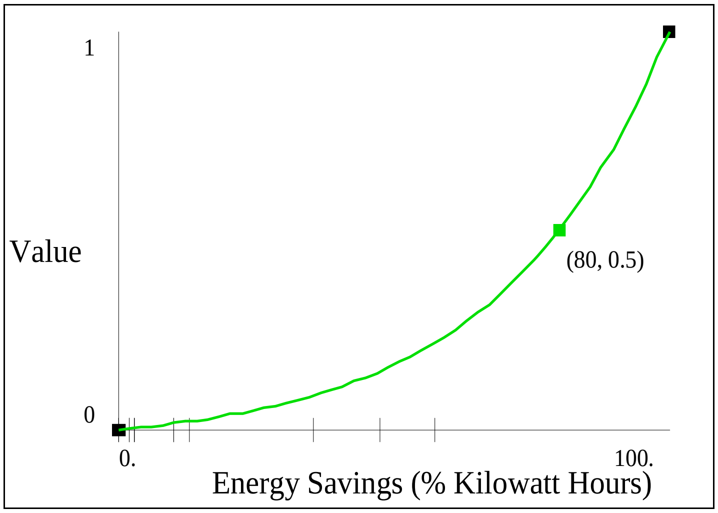

Figure A1. SDVF for Northeast AFB Energy Savings Evaluation Measure. The continuous function is an exponentially increasing. The decision maker wants a technology that will save a large percentage of the energy.

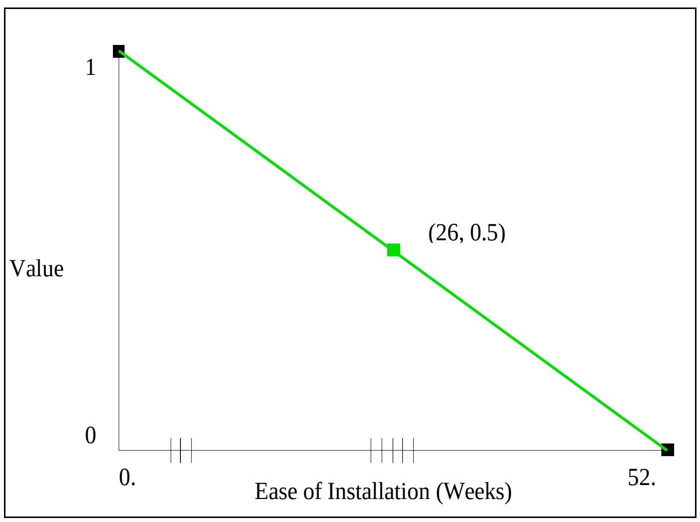

Figure A2. SDVF for Northeast AFB Ease of Installation Evaluation Measure. The function is a linear function that is monotonically decreasing.

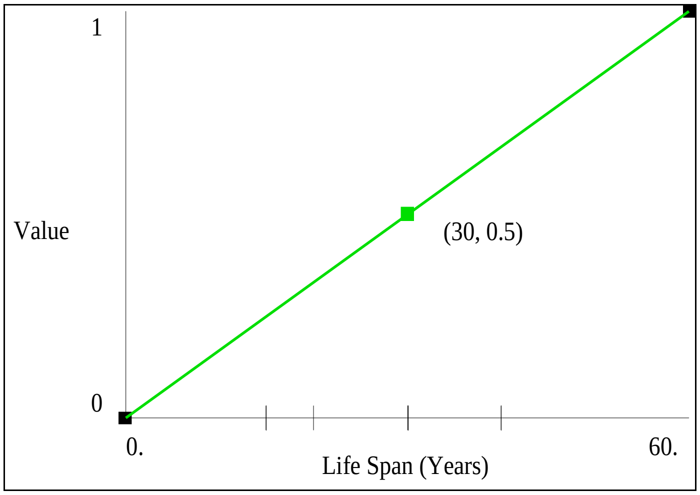

Figure A3. SDVF for Northeast AFB Life Span Evaluation Measure. The function is a linear function that is monotonically increasing.

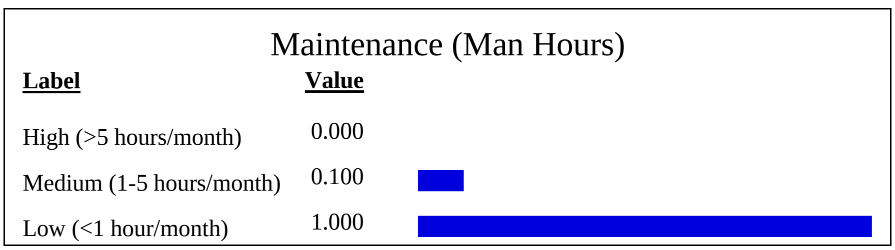

Figure A4. SDVF for Northeast AFB Maintenance Evaluation Measure. The function is discrete and categorical.

