# VALUE FOCUSED THINKING ANALYSIS OF C-BAND AUSTRALIA RADAR OPERATIONS

THESIS

Samuel Ray Grothman, Captain, USSF

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Samuel Ray Grothman, BS

Captain, USSF

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Samuel Ray Grothman, BS

Captain, USSF

Committee Membership:

Alfred E. Thal, Jr., PhD
Chair

Brent T. Langhals, PhD
Member

Jonathan D. Ritschel, PhD
Member

Edward D. White III, PhD
Member

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## Abstract

The radars used for Space Domain Awareness (SDA) are inherently all-weather, day/night sensors capable of around the clock operations. Despite this fact, some radars are operated for fewer than their maximum operating capabilities. The decision-making process for selecting the operating hours of a sensor has historically been based on only a few factors or just one. This research uses the techniques in Value Focused Thinking to develop an evaluation process to score possible alternatives and find the alternative with the most value for the decision maker. By investigating the value that is added by operating an SDA radar, it is possible to create a quantitative evaluation process for determining the most efficient operating schedule for an SDA radar that maximizes benefits to users while minimizing operating costs. In this research, a specific radar is used for the development of this technique. By evaluating the C-Band Australia radar, located in Exmouth, Western Australia, the research found that the quantity of data produced by the radar was the most valuable aspect of the radar and minimizing the hours out of mission per day (i.e., downtime) is the best alternative. The analysis in this research explored the trade-offs between added benefits of operating hours with the additional costs those additional hours will incur. As a result, a recommendation for 24/7 operations was produced and a methodology for evaluating other SDA radars was created.

*To my family, especially my wife, for giving me the encouragement needed to complete this journey.*

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Ray Grothman, Captain

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# VALUE FOCUSED THINKING ANALYSIS OF C-BAND AUSTRALIA RADAR OPERATIONS

## I. Introduction

While the volume of space around the earth is large, every year it gets more crowded. In 1957, there were only two orbiting satellites: Sputnik 1 and the upper stage for the Sputnik rocket. Since then, the list of objects in orbit has grown to over 500,000 satellites and debris larger than 1 cm (Liou et al., 2020). As an example, the space launch provider and satellite manufacturer, SpaceX, launches approximately 60 new satellites about every two weeks (Thompson, 2020). Most of these launches, as well as those from other launch providers, are non-threatening, commercial satellites; however, this is not always the case. Space is a warfighting domain and it has been for many years. The current Chief of Space Operation, General Raymond, and others have described the contested nature of space for years (Agrawal & Brooks, 2022). To understand this domain, the United States Space Force (USSF) is charged with the task of monitoring the environment. This research investigates the value that this monitoring provides and how the operating hours of a sensor can be modified to maximize that value.

### Background

Modern countries continue to increase their reliance on space. This includes using space for communications, science and technology development, weather prediction and monitoring, and military intelligence. Because of the increasing dependency on space, the United States (U.S.) developed a network of sensors, called the

Space Surveillance Network (SSN), to continuously monitor satellites in orbit around the earth. The mission of the SSN is to continuously update the catalog of all objects in orbit. This includes space debris, spent rocket bodies, non-functioning satellites, and functional satellites. Knowing what these objects are and identifying their orbits is vital to the successful utilization of the space environment (Raymond, 2020). In the situation of debris, the U.S. needs to know if the flight path and destination of a new satellite is clear or if an existing satellite is in danger of colliding with an object. The U.S. also uses this catalog to verify that the information other countries provide is correct or to discover the purpose of a new object and where it is going when no information is provided (J. Hrovat, personal communication, July 14, 2021). For example, an adversary may publicly announce the launch of a single satellite into a particular orbit but secretly deploy an additional satellite into another orbit. Without the updated information provided by the SSN, the existence of the secret satellite might not be discovered. Finally, maintaining Space Situational Awareness (SSA) improves military readiness by discovering and monitoring foreign military/intelligence satellites. SSA also protects U.S. space assets by tracking the orbits of all objects large enough to cause damage (Graham & Bocquet, 2013). Over the last 20 years, the space environment shifted from a benign environment to a contested environment; with this shift, it has become known as a warfighting domain. As a result, the concept of SSA has transformed into Space Domain Awareness (SDA) and changed its purpose from a basic monitoring role to a tactical warfighting role (Agrawal & Brooks, 2022).

Satellites are very expensive to build, launch, and operate. A large communications satellite for a commercial company costs approximately $150 million to build, then launch costs are in the 10s of millions of dollars, and finally there is the cost to operate the satellite each year (GlobalCom, 2019). All of this leads to an expensive operation but with a large reward. In 2007, it was estimated that space-related business was valued at over $110 billion worldwide with the value increasing (OECD, 2007). On the military side, a major satellite acquisition such as the Advanced Extremely High Frequency (AEHF) cost approximately $850 million per satellite, with every launch costing in excess of $200 million (GlobalCom, 2019). There are also the missions that are enabled by satellites such as remotely piloted aircraft operations, and there is the intelligence that is gathered by satellites. All of these satellites require protection; specifically, protection from accidental collisions with debris and protection from deliberate attacks. The SDA data collected by the electro-optical and radar sensors of the SSN provides the information needed to enable both the space industry and the military use of space.

As of 2013, United States Strategic Command tracks over 500,000 space objects, including operational and defunct satellites and pieces of debris (Liou et al., 2020). Since these objects pose a collision risk, the U.S. deployed the SSN with over 25 sensors worldwide to provide the coverage and the timeliness needed for SDA. Since the 1960s, the Air Force has been adding new sensors and modernizing old sensors to accomplish this mission. These sensors are generally divided into two groups: ground-based electro-optical (EO) sensors and ground-based radar sensors (Baird, 2013). In recent years, a third group was created: space-based EO sensors. The space-based EO sensors are orbiting satellites with telescopes that track other satellites. Both types of EO sensors have excellent capabilities with low operating costs and fast search abilities but rely on the sun to illuminate their targets. This limits when they are able to operate. Ground-based EO is limited to operations on clear nights and space-based EO cannot point too close to the sun or risk being blinded. Having these limitations presents an opportunity for adversaries to plan around these times. In order to cover these limitations, more expensive ground-based radars are used.

Radar sensors have the advantage of day and night operations and can operate during all but the most extreme weather conditions. In 2015, the utility of radars was compared to optical systems and the radar outperformed in all areas of investigation (Graham, 2015). These radar sensors may be further divided into two sub-groups: mechanical radars and phased array radars. Mechanical radars have a large dish that is pointed at a single object at a time. Phased array radars use an array of hundreds or thousands of small radar transmitters and receivers that work together to track many objects simultaneously. While the purchase price and complexity of a phased array radar is decreasing, it is still significantly more expensive than a mechanical radar (Baird, 2013).

One of the newest sensors in the SSN is the C-Band Australia radar. This is an older mechanical radar that was initially located in Western Australia to track Apollo missions on their way to and from the moon. At the conclusion of the Apollo program, the radar was dismantled and placed into storage until 2004 when it was reassembled on the island of Antigua to track launches out of Cape Canaveral, Florida. Then in 2013, the radar was dismantled again and shipped back to Western Australia with a new mission to support SDA. At this new location, the C-Band Australia radar is the only SSN sensor in a 3,000-mile radius and provides coverage to what was previously a blind spot in surveillance.  Early analysis of the radar's performance was conducted by Graham (2013), before the relocation, and found the radar to be effective at detecting 1 square meter objects in Low Earth Orbit (LOE), which is the approximate size of most LEO payloads (Graham & Bocquet, 2013).

This sensor also represents a joint partnership with the Australian military.  The U.S. paid for the radar and the relocation, but the operating cost is shared between the two countries.  This allows Australia to enter the SDA arena without requiring the large initial investment of designing and building a sensor.  The U.S. benefits by having a sensor in a region lacking any SDA coverage.  Additionally, the radar is operated by Australian military members, thereby keeping the training and manning burden on the U.S. low.

Unfortunately, this radar is at a significant disadvantage compared to other radars. While the C-Band Australia radar is technically capable of operating 24/7 and in all weather conditions, operations are currently limited to about 9.5 hours per day.  Initially, this was to reduce the expenses for the Australian military as they stood up their new space operations unit.  Since that time, the space environment has changed and the Australian military has changed.  After 3 years of operations, the Australian space operations unit is now larger and is no longer a novice at the mission.  These experienced members can conduct the mission while also training new members to operate the system.  As new members are trained, they further increase the size and overall ability of the unit.  For this reason, the need to limit the workload of the operational unit is no longer necessary and it is time to increase the number of operating hours for the system.

While the C-Band Australia radar is continuing to increase its usefulness, it is still an old sensor and there is a limit to its potential. The same is true for many of the other SSN sensors. For this reason, the SSN is constantly growing with the C-Band Australia radar becoming operational in 2017; a large phased array radar, called Space Fence, was added in 2020; a ground-based EO sensor, called Space Surveillance Telescope, will come online in 2022; and more radars will be deployed in the coming years. All of these sensors provide advanced capabilities but at a high price tag. Most new SSN sensors cost hundreds of millions of dollars and, in the case of Space Fence, the cost was over $1 billion (Whalley, 2015). This price was justified since the data is vitally important and there was no other option. In recent years, however, commercial companies have started providing tracking data to satellite operators, which represents an alternative to USSF-developed sensors. These companies use ground-based radars and telescopes in the same way as the SSN sensors and get compensated on a per observation basis (Sullivan et al., 2012).

To find the ideal operating hours for the C-Band Australia radar, identifying the value of the radar system is needed. In the case of the C-Band Australia radar, the high-level considerations for value are the operating hours, the timing of the operating hours, and the hardware health. The number of daily operating hours impacts the quantity of data the system can produce as well as impact the staffing for the operator and maintainers. Timing of the operational day will have different impacts on the staffing, and hardware health will have operational availability and long-term supportability implications. By breaking down the values for the SDA mission, decision-makers will have insight into operational tradeoffs for the radar. No published works consolidate the values for an SDA system.  Instead, most existing research focuses on the overall SDA enterprise which is useful for higher level decisions that impact the overarching architecture but there is also a need to make value-based decision at the individual sensor level.

Why are most radars expected to be 24/7 systems and why is the C-Band Australia radar different?  SDA is a 24/7 mission and, on the surface, it makes sense that all the sensors should also be 24/7.  Unfortunately, radars do not operate truly uninterrupted.  There is always some amount of time when a given radar or other sensor is unavailable.  For telescopes, that downtime is dictated by nighttime hours and cloud cover.  For most radars, the systems operate 24/7 and downtime is the result of planned maintenance.  However, this is not the case with the C-Band Australia radar.  Based on a Memorandum of Understanding between the U.S. and Australia, it currently operates less than 12 hours per day even though it has a dedicated SDA mission.  SDA has many applications and the space environment is constantly changing, which drives a need to constantly monitor the space environment.  The C-Band Australia radar has the all-weather, day/night capability inherent to a radar, but its utility is limited because of its limited operating hours.  There are alternatives to the current operating hours.  These hours are combinations of increasing operating hours, shifting when the radar operates during each day, and having one or more operational periods per day.  All these changes impact the radar’s value and costs.

## Problem Statement

Additional useful information for users can be generated; however, this would entail a corresponding increase in costs to run the radar. As a result, the problem becomes finding the most efficient operating schedule for the C-Band Australia radar that maximizes benefits to users while minimizing operating costs. Assessing potential alternatives using quantifiable metrics will find a suitable answer to the above problem statement. By using quantifiable metrics, alternatives can be assessed.

## Research Objectives

This research will not simply increase the radar's operating hours from less than 12 hours per day to 24/7 operations. Instead, this research will evaluate a broad set of potential alternatives to balance the increases to the radar's utility and the increased costs. Therefore, the research objective can be stated as: Determine the operating schedule for the C-Band Australia radar that maximizes the system's value for the decision-maker. To address this research objective, the following investigative questions were addressed.

1. What are the specific values that address the decision-maker's objectives for the radar?
2. What are the possible alternatives to the existing C-Band Australia radar operational schedule?
3. Which schedule alternatives produce the most value?

## Methodology

To conduct this research, a decision analysis methodology for comparing alternatives was necessary. The methodology selected for this research was the Value Focused Thinking (VFT) process, which identifies what the decision-maker values when evaluating the alternatives to a problem (Keeney, 1992). Applied to this research, it must be determined what the decision-makers value regarding the C-Band Australia radar. This radar system has multiple organizations that depend on its output, with each organization having different opinions on what is valued. The first organization to consider is the program office, which is primarily focused on the sustainment of the radar. Their values will capture ways to minimize depot costs while maximizing long-term hardware health. Then next organization interested in the C-Band Australia radar is the user of the radar data, the Combined Space Operations Center (CSpOC) at Vandenberg Space Force Base. These users value quantity of data and timeliness of the data above all other factors. Finally, there is the Australian program office responsible for operating the radar and the contractors maintaining the radar. Based on their published responsibilities and the missions they support; they value the timing of when the system is operating and how that impacts the staffing requirements for the system. The values for the specific organizations are further refined by reviewing published Air Force and Space Force doctrine and decisions made on past, present, and future SDA sensors, as well as correspondence with active users of SDA data.

Once the values are defined with sufficient complexity and depth, they are organized into a hierarchy with the overarching problem statement being broken down into multiple tiers in the hierarchy. Finally, the values reach a level where they cannot be broken down any further and are specific, unique measures (Keeney, 1992). The measure can be scored; however, a raw score between measures is rarely useful. A common example uses characteristics of a truck when buying a new truck. One measure might be fuel economy and another measure might be ground clearance; 19 miles per gallon is not comparable to 17 inches. For this reason, a value function is necessary to create a uniform scale to score the alternatives (Jurk et al., 2004). The final step of the value hierarchy development involves weighting the values and measures (Jurk et al., 2004). This step is necessary because not all measures have the same impact on the final alternative score as other measures. The weights are dependent on the guidance received from the decision-maker or, in the absence of decision-maker inputs, past decision and published guidance can be used to estimate the weights for the decision-maker. This research did not have direct access to the decision-maker and instead relied on alternative sources for input.

Moving on from the hierarchy development, VFT requires alternatives that have the goal of achieving the objective (Keeney, 1992). When developing alternatives for this research, variations on the operating hours were explored. Initially the alternatives are a simple increase in operating hours, then the operational day is broken into multiple shifts in a day, then the operational day shifted to different times in the day. All of these alternatives result in different value scores and seek out different combinations of values to find the combination with the highest possible score.

The final phase of the VFT process scores the alternative, determines the best performing alternatives, and also conducts a sensitivity analysis on the alternatives (Jurk et al., 2004). Using the raw scores for each measure, the weights are applied and a final, overall score is created for each of the alternatives. These are ranked to find the highest performing alternative in the deterministic analysis. Finally, the VFT process concludes with the sensitivity analysis for the ten best alternatives. In many cases, the sensitivity analysis is conducted on all of the alternatives; however, in the case of this research, only the ten highest performing alternatives received the sensitivity analysis. This choice was made to reduce confusion with low scoring alternatives and only focus on the best performing ones. This sensitivity analysis is especially important in this research since the decision-maker was not directly involved in the weighting of the values and measures. The sensitivity analysis provides insight into which alternatives are impacted by changes to value weights and by how much (Jurk et al., 2004). This is useful for evaluating areas of future research and for informing the decision-maker.

### Significance of Study

The sponsor of this research is the Space Domain Awareness Division of the Space and Missiles Systems Center at Peterson Air Force Base, Colorado (SMC/SPG). The insights and recommendations from this research will be presented to the leadership of SMC/SPG. Due to the partnership between the U.S. and Australia with the C-Band Australia radar, the recommendations will also be presented to the Australian program office. Additionally, the leadership of the operational units will be presented with the recommendation for the operational hours of the system. With this information, the leaders of the radar units will be able to make a more informed decision regarding the operating hours of the C-Band Australia radar. It is understood that many factors outside of the factors considered here can dictate policy, especially when coordinating efforts with international partners and considering a global sensor network. The goal of this research is to provide the information necessary to extract the maximum productivity from this system, with the hope that it will outweigh other objections.

## Thesis Overview

The remainder of this thesis will follow the following outline. Chapter II will be a literature review to examine existing research in the area of Value Focused Thinking, operating considerations for radar systems, and the benefits of SDA systems. Since this subject has very limited material, the chapter will also discuss where research is lacking or non-existent. Following the literature review, the details of the methodology will be explored in Chapter III. The first six steps in the VFT process will be developed in the chapter, starting with the identification of the problem and ending with the generation of the alternatives. With the value hierarchy created and the alternatives generated, Chapter IV will continue the VFT process with alternative scoring, deterministic analysis, and the sensitivity analysis. These three steps of the VFT process will constitute the analysis and results portion of the study. The thesis will end with conclusions and recommendations in Chapter V, which will also explore potential future research areas on this subject.

# II.  Literature Review

This chapter covers a selection of other works that support the need for further investigation on this research topic.  The material in this chapter focuses on works that surround but do not completely address the specific research objectives detailed in the previous chapter.  The primary focus areas will be Value Focused Thinking, Cost Considerations, and Radar Performance and Production.  Throughout this chapter, there will be links created between the existing body of research relevant to this research topic and the specific investigative questions.

## Value Focused Thinking

The first investigative question of this research concerns the specific values that address the decision-maker's objectives for the C-Band Australia radar.  This radar is not directly analogous to other systems.  Direct comparisons are difficult and for the most part, non-existent.  This makes it more challenging to evaluate from a cost and benefit perspective.  Fortunately, there are decision-making tools available that have shown success addressing similar problems.  Possibly the most popular of the tools is the Value Focused Thinking (VFT) methodology (Jurk, 2002).  The standard VFT process was popularized by Keeney (1992).  Since then, the methodology has been championed by other researchers and found widespread applications.  Many of these past applications help inform the topics of this research.  VFT requires a deep understanding of what a decision-maker values as an outcome.  When applied to a business, maximizing profits is among the top values.  In the case of the C-Band Australia radar, the U.S. military is not a business and it does not set out to make a profit; therefore, other values must be identified. The mission of the C-Band Australia radar is to provide Space Domain Awareness (SDA) data to the SDA catalog. This is a unique mission applicable to only a few systems in the world but not unique to the point of zero similarities. Parnell et al. (1998) identified the technological research areas needing research and development investment that will provide the most value to the Air Force in 2025. Their study effectively used the VFT principles in the military decision-making process. Additionally, the Parnell et al. (1998) study showed how to find the value of military objectives. This section details past studies on the applications of VFT and how previous researchers defined the concept of value.

### Applications of Value Focused Thinking

As part of the overarching objective of this research, detailed information about the costs to operate and maintain the radar is needed. Program office records are able to provide the information required. The more challenging investigation is the determination of the system's value. The radar is not creating a consumer product. Evaluation of factory up-time and down-time opportunity costs are well defined in literature. The value of SDA data is less quantifiable. In these situations, there are a couple of options to address this problem. When faced with similar decisions, past researchers used the VFT process to evaluate alternatives based on the objective's values.

The primary advocate for VFT has been Keeney (1992). His ten-step VFT process assigned quantifiable evaluation measures to what a decision maker values in order to develop value functions and value models to ultimately make a decision and chose a solution to the original problem. By focusing on what is valued, it is possible to look past what is not value added and arrive at a better solution. The ten-step VFT process flow is shown in Figure 1, and the following paragraphs expand on each step using Jurk et al. (2004) as a source for the process breakdown. The process breakdown will follow a simple problem of selecting a truck to purchase. Another example of a simplified breakdown comes from Keeney (2008) in which he applies the VFT process to a military acquisition program demonstrating the versatility of the VFT process and the applicability to military applications.

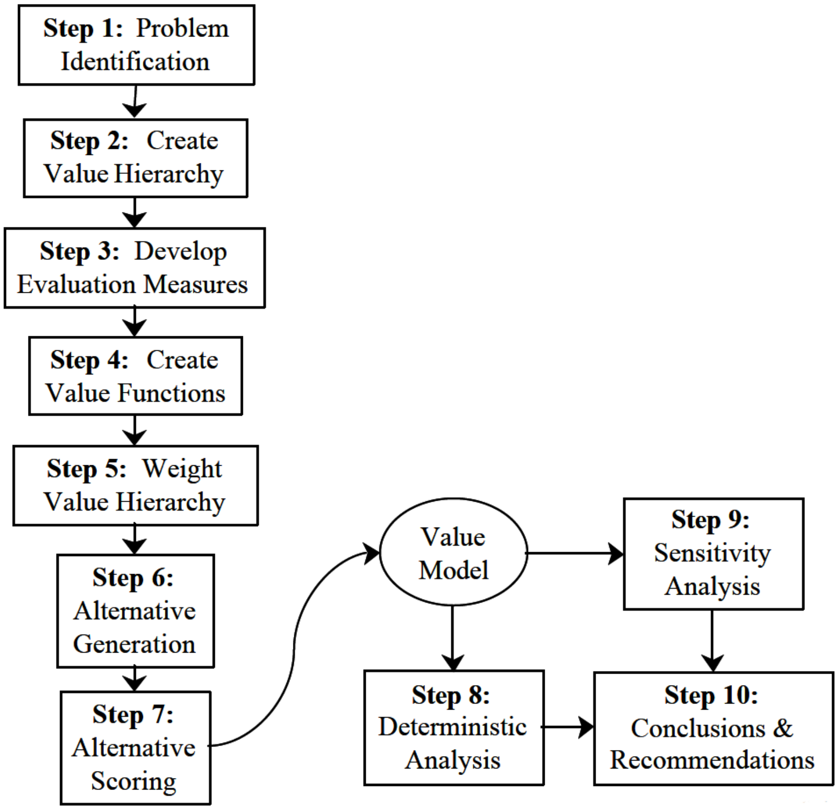


Figure 1. VFT 10-Step Process Flow Chart (Jurk et al., 2004)

The first step in this process is to identify the problem. A relevant decision at the end of the VFT process is only possible if the problem statement is clearly defined. Once a problem is identified, step two constructs the value hierarchy. The value hierarchy can be as simple as a single level or many different levels based on the complexity of the problem being evaluated. In Jurk (2002), a simplified example was used with the fundamental objective of buying the best truck to illustrate the VFT process. This problem resulted in two levels of the hierarchy with the six lowest-level values specifically defining the higher-level values (Figure 2).

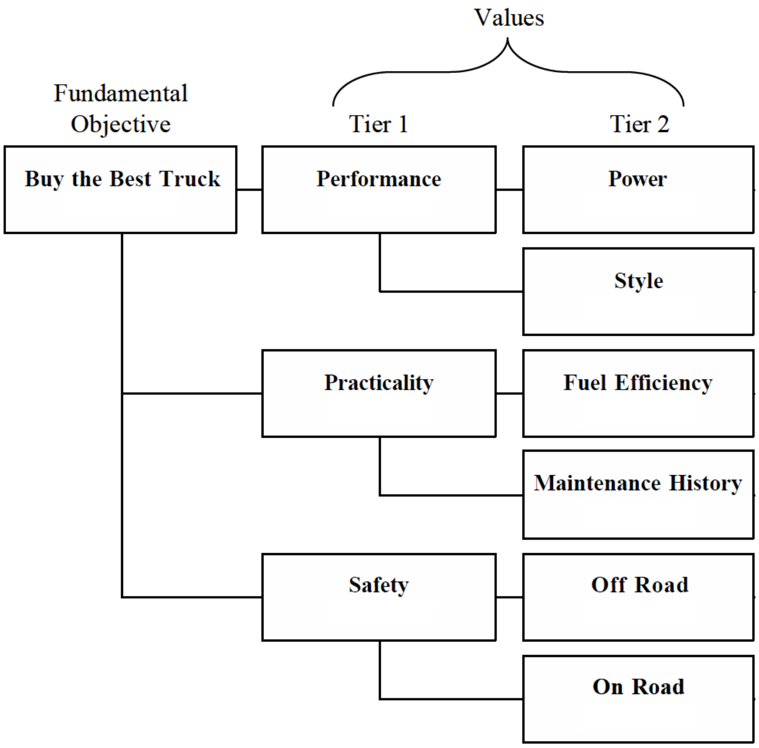


Figure 2. *Buy the Best Truck* Value Hierarchy (Jurk, 2002)

The third step is to develop evaluation measures. These measures must describe how each of the lowest level values performs in an unambiguous way that is clear and relevant to the decision-maker.  While multiple measures for a single value is possible, Jurk (2002) found that the best practice is to use the fewest possible measures per value. He concluded that as more measures are added, the perceived importance of the value increased and created a bias in the decision-making process.  Keeping the measures to a minimum reduces that potential for bias.  Figure 3 expands the Value Hierarchy from Figure 2 to include the measures.  In this example, no value has more than two measures, with one third of the values only being assigned a single measure.

