



**Measuring Human Systems Integration in
Directed Energy Weapon Acquisition Programs**

THESIS

Zachary A. Novitske, Major, USA

AFIT-ENS-MS-19-M-142

**DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY**

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

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DIRECTED ENERGY WEAPON ACQUISITION PROGRAMS

THESIS

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Zachary A. Novitske, M.B.A.

Major, USA

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Zachary A. Novitske, M.B.A.
Major, USA

Committee Membership:

LTC Christopher M. Smith, PhD
Chair

Alfred E. Thal, Jr., PhD
Co-Chair

Lt Col Marcelo Zawadzki, PhD
Member

Abstract

Directed energy weapons (DEW) are of interest to the armed forces as they search for more effective ways to deal with evolving threats. The development of these weapons has been ongoing for almost 40 years, despite only one operational fielding by the U.S. Navy in 2014. Some reasons for DEW's lack of adoption by the services include cost overruns and unclear requirements. Early adoption of human systems integration (HSI) in the military's acquisition process is shown to provide substantial cost savings over the life of the system. Quantifying the application of HSI within a DEW acquisition program is addressed through decision analysis using value-focused thinking (VFT). The VFT model helps program managers and HSI practitioners balance total system performance and cost of ownership. Knowledge gathered from expert elicitation was used to create the decision model consisting of objectives in a hierarchal format. The proposed VFT model is a beginning step that allows for an objective analysis of HSI efforts in a DEW acquisition program. Further work is required to make the model practical for use.

Dedicated to my wife and children for their continued sacrifice on my behalf.

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Zachary A. Novitske

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MEASURING HUMAN SYSTEMS INTEGRATION IN DIRECTED ENERGY WEAPON ACQUISITION PROGRAMS

I. Introduction

Science fiction has long had a love affair with the laser. The Martians in H.G. Wells' 1898 book *The War of the Worlds* used invisible heat ray weapons. The 1964 James Bond film *Goldfinger* portrayed the use of a laser beam that could cut through solid gold. Perhaps the most well-known use of a laser in science fiction is the Death Star from *Star Wars*, which can destroy entire planets. These classic examples depict lasers exclusively as weapons and spawned real-life application of such devices. Wells' heat ray weapons are seen today as infrared lasers. The James Bond laser foreshadowed extensive industrial laser use in the 1970s. Unsurprisingly, laser technology has not yet reached the level depicted in *Star Wars*.

Lasers are the most easily recognized type of directed energy (DE) and have so far taken the majority of the monetary investment into these programs (Welch & Hermann, 2007). However, the energy also comes in several other forms such as high-powered microwaves (HPM), particle-beams, and sonic or ultrasonic waves (Antal, 2013). All forms of DE hold potential for weaponization due to some advantages over conventional weapons. Directed energy weapons (DEW) are more precise, have a lower cost per shot, and can be scaled. A criticism of some currently used kinetic weapons is their high cost relative to the target they are neutralizing. DEWs promise to reverse the cost so the threat being neutralized is more expensive than the weapon being used to

target it. However, DEWs are at a disadvantage in that they are line-of-sight weapons with no indirect fire capability. DEWs also suffer from beam attenuation, which is the reduction in intensity of the beam as it passes through matter (McKetty, 1998). Matter in the atmosphere such as dust, smoke, and water vapor can cause the beam to attenuate, by no means a small problem in adverse weather conditions where conventional kinetic weapons may function better.

The weaponization of lasers are of interest to all branches of the military as they look towards the future in search of more effective ways to deal with evolving threats. Lasers are generally agreed to hold the most promise for a wide range of applications such as destroying incoming projectiles or disabling vehicles. The laser as a weapon is still developing as work is done to increase power and range while using less energy and occupying a smaller footprint. As research and development continues, the first fielding of such weapons has already taken place by the U.S. Navy in 2014 (Feickert, 2018) and the next step for the military is determining which platforms to use laser-based weapons on and for what application. Considerations for these next generation weapons include initial and operating costs, personnel and training requirements, safety concerns, and possible ethical dilemmas.