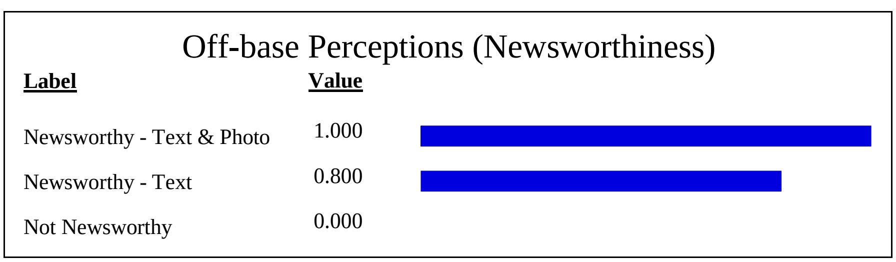

Figure A5. SDVF for Northeast AFB Off-base Perceptions Evaluation Measure. The function is discrete and categorical.

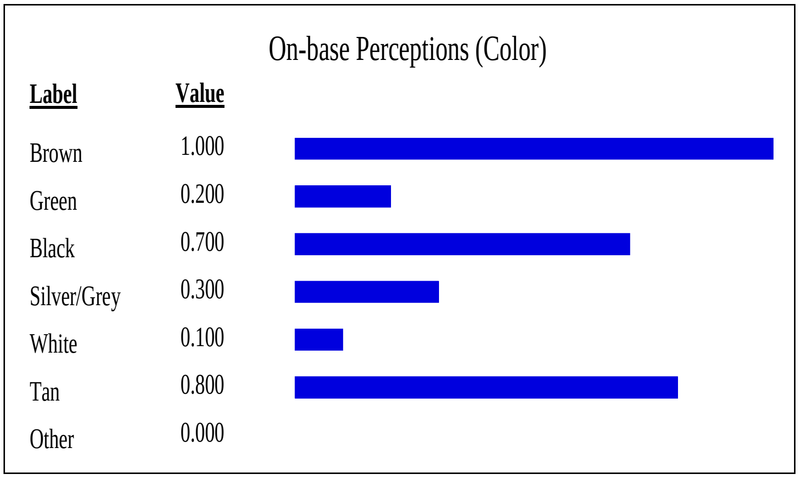

Figure A6. Continuous SDVF for Northeast AFB On-base Perceptions Evaluation Measure. The function is discrete and categorical.

Appendix A (Cont.): SDVFs for All Evaluation Measures

Southeast AFB Evaluation Measures SDVFs

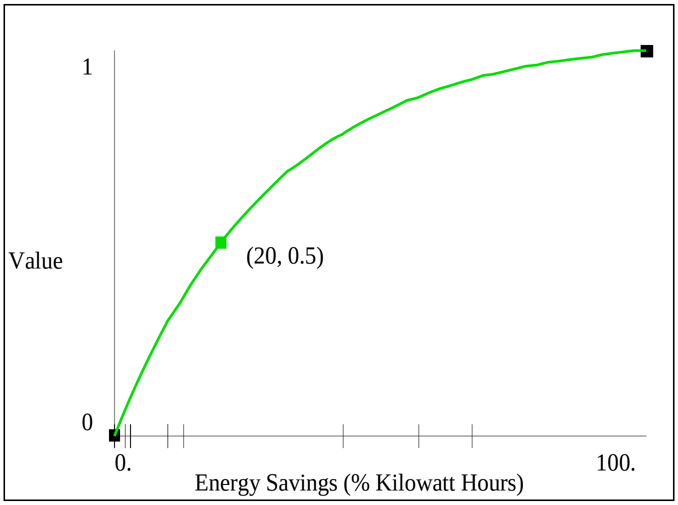

Figure A7. SDVF for Southeast AFB Energy Savings Evaluation Measure. The function is continuous, monotonically increasing, and exponential.