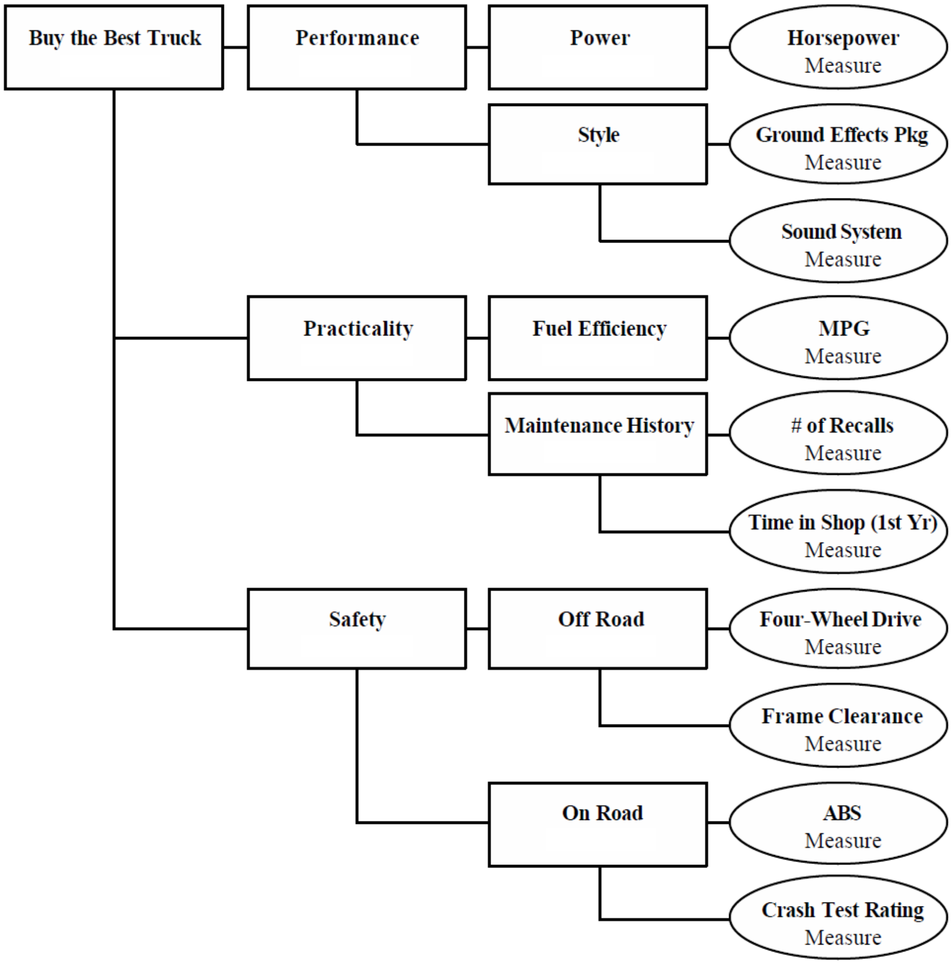


Figure 3.  *Buy the Best Truck* Value Hierarchy with Measures (Jurk, 2002)

In the fourth step of the VFT process, Keeney (1992) converts the output of each measure by creating a value function as a scaling factor.  This scaling factor is a value from 0 to 1 and allows the individual value measures to all be converted to a common scoring unit based on value (Jurk et al., 2004).  This prevents the issue of comparing values with different units (e.g., comparing feet to dollars).  This scaling function also creates separation between the alternatives.  The most desirable alternative would be scaled to a 1 and the least desirable alternative a 0.  Without the scaling factor, the measures are difficult to compare effectively and confuses the decision-maker (Jurk et al., 2004).

Once the scaling factor is applied to each of the measures, step five creates a weight for every value and measure (Keeney, 1992).  By assigning weights to the hierarchy, the decision-maker has control over what is important in the overall decision. It is important to apply the weights correctly with the local weights for each tier within a given branch summing to 1.  Figure 4 continues the development of the value hierarchy by adding the local weights.  This simple example demonstrates how the local weights all sum to 1 within a tier's branch and the measures for each value also sum to 1.  This weighting process is by nature subjective and can only be informed by the decision-maker's preferences.  In order to organize this process, Jurk (2002) recommends a bottom-up, least important first method to guide the decision-maker though the weighting process.  By starting at the lowest level and with the least important measure and working up through the most important measure then progressively through the tiers to the highest-level tier, the decision-maker understands the breakdown of the weighting and the measure's relative importance within a value.

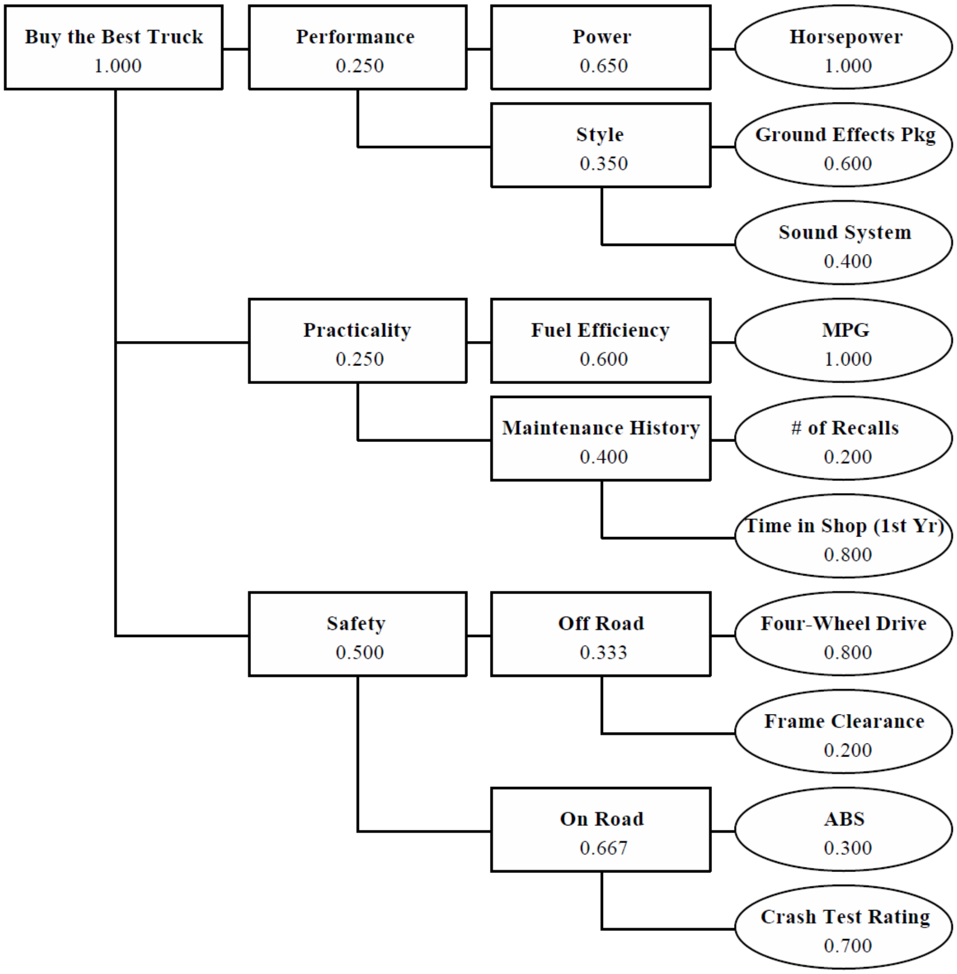


Figure 4. *Buy the Best Truck* Value Hierarchy with Measures and Local Weights (Jurk, 2002)

Before wrapping up step five, global weights must be determined (Keeney, 1992). This is a function of how much the local weights contribute to the originally identified problem. This can only be applied after the local weighting is decided upon by the decision-maker and is a simple process of multiplying the local weights of the higher-level tier. At the end of the global weighting process, the sum of the weights on each tier in the hierarchy will be 1. Figure 5 updates the hierarchy with the global weights.

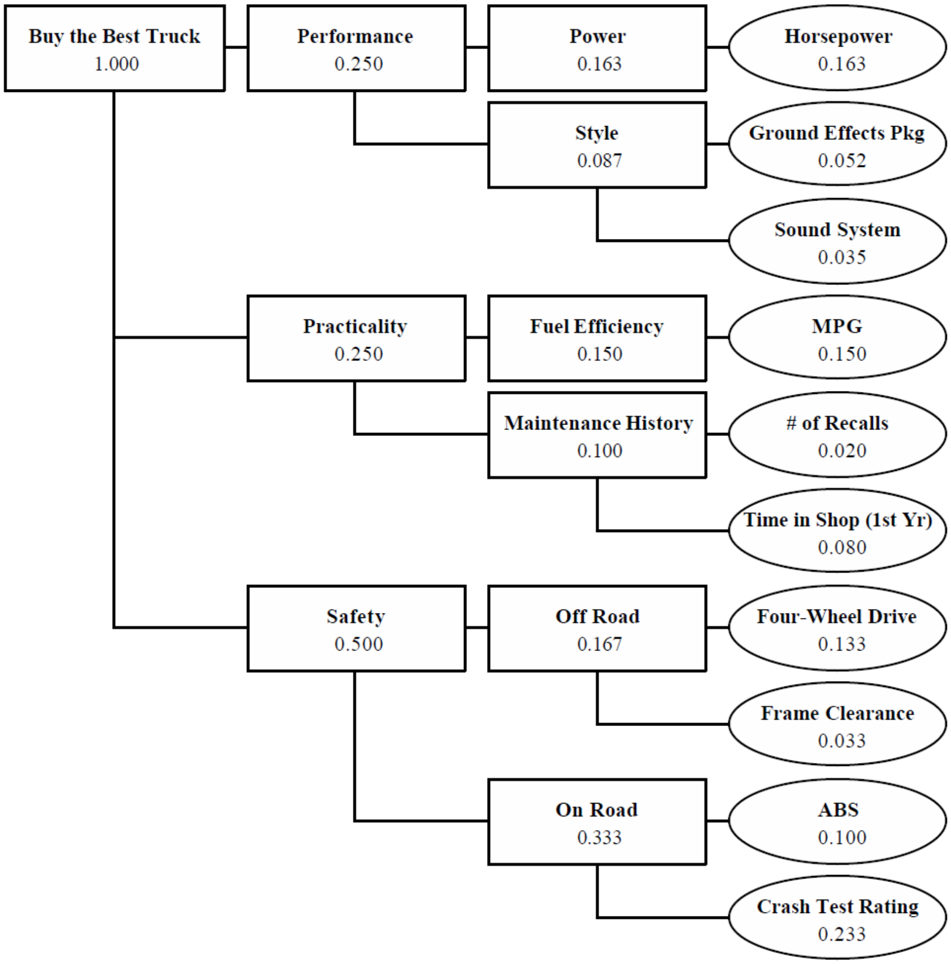


Figure 5. *Buy the Best Truck* Value Hierarchy with Measures and Global Weights (Jurk, 2002)

The first five steps of the VFT process builds the value hierarchy. The VFT process continues with step six, which begins the alternative analysis phase. In step six, multiple alternatives are created with the goal of seeking out as many alternatives as possible. Only the values established earlier should contribute to the development of alternatives (Jurk, 2002). Once the alternatives are identified, they are scored in step seven of the VFT process. The measures created in step three should have been developed such that they are all unambiguous and directly measurable; however, it is important for the scorers to apply their scores with consistency and provide justification for the scores (Jurk, 2002). Step eight is called deterministic analysis and the scores for each measure are calculated according the previously developed hierarchy to find a single value score for every alternative. Sensitivity analysis is then performed on the scored alternatives in step nine of the VFT process and involves adjusting the weights assigned earlier and recording the impacts (Keeney, 1992). The sensitivity analysis shows where changes to the weights will impact the final scores of each alternative and more importantly, it shows how the rank ordering of the alternatives changes and thus indicates if the decision is sensitive to changes in the weights. The final step in the VFT process is to present the findings to the decision-maker who ultimately selects their preferred alternative. Jurk (2002) makes a special effort to emphasize that the VFT does not replace the decision-maker, instead it is a tool that decision-makers have available. With the simple example of a purchasing a truck, the VFT process might be all that is used, but more complex problems will have other factors not capable of being captured in the VFT process, such as political pressures or public opinion that will compete with the VFT findings.

Through both halves of the VFT process, value hierarchy and alternative analysis, identifying value is critically important. In the case of the C-Band Australia radar, the radar produces space surveillance data and currently operates at the maximum of its technological capabilities; therefore, its accuracy and ability to detect space objects will not change. All that can be changed is the quantity of data that it can produce, which is directly related to its operational hours. To better understand this SDA data, the next three sections will take closer look at the value considerations of SDA data.

## Value of SDA Data

Space is a warfighting domain in the same way that land, sea, and air are warfighting domains. The space domain may have spent the first three decades as a peaceful environment free to operate in, through, and from, but this changed quickly in the last ten years (Hitchens, 2021). Adversaries are using space for hostile actions, and most of the major superpowers have tested anti-satellite weapons. With these events and others, the purely peaceful space environment is gone and the warfighting domain was created.

In December of 2019, the United States stood up the Space Force as a separate service to organize, train, and equip the forces needed operate in the space domain. Until the creation of the Space Force, the U.S. Air Force held the responsibility of providing space forces. As such, the Air Force created specific doctrine to address this need. Air Force Doctrine Publication (AFDP) 3-14 (LeMay Center for Doctrine, 2018) provides the stated principles of Air Force policy for Counterspace Operations. Within AFDP 3-14, Space Situational Awareness (SSA) is specifically called out and detailed in a dedicated section. In AFDP 3-14 (2018), the need for SSA is described as foundational and fundamental in support of space operations. The doctrine goes on to breakdown SSA into four functional capabilities: Detect/Track/Identify, Threat Warning and Assessment, Characterization, and Data Integration and Exploitation. The C-Band Australia radar provides three of these four capabilities.

Beyond existing doctrine from the Air Force, the new Space Force is also developing its own doctrine. Currently, this is only a single document but additional documents will be developed with time. The Space Capstone Publication (SCP) places a similar emphasis on SSA (referred to as Space Domain Awareness to emphasize the warfighting nature of space). This document goes beyond the description in AFDP 3-14 and describes how imperative it is to have timely knowledge of all factors and actors (Raymond, 2020). Without this knowledge, continued access to and operations in space will be in jeopardy. At the inter-service level, Joint Publication 3-14 echoes the needs for SDA data when operating in a joint environment (Joint Chiefs of Staff, 2020).

Finally, in a recent interview, Lt Gen Stephen Whiting, Commander of U.S. Space Force Space Operations Command, told a reporter that “we definitely want more sensors” and “we still have more requirements than dollars” (Edwards, 2021). Official doctrine and statements by leadership like this clearly show what is valued in the world of SDA. More data is better, more sensors are better, and timely delivery of the data is required. All these factors drive to additional operating hours from the C-Band Australia radar, but this must be done in a cost-efficient manner.

The previous paragraphs looked at what USSF leadership values from SDA data. The following paragraphs will look at what users of SDA data value. The 18th Space Control Squadron, located at Vandenberg Space Force Base, is responsible for maintaining a catalog of all space objects on behalf of U.S. Space Command and the Combined Force Space Component Command. The users at the 18th Space Control Squadron take the data from the sensors and use that to create and update the space catalog. This catalog and the data that populates it are vital for safely operating in space and for effective military space operations (McKissock et al., 2017). In an email exchange with one of these users, a U.S. Space Force Captain further confirms the need for the data and the value specifically placed on quantity and the timeliness of data (J. Hrovat, personal communication, July 14, 2021). His insight into the day-to-day workings of the 18th Space Control Squadron and the value they place on the data shows the need for more data collection ability. In its current operating schedule, the C-Band Australia radar has the potential to provide that data from an increase in its operating hours.

This represents firsthand knowledge describing the need for more data and timely data. As mentioned at the beginning of this section, the shift in posture from a benign to warfighter domain in space happened recently. As such, there are limited resources available directly related to SDA data. However, other fields of study rely on data in a way similar to how the military relies on SDA data. Therefore, the next two sections look at examples from the weather forecasting community and the value it places on timeliness of data.

### Value of Having More Data

In the previous section, it has been stated over and over again that SDA requires more data. Weather forecasters are asking for the same thing. In the case of weather predictions, forecasters are constantly adding more sensors to collect more data. The website WUnderground.com (2022) states that they rely on a constantly expanding network of personal weather stations, currently with more than 250,000 sites, and thousands of commercial and government sensor sites to forecast the weather. They use the additional data gathered by these personal weather stations to produce more accurate and more frequent weather forecasts.  Similarly, the users of SDA data are requesting more data with more frequent updates (J. Hrovat, personal communication, July 14, 2021).

Beyond the free weather forecast sites, specific investigations show that more data provides better forecasts.  When predicting tornados in Oklahoma and Kansas, Benjamin et al. (2004) used radar wind profilers to detect wind speed and direction at different altitudes.  They showed the value of these sensors in predicting tornados by using standard forecasting tools to create forecasts 3 to 12 hours into the future.  The tools used all the available sensors including the wind profilers.  This forecast was re-created without the wind profiler data.  Even without the wind profiler date, the forecasting tools still had sufficient data sources to create a forecast for the area of interest.  Weather forecasters have many different types of sensors available, and it is easy to think that one more data source would not make a difference.  That was found to not be the case. Benjamin et al. (2004) found that more data was beneficial in refining the accuracy of the forecast.  Their research went as far as recommending an expansion of the wind profiler network to further increase the data sources available to forecasters.  In a similar way, adding more output from the C-Band Australia radar can help refine the predictions and awareness of the space environment.

Existing research supports this need for more SDA data.  By incorporating the dominant data volume factors for SDA data collection, Blake et al. (2014) created an estimate of the total volume of SDA data.  The primary factors in their data volume estimates are bytes per observation/image, number of objects requiring tracking, the frequency that each object must be tracked, a scaling factor to account for accuracy goals, and a scaling factor to capture inefficiencies. Their estimate found that the total SDA network is currently only capable of collecting about 1.5 gigabytes of data per year (Blake et al., 2014). The researchers assess that this is not sufficient to effectively inform leaders for the current SDA environment. The need currently exceeds the SDA network's ability to provide the data by about 10.5 gigabytes (Blake et al., 2014). This can be stated another way by saying that the SDA network needs to produce about 7 times more data to meet the demand.

While data production is one way to illustrate the need for more data, total network collection is not something controllable by the C-Band Australia radar; even an impossible ten-fold increase in that radar's output would not solve the data shortfall discovered by Blake et al. (2014). The shortfall is primarily in the revisit rate of the network. Currently, active satellites are only tracked about once every 3 days, whereas the current need is for daily tracking of all active satellites. By providing the network with additional hours from the C-Band Australia radar, the network can get closer to meeting that data need. By looking out into the future, there will be more satellites and a greater need for awareness. This drives the data requirement up to 30 gigabytes of data per year, further stressing the network (Blake et al., 2014).

### Value of Timely Data

While it is clear that more data is useful, there is also a timeliness factor associated with the data. An SDA sensor that tracks every speck of debris in orbit for one hour would create a tremendous amount of data, but if that data is followed by 23 hours of no data production, then the sensor losses value overall. In other words, a regular stream of data becomes a useful measure of sensor value. The space environment is always changing; therefore, without regular updates, the delivered data becomes stale and less useful.

Returning to the example of weather forecasting, not only is the quantity of data necessary for accurate predictions but so is the timely delivery of data. Sensor data delayed by hours or even minutes can make the difference in saving lives when predicting severe weather. In developed countries, access to weather data in near-real-time is easy. In developing countries, this data is hard to come by. To combat this issue in Uganda, for example, new sensor designs are being studied with a focus on low cost, local sourcing, and low power and data demands to meet an end goal of improving the prediction of weather patterns for agricultural and public safety needs of the country (Nsabagwa et al., 2019).

In the investigation of Uganda's weather sensors, a high priority was placed on timely data delivery. While no exact requirement was stated, Nsabagwa et al. (2019) repeatedly made comments about no interruption and no delays. In the selection of the data transmission, path reliability and speed were the primary drivers with cost being third. If an unreliable path was used, then the data flow would be interrupted. If a low bandwidth path was used, then the data would be slow in delivery. Both options were unacceptable to the Uganda weather stations. The solution was to minimize the amount of data that needed to be sent by careful data processing onboard the sensor. This allowed for more stable but lower bandwidth data paths to be used while still providing 24/7/365 data collection and reporting.

In the world of SDA, this is similar. The SDA network requires continuous updates to its data catalog to accurately predict events in space. While the SDA network has many sensors to provide global coverage, any time a sensor is offline, there is a decrease in the amount of data being delivered and the timeliness that data. Not all sensors have redundant coverage with another sensor. This means there are gaps in the network's coverage, and these gaps create a delay in updates for space object positioning. This assessment is backed up by the statement from USSF Col. Scott Brodeur, director of Space Command's National Space Defense Center (NSDC) and director of operations at the Joint Task Force-Space Defense (JTF-SD). While speaking at a 2021 conference in Maui, he detailed the need for more SDA data and the need to receive it quickly (Hitchens, 2021).

In a similar manner to estimating the volume of data needed for effective SDA, Blake et al. (2014) assessed the rate at which updates need to be provided. Their assessment found that the threshold requirement was daily observations for all active satellites larger than 3 cm in diameter. They also assessed that in the near future the threshold rate requirement will increases to twice-daily observations and the minimum detectable object size requirement will include objects larger than 1 cm (Blake et al., 2014).

## Cost Considerations

While it is always possible to add new sensors to the network, the next section will show that it can be extremely expensive to create a new sensor or repurpose existing sensor for the SDA mission. An alternative is to extend the operating hours of an existing sensor and provide support to the network to decrease the time between observations.

## Cost of Equipment Downtime (Opportunity Costs)

Idle equipment has an associated opportunity cost. The Air Force built a radar in Australia with the purpose of producing SDA data and when the radar is down for planned or unplanned reasons, there is an opportunity cost associated with the downtime. In the previous sections, the value of SDA data and the need for timely data was discussed. Downtime has a negative impact on both of these measures. Therefore, this section provides examples of the financial impacts of downtime.

The total cost of ownership for construction equipment captures the cost of the equipment in terms of cost per hour. This is important for tracking equipment costs. Kannan (2011) investigated equipment repair polices and replacement policies. This total cost of ownership concept is also applicable to the C-Band Australia radar. Where Kannan (2011) was investigating costs associated specifically with construction equipment, the idea applies to other areas of study as well. Anytime equipment is not operating for its intended function, there is an opportunity cost incurred.

Network infrastructure providers are a suitable analogy to the C-Band Australia radar. Both provide a service to a user. In the case of the network infrastructure provider, it is network connectivity through copper and fiber optic lines, servers, routers, and data handling services. In the case of the C-Band Australia radar, it is providing SDA data to the SDA catalog. All systems will require downtime for planned maintenance, and there are many methods for minimizing that downtime. Similarly, unplanned downtime also has a cost in both examples. In a recent study, it was found that every hour of downtime costs a network infrastructure provider at least $100,000 (Walsh, 2021). In the case of the C-Band Australia radar, there is not a clear dollar amount that was lost; however, there are intangibles impacted by downtime just like the intangibles from network outages.

Walsh (2021) describes a small collection of negative impacts associated with downtime. Two standout impacts are reputational damage and loss of productivity (Walsh, 2021). These resonate with the C-Band Australia radar. When the radar only operates 9 to 10 hours per day, it can be considered an unreliable sensor. When the 18th Space Control Squadron needs data, and it has already been established that they need data all the time, and the C-Band Australia radar is operational less than half the day, they cannot rely on getting data when they need it. This is not to say that a sensor must operate 24/7; however, a less than half time sensor is well short of the demands of the user. This reputational damage leads to a lack of trust regarding the sensor and results in other sensors being used to fill that gap. This creates a loss of overall SDA system productivity and further reduces the effectiveness of the SDA network.