The U.S. does not own a monopoly on DEWs. Adversaries, potential adversaries, and allies have varying degrees of their own DEW programs. Although not proven, there were claims of sonic and ultrasonic attacks on U.S. diplomats in both Cuba and China in recent years (Fu, Xu, & Yan, 2018). Sonic, or audible, devices are already used throughout the world by police and military forces as crowd control devices. Recognizing that some of the DE technology is already viable and fielded, a real concern of military

officials is being outpaced by other countries' DEW technology and procurement. The John S. McCain National Defense Authorization Act for Fiscal Year 2019 reflects these sentiments with \$915 million authorized for DE research, development, test, and evaluation; additionally, \$22 million was authorized for the construction of a directed energy systems integration lab (115th Congress, 2018). This proves a willingness of the government to trust in the Department of Defense's (DoD) assessment that monetary resources should be applied to the DE field to further the military's capabilities.

Getting DEWs in the military's arsenal is a process. The military acquisition process is broken into five phases: material solution analysis, technology development, engineering and manufacturing development, production and deployment, and operations and support (Carr & Greene, 2009b). Preceding those five phases is the first stage, development. In the most general sense, this is where an operational requirement is identified, potential alternatives are analyzed, Congress authorizes and appropriates funds, proposals are gathered, and contractors are selected to begin work on the program (Fox, Allen, Lassman, Moody, & Shiman, 2011). The entire process is long, arduous, and subject to much bureaucracy.

Cost overruns are an almost inevitable part of military acquisition programs. Many major defense programs take at least 15 years to come to fruition while also coming in over double the budget and being delivered with less capability than originally defined (Fox et al., 2011). Without completely revamping the military acquisition process, there are multiple ways in which the risk of outrunning the budget can be mitigated. One method is to take a multitude of factors into account at the beginning of the program using proven techniques such as decision analysis. Some factors indicating

decision analysis may be a good choice for DEW acquisition are complexity, conflicting consequences, and uncertainty. The DEW, acquisition process, and HSI are all complex entities by themselves. The ability to quantify values in decision analysis reduces the complexity to a point where it can be understood and analyzed. Decision analysis is good for problems with conflicting consequences because of its use of objective trade-offs. That is, risk may be reduced in one area while simultaneously increasing another area (Goel, 1992). Finally, the uncertainty of outcomes lends itself to decision analysis through its use of value functions for decisions made under certainty and utility functions for decisions made under uncertainty.

Part of systems engineering (SE) includes the relationship between the human and the system. This management process is known as human systems integration (HSI). NASA's depiction of 32 programs in Figure 1 show that those investing less than 5% on SE are almost guaranteed an 80% or greater overrun. Applying decision analysis techniques on HSI within DEW programs could give the project a better chance of meeting its time and budget goals.

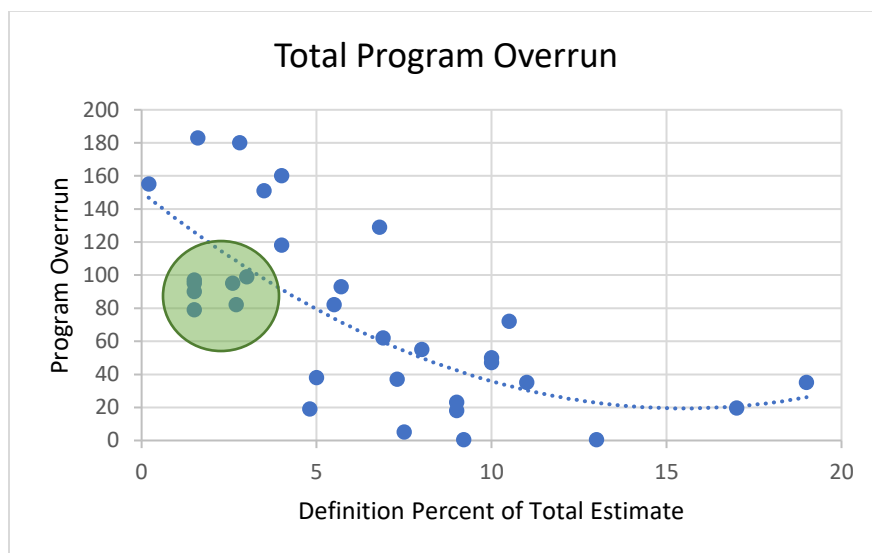


Figure 1. Total Program Overrun (adapted) (Gruhl, 1992)

The information shown in Figure 1 demonstrates that “defining the project” is often underfunded and overlooked, thereby costing significant amounts of extra money. This coincides with Figure 2, which shows the estimated HSI investment range. This research does not investigate the actual monetary values but instead focuses on the evaluation of HSI based on HSI's importance as demonstrated in Figure 1 and Figure 2.