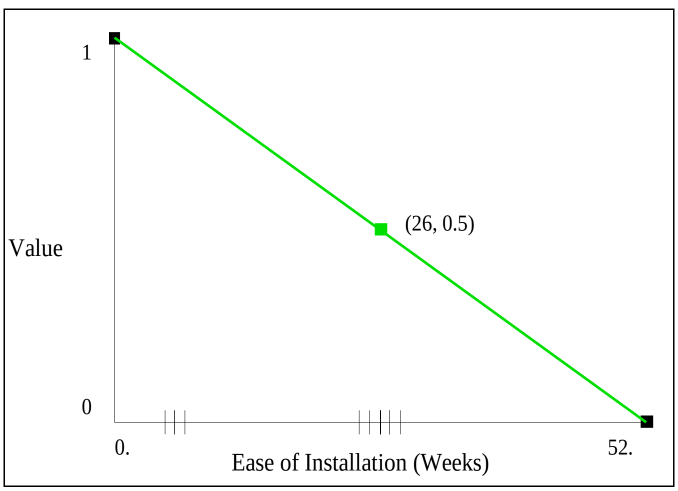

Figure A8. SDVF for Southeast AFB Ease of Installation Evaluation Measure. The continuous function is linear and decreasing.

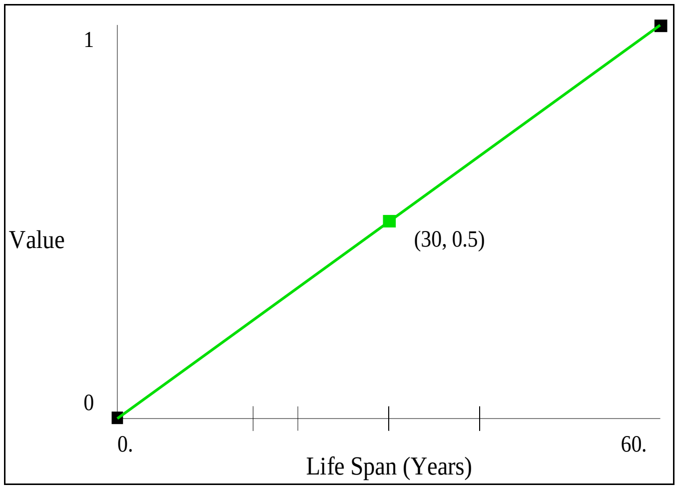

Figure A9. SDVF for Southeast AFB Life Span Evaluation Measure. The function is linear and increasing.

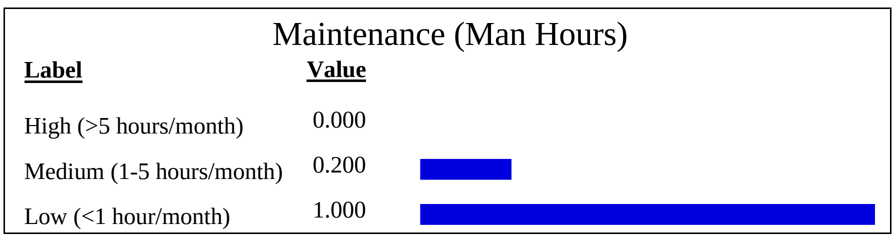

Figure A10. SDVF for Southeast AFB Maintenance Evaluation Measure. This a discrete, categorical function.

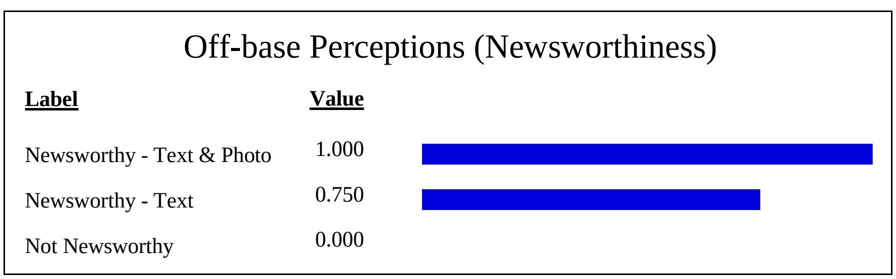

Figure A11. SDVF for Southeast AFB Off-base Perceptions Evaluation Measure. This a discrete, categorical function.

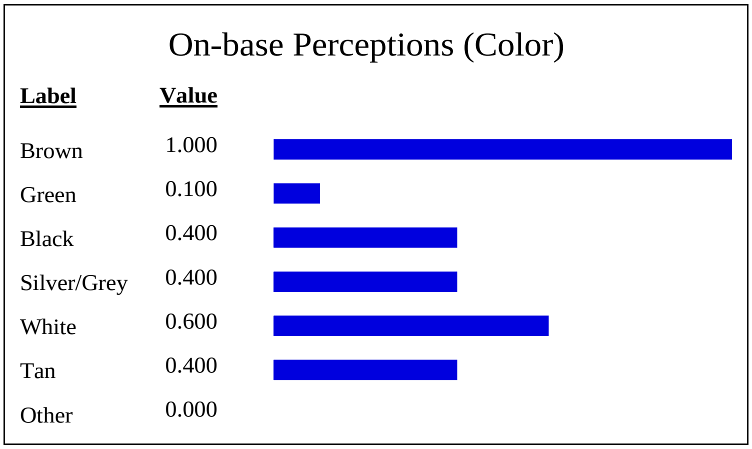

Figure A12. SDVF for Southeast AFB On-base Perceptions Evaluation Measure.
This a discrete, categorical function.