## Radar Cost Estimating

The previous section examined the cost of downtime for existing radars. No complex electro-mechanical system can run indefinitely, there will always be a need for planned and unplanned downtime. Additionally, no single radar can provide all the data necessary for the SDA mission. The U.S. Space Force has built a network of sensors to provide redundancy and resiliency into the network and to provide the necessary coverage of the satellites.  It is important to have this network with overlapping capabilities and coverage but at the same time, adding more sensors to the network adds substantial cost.  This section focuses on the costs associated with adding radars to cover the downtime of sensors already in the network.

Large modern space surveillance radars are rare, and most are found within the military forces.  As such, cost information is more difficult to uncover than other large systems.  While this information is uncommon, it is not altogether unavailable.  A recent military acquisition is the U.S. Space Force's Space Fence.  This large radar is a modern design with a mission to track objects in low earth orbit (Whalley, 2015).  This radar will have capabilities unmatched by any other radar and will be dedicated to the SDA mission.  This provides two benefits.  The first comes from the radar's capabilities.  It will be able to detect more objects at once and detect smaller object than ever before.  This provides missing data to the Space Catalog, which results in a more complete picture of the space domain.  The second benefit comes from the radar's dedicated SDA mission.  This allows for an uninterrupted flow of SDA data to the Space Catalog.  This fulfills two of the missions of the Space Catalog (J. Hrovat, personal communication, July 14, 2021).

During the acquisition of Space Fence system, the program office defended the system's budget.  This was captured in 2016 with the Selected Acquisition Report (SAR) providing cost estimate details using the Air Force Total Ownership Cost tool.  This estimate made several assumptions.  One was the selection of 20 years as the design life, and another one was that only a single Space Fence will be built.  The 20-year life affects the operating cost estimate because the standup of the depot facilities is amortized over the 20 years (Whalley, 2015). A shorter or longer life will impact this estimate. By limiting the estimate to a single Space Fence radar, the estimate does not consider the opportunity for operations and sustainment cost savings with additional sites. In 2016, additional sites were considered but not approved. In 2021, these sites are still not approved but are being considered even more strongly. With these assumptions, the SAR estimated a procurement cost of $1.5 billion, an annual operating and sustainment cost of $60 million per year, and a total operating and sustainment cost of $1.204 billion over the life of the system (Whalley, 2015). As will be shown in this research, adding operational hours to the C-Band Australia radar provides great value to the SDA network, thereby providing a more efficient alternative to acquiring costly new radars.

In a similar example, a large radar was built on the island of Kwajalein in the Marshall Islands. This served as a prototype for the Missile Defense Agency. The system was used successfully in the 1990s but has remained primarily idle in recent years (Crawford et al., 1999). Recognizing the need for a missile defense radar on the east coast of the United States, it was proposed to Congress to fund a project to refurbish the radar and move it to the eastern United States. This project cost was estimated by the Congressional Budget Office in 2013 to cost $140 million, which would fund the operation of the radar for 18 months in part of 2017 and through 2018 (Gullo, 2013). Once again, the value of keeping existing radars operational proves to be more beneficial when considering the high cost of refurbishing existing radars.

## Power Cycling Equipment

A final cost consideration is relatively minor but it affects more than just the C-Band Australia radar. This is the effect of power cycling the radar equipment each time it reaches the end of an operational day. This section begins with a review of the impacts power cycling has on a simple lightbulb from work done by the Department of Energy. The impacts of power cycling are then applied to data centers and server equipment, both of which are relevant to the C-Band Australia radar.

It is commonly mentioned that computers and other electronics should remain powered on to increase their life. This is said for complex server farms and for simple items like a lightbulb (Department of Energy, 2021). The thinking behind this statement is that frequent power cycles wear out the components and eventually leads to failure. Some people even advocate for leaving a lightbulb on when leaving a room for a short time because they believe the power cycling will wear out the bulb sooner. There is some science backing up this claim. To turn on a lightbulb, there is an initial flow of current that is much higher than the current used to keep the light on. Where the argument for keeping a light turned on breaks down is the duration of the flow. For most lightbulbs, the flow is less than one second in duration; therefore, when accounting for energy costs and the replacement cost of a lightbulb, it is more efficient to turn off the bulb whenever it is not needed (Department of Energy, 2021).

The argument for powering off a lightbulb in all situations is valid because of the low consequences of a burnt-out bulb and the low replacement cost. However, the decision is not as straightforward when a system's uptime is much more important and when the components are much more expensive. To find the answer to this decision, a deeper understanding of what is happening is required.  An easy way to describe the situation is by comparing it to the traditional failure rate bathtub curve shown in Figure 6. In this curve, the component experiences failure early in life.  At the other end of the bathtub, there is the wear out area.  In this area, the stress of operations leads to a component failure.  By repeated power cycling, there is a repeated thermal cycle and this increases the wear on the component (Wang et al., 2008).

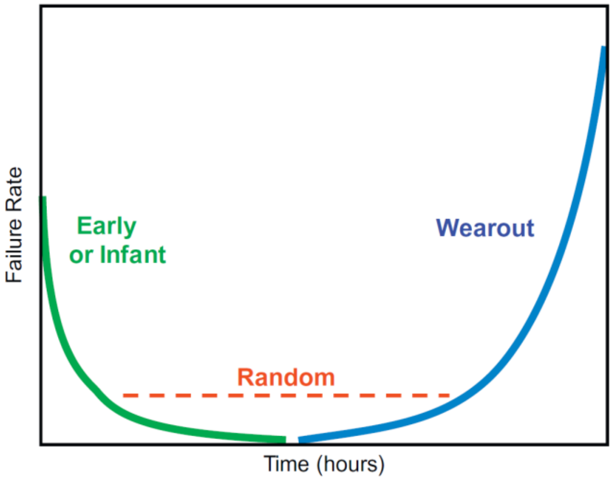


Figure 6.  Traditional Bathtub Curve (Roesch, 2012)

By power cycling a system or component, the damage is not directly created by the electricity flowing through the wiring.  Wang et al. (2008) found that when power is applied to a component, heat is generated.  The component warms up from the ambient temperature of the environment and reaches a new steady state temperature determined by the cooling characteristics of the component.  This change in temperature creates a thermal stress.  Matsuoka (1982) investigated component failures in the complex systems that comprise a nuclear reactor.  A more recent study by Wang, et al. (2008) investigated the individual components at the board-level and discovered that soldered joints and traveling wave tubes were susceptible to thermal cycling.  All of these components are found throughout radar systems, and the C-Band Australia radar is no exception.

Every time the radar is powered up, all of the electronics get warmed up.  Some of this warm-up is required before the components will operate properly.  Based on radar operating manuals, the C-Band Australia radar requires no less than 45 minutes of startup time (Space and Missile Systems Center, 2016).  The majority of that time is spent waiting for temperatures to reach the operational level.  In addition to the desired heating, undesired heating occurs when circuit boards and transformers get hot from the flow of electricity and need to be cooled by forced air or chilled water.  In either case, at the end of the operational day, the equipment is powered off and the equipment returns to room temperature.  This process is repeated for the life of the equipment.

For personal electronics, it makes sense to turn off a computer overnight or when it is not being used.  It saves money and is only an inconvenience when it is not available.  In critical server equipment though, failed equipment may cause significant issues for the users.  There still might be cost savings by powering off servers at the end of the day, but if that power cycling leads to increased failures, the savings may not be justified (Bishop, 2019).  In the case of the C-Band Australia radar, leaving the radar system powered on 24/7 only makes sense if the site is manned 24/7.  There is a level of danger and risk associated with the radar that is greater than a normal server room.  The radar system has mechanical components that move equipment weighing thousands of pounds, and there are several components that operate at tens of thousands of volts of electricity.  Leaving a powered-on radar system unattended poses a serious risk.  That being said, as operating hours for the radar increase, it may become cost effective to leave a minimal maintenance crew on-site to monitor the system during downtime if it prevents a power cycle.

## Radar Performance and SDA Production

So far this literature review has focused on the value of SDA data and the cost of radar systems. This final section will look at what the radar is capable of producing. The technical capabilities of the radar are governed by the radar range equation shown as Equation 1 (Graham & Bocquet, 2013). This equation determines the minimum size object the radar can detect at a given range and determines the maximum detectable range of an object for a given size. By using the space catalog in combination with this equation and the physical characteristics of the radar, the number of objects in orbit that are detectable to the radar can be found (Graham & Bocquet, 2013).

$$R_{max} \cong \left[\frac{P_t G_t A_e G_{int} \sigma}{(4\pi)^2 (S/N)_{min} k T_S B_N L_S}\right]^{1/4} \quad (1)$$

where $P_t$ = Average transmit power, σ = Target Radar Cross Section (RCS), $G_t$ = Transmit antenna gain, $T_s$ = Radar system noise temperature, $A_e$ = Receiver antenna effective area, $B_N$ = Noise bandwidth, $G_{int}$ = Integration gain, $L_s$ = System losses, and $(S/N)_{min}$ = Minimum Signal to Noise Ratio (SNR) required for detection

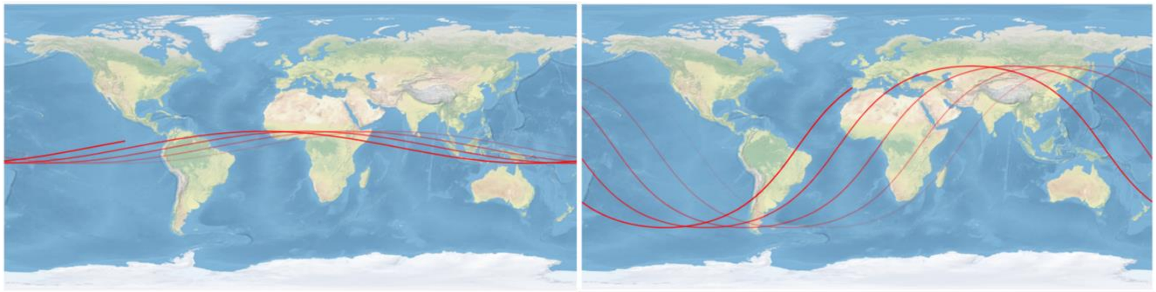
Using Equation 1, Graham and Bocquet (2013) used the radar operating parameters to determine the operating capabilities of the radar. The transmitter for the radar is a ETM 305C transmitter for which the frequency, peak power, pulse repetition rate, and pulse width are known values (Space and Missile Systems Center, 2016). Radars with similar designs use common values for the beam width, antenna size, antenna gain, integration gain, required SNR, system noise temp, noise bandwidth, and system losses (Graham & Bocquet, 2013). Average power is calculated by multiplying the peak power by the duty factor. To maximize the radar performance, this radar will be operating at maximum pulse width exclusively allowing the maximum duty factor was calculated based on the ratio of the pulse width to the pulse repetition frequency. All of these operating values are listed in Table 1.

Table 1. C-Band Australia Operating Parameters (adapted from Graham and Bocquet (2013))

| **Radar Parameter** | **Operating Value** |
|---|---|
| Operating Frequency | 5.4 to 5.9 GHz |
| Peak Power Output | 3.0 MW |
| Pulse Repetition Rates (Maximum) | 160 pps |
| Pulse Width (Maximum) | 25 µs |
| Duty Factor (Maximum) | 0.4% (Calculated) |
| Average Power Output (Maximum) | 12 kW (Calculated) |
| Beam Width | 0.38° |
| Antenna Size | 29 ft |
| Integration Gain | 15 dB |
| Antenna Gain | 53 dB |
| Required SNR | 15 dB |
| System Noise Temp | 578 K |
| Noise Bandwidth | 3 dB |
| System Losses | 4 dB |

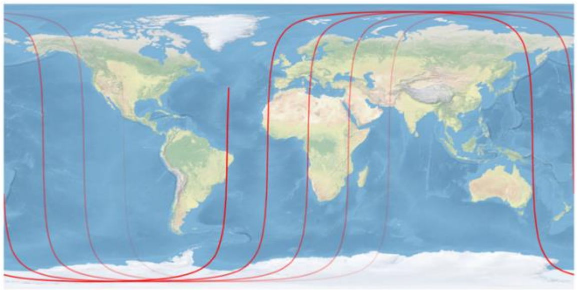
All objects in the unclassified space catalog are detectable by the radar at a range of up to 2,000 km (Graham & Bocquet, 2013). This covers the entire Low Earth Orbit (LEO) region which is the mission area for the radar. Graham (2015) also investigated the impact of longitude and latitude on the coverage of space objects and found that longitude does not impact a sensor's coverage for LEO satellites. While a sensor is limited in what it can see at any given point in time by the horizon, the satellites in orbit move across the earth and the visibility is dictated by the sensor's latitude. Figure 7 demonstrates this situation by showing the ground track of a satellite over a 12-hour period. Low inclination satellites will only be visible by a sensor on the ground near the equator, whereas high inclination satellites are visible at all latitudes. Even a medium inclination orbit like the one used by the International Space Station is visible at all latitudes except the most Southern and Northern locations.

While a satellite might be visible by a ground sensor, some satellite orbits have fewer passes within sight of the ground sensor (Graham, 2015). This can be seen in Figure 7 where a satellite does not pass over every portion of the earth in a 12-hour period; this is most obvious with the high inclination example, but it is also apparent in the medium inclination example. This is where the operating hours of a sensor become important. When a sensor operates less than 24 hours per day, there are opportunities for long periods of time when the sensor cannot see the satellite. Graham's (2015) research demonstrates this relationship between the operating hours of a radar and the mean gap in satellite observations. The gap is initially large with one observation every three days when a radar only operates one hour each day. This is because the satellite is not overhead at the same time each day with the timing of the observation opportunities based on orbital altitude, orbital inclination, and sensor latitude. With these constraints, a single hour of operation per day will only provide an observation opportunity once every three days. As operating hours increase, the gap between observations decreases to where a satellite is observable multiple times per day by the sensor (Graham, 2015).



Low (10°) inclination
satellite in 850 km orbit

Medium (51°) inclination
satellite in 850 km orbit



High (85°) inclination
satellite in 850 km orbit

Figure 7. Examples of Satellite Ground Tracks (Low, 2018)

To demonstrate the observation effects of sensor latitude on observation opportunities, Graham (2015) created a simulation of a typical month of operation using Systems Tool Kit modeling software from Analytical Graphics Inc. One significant limitation in his research is that his simulation ignored the physical limitation of tracking multiple objects in the sensor's field of regard. For example, the C-Band Australia radar has a field of regard encompassing all azimuths and ranging from approximately 5 degrees up to 90 degrees above the horizon. However, the radar is limited to a field of view of just 0.38 degrees at any point in time. Therefore, only objects within that narrow field of view are observed. The radar must physically slew its antenna between observations. Graham (2015) acknowledged this but did not account for this; therefore, his expectations of performance were overly optimistic. Therefore, the investigation conducted in the current research will look at real, operational metrics from the radar to find the true number of observations per hour that can be expected.

The overall task of SDA is not the responsibility of a single sensor. The U.S. Air Force and not the U.S. Space Force built, maintains, and upgrades a network of sensors to accomplish this mission. Figure 8 shows the approximate field of regard for the various radars performing this mission with dedicated sensors shown in green, contributing sensors shown in yellow, and collateral sensors shown in red (Graham, 2015). The thick green circle was added to show the C-Band Australia radar location and coverage, which illustrates the additional southern hemisphere coverage that it provides.

In addition to the radar sensors, there are also military-operated telescopes accomplishing this mission and an ever-growing network of commercial telescopes and radars. The U.S. Space Force is tapping into these commercial assets by using the SDA Marketplace (Thibault, 2021). This marketplace will allow the government to purchase the data produced by commercial companies to augment the SDA network. The idea of an SDA Marketplace is not new. For over a decade, research has been published detailing how the marketplace will benefit the military and improve SDA. This work has focused on the competitive nature of the marketplace (Blake et al., 2014), the volume of data that is needed from the marketplace (Sullivan et al., 2012), and many other topics. However, the actual cost of that data is not disclosed. This number needs to be in-line with the costs of operating a military system organically. If the costs are too high, the military might consider building and operating their own sensor; however, if the costs are too low, commercial companies may not be interested in providing this service.

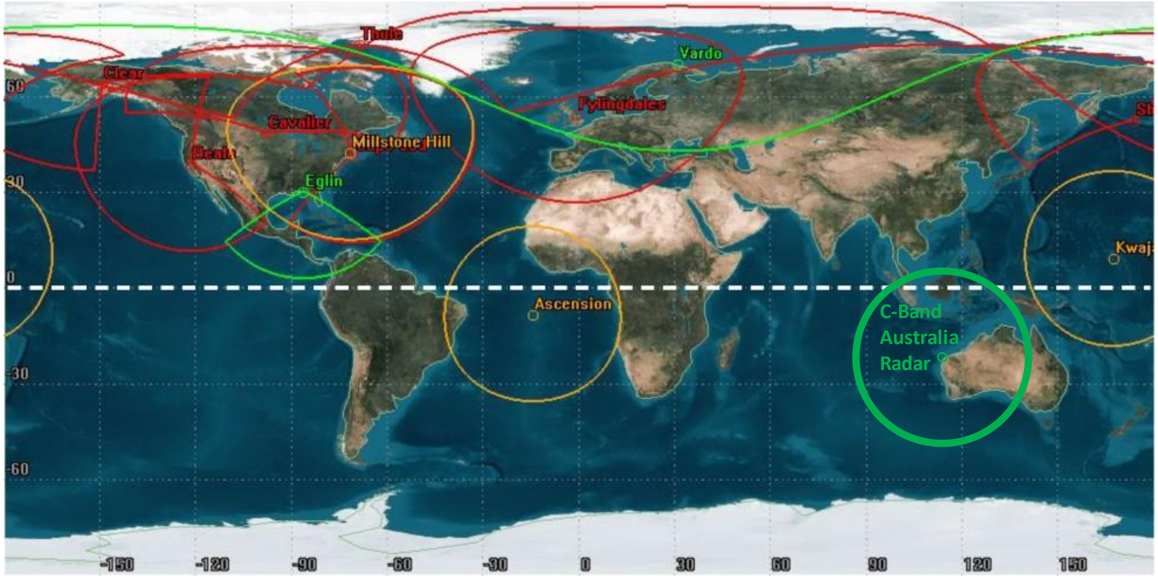


Figure 8. Coverage SSN Sensors at 800 km Orbit (Graham, 2015)

# III.  Methodology

The C-Band Australia radar is unique among the Space Domain Awareness (SDA) radars in that it is the only dedicated radar sensor that operates less than 24 hours per day.  By changing the operating hours of the radar, it is possible to increase the benefits of the radar but there will be an associated cost.  Finding the most efficient schedule for the C-Band Australia radar that maximizes benefits to users while minimizing operating costs is the primary research objective of this investigation.  To do this, the Value Focused Thinking (VFT) processes will be used.  Using the 10-step VFT process described in Chapter II, alternatives will be scored to evaluate different options for increasing the operating hours of the radar.  This investigation will use the results of the scoring to perform a sensitivity analysis on the individual measures.  The sensitivity analysis will show where changes in the weighting of values and measures affects the results of the scoring.  Figure 9 is a simplified process flow of the VFT process used in this investigation.

## VFT Step 1:  Problem Identification

The identified problem will come directly from the primary research objective of this investigation:  What is the correct number of operating hours per day that provides the most operational benefit while limiting the costs for operating and sustaining the C-Band Australia radar?  This question looks at the costs and the benefits of operating the radar to find the balance where the value from increased operating time outweighs the increased costs.

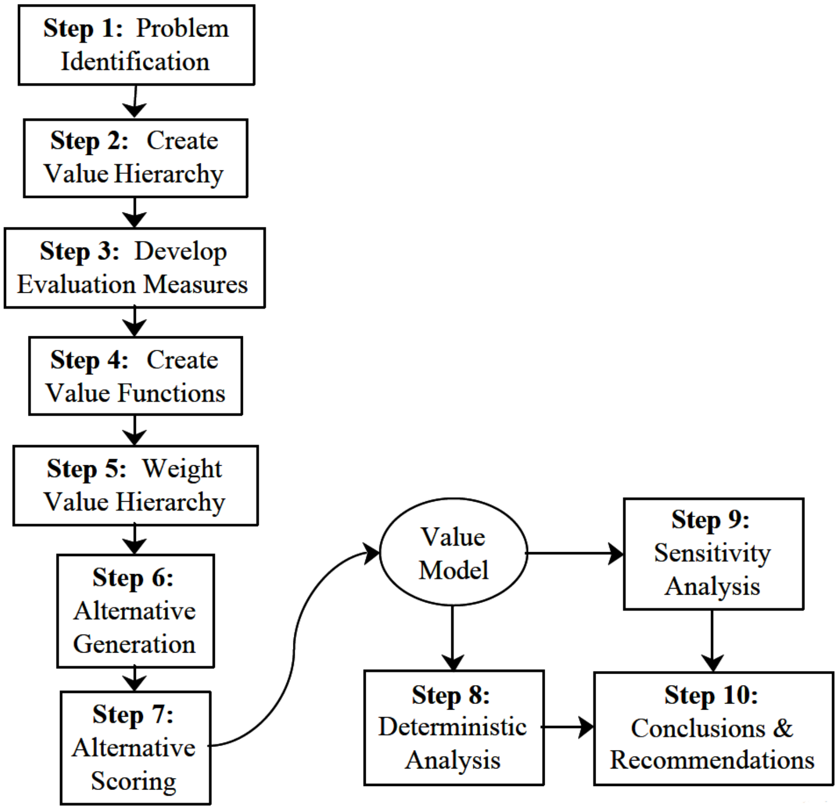


Figure 9. VFT 10-Step Process Flow Chart (Jurk et al., 2004)

## VFT Step 2: Create Value Hierarchy

The next step in the process builds the value hierarchy and this hierarchy was developed through a combination of consulting published guidance, review of past Air Force decisions, and engineering judgement. The preferred method for developing the value hierarchy is by directly consulting with the decision-maker; this method is classified by Parnell (2007) as the "Platinum Standard" because it creates the best possible outcome. However, Parnell (2007) recognizes that direct consultation is not always possible and characterized a "Combined Standard" where some decision-maker interaction is combined with review of approved and relevant documentation. As an alternative to direct decision-maker input, the researcher uses his/her engineering judgment to interpret past decisions and official guidance. This does not represent the best development process but is assessed to be a suitable substitute and was the approach used for the current research effort..

The primary research objective focuses on the costs and the benefits of the radar; therefore, these are used as the starting point for developing the value hierarchy. It is possible to increase the scope of the investigation to include the interactions between other radars or how radar operations complement telescope operations; however, the intent is to specifically focus on the C-Band Australia radar and not external factors. The first-tier values separate into three branches: “Operating Hours”, “Ops Timing”, and “Hardware Health”. When breaking down the overarching objective for the first tier, published guidance for SDA systems and interactions with the users of the SDA data emphasized the need for a greater quantity of data and consistency or uninterrupted flow of that data (J. Hrovat, personal communication, July 14, 2021; Raymond, 2020). In the case of the C-Band Australia radar, the only way to increase the amount of data produced is to increase the operating hours of the radar since the radar already operates at maximum capacity for a given hour of operations. This creates the first branch in the first tier of the value hierarchy, “Operating Hours”.

The second branch, “Ops Timing”, was created because of the need to explore when the operational day is occurring for the radar. Increasing or changing when the radar operates has impacts on that alternative’s values, specifically how those operating hours impact the maintainers at the site and supporting organizations in the U.S. The values in this branch are unique to those in the first branch.

Finally, the third branch focuses on the hardware impacts to changes to the current operating schedule. As described in Chapter II, there are hardware ramifications to power cycling electronic hardware. This branch captures those impacts for the various alternatives. All three of these branches and their further breakdown are described in the following paragraphs.