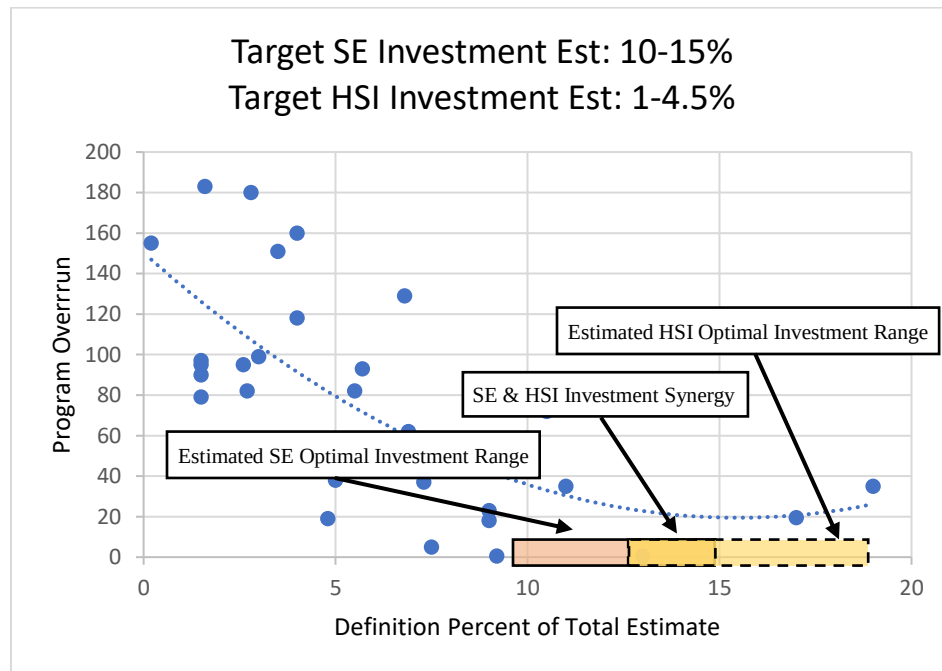


Figure 2. HSI Investment Estimate (adapted) from Impact of SE at NASA (as cited in Booth, 2009)

1.1 Background

The Air Force published the results of the *Air Superiority 2030 Flight Plan* study (Department of the Air Force, 2016) into developing capabilities to maintain air superiority in 2030 and beyond. It shows the Air Force expects threats to its air superiority to evolve along two major fronts over the next 11 years, traditional threat systems and a series of comprehensive capabilities. It is understood that near-peers have

advanced fighter aircraft, sensors, and weapons. However, these traditional technological threats are quickly spreading to other countries and the Air Force sees increasing threats in ever expanding locations and scenarios. The second threat comprises capabilities that negate the Air Force's current advantages in the space domain; it includes increased number and complexity of cyberspace threats, and increased sophistication of air threats like hypersonic missiles and conventional ballistic missile systems. The Air Force does not see itself as capable of fighting and winning against these emerging threats with its projected force structure and current acquisition process (Department of the Air Force, 2016).

The results of the *Air Superiority 2030 Flight Plan* invariably lead to the need for new or improved technology and systems. The study (Department of the Air Force, 2016) recognizes the development of next generation weapon systems often becomes mired in cycles of ever increasing costs in part due to technology that has not caught up to the idea. The culprit exists in many forms whether it be an overly aggressive timeline, not devoting enough resources to the project, or not focusing on the right problem. Formal acquisition programs generally do not mesh well with cutting edge technology and inevitably underperform. Because of these problems, the Air Force chartered Enterprise Capability Collaboration Team (2016) recommends shifting the focus from "next generation" platforms to a collaborative effort between science and technology, acquisition, requirements, and industry professionals. The new approach requires adaptable and affordable processes.