West AFB Evaluation Measure SDVFs

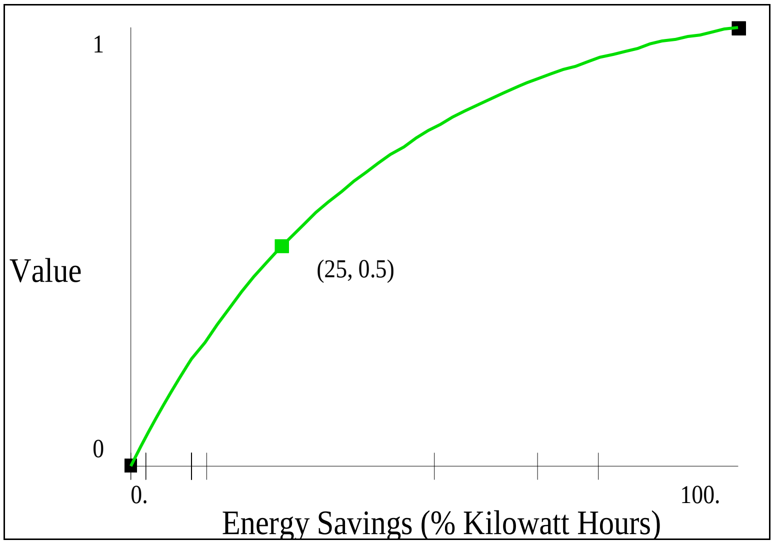

Figure A13. SDVF for West AFB Energy Savings Evaluation Measure. The function is monotonically increasing and exponential.

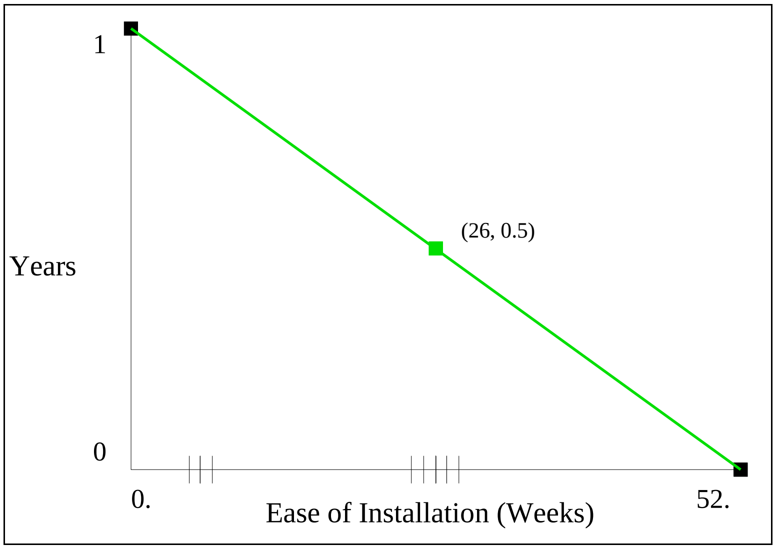

Figure A14. SDVF for West AFB Ease of Installation Evaluation Measure. The continuous function is linear and monotonically decreasing.

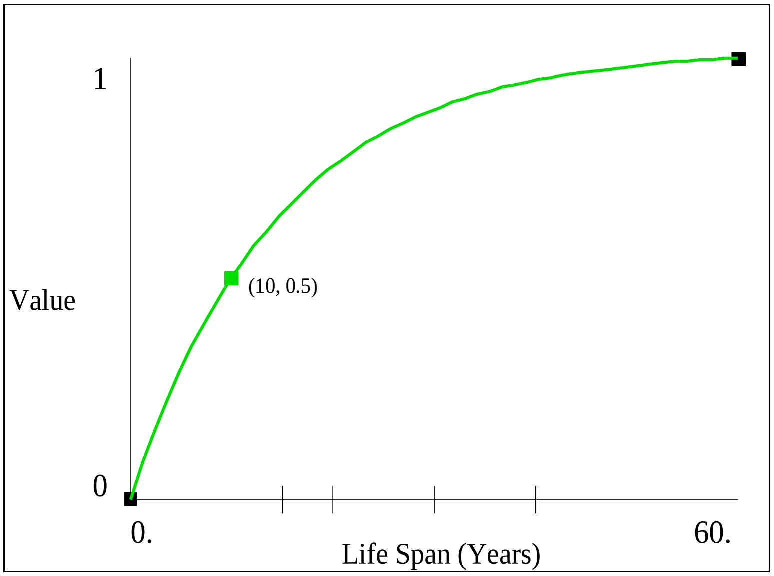

Figure A15. SDVF for West AFB Life Span Evaluation Measure. The continuous function is monotonically increasing and exponential.