The “Operating Hours” branch captures all the values that are related to the number of operating hours for the radar. The previous chapter identified that the user’s need starts with the quantity of data. The C-Band Australia radar already operates at the maximum capacity per hour; therefore, the only way to increase the amount of data that is produced is to increase the amount of operational time. The “Amount of Data” value captures this change. As operating hours per day change, the efficiency of those hours will also change. The “Efficiency” value measures the impacts that different schedules will have on the overall cost and production efficiency for the radar.

After the “Operating Hours” branch, there is the “Ops Timing” branch, which contains the “Ops During U.S. Day” value. This value captures the effects of when the operating hours occur in an operational day. Currently, they align with daytime in Western Australia but that can be changed with new schedules. The other value in this branch is the “Shared Staffing” value that measure the benefits of sharing staffing resources across other systems at the site. The final branch is the “Hardware Health” branch with a single value for “Power Cycling”. The previous chapter provided examples of the benefits of minimal or now power cycling and this value identifies these changes. All of these values are shown in the overall value hierarchy in Figure 10.

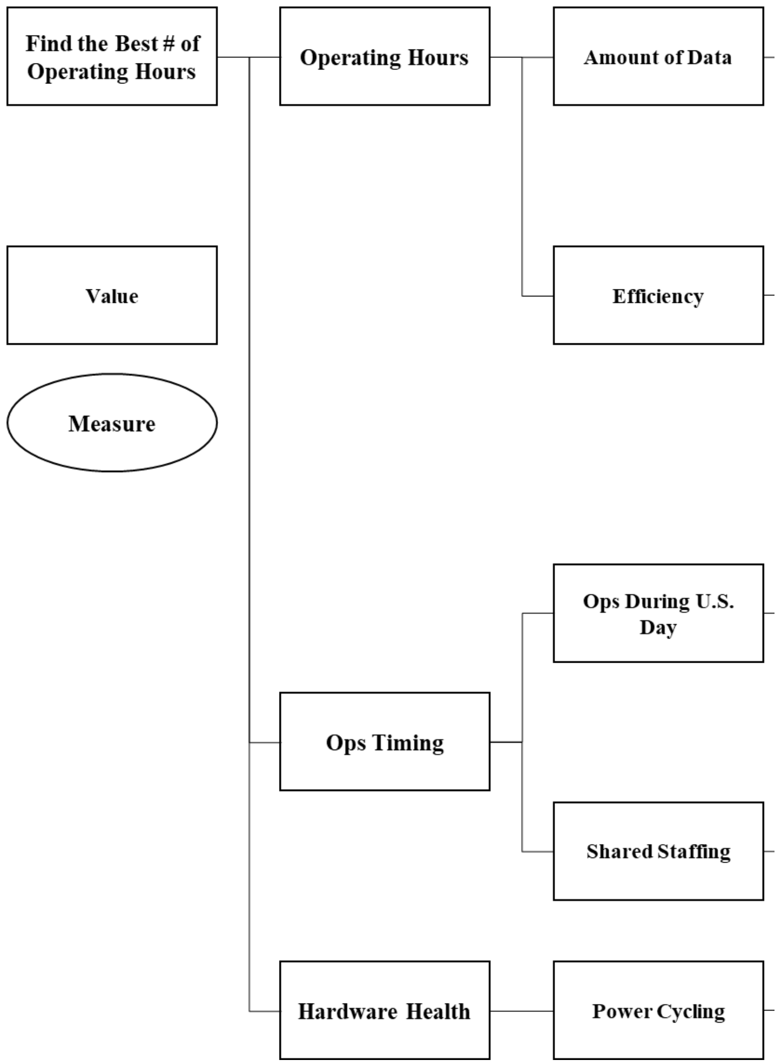


Figure 10. Value Hierarchy

### VFT Step 3: Develop Evaluation Measures

In step three, the value hierarchy is further broken down into the specific measures that will be scored for each alternative. Similar to the values in the previous step, these measures were developed through a combination of consulting published guidance, review of past Air Force decisions, and the researcher's engineering judgement based on experience in the field to interpret the guidance and past decisions. The problem identified in step one is composed of seven individual measures with each second-tier value mapping to either one or two specific measures. While there might not be many tiers or individual measures, this value hierarchy captures the applicable values of the C-Band Australia radar that address the identified problem. Figure 11 shows the full value hierarchy with associated measures. The following sections will provide a detailed description of each measure.

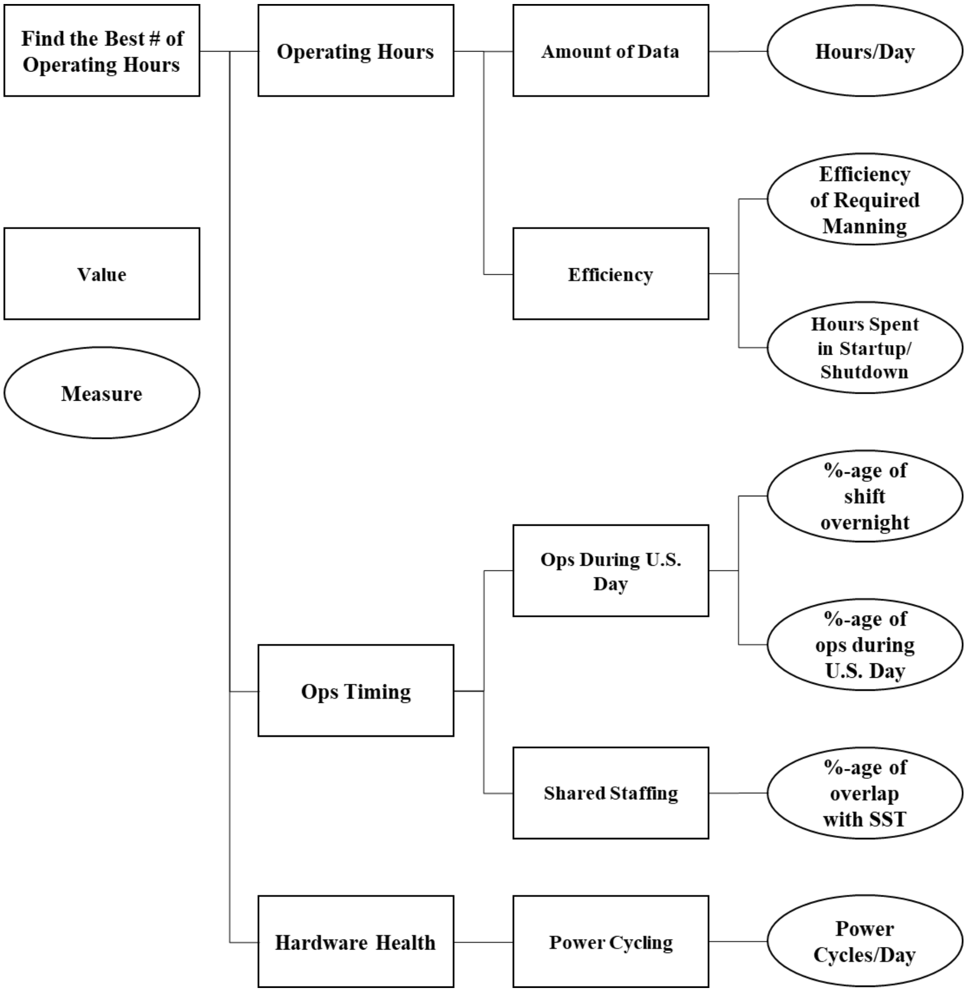


Figure 11. Value Hierarchy with Measures

### Hours/Day Measure

The first measure for the hierarchy, “Hours/Day,” exclusively considers the operating hours in a 24-hour period without considering any other factors. This measure is directly addressing the customer’s need for more data. Under the current operating conditions, once an operational day begins the radar operates with as little downtime between observations as possible, meaning the radar goes from one tasked object to the next. Humans and software tools optimize the schedule for the radar in order to collect as much data as possible in the operational hours. For this reason, increasing hours available for data collection is directly related to the radar’s total data output.

### Efficiency of Required Manning Measure

The “Efficiency of Required Manning” measure captures factors such as shifts with more personnel than required. The maintainers at the radar site power on the radar, perform calibrations, conduct preventive maintenance, and respond to corrective maintenance activities. Changes to radar operations will impact this contract by increasing the manning required to support the radar. The specific manning changes and personnel schedules cannot be known exactly without detailed proposals from the support contractor, but conservative estimates can be made for the purposes of this investigation. These conservative estimates will be bounded by the following four assumptions.

1. No maintainer shift will be greater than 12 hours.
2. No maintainer shift will be less than 8 hours.
3. Shifts will not be scheduled more than 5 days in a row.
4. Maintainers will not be regularly scheduled for less than 40 hours per work week.

These assumptions are put in place to avoid maintainer work schedules that would create an unsafe work environment (e.g., 12+ hour work day) or undesirable work environment (e.g., 7-day work-weeks with only 5 hours per shift). Unrealistic work schedules will not accurately predict maintenance personnel costs and will at best make it difficult to hire qualified worker or at worst create a dangerous work place. By following these constraints, there will be operating schedules with inefficient manning levels. By going from 12 hours to 13 hours per day, the existing crew cannot add an extra hour because that breaks assumption number 1. Instead, an additional crew must be added and to avoid violating assumption number 2, that crew will overlap with the original crew for several hours. This reduces the efficiency of the manning schedule and creates discrete manning levels as hours are added to the operational day or the hours are shifted around.

### Hours Spent in Startup/Shutdown Measure

Similar to the previous measure, there is the possibility to lose efficiency in the operating day with the startup and shutdown times. Before and after every operational period, there is time spent performing maintenance, conducting calibrations, and powering off or powering on the radar. This time requires maintainer support but does not produce a useful product. While it might be beneficial to break up the operational day into more than one operational period, this increases the time spent in the startup or shutdown phase and reduces efficiency. This measure will score the alternatives higher or lower depending on if the alternative increases or decreases the daily startup and shutdown time.

### Percentage of Shifts in Off Hours Measure

The current radar operations are scheduled for 0700 to 1900 local time in Western Australia. This creates an easy-to-accommodate schedule for the on-site maintainers and the operators. If the schedule is changed and more operating hours are added to the night time, it will be more difficult for the existing worker to accommodate and will also make it more difficult to hire future workers to maintain and operate the system. This measure will score alternatives with greater percentages of hours outside of 0700 to 1900 local time lower.

### Percentage of Ops during U.S. Day Measure

Similar to how the previous measure scores the local daytime operations higher, this measure scores U.S. daytime operations higher. This is unique from the previous measure and these measures will be weighted differently and will address unique advantages for the system. By having operations during daytime in the U.S., there are advantages from the user perspective. The Combined Space Operations Center (CSpOC) in California or the National Air and Space Intelligence Center (NASIC) in Ohio can reach out to operators of the radar directly with questions or comments. Another advantage comes from the program office’s ability to reach maintainers directly without needing to wait for the message to reach them on the next shift.

### Percentage of Overlap with SST Measure

While this research intends to limit the scope to just the C-Band Australia radar, it is necessary to consider systems immediately adjacent to the radar. The small town of

Exmouth, Western Australia, and the Naval Communications Station Harold E. Holt also host an SDA telescope. This telescope is known as the Space Surveillance Telescope (SST), and it is the most advanced ground-based telescope in use for the SDA mission. SST follows a similar operations and support construct as the C-Band Australia radar where Australia contractors maintain it and Australian military operate it, but the mission equipment is U.S. property and it fulfills a multi-national SDA mission. Because of the proximity to the C-Band Australia radar, the maintenance contracts are combined to provide management efficiencies. To further increase efficiencies, it will be valuable to have the systems overlapping in operations in order to share maintenance support. For this reason, a measure covers how much time the C-Band Australia radar and the SST are both in operation. Current operations have almost no overlap since the radar operates during the daytime and the telescope operates during the night. Changes to when radar operations are conducted or the number of hours per day will change this level of overlap.

### Power-cycling Measure

The "Power-cycling" measure captures how many times the radar system is power cycled daily. Every day the radar is powered off at the end of the operational day and then powered up again before the next day's scheduled operations. This results in one system power cycle per day. The previous chapter reviewed how a power cycle has potential damaging effects for electronics. In the current operational configuration and manning agreement, this single power cycle per day makes sense. The radar has many high voltage components and some large moving parts that create a hazard if the site is left unattended while the system is energized.  For that reason, the radar must be powered off during the 12+ hours that it is unattended each day.

The negative impacts of a power cycle are not ignored by the maintainers and program office for the radar.  While the high-power radar components are powered off each day, the computer components and server equipment are powered on 24/7.  This is done specifically to avoid the damaging effects of power cycles.  This practice is allowed because the hazards are lower, since the computer components and server equipment have no moving parts and no high voltage.  It would be possible to keep the high-power radar components powered on all the time but maintainers would be required to be present to mitigate the safety risk.  This reduces the number of power cycles to zero but will increase electricity costs and maintainer costs.

### VFT Step 4:  Create Value Functions

Step four in the VFT process creates the value functions, or scaling functions, to put all the measures on a scale between zero and one.  All the value functions are categorical for various reasons and were developed through the interpretation of relevant guiding documents for SDA.  The "Hours/Day" measure has 13 discrete increments of operating hours ranging from the current schedule of 10 hours per day up to the maximum number of operating hours per day of 22 hours.  This value function has the potential to be linear since operational time does not need to increase by single hour increments.  For the purposes of this investigation though, the alternatives were simplified to one-hour increments and the categorical format eases the scoring.  In the case of the "Efficiency of Required Manning" measure, linear was also possible but categorical was selected for several reasons. First, it was desired to have a non-linear change to the scoring. Perfectly efficient use of manhours results in a perfect score but a small loss of efficiency is not entirely bad since a small amount of additional staffing could allow for additional, non-critical, task to be completed such as training or administrative work. As the inefficiencies increase, the score quickly drops off. By using categories, it also allows for some variations in how a shift is scheduled without changes to the score.

The "Hours Spent in Startup/Shutdown" measure is clearly categorical because there are only so many options for this measure. Each alternative will only have 2, 3, 4, or greater than 4 hours in operation. The C-Band Australia radar is like most radars of its type and it cannot be operated continuously without degrading hardware or performance. For this reason, there will always be maintenance periods even if not technically in startup or shutdown; this measure captures what is budgeted for these activities each day. In reality, the value will vary some since different tasks are required each day, but the budgeted time creates discrete categories.

"Percentage of Shifts in Off Hours", Percentage of Ops during U.S. Day", and "Percentage of Overlap with SST" all capture different aspects of the value hierarchy but follow similar value function logic. As a greater percentage of operating hours are added outside the daytime in Western Australia, there will be more stresses placed on the on-site maintainers. In general, it is less desirable to work at night versus during the day, there are challenges to switching schedules, and it may be difficult to hire qualified workers if night shifts are possible. Small changes will not affect scoring but discrete categories score the increase in maintainer stress. In a similar fashion, as hours are added during the U.S. day, productivity increases and alternative scores increase. This comes from shortened feedback timelines from depot support to on-site maintainers, from immediate response to Combined Space Operations (CSpOC) tasking, from improved feedback between the program office and maintainers, and other factors. Additionally, as the changes to operating hours coincide with SST operations, there is an increase in value. Again, small variations in the schedule will not affect the scoring but the general trend of increases to productivity will be captured by the categories.

Finally, the "Power Cycles/Day" measure follows the same line of thinking as the "Hours Spent in Startup/Shutdown" measure. There are only four categories that the alternatives can have, 0, 1, 2, or 3 power cycles per day. For this reason, other value function formats would be unsuitable and categorical is used here. Figures 12 and 13 are examples of scaling functions used in this investigation with the full set of scaling functions included in appendix A.

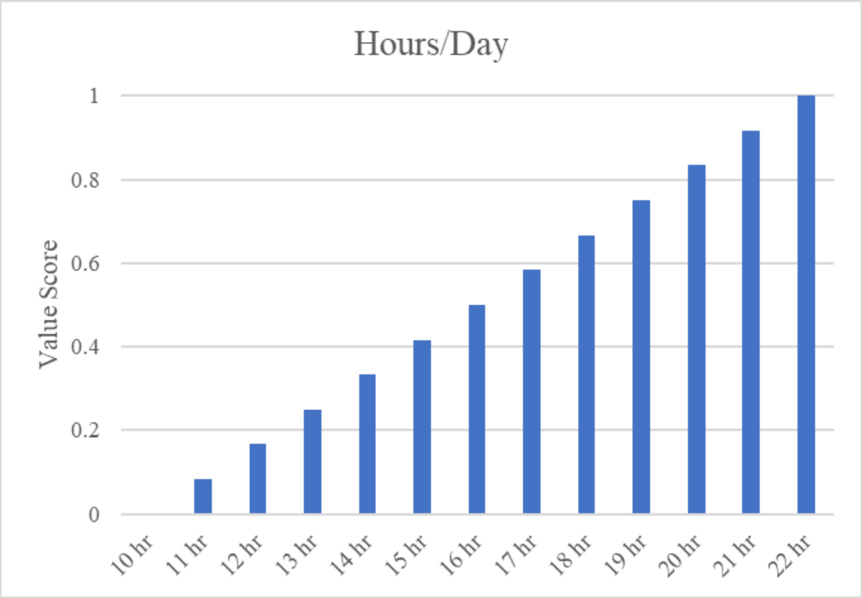


Figure 12. Increasing Value Function Example

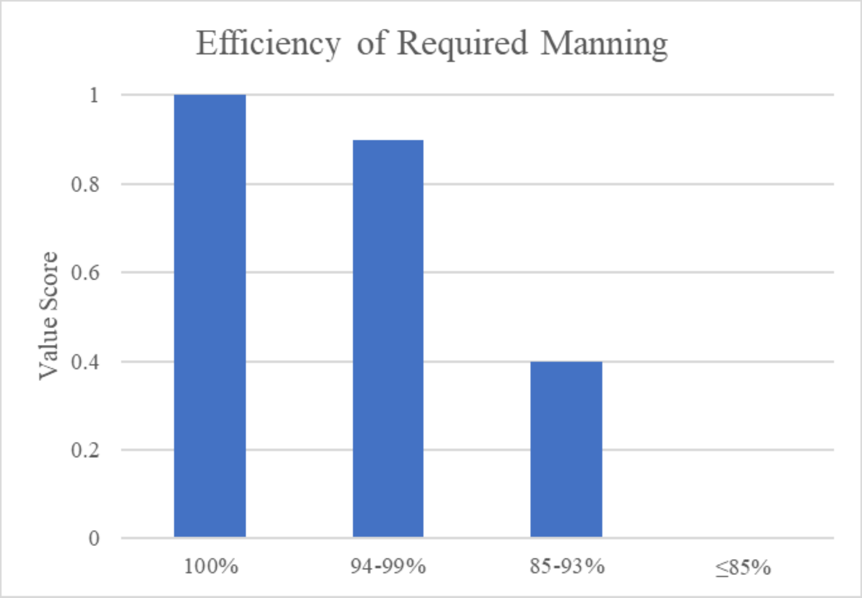


Figure 13. Decreasing Value Function Example

This investigation will not include exact values for costs associated with each measure; only the value function score will be reported. This is to protect sensitive cost information derived from contract values, program office budgets, and competitive labor rates. These specific details were available during the analysis but will not be reported to prevent the unnecessary disclosure of financial information. The exact dollar amounts used in the scoring process later does not provide any additional insight not already available in the value function scores.

### VFT Step 5: Weight Value Hierarchy

Next in the VFT process is step five where local and global weights are assigned to the value hierarchy. As discussed in the previous chapter, weights are used by the VFT process to identify relative importance. First, the tiers, values, and measures are assigned local weights in an algebraic manner that is described later. The local weights all sum to 1 within each tier in each branch. In the value hierarchy for this investigation, the first branch includes “Operating Hours”, “Ops Timing”, and “Hardware Health”. Between these, “Operating Hours” is the most important and received the highest weighting and “Hardware Health” was the least important. Looking at just the “Operating Hours” branch, there are two values splitting off of that. The more important of the two is “Amount of Data” and it received a higher weight than the “Efficiency” value. Within “Amount of Data”, there is only one measure and it receives the full weight of 1 for the local weights.

Once the local weights are assigned, the global weights are calculated. This involves multiplying the weights along the path of the value hierarchy. Using the “Efficiency of Required Manning” as an example, 0.652 x 0.250 x 0.715 = 0.1165. The sum of the global weights for all the measures equal 1 and the sum of the values within each tier also equal 1. The local and global weights for the value hierarchy are shown in Figure 14.

The preferred technique for assigning the weights is through direct interaction with the decision-maker or decision-maker delegates. There are processes for the decision-makers to vote on the weighting scores, consult on the differences, and then rescore the measures. This process is repeated until the scoring panel reaches a consensus. In this investigation, the decision-maker is not available for this level of involvement. Instead, an algebraic weighting method is used and is informed by personal experience, past choices made by the decision-maker, and a review of applicable policy. Measures with the highest importance received the highest weight; conversely, measures with the lowest importance received the lowest weight.

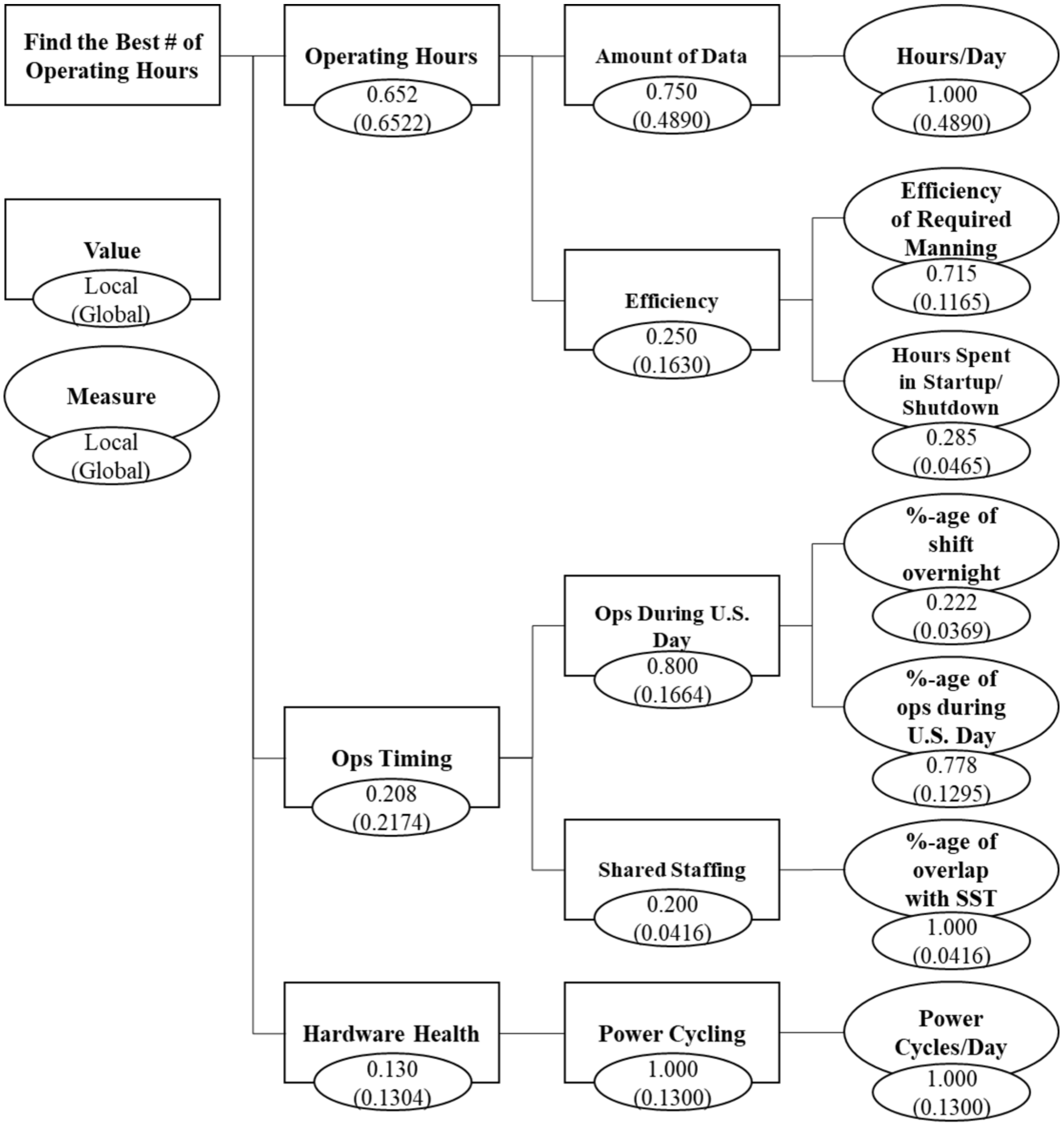


Figure 14. Value Hierarchy with Local and Global Weights

This method is applied at every branch of the hierarchy. In the first branch, "Operating Hours" was decided to be the most important and received a weight approximately three times that of "Ops Timing" and approximately five times that of "Hardware Health". On the next branch, "Amount of Data" was weighted three times that of "Efficiency". In the second branch of tier two, "Ops During U.S. Day" was more important than “Shared Staffing” with a weight four times that of “Shared Staffing”. There is a third branch in tier two; however, it has a single value and receives the full amount of that branch’s weight. This is also the case with the “Hours/Day”, “Percentage of Overlap with SST”, and “Power Cycles/Day” measures. Of the other measure, “Efficiency of Required Manning” is weighted 2.5 times more than “Hours Spent in Startup/Shutdown”. Finally, “Percentage of Ops During U.S. Day” has a weight 3.5 times that of “Percentage of Shift Overnight”.