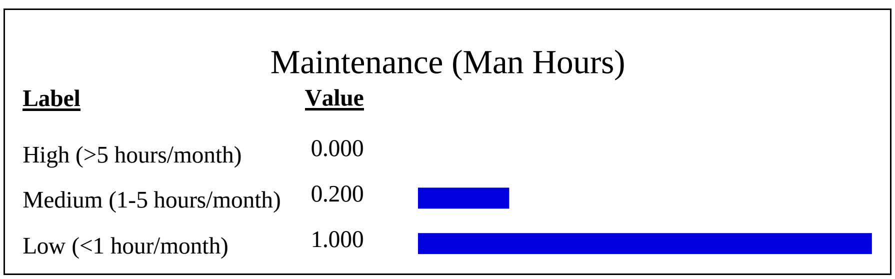

Figure A16. SDVF for West AFB Maintenance Evaluation Measure. This a discrete, categorical function.

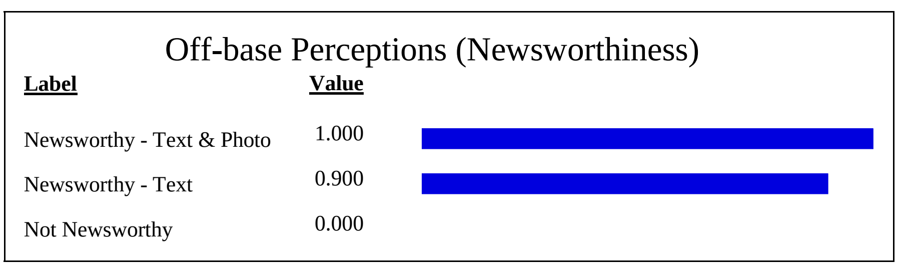

Figure A17. SDVF for West AFB Off-base Perceptions Evaluation Measure. This a discrete, categorical function.

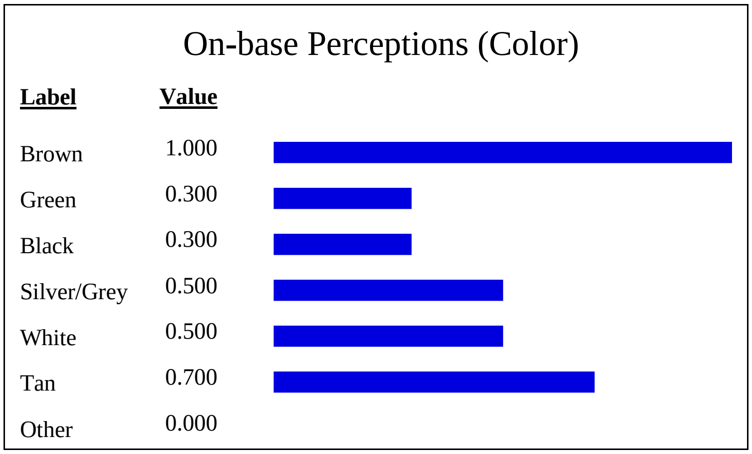

Figure A18. SDVF for West AFB On-base Perceptions Evaluation Measure. This a discrete, categorical function.

Appendix B: Details of an Air Force Generic Facility

Office Building
2-story (2 floors above grade)
25,000 sq ft
Oriented North
Floor to Floor Height: 12 ft.
Floor to Ceiling height: 9 ft.

Roof Construction:
Metal Frame, > 24 in o.c.
3-ply built-up roof
Gravel finish

Setpoints:
Occupied: Cool: 76°F Heat: 70°F
Unoccupied: Cool: 82°F Heat: 64°F

Table B1. Energy Use Per Year (EQuest Simulation)

	Electric (kWh)	Gas (BTU)	Gas (kWh)	Total Energy (kWh)	$/kWh	Total Energy ($)
BUR NE	240410	311330000	91219.69	331629.69	0.1111	$36,844.06
BUR SE	269750	81620000	23914.66	293664.66	0.0715	$20,997.02
BUR W	307640	33100000	9698.30	317338.30	0.0913	$28,972.99
SSMR NE	239190	323650000	94829.45	334019.45	0.1111	$37,109.56
SSMR SE	268120	86240000	25268.32	293388.32	0.0715	$20,977.26
SSMR W	305830	33580000	9838.94	315668.94	0.0913	$28,820.57

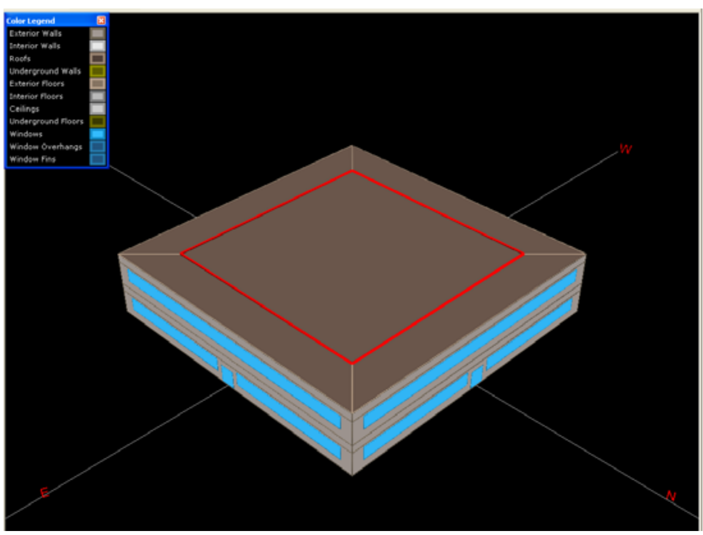

Figure B1. Generic Air Force Facility

Appendix C: Raw Data for Evaluation Measures

Table C1. Raw Data for Alternatives at Northeast AFB.

Alternatives	Color	Ease of Installation (Weeks)	Energy Savings (% Per Year)	Man Hours (High, Med, Low)	Newsworthiness (No, Yes w/Pic, Yes wo/Pic)	Life Span (Years)
BUR	Tan	5	0	Med	No	15
BUR w/Cool Roof Coating	White	6	2	Med	Yes wo/Pic	20
BUR w/Solar Panels	Black	7	47.4	Med	Yes w/Pic	15
BUR w/Solar Thermal System	Black	6	3	Med	Yes w/Pic	15
Green Roof Extensive	Green	24	10	High	Yes w/Pic	40
Green Roof Extensive w/Solar Panels	Green	26	57.4	High	Yes w/Pic	40
Green Roof Extensive w/Solar Thermal System	Green	25	13	High	Yes w/Pic	40
Green Roof Intensive	Green	26	10	High	Yes w/Pic	40
Standing Seam Metal Roof	Brown	26	0	Low	No	30
SSMR w/Cool Roof Coating	White	27	2	Low	Yes wo/Pic	30
SSMR w/Solar Panels	Black	28	35.5	Low	Yes w/Pic	30
SSMR w/Solar Thermal System	Brown	27	3	Low	Yes w/Pic	30

Table C2. Raw Data for Alternatives at Southeast AFB.

Alternatives	Color	Ease of Installation (Weeks)	Energy Savings (% Per Year)	Man Hours (High, Med, Low)	Newsworthiness (No, Yes w/Pic, Yes wo/Pic)	Life Span (Years)
BUR	Tan	5	0	Med	No	15
BUR w/Cool Roof Coating	White	6	2	Med	Yes wo/Pic	20
BUR w/Solar Panels	Black	7	57.4	Med	Yes w/Pic	15
BUR w/Solar Thermal System	Black	6	3	Med	Yes w/Pic	15
Green Roof Extensive	Green	24	10	High	Yes w/Pic	40
Green Roof Extensive w/Solar Panels	Green	26	67.4	High	Yes w/Pic	40
Green Roof Extensive w/Solar Thermal System	Green	25	13	High	Yes w/Pic	40
Green Roof Intensive	Green	26	10	High	Yes w/Pic	40
Standing Seam Metal Roof	Brown	26	0	Low	No	30
SSMR w/Cool Roof Coating	White	27	2	Low	Yes wo/Pic	30
SSMR w/Solar Panels	Black	28	43.1	Low	Yes w/Pic	30
SSMR w/Solar Thermal System	Brown	27	3	Low	Yes w/Pic	30

Table C3. Raw Data for Alternatives at West AFB.