It is understood that the selected weighting method has weaknesses when compared to methods with direct interaction with the decision-maker. For this reason, a sensitivity analysis will be performed on the scored results. This sensitivity analysis will uncover how each alternative’s score changes when the weights are changed. Equipped with this information, the measure most sensitive to weight changes can be isolated for future investigations at a deeper level.

### VFT Step 6: Alternative Generation

For alternative generation, this investigation considered 32 alternatives. At a high level, the alternatives are made up of five types plus the current baseline. The first type is adding operating hours to the current 10-hour operational day up to 22 hours per day with no other changes. The next type creates two operational periods per day with increasing lengths of operational time in each period. The third type is similar but with three operational periods per day. The fourth type uses three operational periods but adds a minimum crew to monitor the equipment during the non-operational time in order to have no power cycles. The fifth and final time keeps the same operating hours at the current operating schedule but shifts the timing of those hours to be at a different time of day. Table 2 lists the 32 alternatives to be evaluated by grouping them by the different types of alternatives: Current Ops, 1-hour increments of Current Ops, two ops periods per day increasing in 1-hour increments, three ops periods per day increasing in 1-hour increments, two options for zero power cycles, and shifted operations.

Table 2. Alternatives

| Alternative # | Name | Description |
|---|---|---|
| 1 | Current Ops | Ten hours of operations with two hours of maintenance in one operational period |
| 2 through 13 | Current Ops +1 through +12 | Eleven through twenty-two hours of operations with two hours of maintenance in one operational period |
| 14 through 20 | Two Sets of 5 through 11 | Two 5-hour through 11-hour ops periods with 1 hour of maintenance with each period per day |
| 21 through 23 | Three Sets of 5 through 7 | Three 5-hour through 7-hour ops periods with 1 hour of maintenance with each block per day |
| 24 and 25 | Safety Crew 2 hr and 1 hr | Three 5-hour and 6-hour ops periods with 1 hour of maintenance on each period per day and monitor while the equipment stays powered on (0 power cycles) |
| 26 through 32 | Shifted Ops | Previous alternatives with a shift in the ops time covering different hours in the day. |

### Methodology Summary

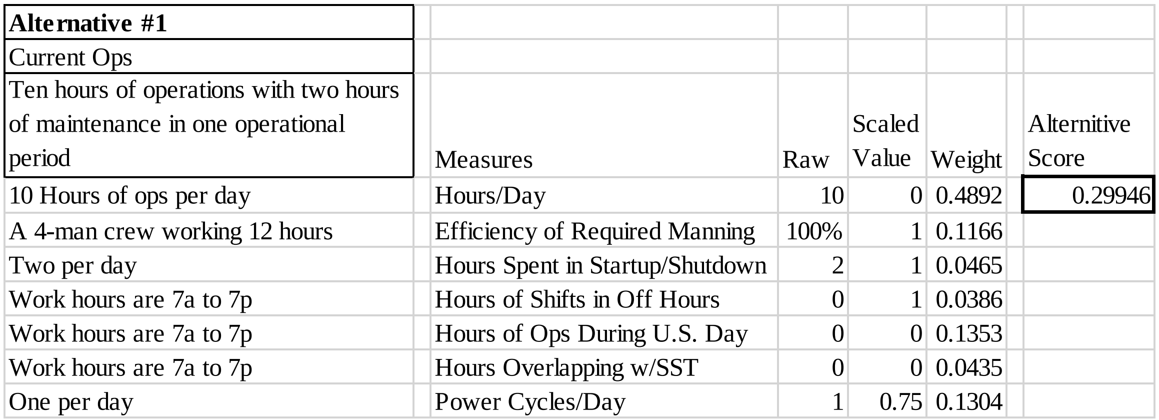
No methodology exists that perfectly captures every aspect of a decision, especially decisions as complex as a radar system, but the VFT method allows the decision authorities to focus on only the parameters they value. This limits bias while normalizing the measures they are comparing. Additionally, the tools at the end of the process (deterministic analysis and sensitivity analysis) deepen the insight into the alternatives.  This investigation continues by scoring each of the alternatives and performing the deterministic and sensitivity analyses.

# IV. Analysis and Results

In the previous chapter, the first six steps of the Value Focused Thinking (VFT) process were accomplished. In this chapter, the process continues with steps seven, eight, and nine. After developing the alternatives in the previous chapter, they are scored and then ordered from highest score to lowest. The chapter concludes with sensitivity analysis performed on all the measures. This chapter contains the analysis processes necessary for the final step of the VFT process: Results and Conclusions.

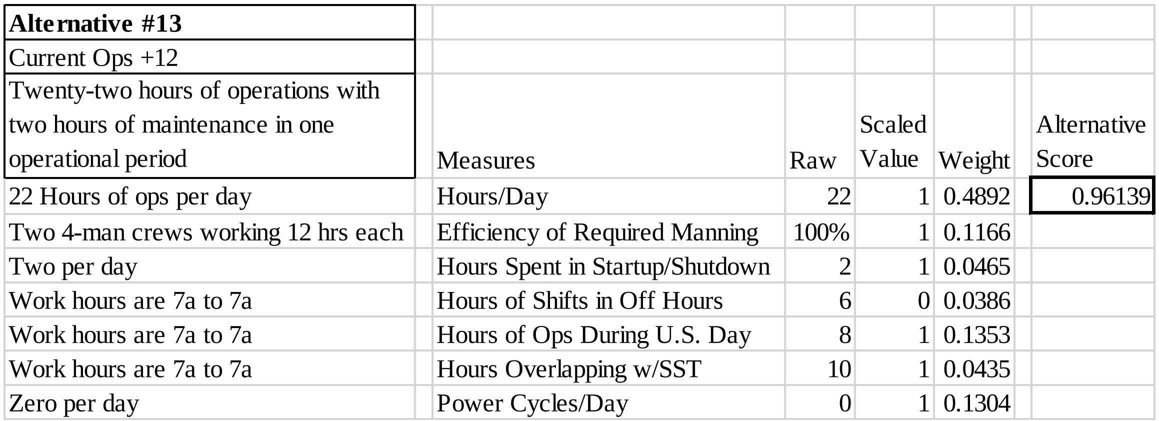
## VFT Step 7: Alternative Scoring

With the value hierarchy created, measures weighted, and alternatives identified, the VFT process continues by scoring each of the alternatives. Each of the 32 alternatives received value scores based on the individual weighted measures described in the previous chapter. All 32 alternatives are shown in Appendix B with the raw and component scores. Figures 15 and 16 represent the scoring for two examples; one is the current operations alternative and the other is a representative alternative.



| | | | | | |
|---|---|---|---|---|---|
| **Alternative #1** | | | | | |
| Current Ops | | | | | |
| Ten hours of operations with two hours of maintenance in one operational period | Measures | Raw | Scaled Value | Weight | Alternitive Score |
| 10 Hours of ops per day | Hours/Day | 10 | 0 | 0.4892 | 0.29946 |
| A 4-man crew working 12 hours | Efficiency of Required Manning | 100% | 1 | 0.1166 | |
| Two per day | Hours Spent in Startup/Shutdown | 2 | 1 | 0.0465 | |
| Work hours are 7a to 7p | Hours of Shifts in Off Hours | 0 | 1 | 0.0386 | |
| Work hours are 7a to 7p | Hours of Ops During U.S. Day | 0 | 0 | 0.1353 | |
| Work hours are 7a to 7p | Hours Overlapping w/SST | 0 | 0 | 0.0435 | |
| One per day | Power Cycles/Day | 1 | 0.75 | 0.1304 | |

Figure 15. Scored Alternative for Current Operations



| | | | | | |
|---|---|---|---|---|---|
| **Alternative #13** | | | | | |
| Current Ops +12 | | | | | |
| Twenty-two hours of operations with two hours of maintenance in one operational period | Measures | Raw | Scaled Value | Weight | Alternative Score |
| 22 Hours of ops per day | Hours/Day | 22 | 1 | 0.4892 | 0.96139 |
| Two 4-man crews working 12 hrs each | Efficiency of Required Manning | 100% | 1 | 0.1166 | |
| Two per day | Hours Spent in Startup/Shutdown | 2 | 1 | 0.0465 | |
| Work hours are 7a to 7a | Hours of Shifts in Off Hours | 6 | 0 | 0.0386 | |
| Work hours are 7a to 7a | Hours of Ops During U.S. Day | 8 | 1 | 0.1353 | |
| Work hours are 7a to 7a | Hours Overlapping w/SST | 10 | 1 | 0.0435 | |
| Zero per day | Power Cycles/Day | 0 | 1 | 0.1304 | |

Figure 16. Scored Alternative for Current Ops +12

## VFT Step 8: Deterministic Analysis

Following the scoring of measures, the total weighted scores of the alternatives are combined using the value function, which is derived from the value hierarchy, to create a single value for each alternative. This process is the deterministic analysis and is step eight in the ten-step VFT process. This single value allows each alternative to be compared and ranked to find the alternative with the most value. The following table (Table 3) shows the ranked order of the 32 alternatives with their value score.

Table 3. Ranked Order of Alternatives with Scores

| Alternative # | Name | Description | Score |
|---|---|---|---|
| 13 | Current Ops +12 | Twenty-two hours of operations with two hours of maintenance in one operational period | 0.9614 |
| 20 | Two Sets of 11 | Two 11-hour ops periods with 1 hour of maintenance with each period per day | 0.9614 |
| 12 | Current Ops +11 | Twenty-one hours of operations with two hours of maintenance in one operational period | 0.8764 |
| 11 | Current Ops +10 | Twenty hours of operations with two hours of maintenance in one operational period | 0.8473 |
| 19 | Two Sets of 10 | Two 10-hour ops periods with 1 hour of maintenance with each period per day | 0.7821 |
| 23 | Three Sets of 7 | Three 5-hour ops periods with 1 hour of maintenance with each block per day | 0.7809 |
| 10 | Current Ops +9 | Nineteen hours of operations with two hours of maintenance in one operational period | 0.7610 |
| 9 | Current Ops +8 | Eighteen hours of operations with two hours of maintenance in one operational period | 0.7232 |
| 18 | Two Sets of 9 | Two 9-hour ops periods with 1 hour of maintenance with each period per day | 0.7005 |
| 27 | Flipped 18 hr | flipped work hours in an 18 hour shift. 16 hours of ops with 2 hours of maintenance support each day. | 0.6842 |
| 31 | Shifted 18 - Night | 18 hours shift shifted to start at 12p. With 16 hours of ops and 2 hours of maintenance. | 0.6842 |
| 25 | Safety Crew 1 hr | Three 6-hour ops periods with 1 hour of maintenance on each period per day and monitor while the equipment stays powered on (0 power cycles) | 0.6818 |
| 8 | Current Ops +7 | Seventeen hours of operations with two hours of maintenance in one operational period | 0.6497 |
| 30 | Shifted 18 - Day | 18 hours shift shifted to start at 12a. With 16 hours of ops and 2 hours of maintenance. | 0.6457 |
| 7 | Current Ops +6 | Sixteen hours of operations with two hours of maintenance in one operational period | 0.6119 |
| 22 | Three Sets of 6 | Three 5-hour ops periods with 1 hour of maintenance with each block per day | 0.5887 |
| 17 | Two Sets of 8 | Two 8-hour ops periods with 1 hour of maintenance with each period per day | 0.5852 |
| 24 | Safety Crew 2 hr | Three 5-hour ops periods with 1 hour of maintenance on each period per day and monitor while the equipment stays powered on (0 power cycles) | 0.5595 |
| 6 | Current Ops +5 | Fifteen hours of operations with two hours of maintenance in one operational period | 0.5384 |
| 5 | Current Ops +4 | Fourteen hours of operations with two hours of maintenance in one operational period | 0.5006 |
| 16 | Two Sets of 7 | Two 7-hour ops periods with 1 hour of maintenance with each period per day | 0.4950 |
| 26 | Flipped Ops | Current operations with flipped work hours. 10 hours of ops with 2 hours of maintenance support each day. | 0.4396 |
| 4 | Current Ops +3 | Thirteen hours of operations with two hours of maintenance in one operational period | 0.4275 |
| 21 | Three Sets of 5 | Three 5-hour ops periods with 1 hour of maintenance with each block per day | 0.4198 |
| 29 | Midnight - Noon | 12 hour shift starting at 12a and ending at 12p | 0.4012 |
| 28 | Noon - Midnight | 12 hour shift starting at 12p and ending at 12a | 0.3462 |
| 15 | Two Sets of 6 | Two 6-hour ops periods with 1 hour of maintenance with each period per day | 0.3435 |
| 3 | Current Ops +2 | Twelve hours of operations with two hours of maintenance in one operational period | 0.3197 |
| 1 | Current Ops | Ten hours of operations with two hours of maintenance in one operational period | 0.2995 |
| 2 | Current Ops +1 | Eleven hours of operations with two hours of maintenance in one operational period | 0.2323 |
| 14 | Two Sets of 5 | Two 5-hour ops periods with 1 hour of maintenance with each period per day | 0.2153 |
| 32 | Shifted Sets of 5 | Two five-hour shift shifted to start at 4a and 4p. | 0.1689 |

The highest scored alternative was Alternative 13 with a total score of 0.9614. This alternative operates the radar for the maximum amount of time per day, which is 22 hours of operations with 2 hours of scheduled maintenance. The lowest scoring alternative was alternative 25 with a score of 0.1689. This alternative split the 10 hours of operations into two operational periods with one hour of maintenance on each period. This leads to the fewest operating hours investigated in this research and also results in manning that is inefficient due to the constraint of not having work shifts scheduled for less than eight hours. The combination of wasted manning and minimum operating hours created the lowest score of the alternatives.

Two pairs of alternatives have the same scores. Alternatives 13 and 20 were developed with different processes; one single shift versus two shifts on opposite sides of the day. When the operating hours reached their maximum possible, 22 hours per day, they effectively became the same alternative with all the measures scoring the same. Alternatives 27 and 31 have the same number of work hours but the hours are in different parts of the day. The hours used for these created the same effect on the scores even though the work hours are different.

The scores are well distributed between the highest and lowest scoring alternatives with the difference between scores for two adjacent alternatives being less than 0.04 points with only six exceptions. The largest gap is between the highest scored alternatives (13 and 20) and alternative 12 with a drop in value score of 0.085. This large drop is attributed to a reduction in manning efficiency and going from zero power cycles to one power cycle. Both these measures are weighted highly in the value hierarchy. The other exceptions with larger score gaps have no significant attributable cause for the slightly larger gap. The analysis identified no clusters in the alternative scores.

A clear trend is visible in the score with increasing operating hours; there is an increase in value score even when manning inefficiencies and the other measures are factored in.  This is likely due to the high weight assigned to the operating hours.  This level of weighting was deliberately selected based on inputs from users of the data and from published Air Force and Space Force guidance.  The next step in the VFT process applies sensitivity analysis to the alternative scores to find alternatives most affected by changes to the measure's weights.

### VFT Step 9:  Sensitivity Analysis

While the initial ranking of the alternatives is useful, it assumes that weights from the value hierarchy are perfect.  This is not the case; these values will always have some level of subjectivity to them.  As leaders come and go from the C-Band Australia radar program, the measures will be valued differently by different people.  In the case of this research, assumptions were made on the weights based on past experiences and review of existing Space Domain Awareness (SDA) literature.  For that reason, step nine, sensitivity analysis, has added importance.  By performing the sensitivity analysis, it is possible to see how the measure's weights impact the overall value scores.

Varying the weight of each of the seven measures individually from 0 to 1 shows the impact that measure has on the overall alternative scores.  At the same time one measure's weight is varied, the other 6 measure's weights receive a proportional adjustment to maintain the original relative weights.  Due to the complexity of scoring the 32 alternatives with the sensitivity analysis, only the top ten alternatives from the original weighting were evaluated.  Focusing on these top scores removes the low performing alternatives and allows the analysis to focus on just the scores of interest.

Table 4 shows the top ten alternatives with their alternative number, short name, and their original value score.

Table 4. Top Ten Alternatives from Original Weighted Scores

| Alternative # | Name | Description | Score |
|---|---|---|---|
| 13 | Current Ops +12 | Twenty-two hours of operations with two hours of maintenance in one operational period | 0.9614 |
| 12 | Current Ops +11 | Twenty-one hours of operations with two hours of maintenance in one operational period | 0.8764 |
| 11 | Current Ops +10 | Twenty hours of operations with two hours of maintenance in one operational period | 0.8473 |
| 19 | Two Sets of 10 | Two 10-hour ops periods with 1 hour of maintenance with each period per day | 0.7821 |
| 23 | Three Sets of 7 | Three 5-hour ops periods with 1 hour of maintenance with each block per day | 0.7809 |
| 10 | Current Ops +9 | Nineteen hours of operations with two hours of maintenance in one operational period | 0.7610 |
| 9 | Current Ops +8 | Eighteen hours of operations with two hours of maintenance in one operational period | 0.7232 |
| 18 | Two Sets of 9 | Two 9-hour ops periods with 1 hour of maintenance with each period per day | 0.7005 |
| 27 | Flipped 18 hr | flipped work hours in an 18 hour shift. 16 hours of ops with 2 hours of maintenance support each day. | 0.6842 |
| 25 | Safety Crew 1 hr | Three 6-hour ops periods with 1 hour of maintenance on each period per day and monitor while the equipment stays powered on (0 power cycles) | 0.6818 |

Sensitivity analysis was first applied to the “Hours/Day” measure. As the “Hours/Day” weight changed, alternative 13 remained the highest scoring alternative; however, alternatives 23 and 27 saw large changes. Alternative 23 was a middle performing alternative under the original weight but swung from the lowest performer when “Hours/Day” was a zero weight and to the second highest alternative when it was a weight of one. The opposite was true for alternative 27 which starts with a high score and quickly drops to the lowest scored alternative when the weight for “Hours/Day” is varied from zero to one. Overall, this measure does not see much impact to weighting changes with no change to the top three alternatives until the weights are changed by about +/-20%. Figure 17 shows the movement of all ten alternatives under investigation and includes a vertical line with the original global weight.

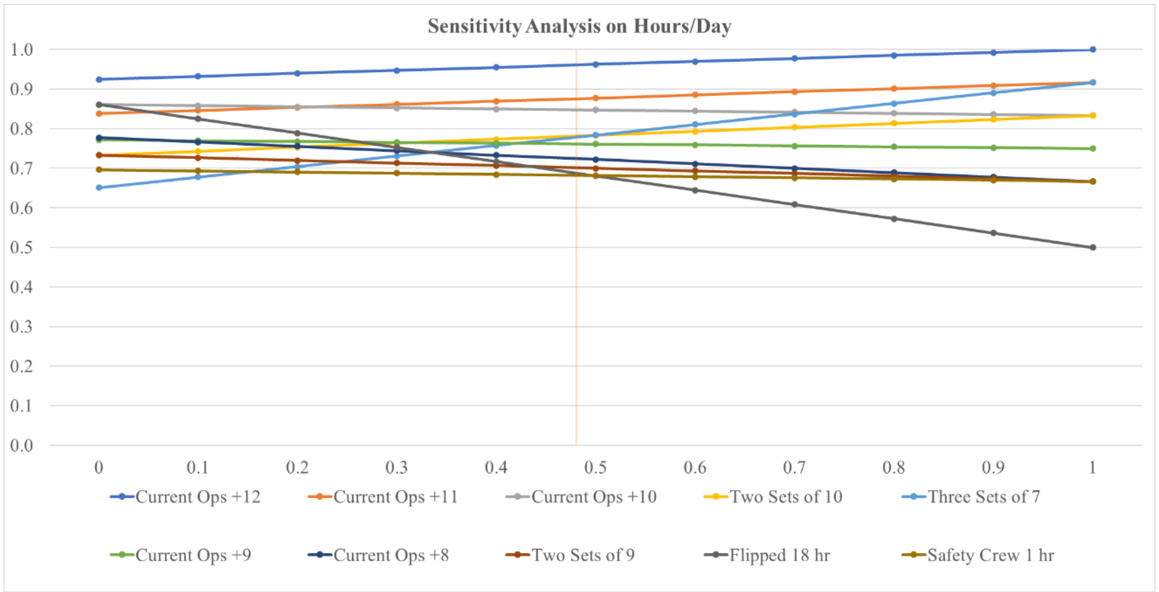


Figure 17. Sensitivity Analysis on "Hours/Day"

Continuing to the next measure, "Efficiency of Required Manning", the sensitivity analysis found that nine of the ten alternatives saw an increase in overall score as the "Efficiency of Required Manning" weight increases. Alternatives 12 and 10 only saw a small increase in score but it was none the less an increase. The outlier was alternative 25; as "Efficiency of Required Manning" increased in weight, the score for alternative 25 quickly approached zero due to this alternative only having an efficiency of 75% and receiving a score of zero for this measure. Figure 18 shows the overall impact of the "Efficiency of Required Manning" sensitivity analysis.

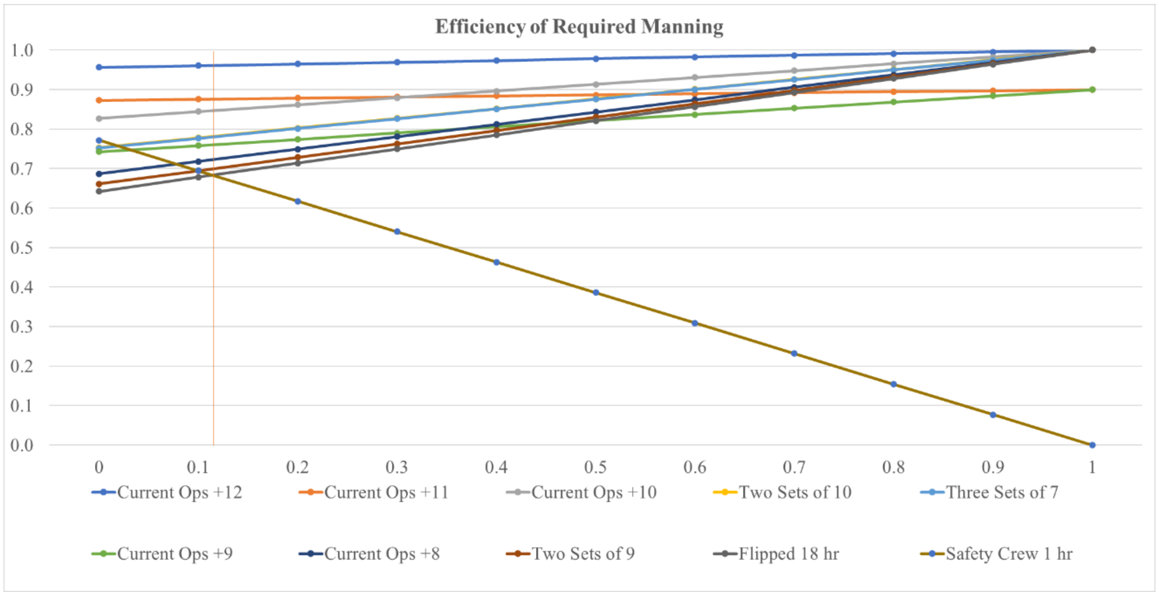


Figure 18. Sensitivity Analysis on “Efficiency of Required Manning”

In the sensitivity analysis for “Hours Spent in Startup/Shutdown”, all the alternatives have an increase in score. The only alternative not ultimately reaching a score of one was alternative 23. This alternative only had a slight score increase and ultimately received a maximum score of 0.8 when “Hours Spent in Startup/Shutdown” was weighted as one. This is because alternative 23 was the only alternative in the top ten with more than two hours in startup/shutdown. Figure 19 clearly shows the difference between alternative 23’s behavior and the other nine alternatives.