Alternatives	Color	Ease of Installation (Weeks)	Energy Savings (% Per Year)	Man Hours (High, Med, Low)	Newsworthiness (No, Yes w/Pic, Yes wo/Pic)	Life Span (Years)
BUR	Tan	5	0	Med	No	15
BUR w/Cool Roof Coating	White	6	10	Med	Yes wo/Pic	20
BUR w/Solar Panels	Black	7	67	Med	Yes w/Pic	15
BUR w/Solar Thermal System	Black	6	2.5	Med	Yes w/Pic	15
Green Roof Extensive	Green	24	10	High	Yes w/Pic	40
Green Roof Extensive w/Solar Panels	Green	26	77	High	Yes w/Pic	40
Green Roof Extensive w/Solar Thermal System	Green	25	12.5	High	Yes w/Pic	40
Green Roof Intensive	Green	26	10	High	Yes w/Pic	40
Standing Seam Metal Roof	Brown	26	0	Low	No	30
SSMR w/Cool Roof Coating	White	27	10	Low	Yes wo/Pic	30
SSMR w/Solar Panels	Black	28	50.2	Low	Yes w/Pic	30
SSMR w/Solar Thermal System	Brown	27	2.5	Low	Yes w/Pic	30

Appendix D: Cost Data

Table D1. Installation Cost with Cost Factors.

Alternative	Cost ($)	Location Cost Factor NE	Cost NE ($)	Location Cost Factor SE	Cost SE ($)	Location Cost Factor W	Cost W ($)
BUR	$35,000.00	1.098	$38,430.00	0.75	$26,250.00	0.876	$30,660.00
BUR w/Cool Roof Coating	$53,750.00	1.098	$59,017.50	0.75	$40,312.50	0.876	$47,085.00
BUR w/Solar Panels	$785,000.00	1.098	$861,930.00	0.75	$588,750.00	0.876	$687,660.00
BUR w/Solar Thermal System	$50,000.00	1.098	$54,900.00	0.75	$37,500.00	0.876	$43,800.00
Green Roof Extensive	$187,500.00	1.098	$205,875.00	0.75	$140,625.00	0.876	$164,250.00
Green Roof Extensive w/Solar Panels	$937,500.00	1.098	$1,029,375.00	0.75	$703,125.00	0.876	$821,250.00
Green Roof Extensive w/Solar Thermal System	$202,500.00	1.098	$222,345.00	0.75	$151,875.00	0.876	$177,390.00
Green Roof Intensive	$335,625.00	1.098	$368,516.25	0.75	$251,718.75	0.876	$294,007.50
Standing Seam Metal Roof	$100,000.00	1.098	$109,800.00	0.75	$75,000.00	0.876	$87,600.00
SSMR w/Cool Roof Coating	$118,750.00	1.098	$130,387.50	0.75	$89,062.50	0.876	$104,025.00
SSMR w/Solar Panels	$850,000.00	1.098	$933,300.00	0.75	$637,500.00	0.876	$744,600.00
SSMR w/Solar Thermal System	$115,000.00	1.098	$126,270.00	0.75	$86,250.00	0.876	$100,740.00

Table D2. Cost Calculations for Northeast AFB.

Alternatives	Life Span (Years)	Energy Savings (% Per Year)	Energy Savings (kWh Per Year)	Energy Savings ($ Per Year)	Installation Cost ($)	Payback Period (Years)	Alternative VFT Score	Cost Value Ratio (Value vs $)
BUR	15	0	0	$0.00	$38,430.00	0	0.258	0.67
BUR w/Cool Roof Coating	20	2	6633	$736.88	$59,017.50	80	0.247	0.42
BUR w/Solar Panels	15	47.4	157192	$17,464.08	$861,930.00	49	0.331	0.04
BUR w/Solar Thermal System	15	3	9949	$1,105.32	$54,900.00	50	0.297	0.54
Green Roof Extensive	40	10	33163	$3,684.41	$205,875.00	56	0.294	0.14
Green Roof Extensive w/Solar Panels	40	57.4	190355	$21,148.49	$1,029,375.00	49	0.341	0.03
Green Roof Extensive w/Solar Thermal System	40	13	43112	$4,789.73	$222,345.00	46	0.294	0.13
Green Roof Intensive	40	10	33163	$3,684.41	$368,516.25	100	0.290	0.08
Standing Seam Metal Roof	30	0	0	$0.00	$109,800.00	0	0.525	0.48
SSMR w/Cool Roof Coating	30	2	6633	$736.88	$130,387.50	177	0.474	0.36
SSMR w/Solar Panels	30	35.5	117729	$13,079.64	$933,300.00	71	0.563	0.06
SSMR w/Solar Thermal System	30	3	9949	$1,105.32	$126,270.00	114	0.574	0.45

Table D3. Cost Calculation for Southeast AFB.

Alternatives	Life Span (Years)	Energy Savings (% Per Year)	Energy Savings (kWh Per Year)	Energy Savings ($ Per Year)	Installation Cost ($)	Payback Period (Years)	Alternative VFT Score	Cost Value Ratio (Value vs $)
BUR	15	0	0	$0.00	$26,250.00	0	0.240	0.91
BUR w/Cool Roof Coating	20	2	5873	$419.94	$40,312.50	96	0.342	0.85
BUR w/Solar Panels	15	57.4	168564	$12,052.29	$588,750.00	49	0.551	0.09
BUR w/Solar Thermal System	15	3	8810	$629.91	$37,500.00	60	0.318	0.85
Green Roof Extensive	40	10	29366	$2,099.70	$140,625.00	67	0.339	0.24
Green Roof Extensive w/Solar Panels	40	67.4	197930	$14,151.99	$703,125.00	50	0.526	0.07
Green Roof Extensive w/Solar Thermal System	40	13	38176	$2,729.61	$151,875.00	56	0.359	0.24
Green Roof Intensive	40	10	29366	$2,099.70	$251,718.75	120	0.336	0.13
Standing Seam Metal Roof	30	0	0	$0.00	$75,000.00	0	0.500	0.67
SSMR w/Cool Roof Coating	30	2	5873	$419.94	$89,062.50	212	0.495	0.56
SSMR w/Solar Panels	30	43.1	126569	$9,049.72	$637,500.00	70	0.692	0.11
SSMR w/Solar Thermal System	30	3	8810	$629.91	$86,250.00	137	0.577	0.67

Table D4. Cost Calculation for Northeast AFB.

Alternatives	Life Span (Years)	Energy Savings (% Per Year)	Energy Savings (kWh Per Year)	Energy Savings ($ Per Year)	Installation Cost ($)	Payback Period (Years)	Alternative VFT Score	Cost Value Ratio (Value vs $)
BUR	15	0	0	$0.00	$30,660.00	0	0.448	1.46
BUR w/Cool Roof Coating	20	10	31734	$2,897.30	$47,085.00	16	0.585	1.24
BUR w/Solar Panels	15	67	212617	$19,411.90	$687,660.00	35	0.610	0.09
BUR w/Solar Thermal System	15	2.5	7933	$724.32	$43,800.00	60	0.531	1.21
Green Roof Extensive	40	10	31734	$2,897.30	$164,250.00	57	0.552	0.34
Green Roof Extensive w/Solar Panels	40	77	244350	$22,309.20	$821,250.00	37	0.554	0.07
Green Roof Extensive w/Solar Thermal System	40	12.5	39667	$3,621.62	$177,390.00	49	0.554	0.31
Green Roof Intensive	40	10	31734	$2,897.30	$294,007.50	101	0.546	0.19
Standing Seam Metal Roof	30	0	0	$0.00	$87,600.00	0	0.684	0.78
SSMR w/Cool Roof Coating	30	10	31734	$2,897.30	$104,025.00	36	0.770	0.74
SSMR w/Solar Panels	30	50.2	159304	$14,544.44	$744,600.00	51	0.821	0.11
SSMR w/Solar Thermal System	30	2.5	7933	$724.32	$100,740.00	139	0.788	0.78

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Vita

Captain Michael J. McCourt graduated from Gibson City High School in Gibson City, Illinois. He entered undergraduate studies at the University of Illinois in Champaign, Illinois where he graduated with a Bachelor of Science degree in Mechanical Engineering in May 1999. He was commissioned through Officer Training School at Maxwell AFB in April 2002.

His first assignment was with the 89th Civil Engineering Squadron at Andrews AFB. There he served as a project manager, as well as the chief of programming. He deployed to Kirkuk, Iraq in support of Operation Iraqi Freedom in November 2003 and served as a project engineer with the 506th Expeditionary Civil Engineering Squadron. In August 2005, Capt McCourt entered the Graduate School of Engineering and Management, Air Force Institute of Technology, Wright Patterson AFB, Ohio. Upon graduation Capt McCourt will be assigned to the Air Force Center for Environmental Excellence.

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14. ABSTRACT

The Air Force has a large inventory of low-sloping built up roofs (BURs) and millions of dollars are spent each year retrofitting these systems. The DOD has been directed to reduce non-renewable energy consumption by using energy-efficient technologies. These two details present a great opportunity to use the open roof space to install energy-efficient roofing technologies. The purpose of this research is to provide Air Force decision makers with a tool to assist them in deciding what roofing technologies should be installed on facilities. Value Focused-Thinking is the methodology used to construct the model, in which values were used, instead of alternatives, to create the model. Data was collected from three different Air Force bases and values from three different Air Force Base Civil Engineers were used to evaluate the alternatives. The results show that based on current technologies these decision makers would be best served to retrofit BURs with standing seam metal roofs with some energy-efficient technologies added.

15. SUBJECT TERMS

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