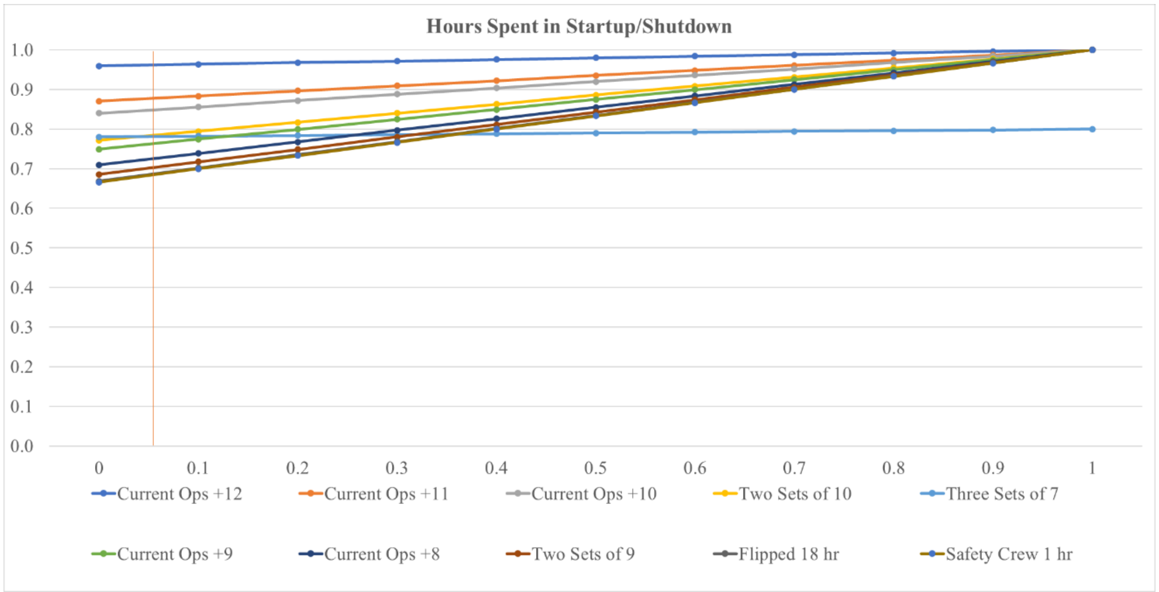


Figure 19. Sensitivity Analysis on "Hours Spent in Startup/Shutdown"

The impact of varying "Hours of Shift in Off Hours" did not yield any noticeable differences between the ten alternatives. All had steadily decreased value scores and reached zero when "Hours of Shift in Off Hours" reached one with the only differentiating characteristic being the slope of the decrease and that was related to their original value scores. Figure 20 shows this steady decrease in value score will all the alternatives converging on zero and the order of alternatives not changing over the analysis.

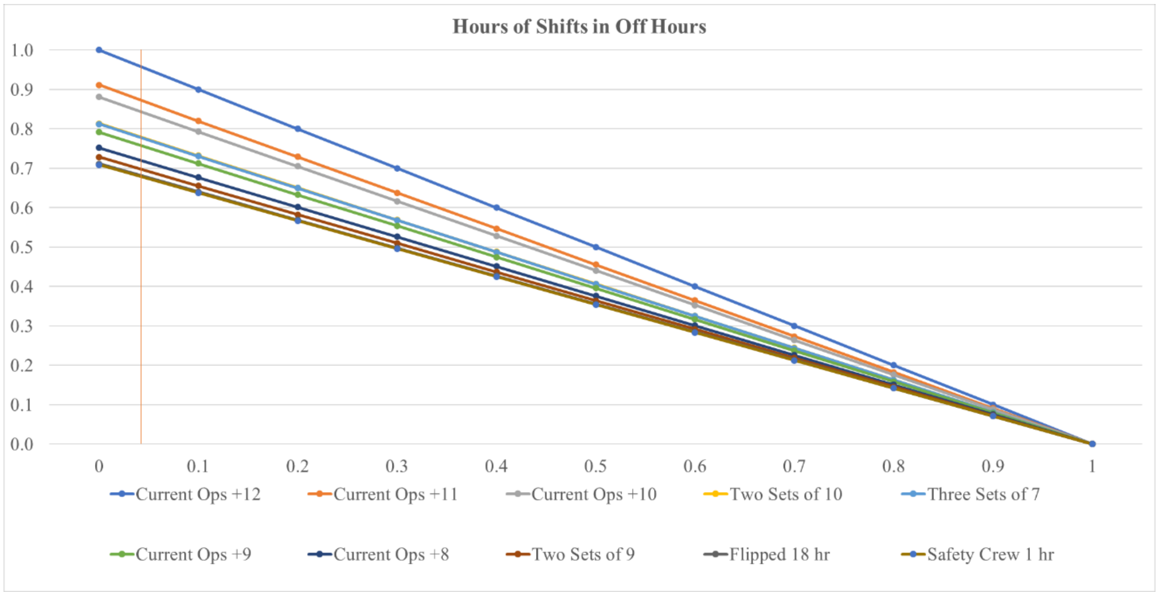


Figure 20. Sensitivity Analysis on “Hours of Shift in Off Hours”

Applying the sensitivity analysis to the “Hours of Ops During U.S. Day” measure resulted in a similar effect as the “Hours Spent in Startup/Shutdown” measure. In this case, two alternatives converged on 0.75 and the other eight converged on 1. Alternative 10 had a slight decrease in value score and alternative 9 had a slight increase before ending at 0.75. In the case of these two alternatives, both had less than the maximum hours during the U.S. day. For this reason, they arrived at a score of 0.75 when the “Hours of Ops During U.S. Day” reached a weight of 1. Figure 21 clearly shows the effects of the sensitivity analysis and the two separate paths that the alternatives take.

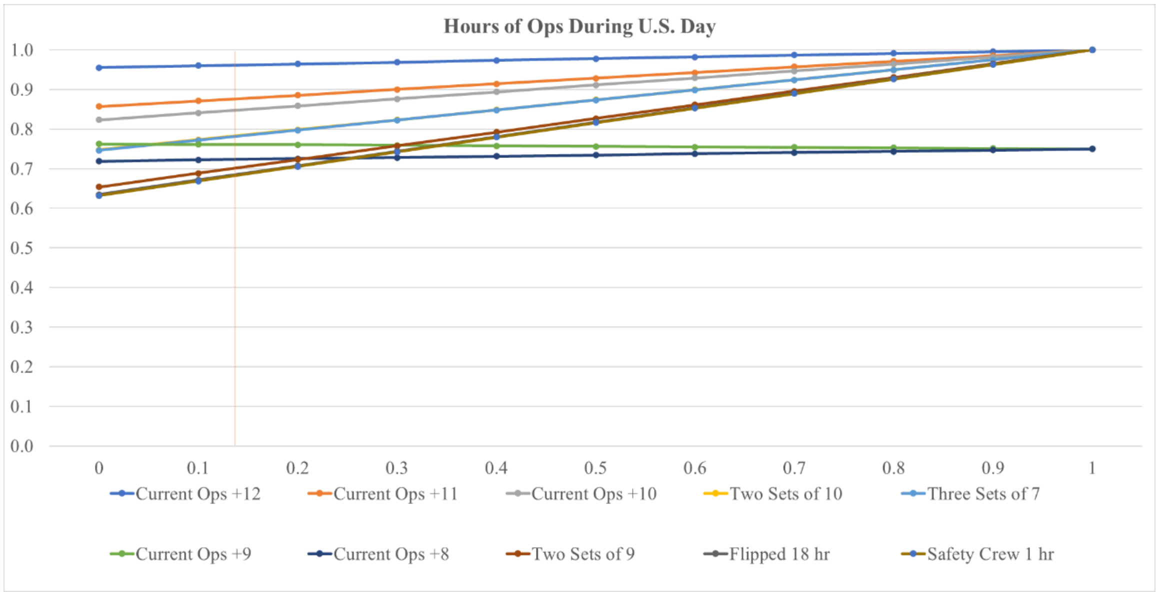


Figure 21. Sensitivity Analysis on “Hours of Ops During U.S. Day”

The result of the sensitivity analysis on the “Hours Overlapping w/SST” measure is another example with all the alternatives converging on one with the exception of a single alternative. Here it is alternative 9 and it increases its value score to 0.8. As with the previous example, alternative 9 is not maximizing the number of overlapping hours tracked in this measure whereas the other alternatives do. Figure 22 shows the sensitivity analysis for this measure is comparable to the “Hours of Ops During U.S. Day” and “Hours Spent in Startup/Shutdown” figures.

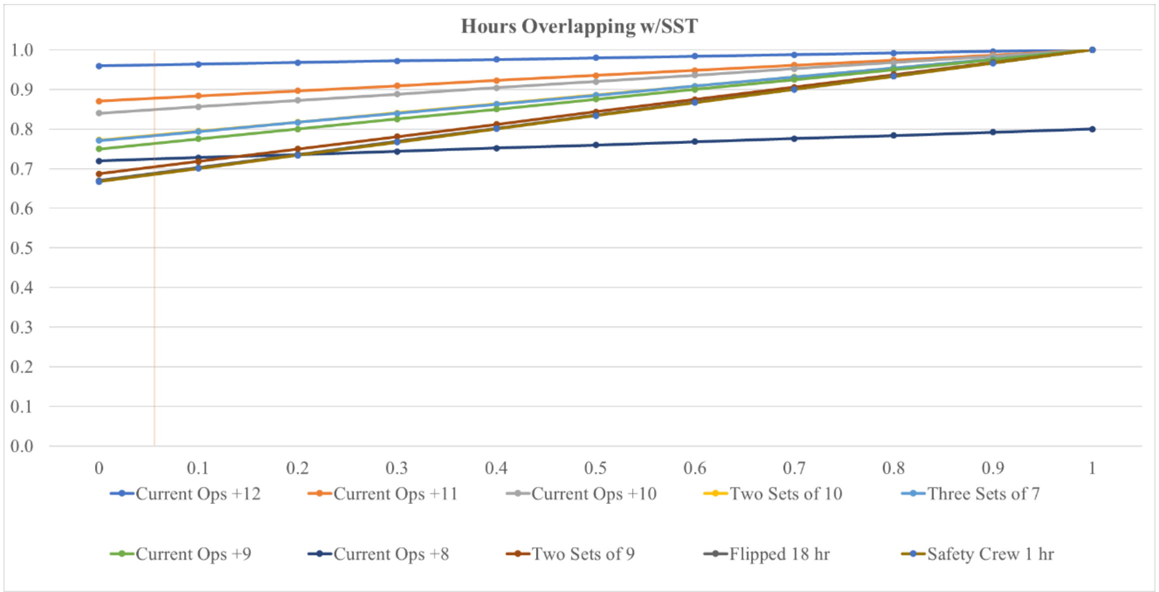


Figure 22. Sensitivity Analysis on "Hours Overlapping with SST"

The final measure to receive the sensitivity analysis was "Power Cycles/Day," and this analysis has the most interesting outcome. In most of the previous cases, the alternatives converged on only one or two value scores when the weight under investigation was weighted at 1. In this case, there are four different scores that are converged on and the rank order of the alternatives changes. A good example, as seen in Figure 23, is alternative 23. This alternative starts with a tie as the second highest score when "Power Cycles/Day" was weighted 0, then quickly drops to a middle-ranked alternative at the original global weight, before finally arriving at 0 value score when "Power Cycles/Day" is weighted 1. A similar effect is seen with alternatives 19 and 18 but to a lesser extent. The only alternatives with any significant increase in value score are alternatives 13 and 25. In the case of alternative 25, it ranges from the lowest ranked score when "Power Cycles/Day" is at 0 and at the original global weight but is tied for the highest ranked alternative for a weight of 1.  This alternative received the maximum score for having zero power cycles each day but also received the minimum score for the efficiency of the manning.  These two reasons drove it to be both a high performing and low performing alternative for this sensitivity analysis.

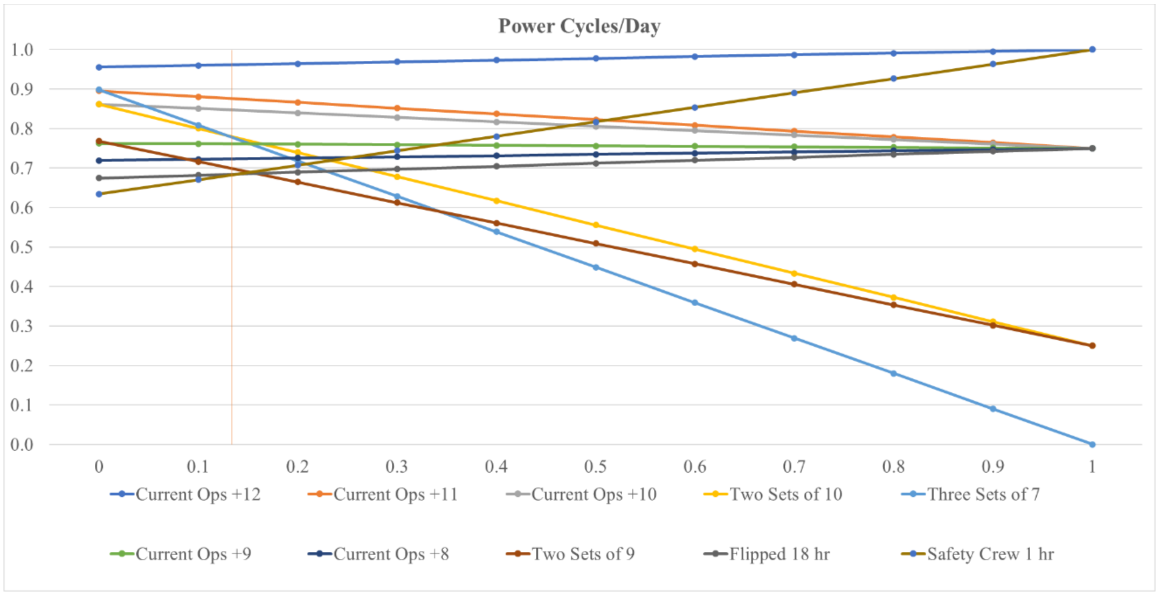


Figure 23.  Sensitivity Analysis on "Power Cycles/Day"

## Analysis Summary

In every step of the sensitivity analysis, regardless of how other alternatives change ranking, there is one alternative that is always the highest scored alternative, alternative 13.  This alternative sees minimal impact from varying the weights of the measures with a variation of less than 0.1 for every scenario except one.  Other alternatives regularly see variations greater than 0.3 and in the case of alternative 23, the score swings by 0.9 for the "Power Cycles/Day" analysis.  Across all possible measure weights, alternative 13, Current Ops +12, was the least sensitive to change and always the highest value score.

This investigation continues in the next chapter with the final step of the VFT process. This chapter presented the details of the analysis phase of the investigation with scoring of alternative followed by deterministic and sensitivity analysis on the scores and weights. The final chapter will contain full summary of the result as well as investigation conclusions and recommendations for further research.

# V.  Conclusions and Recommendations

This chapter concludes this research work by explaining the characteristics of the alternative that created the highest value and provides details of the recommended alternative.  Chapter V will also explore where other alternatives failed to reach a high value score.  Finally, a recommendation will be described for the best number of operating hours for the C-Band Australia radar that maximizes the radar’s value.  Additionally, this chapter will identify potential areas of further research.

## VFT Step 10:  Conclusions and Recommendations

The VFT process finishes with the tenth step:  recommendation.  This step is the culmination of the VFT process and presents the decision-maker with the findings of the analysis.  This step finds the useful information for the investigation, summarizes it, and ultimately recommends an alternative for the decision-maker to act on.  As explained by Keeney (1992), the VFT process does not replace the decision-maker.  The opposite is true since decision-maker involvement is necessary to inform the VFT process and ultimately the decision-maker has the ability to accept, reject, or recommend modifications to the process’s recommendation.  In the case of this thesis, the decision-maker was not available.  Explained below are the conclusion and recommendations for this research.

## Recommendation to the Decision-Maker

Of the 32 alternatives developed in this investigation, alternative 13 performed the best. This alternative involves an increase from the current operating hours to the maximum hours available, with 22 hours in operations and 2 hours for planned maintenance. By adding 12 hours to the current operational schedule, the overall value score increased significantly. Beyond just the "Hours per Day" measure, this alternative also received maximum scores on every measure except one. By creating an around-the-clock operator and maintainer need, the "Efficiency of Required Manning" measure was at 100% efficiency and received the maximum value score. "Hours Spent in Startup/Shutdown", "Hours of Ops During U.S. Day", and "Hours Overlapping w/SST" all earned maximum value scores from the 24/7 schedule. Finally, with the radar operating nearly the full day with only 2 hours for planned maintenance, the radar hardware does not need to be powered down. By having zero power cycles, the radar hardware is less likely to receive damage from power cycles and the alternative received the full score on the "Power Cycle/Day" measure.

The only area of weakness for this alternative was with the "Hours of Shift in Off Hours" measure. This measure considers the fact that various factors make overnight shifts undesirable and less valuable. First, working during normal daytime hours is a more natural schedule and has less impact on the crews who operate and maintain the radar. From the staffing perspective, it can be more difficult to hire competent workers if they know overnight shifts are a possibility. It has also been shown that night shift workers are more likely to experience workplace injuries (Stimpfel et al., 2015). Where 24/7 operations will gain high scores on other measures, it will naturally receive low scores on this measure. Other alternatives shifted hours around so that alternatives with nearly the full number of operating hours were able to avoid some of the penalty of the "Hours of Shift in Off Hours" measure, but they could not completely avoid this penalty without significant reductions to the "Hours per Day" measure.

Bottom line, the recommendation of alternative 13 achieves the maximum scores for the decision-maker's values. However, the range between the top alternative and the third-place alternative was only 0.114 with alternative 13 receiving a 0.961, alternative 12 receiving a 0.876, and alternative 11 receiving a 0.847. All three are high performing alternatives and should be presented to the decision-maker. Additionally, the current operational schedule of 10 hours of operations and 2 hours of maintenance per day should be presented to show that it was the fourth worst out of the 32 alternatives, receiving a score of only 0.2995. This demonstrates the need for a change in schedule with an emphasis on how much potential value is lost. Sensitivity analysis was not considered for this alternative because only the most extreme shifts in weighting would raise the score to a point where it becomes competitive. Finally, it should be noted that this research did not have the decision-maker directly create or weight the measures; for this reason, the sensitivity analysis has extra importance. Even with shifts in the weighting of the measures, Alternative 13 remains at the top in all but the most extreme scenarios. This alternative maximizes the operating hours to get the most value from the C-Band Australia radar.

## Recommendations for Future Work

This research investigated the aspects of the C-Band Australia radar that provide value to the decision-makers. Through this investigation, the individual characteristics for the radar and the site contributed to the final conclusion; however, this work uncovered areas where follow-up research may be warranted. Discussed below are four possible areas for future research.

### Enterprise SDA Investigation

This research deliberately limited the scope of the investigation to just the C-Band Australia radar. This was done to allow for a dedicated and focused effort to address the operating hours of the radar. This also removed variables that would have complicated the investigation and increased the scope beyond what was necessary to answer the question for the C-Band Australia radar. By isolating the variables to only those directly connected to the C-Band Australia radar, it was possible to find exactly what was considered valuable to the decision-maker when deciding on C-Band Australia radar operating hours.

In the future though, the research should be expanded to investigate the entire SDA network and make decisions beyond the operating hour of just a single sensor. Instead, future research should answer enterprise level questions. Examples of enterprise questions would be whether to add or remove sensors to the network or decisions comparing the opportunity costs of operating hours across the full network. By considering the values from an enterprise perspective, a more complete SDA picture is possible.

## Source of Staffing for Increased Operating Hours

In this research, constraints were placed on how staffing was added to support the changes in operating hours. Those constrains were explained in detail along with the rationale behind creating them; however, with further research, it might be possible to identify staffing options not considered in this research that would meet the needs of the alternatives. This would require experience or research into the intricacies of personnel management.

Further staffing considerations should investigate the possibility of sharing operations personnel between Australia and the U.S. Currently, Australian military members operate the radar. The U.S. military also operates radars with similar capabilities and missions. With the similarities between the operational units, it would be possible for the U.S. military to take over some of the new operating hours for the C-Band Australia radar. This concept of operations would require hardware modifications to both the radar and the gaining operational unit to allow for the remote operations. One potential benefit of this could include strengthening the partnership between Australia and U.S. The importance of this benefit and discovery of other benefits would be found with further research in the area.

## Hardware Failure Rates

During the relocation and initial operations of the C-Band Australia radar, the U.S. program office commissioned a sustainment study through Riverside Research Institute in New York. This report by Riverside Research Institute (2016) decomposed the full parts list for the radar and investigated each part to find the Mean Time Between

Failure (MTBF) rates. Since this work occurred at the beginning of radar operations, the MTBF values were based on similar items, reference values, and engineering judgement and not on operational failure rates from the radar. Now that the C-Band Australia radar has been in operation for several years, it would be valuable to re-accomplish the study and use the operational data gathered since the radar started full operations. Armed with this improved MTBF data, it would be possible to better evaluate the impacts that changing the operational hours has on the radar hardware. The hardware health measure in this research could be further broken down to include the impacts on the hardware.

### Measure Weighting

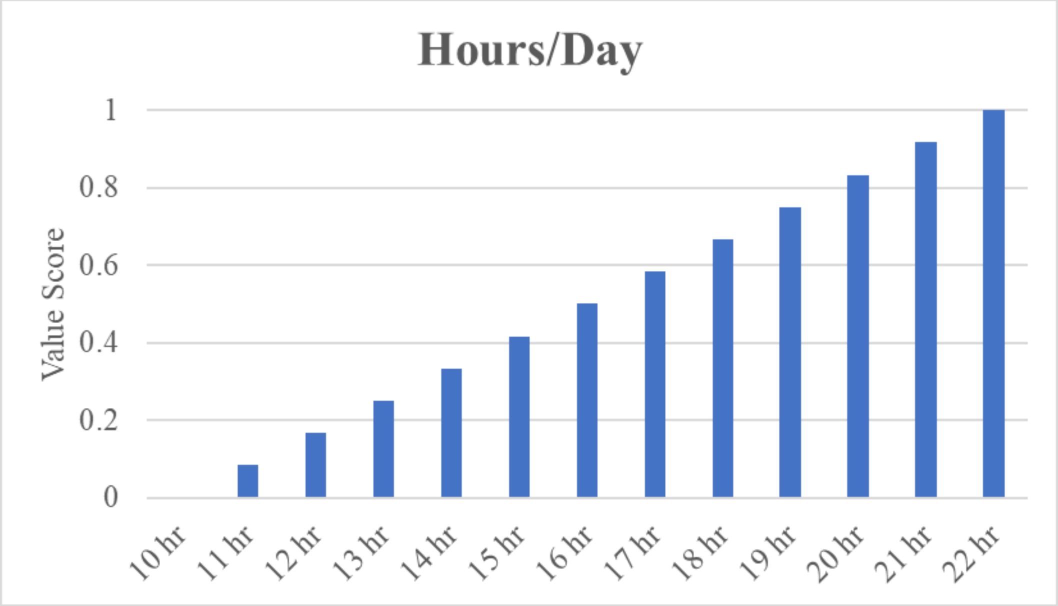
Finally, this research could be improved with dedicated involvement from the decision-maker. As explained in previous chapters, the decision-maker sponsored the work but was not available to create the value hierarchy and weights. While documentation, published guidance, and engineering judgment are proven methods of building and weighting the value hierarchy (Parnell, 2007), having direct involvement from the decision-maker will further refine the analysis from this research. This decision-maker involvement is further complicated by the fact that multiple offices are involved in the decision-making process. From the U.S. program office, the Australian program office, and the operational units, all decision-makers would need to dedicate time to advance this research. Even with those challenges, the VFT methodology has been shown to work and this research is another example of that success. Based on these reasons, it is recommended that this additional effort be undertaken to continue the advancement of the research.

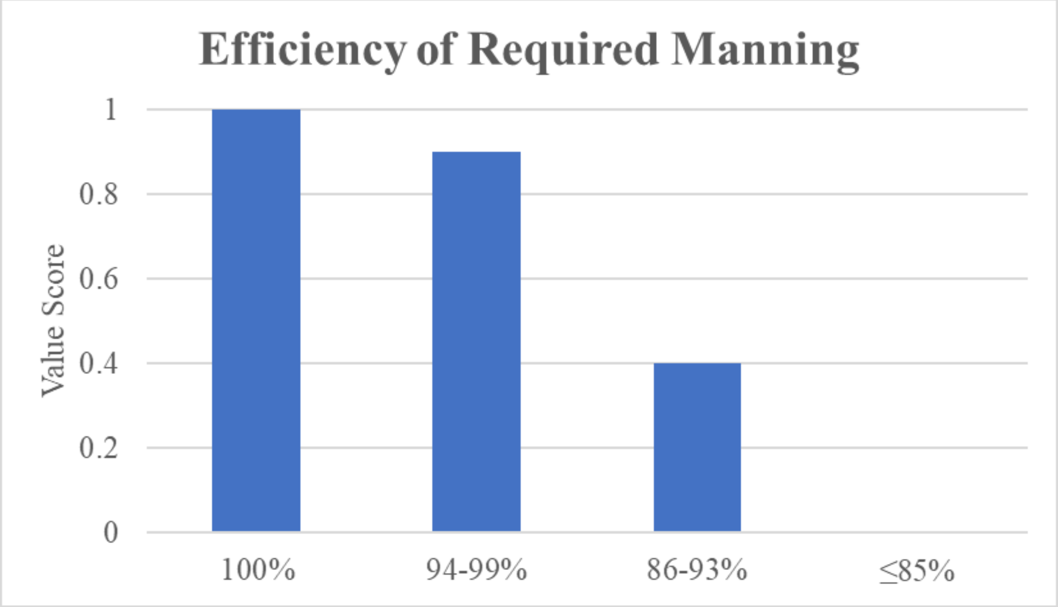
Related to this topic, it would be possible to further refine the development of the value functions of the measures. Currently, the value functions are created using guiding documents, subject matter expertise, or decision-maker inputs when available. Alternatively, it would be possible to apply Bayesian statistical inference to create a probability function for the value functions, then perform a simulation over that probability to determine the shape of the value function curves. It is uncommon to apply Bayesian statistical inference to the value functions; however, it may provide useful results when direct decision-maker engagement is not possible.

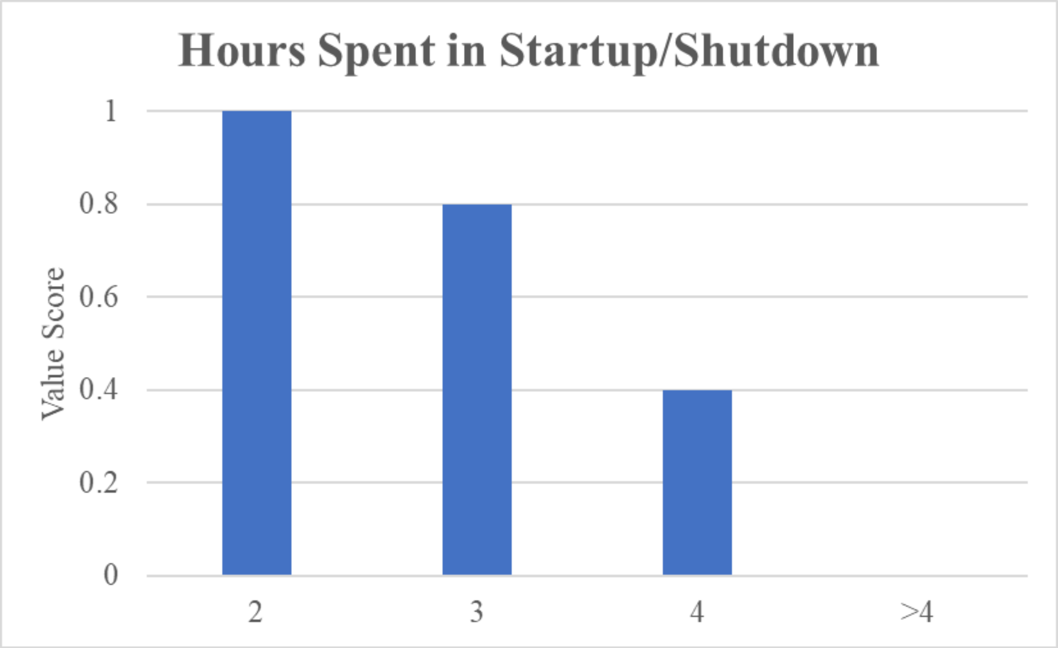
### Concluding Remarks

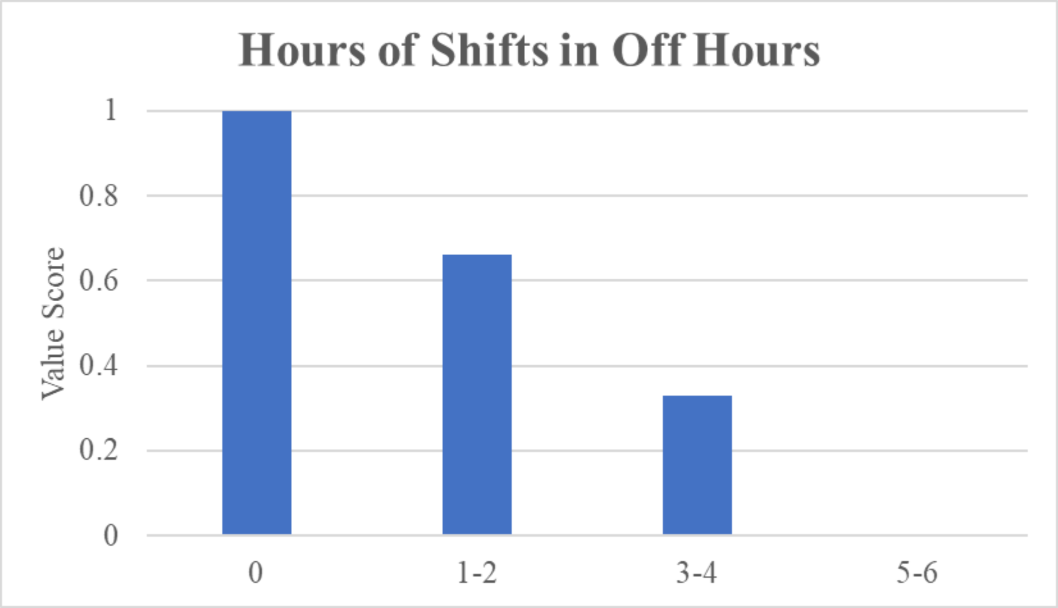
This research has two significant outcomes. The first is the research objective. It is recommended that the C-Band Australia radar operate 22 hours per day and reserve 2 hours per day for maintenance. This alternative maximizes the values created in this process and was the best performing alternative. The second outcome was demonstrating that the VFT process is a useful tool to evaluate operating hours of and SDA system. By engaging with decision-makers or studying published guidance, it is possible to build a value hierarchy, appropriately weight the measures, score the alternatives, conduct analysis on the results, and arrive at an actionable recommendation. The decision-makers for the C-Band Australia radar will be able to use both these outcomes in the future for both C-Band Australia radar operating hour considerations and on other SDA sensor decisions.

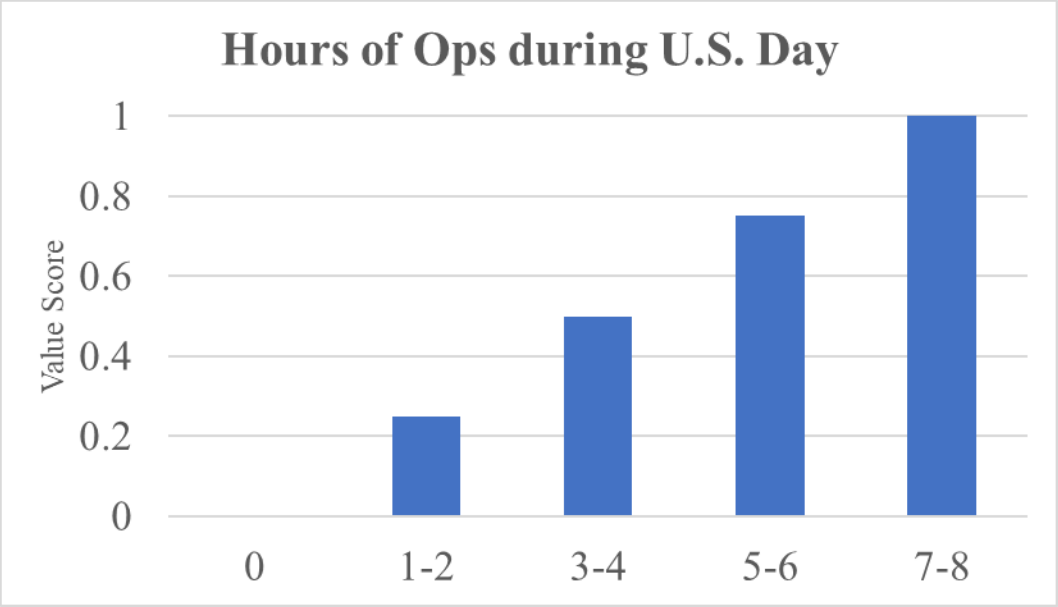
# Appendix A.  Scaling Functions

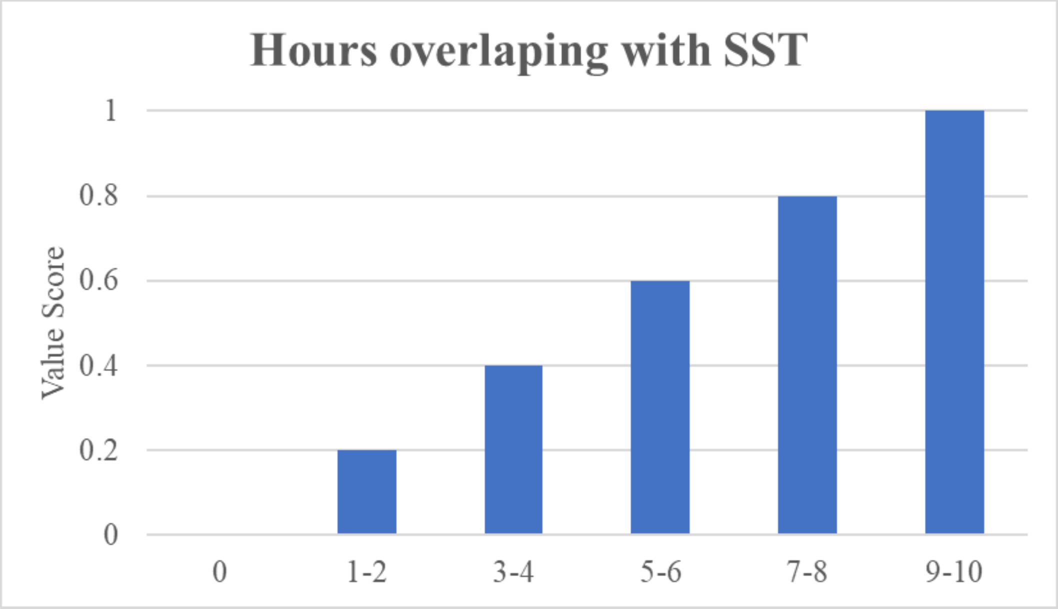


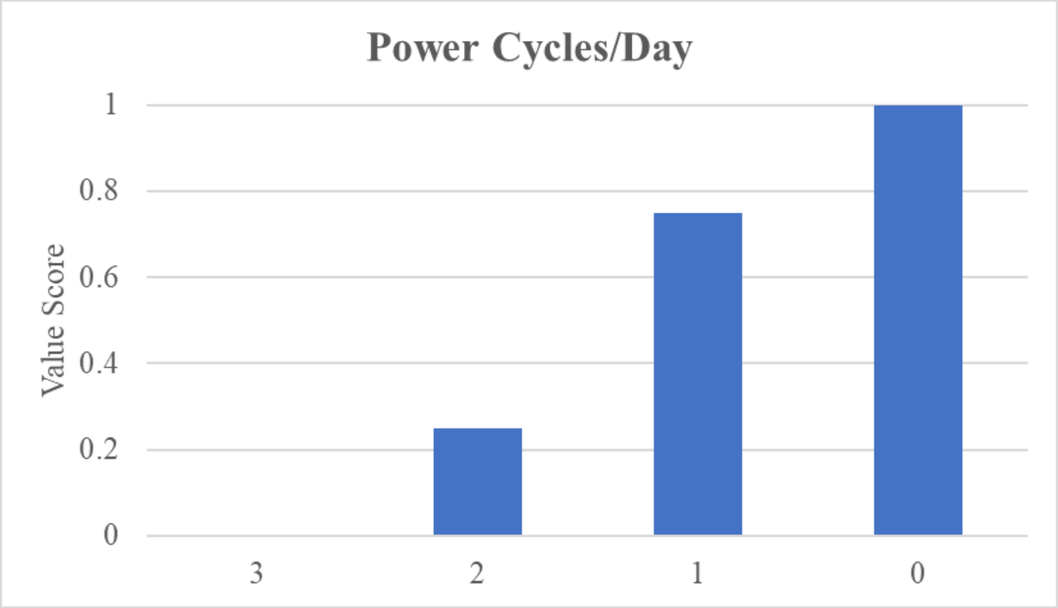



Hours Spent in Startup/Shutdown
Value Score
1
0.8
0.6
0.4
0.2
0
2
3
4
>4


Hours of Shifts in Off Hours
Value Score
1
0.8
0.6
0.4
0.2
0
0
1-2
3-4
5-6


Hours of Ops during U.S. Day
Value Score
1
0.8
0.6
0.4
0.2
0
0
1-2
3-4
5-6
7-8


Hours overlaping with SST
Value Score
1
0.8
0.6
0.4
0.2
0
0
1-2
3-4
5-6
7-8
9-10


Power Cycles/Day
Value Score
1
0.8
0.6
0.4
0.2
0
3
2
1
0

# Appendix B. Scored Alternatives

| **Alternative #1** | | | | | |
|---|---|---|---|---|---|
| Current Ops | | | | | |
| Ten hours of operations with two hours of maintenance in one operational period | Measures | Raw | Scaled Value | Weight | Alternitive Score |
| 10 Hours of ops per day | Hours/Day | 10 | 0 | 0.4892 | 0.29946 |
| A 4-man crew working 12 hours | Efficiency of Required Manning | 100% | 1 | 0.1166 | |
| Two per day | Hours Spent in Startup/Shutdown | 2 | 1 | 0.0465 | |
| Work hours are 7a to 7p | Hours of Shifts in Off Hours | 0 | 1 | 0.0386 | |
| Work hours are 7a to 7p | Hours of Ops During U.S. Day | 0 | 0 | 0.1353 | |
| Work hours are 7a to 7p | Hours Overlapping w/SST | 0 | 0 | 0.0435 | |
| One per day | Power Cycles/Day | 1 | 0.75 | 0.1304 | |

| **Alternative #2** | | | | | |
|---|---|---|---|---|---|
| Current Ops +1 | | | | | |
| Eleven hours of operations with two hours of maintenance in one operational period | Measures | Raw | Scaled Value | Weight | Alternative Score |
| 11 Hours of ops per day | Hours/Day | 11 | 0.083 | 0.4892 | 0.23234 |
| A 4-man crew working 12 hours | Efficiency of Required Manning | 81% | 0 | 0.1166 | |
| Two per day | Hours Spent in Startup/Shutdown | 2 | 1 | 0.0465 | |
| Work hours are 7a to 8p | Hours of Shifts in Off Hours | 0 | 1 | 0.0386 | |
| Work hours are 7a to 8p | Hours of Ops During U.S. Day | 0 | 0 | 0.1353 | |
| Work hours are 7a to 8p | Hours Overlapping w/SST | 1 | 0.2 | 0.0435 | |
| One per day | Power Cycles/Day | 1 | 0.75 | 0.1304 | |

| **Alternative #3** | | | | | |
|---|---|---|---|---|---|
| Current Ops +2 | | | | | |
| Twelve hours of operations with two hours of maintenance in one operational period | Measures | Raw | Scaled Value | Weight | Alternative Score |
| 12 Hours of ops per day | Hours/Day | 12 | 0.167 | 0.4892 | 0.31973 |
| A 4-man crew working 12 hours | Efficiency of Required Manning | 88% | 0.4 | 0.1166 | |
| Two per day | Hours Spent in Startup/Shutdown | 2 | 1 | 0.0465 | |
| Work hours are 7a to 9p | Hours of Shifts in Off Hours | 0 | 1 | 0.0386 | |
| Work hours are 7a to 9p | Hours of Ops During U.S. Day | 0 | 0 | 0.1353 | |
| Work hours are 7a to 9p | Hours Overlapping w/SST | 2 | 0.2 | 0.0435 | |
| One per day | Power Cycles/Day | 1 | 0.75 | 0.1304 | |

| | | | | | |
|---|---|---|---|---|---|
| **Alternative #4** | | | | | |
| Current Ops +3 | | | | | |
| Thirteen hours of operations with two hours of maintenance in one operational period | Measures | Raw | Scaled Value | Weight | Alternative Score |
| 13 Hours of ops per day | Hours/Day | 13 | 0.25 | 0.4892 | 0.42748 |
| A 4-man crew working 12 hours | Efficiency of Required Manning | 94% | 0.9 | 0.1166 | |
| Two per day | Hours Spent in Startup/Shutdown | 2 | 1 | 0.0465 | |
| Work hours are 7a to 10p | Hours of Shifts in Off Hours | 0 | 1 | 0.0386 | |
| Work hours are 7a to 10p | Hours of Ops During U.S. Day | 0 | 0 | 0.1353 | |
| Work hours are 7a to 10p | Hours Overlapping w/SST | 3 | 0.4 | 0.0435 | |
| One per day | Power Cycles/Day | 1 | 0.75 | 0.1304 | |

| | | | | | |
|---|---|---|---|---|---|
| **Alternative #5** | | | | | |
| Current Ops +4 | | | | | |
| Fourteen hours of operations with two hours of maintenance in one operational period | Measures | Raw | Scaled Value | Weight | Alternative Score |
| 14 Hours of ops per day | Hours/Day | 14 | 0.333 | 0.4892 | 0.50060 |
| A 4-man crew working 12 hours | Efficiency of Required Manning | 100% | 1 | 0.1166 | |
| Two per day | Hours Spent in Startup/Shutdown | 2 | 1 | 0.0465 | |
| Work hours are 7a to 11p | Hours of Shifts in Off Hours | 1 | 0.66 | 0.0386 | |
| Work hours are 7a to 11p | Hours of Ops During U.S. Day | 1 | 0.25 | 0.1353 | |
| Work hours are 7a to 11p | Hours Overlapping w/SST | 4 | 0.4 | 0.0435 | |
| One per day | Power Cycles/Day | 1 | 0.75 | 0.1304 | |

| | | | | | |
|---|---|---|---|---|---|
| **Alternative #6** | | | | | |
| Current Ops +5 | | | | | |
| Fifteen hours of operations with two hours of maintenance in one operational period | Measures | Raw | Scaled Value | Weight | Alternative Score |
| 15 Hours of ops per day | Hours/Day | 15 | 0.417 | 0.4892 | 0.53840 |
| A 4-man crew working 12 hours | Efficiency of Required Manning | 94% | 0.9 | 0.1166 | |
| Two per day | Hours Spent in Startup/Shutdown | 2 | 1 | 0.0465 | |
| Work hours are 7a to 12a | Hours of Shifts in Off Hours | 2 | 0.66 | 0.0386 | |
| Work hours are 7a to 12a | Hours of Ops During U.S. Day | 2 | 0.25 | 0.1353 | |
| Work hours are 7a to 12a | Hours Overlapping w/SST | 5 | 0.6 | 0.0435 | |
| One per day | Power Cycles/Day | 1 | 0.75 | 0.1304 | |

| **Alternative #7** | | | | | |
|---|---|---|---|---|---|
| Current Ops +6 | | | | | |
| Sixteen hours of operations with two hours of maintenance in one operational period | Measures | Raw | Scaled Value | Weight | Alternative Score |
| 16 Hours of ops per day | Hours/Day | 16 | 0.5 | 0.4892 | 0.61191 |
| A 4-man crew working 12 hours | Efficiency of Required Manning | 100% | 1 | 0.1166 | |
| Two per day | Hours Spent in Startup/Shutdown | 2 | 1 | 0.0465 | |
| Work hours are 7a to 1a | Hours of Shifts in Off Hours | 3 | 0.33 | 0.0386 | |
| Work hours are 7a to 1a | Hours of Ops During U.S. Day | 3 | 0.5 | 0.1353 | |
| Work hours are 7a to 1a | Hours Overlapping w/SST | 6 | 0.6 | 0.0435 | |
| One per day | Power Cycles/Day | 1 | 0.75 | 0.1304 | |

| **Alternative #8** | | | | | |
|---|---|---|---|---|---|
| Current Ops +7 | | | | | |
| Seventeen hours of operations with two hours of maintenance in one operational period | Measures | Raw | Scaled Value | Weight | Alternative Score |
| 17 Hours of ops per day | Hours/Day | 17 | 0.583 | 0.4892 | 0.64971 |
| A 4-man crew working 12 hours | Efficiency of Required Manning | 95% | 0.9 | 0.1166 | |
| Two per day | Hours Spent in Startup/Shutdown | 2 | 1 | 0.0465 | |
| Work hours are 7a to 2a | Hours of Shifts in Off Hours | 4 | 0.33 | 0.0386 | |
| Work hours are 7a to 2a | Hours of Ops During U.S. Day | 4 | 0.5 | 0.1353 | |
| Work hours are 7a to 2a | Hours Overlapping w/SST | 7 | 0.8 | 0.0435 | |
| One per day | Power Cycles/Day | 1 | 0.75 | 0.1304 | |

| **Alternative #9** | | | | | |
|---|---|---|---|---|---|
| Current Ops +8 | | | | | |
| Eighteen hours of operations with two hours of maintenance in one operational period | Measures | Raw | Scaled Value | Weight | Alternative Score |
| 18 Hours of ops per day | Hours/Day | 18 | 0.667 | 0.4892 | 0.72322 |
| A 4-man crew working 12 hours | Efficiency of Required Manning | 100% | 1 | 0.1166 | |
| Two per day | Hours Spent in Startup/Shutdown | 2 | 1 | 0.0465 | |
| Work hours are 7a to 3a | Hours of Shifts in Off Hours | 5 | 0 | 0.0386 | |
| Work hours are 7a to 3a | Hours of Ops During U.S. Day | 5 | 0.75 | 0.1353 | |
| Work hours are 7a to 3a | Hours Overlapping w/SST | 8 | 0.8 | 0.0435 | |
| One per day | Power Cycles/Day | 1 | 0.75 | 0.1304 | |

| **Alternative #10** | | | | | |
|---|---|---|---|---|---|
| Current Ops +9 | | | | | |
| Nineteen hours of operations with two hours of maintenance in one operational period | Measures | Raw | Scaled Value | Weight | Alternative Score |
| 19 Hours of ops per day | Hours/Day | 19 | 0.75 | 0.4892 | 0.76102 |
| A 4-man crew working 12 hours | Efficiency of Required Manning | 95% | 0.9 | 0.1166 | |
| Two per day | Hours Spent in Startup/Shutdown | 2 | 1 | 0.0465 | |
| Work hours are 7a to 4a | Hours of Shifts in Off Hours | 6 | 0 | 0.0386 | |
| Work hours are 7a to 4a | Hours of Ops During U.S. Day | 6 | 0.75 | 0.1353 | |
| Work hours are 7a to 4a | Hours Overlapping w/SST | 9 | 1 | 0.0435 | |
| One per day | Power Cycles/Day | 1 | 0.75 | 0.1304 | |

| **Alternative #11** | | | | | |
|---|---|---|---|---|---|
| Current Ops +10 | | | | | |
| Twenty hours of operations with two hours of maintenance in one operational period | Measures | Raw | Scaled Value | Weight | Alternative Score |
| 20 Hours of ops per day | Hours/Day | 20 | 0.833 | 0.4892 | 0.84726 |
| A 4-man crew working 12 hours | Efficiency of Required Manning | 100% | 1 | 0.1166 | |
| Two per day | Hours Spent in Startup/Shutdown | 2 | 1 | 0.0465 | |
| Work hours are 7a to 5a | Hours of Shifts in Off Hours | 6 | 0 | 0.0386 | |
| Work hours are 7a to 5a | Hours of Ops During U.S. Day | 7 | 1 | 0.1353 | |
| Work hours are 7a to 5a | Hours Overlapping w/SST | 10 | 1 | 0.0435 | |
| One per day | Power Cycles/Day | 1 | 0.75 | 0.1304 | |

| **Alternative #12** | | | | | |
|---|---|---|---|---|---|
| Current Ops +11 | | | | | |
| Twenty-one hours of operations with two hours of maintenance in one operational period | Measures | Raw | Scaled Value | Weight | Alternative Score |
| 21 Hours of ops per day | Hours/Day | 21 | 0.917 | 0.4892 | 0.87637 |
| A 4-man crew working 12 hours | Efficiency of Required Manning | 96% | 0.9 | 0.1166 | |
| Two per day | Hours Spent in Startup/Shutdown | 2 | 1 | 0.0465 | |
| Work hours are 7a to 6a | Hours of Shifts in Off Hours | 6 | 0 | 0.0386 | |
| Work hours are 7a to 6a | Hours of Ops During U.S. Day | 8 | 1 | 0.1353 | |
| Work hours are 7a to 6a | Hours Overlapping w/SST | 10 | 1 | 0.0435 | |
| One per day | Power Cycles/Day | 1 | 0.75 | 0.1304 | |

| **Alternative #13** | | | | | |
|---|---|---|---|---|---|
| Current Ops +12 | | | | | |
| Twenty-two hours of operations with two hours of maintenance in one operational period | Measures | Raw | Scaled Value | Weight | Alternative Score |
| 22 Hours of ops per day | Hours/Day | 22 | 1 | 0.4892 | 0.96139 |
| Two 4-man crews working 12 hrs each | Efficiency of Required Manning | 100% | 1 | 0.1166 | |
| Two per day | Hours Spent in Startup/Shutdown | 2 | 1 | 0.0465 | |
| Work hours are 7a to 7a | Hours of Shifts in Off Hours | 6 | 0 | 0.0386 | |
| Work hours are 7a to 7a | Hours of Ops During U.S. Day | 8 | 1 | 0.1353 | |
| Work hours are 7a to 7a | Hours Overlapping w/SST | 10 | 1 | 0.0435 | |
| Zero per day | Power Cycles/Day | 0 | 1 | 0.1304 | |

| **Alternative #14** | | | | | |
|---|---|---|---|---|---|
| Two Sets of 5 | | | | | |
| Two 5-hour ops periods with 1 hour of maintenance with each period per day | Measures | Raw | Scaled Value | Weight | Alternative Score |
| 10 Hours of ops per day | Hours/Day | 10 | 0 | 0.4892 | 0.21534 |
| A 4-man crew working 12 hours | Efficiency of Required Manning | 75% | 0 | 0.1166 | |
| 2 per day | Hours Spent in Startup/Shutdown | 2 | 1 | 0.0465 | |
| Work hours are 7a to 3p and 7p to 3a | Hours of Shifts in Off Hours | 5 | 0 | 0.0386 | |
| Work hours are 7a to 3p and 7p to 3a | Hours of Ops During U.S. Day | 5 | 0.75 | 0.1353 | |
| Work hours are 7a to 3p and 7p to 3a | Hours Overlapping w/SST | 8 | 0.8 | 0.0435 | |
| Two per day | Power Cycles/Day | 2 | 0.25 | 0.1304 | |

| **Alternative #15** | | | | | |
|---|---|---|---|---|---|
| Two Sets of 6 | | | | | |
| Two 6-hour ops periods with 1 hour of maintenance with each period per day | Measures | Raw | Scaled Value | Weight | Alternative Score |
| 12 Hours of ops per day | Hours/Day | 12 | 0.167 | 0.4892 | 0.34349 |
| A 4-man crew working 12 hours | Efficiency of Required Manning | 88% | 0.4 | 0.1166 | |
| 2 per day | Hours Spent in Startup/Shutdown | 2 | 1 | 0.0465 | |
| Work hours are 7a to 3p and 7p to 3a | Hours of Shifts in Off Hours | 5 | 0 | 0.0386 | |
| Work hours are 7a to 3p and 7p to 3a | Hours of Ops During U.S. Day | 5 | 0.75 | 0.1353 | |
| Work hours are 7a to 3p and 7p to 3a | Hours Overlapping w/SST | 8 | 0.8 | 0.0435 | |
| Two per day | Power Cycles/Day | 2 | 0.25 | 0.1304 | |

| **Alternative #16** | | | | | |
|---|---|---|---|---|---|
| Two Sets of 7 | | | | | |
| Two 7-hour ops periods with 1 hour of maintenance with each period per day | Measures | Raw | Scaled Value | Weight | Alternative Score |
| 14 Hours of ops per day | Hours/Day | 14 | 0.333 | 0.4892 | 0.49497 |
| A 4-man crew working 12 hours | Efficiency of Required Manning | 100% | 1 | 0.1166 | |
| 2 per day | Hours Spent in Startup/Shutdown | 2 | 1 | 0.0465 | |
| Work hours are 7a to 3p and 7p to 3a | Hours of Shifts in Off Hours | 5 | 0 | 0.0386 | |
| Work hours are 7a to 3p and 7p to 3a | Hours of Ops During U.S. Day | 5 | 0.75 | 0.1353 | |
| Work hours are 7a to 3p and 7p to 3a | Hours Overlapping w/SST | 8 | 0.8 | 0.0435 | |
| Two per day | Power Cycles/Day | 2 | 0.25 | 0.1304 | |

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| **Alternative #17** |  |  |  |  |  |
| Two Sets of 8 |  |  |  |  |  |
| Two 8-hour ops periods with 1 hour of maintenance with each period per day | Measures | Raw | Scaled Value | Weight | Alternative Score |
| 16 Hours of ops per day | Hours/Day | 16 | 0.5 | 0.4892 | 0.58519 |
| A 4-man crew working 12 hours | Efficiency of Required Manning | 100% | 1 | 0.1166 |  |
| 2 per day | Hours Spent in Startup/Shutdown | 2 | 1 | 0.0465 |  |
| Work hours are 7a to 4p and 7p to 4a | Hours of Shifts in Off Hours | 6 | 0 | 0.0386 |  |
| Work hours are 7a to 4p and 7p to 4a | Hours of Ops During U.S. Day | 6 | 0.75 | 0.1353 |  |
| Work hours are 7a to 4p and 7p to 4a | Hours Overlapping w/SST | 9 | 1 | 0.0435 |  |
| Two per day | Power Cycles/Day | 2 | 0.25 | 0.1304 |  |

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| **Alternative #18** |  |  |  |  |  |
| Two Sets of 9 |  |  |  |  |  |
| Two 9-hour ops periods with 1 hour of maintenance with each period per day | Measures | Raw | Scaled Value | Weight | Alternative Score |
| 18 Hours of ops per day | Hours/Day | 18 | 0.667 | 0.4892 | 0.70054 |
| A 4-man crew working 12 hours | Efficiency of Required Manning | 100% | 1 | 0.1166 |  |
| 2 per day | Hours Spent in Startup/Shutdown | 2 | 1 | 0.0465 |  |
| Work hours are 7a to 5p and 7p to 5a | Hours of Shifts in Off Hours | 6 | 0 | 0.0386 |  |
| Work hours are 7a to 5p and 7p to 5a | Hours of Ops During U.S. Day | 7 | 1 | 0.1353 |  |
| Work hours are 7a to 5p and 7p to 5a | Hours Overlapping w/SST | 10 | 1 | 0.0435 |  |
| Two per day | Power Cycles/Day | 2 | 0.25 | 0.1304 |  |

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| **Alternative #19** |  |  |  |  |  |
| Two Sets of 10 |  |  |  |  |  |
| Two 10-hour ops periods with 1 hour of maintenance with each period per day | Measures | Raw | Scaled Value | Weight | Alternative Score |
| 20 Hours of ops per day | Hours/Day | 20 | 0.833 | 0.4892 | 0.78206 |
| A 4-man crew working 12 hours | Efficiency of Required Manning | 100% | 1 | 0.1166 |  |
| 2 per day | Hours Spent in Startup/Shutdown | 2 | 1 | 0.0465 |  |
| Work hours are 7a to 6p and 7p to 6a | Hours of Shifts in Off Hours | 6 | 0 | 0.0386 |  |
| Work hours are 7a to 6p and 7p to 6a | Hours of Ops During U.S. Day | 8 | 1 | 0.1353 |  |
| Work hours are 7a to 6p and 7p to 6a | Hours Overlapping w/SST | 10 | 1 | 0.0435 |  |
| Two per day | Power Cycles/Day | 2 | 0.25 | 0.1304 |  |

| **Alternative #20** | | | | | | |
|---|---|---|---|---|---|---|
| Two Sets of 11 | | | | | | |
| Two 11-hour ops periods with 1 hour of maintenance with each period per day | Measures | Raw | Scaled Value | Weight | | Alternative Score |
| 22 Hours of ops per day | Hours/Day | 22 | 1 | 0.4892 | | 0.96139 |
| A 4-man crew working 12 hours | Efficiency of Required Manning | 100% | 1 | 0.1166 | | |
| 2 per day | Hours Spent in Startup/Shutdown | 2 | 1 | 0.0465 | | |
| Work hours are 7a to 7p and 7p to 7a | Hours of Shifts in Off Hours | 6 | 0 | 0.0386 | | |
| Work hours are 7a to 7p and 7p to 7a | Hours of Ops During U.S. Day | 8 | 1 | 0.1353 | | |
| Work hours are 7a to 7p and 7p to 7a | Hours Overlapping w/SST | 10 | 1 | 0.0435 | | |
| Zero per day | Power Cycles/Day | 0 | 1 | 0.1304 | | |

| **Alternative #21** | | | | | | |
|---|---|---|---|---|---|---|
| Three Sets of 5 | | | | | | |
| Three 5-hour ops periods with 1 hour of maintenance with each period per day | Measures | Raw | Scaled Value | Weight | | Alternative Score |
| 15 Hours of ops per day | Hours/Day | 15 | 0.417 | 0.4892 | | 0.41978 |
| A 4-man crew working 12 hours | Efficiency of Required Manning | 75% | 0 | 0.1166 | | |
| 3 per day | Hours Spent in Startup/Shutdown | 3 | 0.8 | 0.0465 | | |
| Work hours are 7a-3p and 3p-11p and 11p | Hours of Shifts in Off Hours | 6 | 0 | 0.0386 | | |
| Work hours are 7a-3p and 3p-11p and 11p | Hours of Ops During U.S. Day | 8 | 1 | 0.1353 | | |
| Work hours are 7a-3p and 3p-11p and 11p | Hours Overlapping w/SST | 10 | 1 | 0.0435 | | |
| Three per day | Power Cycles/Day | 3 | 0 | 0.1304 | | |

| **Alternative #22** | | | | | | |
|---|---|---|---|---|---|---|
| Three Sets of 6 | | | | | | |
| Three 6-hour ops periods with 1 hour of maintenance with each period per day | Measures | Raw | Scaled Value | Weight | | Alternative Score |
| 18 Hours of ops per day | Hours/Day | 18 | 0.667 | 0.4892 | | 0.58870 |
| A 4-man crew working 12 hours | Efficiency of Required Manning | 88% | 0.4 | 0.1166 | | |
| 3 per day | Hours Spent in Startup/Shutdown | 3 | 0.8 | 0.0465 | | |
| Work hours are 7a-3p and 3p-11p and 11p | Hours of Shifts in Off Hours | 6 | 0 | 0.0386 | | |
| Work hours are 7a-3p and 3p-11p and 11p | Hours of Ops During U.S. Day | 8 | 1 | 0.1353 | | |
| Work hours are 7a-3p and 3p-11p and 11p | Hours Overlapping w/SST | 10 | 1 | 0.0435 | | |
| Three per day | Power Cycles/Day | 3 | 0 | 0.1304 | | |

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| **Alternative #23** |  |  |  |  |  |
| Three Sets of 7 |  |  |  |  |  |
| Three 7-hour ops periods with 1 hour of maintenance with each period per day | Measures | Raw | Scaled Value | Weight | Alternative Score |
| 21 Hours of ops per day | Hours/Day | 21 | 0.917 | 0.4892 | 0.78093 |
| A 4-man crew working 12 hours | Efficiency of Required Manning | 100% | 1 | 0.1166 |  |
| 3 per day | Hours Spent in Startup/Shutdown | 3 | 0.8 | 0.0465 |  |
| Work hours are 7a-3p and 3p-11p and 11p | Hours of Shifts in Off Hours | 6 | 0 | 0.0386 |  |
| Work hours are 7a-3p and 3p-11p and 11p | Hours of Ops During U.S. Day | 8 | 1 | 0.1353 |  |
| Work hours are 7a-3p and 3p-11p and 11p | Hours Overlapping w/SST | 10 | 1 | 0.0435 |  |
| Three per day | Power Cycles/Day | 3 | 0 | 0.1304 |  |

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| **Alternative #24** |  |  |  |  |  |
| Safety Crew 2 hr |  |  |  |  |  |
| Three 5-hour ops periods with 1 hour of maintenance on each period per day and monitor while the equipment stays powered on (0 power cycles) | Measures | Raw | Scaled Value | Weight | Alternative Score |
| 15 Hours of ops per day | Hours/Day | 15 | 0.417 | 0.4892 | 0.55947 |
| A 4-man crew working 12 hours | Efficiency of Required Manning | 75% | 0 | 0.1166 |  |
| 2 per day | Hours Spent in Startup/Shutdown | 2 | 1 | 0.0465 |  |
| Work hours are 7a-3p and 3p-11p and 11p | Hours of Shifts in Off Hours | 6 | 0 | 0.0386 |  |
| Work hours are 7a-3p and 3p-11p and 11p | Hours of Ops During U.S. Day | 8 | 1 | 0.1353 |  |
| Work hours are 7a-3p and 3p-11p and 11p | Hours Overlapping w/SST | 10 | 1 | 0.0435 |  |
| Zero per day | Power Cycles/Day | 0 | 1 | 0.1304 |  |

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| **Alternative #25** |  |  |  |  |  |
| Safety Crew 1 hr |  |  |  |  |  |
| Three 6-hour ops periods with 1 hour of maintenance on each period per day and monitor while the equipment stays powered on (0 power cycles) | Measures | Raw | Scaled Value | Weight | Alternative Score |
| 18 Hours of ops per day | Hours/Day | 18 | 0.667 | 0.4892 | 0.68176 |
| A 4-man crew working 12 hours | Efficiency of Required Manning | 75% | 0 | 0.1166 |  |
| 2 per day | Hours Spent in Startup/Shutdown | 2 | 1 | 0.0465 |  |
| Work hours are 7a-3p and 3p-11p and 11p | Hours of Shifts in Off Hours | 6 | 0 | 0.0386 |  |
| Work hours are 7a-3p and 3p-11p and 11p | Hours of Ops During U.S. Day | 8 | 1 | 0.1353 |  |
| Work hours are 7a-3p and 3p-11p and 11p | Hours Overlapping w/SST | 10 | 1 | 0.0435 |  |
| Zero per day | Power Cycles/Day | 0 | 1 | 0.1304 |  |

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|---|---|---|---|---|---|
| **Alternative #26** | | | | | |
| Flipped Ops | | | | | |
| Current operations with flipped work hours. 10 hours of ops with 2 hours of maintenance support each day. | Measures | Raw | Scaled Value | Weight | Alternative Score |
| 10 Hours of ops per day | Hours/Day | 10 | 0 | 0.4892 | 0.43964 |
| A 4-man crew working 12 hours | Efficiency of Required Manning | 100% | 1 | 0.1166 | |
| 2 per day | Hours Spent in Startup/Shutdown | 2 | 1 | 0.0465 | |
| Work hours are 7p-7a | Hours of Shifts in Off Hours | 6 | 0 | 0.0386 | |
| Work hours are 7p-7a | Hours of Ops During U.S. Day | 8 | 1 | 0.1353 | |
| Work hours are 7p-7a | Hours Overlapping w/SST | 10 | 1 | 0.0435 | |
| One per day | Power Cycles/Day | 1 | 0.75 | 0.1304 | |

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| **Alternative #27** | | | | | |
| Flipped 18 hr | | | | | |
| flipped work hours in an 18 hour shift. 16 hours of ops with 2 hours of maintenance support each day. | Measures | Raw | Scaled Value | Weight | Alternative Score |
| 16 Hours of ops per day | Hours/Day | 16 | 0.5 | 0.4892 | 0.68421 |
| A 4-man crew working 12 hours | Efficiency of Required Manning | 100% | 1 | 0.1166 | |
| 2 per day | Hours Spent in Startup/Shutdown | 2 | 1 | 0.0465 | |
| Work hours are 7p-1p | Hours of Shifts in Off Hours | 6 | 0 | 0.0386 | |
| Work hours are 7p-1p | Hours of Ops During U.S. Day | 8 | 1 | 0.1353 | |
| Work hours are 7p-1p | Hours Overlapping w/SST | 10 | 1 | 0.0435 | |
| One per day | Power Cycles/Day | 1 | 0.75 | 0.1304 | |

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| **Alternative #28** | | | | | |
| Noon - Midnight | | | | | |
| 12 hour shift starting at 12p and ending at 12a | Measures | Raw | Scaled Value | Weight | Alternative Score |
| 10 Hours of ops per day | Hours/Day | 10 | 0 | 0.4892 | 0.34625 |
| A 4-man crew working 12 hours | Efficiency of Required Manning | 100% | 1 | 0.1166 | |
| 2 per day | Hours Spent in Startup/Shutdown | 2 | 1 | 0.0465 | |
| Work hours are 12p-12a | Hours of Shifts in Off Hours | 2 | 0.66 | 0.0386 | |
| Work hours are 12p-12a | Hours of Ops During U.S. Day | 2 | 0.25 | 0.1353 | |
| Work hours are 12p-12a | Hours Overlapping w/SST | 5 | 0.6 | 0.0435 | |
| One per day | Power Cycles/Day | 1 | 0.75 | 0.1304 | |

| **Alternative #29** | | | | | |
|---|---|---|---|---|---|
| Midnight - noon | | | | | |
| 12 hour shift starting at 12a and ending at 12p | Measures | Raw | Scaled Value | Weight | Alternative Score |
| 10 Hours of ops per day | Hours/Day | 10 | 0 | 0.4892 | 0.40116 |
| A 4-man crew working 12 hours | Efficiency of Required Manning | 100% | 1 | 0.1166 | |
| 2 per day | Hours Spent in Startup/Shutdown | 2 | 1 | 0.0465 | |
| Work hours are 12a-12p | Hours of Shifts in Off Hours | 4 | 0.33 | 0.0386 | |
| Work hours are 12a-12p | Hours of Ops During U.S. Day | 6 | 0.75 | 0.1353 | |
| Work hours are 12a-12p | Hours Overlapping w/SST | 5 | 0.6 | 0.0435 | |
| One per day | Power Cycles/Day | 1 | 0.75 | 0.1304 | |

| **Alternative #30** | | | | | |
|---|---|---|---|---|---|
| Shifted 18 - Day | | | | | |
| 18 hours shift shifted to start at 12a. With 16 hours of ops and 2 hours of maintenance. | Measures | Raw | Scaled Value | Weight | Alternative Score |
| 16 Hours of ops per day | Hours/Day | 16 | 0.5 | 0.4892 | 0.64574 |
| A 4-man crew working 12 hours | Efficiency of Required Manning | 100% | 1 | 0.1166 | |
| 2 per day | Hours Spent in Startup/Shutdown | 2 | 1 | 0.0465 | |
| Work hours are 12a-6p | Hours of Shifts in Off Hours | 4 | 0.33 | 0.0386 | |
| Work hours are 12a-6p | Hours of Ops During U.S. Day | 6 | 0.75 | 0.1353 | |
| Work hours are 12a-6p | Hours Overlapping w/SST | 5 | 0.6 | 0.0435 | |
| One per day | Power Cycles/Day | 1 | 0.75 | 0.1304 | |

| **Alternative #31** | | | | | |
|---|---|---|---|---|---|
| Shifted 18 - Night | | | | | |
| 18 hours shift shifted to start at 12p. With 16 hours of ops and 2 hours of maintenance. | Measures | Raw | Scaled Value | Weight | Alternative Score |
| 16 Hours of ops per day | Hours/Day | 16 | 0.5 | 0.4892 | 0.68421 |
| A 4-man crew working 12 hours | Efficiency of Required Manning | 100% | 1 | 0.1166 | |
| 2 per day | Hours Spent in Startup/Shutdown | 2 | 1 | 0.0465 | |
| Work hours are 12p-6a | Hours of Shifts in Off Hours | 6 | 0 | 0.0386 | |
| Work hours are 12p-6a | Hours of Ops During U.S. Day | 8 | 1 | 0.1353 | |
| Work hours are 12p-6a | Hours Overlapping w/SST | 10 | 1 | 0.0435 | |
| One per day | Power Cycles/Day | 1 | 0.75 | 0.1304 | |

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|---|---|---|---|---|---|
| **Alternative #32** | | | | | |
| Shifted Two Sets of 5 | | | | | |
| Two five-hour shift shifted to start at 4a and 4p. | Measures | Raw | Scaled Value | Weight | Alternative Score |
| 10 Hours of ops per day | Hours/Day | 10 | 0 | 0.4892 | 0.16890 |
| A 4-man crew working 12 hours | Efficiency of Required Manning | 75% | 0 | 0.1166 | |
| 2 per day | Hours Spent in Startup/Shutdown | 2 | 1 | 0.0465 | |
| Work hours are 4a-12p and 2p-10p | Hours of Shifts in Off Hours | 0 | 1 | 0.0386 | |
| Work hours are 4a-12p and 2p-10p | Hours of Ops During U.S. Day | 2 | 0.25 | 0.1353 | |
| Work hours are 4a-12p and 2p-10p | Hours Overlapping w/SST | 4 | 0.4 | 0.0435 | |
| One per day | Power Cycles/Day | 2 | 0.25 | 0.1304 | |

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Lt Col Kelly Greiner
Space and Missile Systems Center
1050 E. Stewart Ave
Peterson SFB, CO 80914
kelly.greiner@spaceforce.mil, (719) 556-2260

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**14. ABSTRACT**

The radars used for Space Domain Awareness (SDA) are inherently all-weather, day/night sensors capable of around the clock operations. Despite this fact, some radars are operated for fewer than their maximum operating capabilities. The decision-making process for selecting the operating hours of a sensor has historically been based on only a few factors or just one. This research uses the techniques in Value Focused Thinking to develop an evaluation process to score possible alternatives and find the alternative with the most value for the decision maker. By investigating the value that is added by operating an SDA radar, it is possible to create a quantitative evaluation process for determining the most efficient operating schedule for an SDA radar that maximizes benefits to users while minimizing operating costs. In this research, a specific radar is used for the development of this technique. By evaluating the C-Band Australia radar, located in Exmouth, Western Australia, the research found that the quantity of data produced by the radar was the most valuable aspect of the radar and minimizing the hours out of mission per day (i.e., downtime) is the best alternative. The analysis in this research explored the trade-offs between added benefits of operating hours with the

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