A way to address the real problem is to use practiced and proven methods early in the acquisition process. One such method is value-focused thinking (VFT), an approach

developed by Keeney (1992) that looks at values as the means to create alternatives and make decisions. VFT is later described as an interactive approach to decision analysis (Parnell, Bresnick, Tani, & Johnson, 2013). Using VFT allows a decision-maker to focus on what really matters. As such, VFT is an excellent candidate to assess the maturity and readiness of potential “game-changing” technologies such as DE. Decision analysis using VFT does a good job of dealing with subjectivity from the entire process.

Any new acquisition program’s total ownership cost can be reduced with the integration of HSI (Honour, Axelband, & Rhodes, 2004; Liu, 2010; Onkham, Karwowski, & Ahram, 2012). As noted in Figure 1, increased investment in the defining phases normally results in reduced program overruns. Although the total savings vary between programs, early investment and realization of SE and HSI generally keeps cost overruns in the negligible to 75% range (Gruhl, 1992), significantly less than the 80-180% range of programs with minimal SE and HSI investment. The DoD acknowledged the fact when they mandated the incorporation of HSI early in the acquisition cycle (Liu, Valerdi, Rhodes, Kimm, & Headen, 2010).

Different agencies and military departments define HSI differently. However, they generally agree that HSI is, in a most general sense, the optimization of total system performance with the human operator. The Air Force divides HSI into nine domains: manpower, personnel, training, environment, safety, occupational health, habitability, survivability, and human factors engineering (Carr & Greene, 2009a). The human factors domain tends to make the most headlines due to its direct relation between the human operator and the system.

1.2 Problem Statement

An overarching goal of defense acquisition could be characterized as, “make America stronger, now and in the future” by administering efficient, quality, state of the art acquisition programs (Ward, 2011). The successful incorporation of HSI into the acquisition effort at the earliest possible point can substantially reduce life cycle costs. While the current methods for applying HSI to acquisition programs are detailed in numerous Air Force manuals and handbooks, it is unknown if there is a better way to measure HSI within a particular program. Simply applying HSI wherever it can be fit in does not determine if the correct HSI domains are being addressed and to what extent trade-offs should be made.

DEWs are billed as a cost-effective solution to using increasingly expensive kinetic weapons to combat adversaries’ progressively sophisticated weapons. DEW development is not unlike other Defense acquisition programs in that there are immense pressures to balance total system performance and cost of ownership. Knowing which HSI elements to incorporate into a program and give priority to can assist decision-makers early in the acquisition process. Assessing how well a DEW acquisition program has incorporated the HSI elements can help the program stay on track and within budget. The inability to determine if HSI efforts are focused correctly is a problem that needs to be addressed.

Knowledge is sometimes defined as individual and institutional. Individuals’ knowledge comes and goes with the individual while institutional knowledge is retained within the organization. A concern of many organizations is losing the knowledge

possessed by individuals as they depart because of the inability to transfer that knowledge into institutional knowledge.

1.3 Objectives and Approach

1.3.1 Objectives

The overall objective of this research is to answer how decision analysis using VFT can be used to assess the application of HSI within a DEW acquisition program.

Four investigative questions are used:

- How can an expert's knowledge of the manpower, personnel, training, human factors, and safety HSI domains be represented in a value hierarchy?
- How can knowledge, both tacit and explicit, be captured from an HSI expert and transferred to someone else?
- How can captured knowledge improve a DEW acquisition program?
- How can the importance of each HSI domain be identified?

1.3.2 Approach

Even though each DEW acquisition program is different in terms of size, scope, and purpose, they all involve some elements of HSI. This analysis will focus on identifying which elements are important so the right amount of time and effort can be put towards those specific elements. The use of decision analysis in this research is largely predicated on its successful application in various other fields. Decision analysis has been used successfully by Ford when deciding whether to produce its own tires, by Pillsbury on whether to use boxes or bags for certain products, and by Honeywell to evaluate the attractiveness of weapons programs (Ulvila & Brown, 1982). As noted by Morais et al. (2013), decision analysis using the VFT philosophy has been used by the

Air Force to select innovative force protection ideas (Jurk, Chambal, & Thal, 2004), the Croatian Armed forces to select an automatic rifle (Peharda & T, 2008), a publishing company to examine the strategic implications of mobile technology (Sheng, Nah, & Siau, 2005), and a tourist management company to assess the vitality of rural areas (Kajanus, Kangasb, & Kurttilac, 2004).

1.4 Assumptions

Decision analysis problems involve some level of uncertainty. The uncertainty can arise from incomplete facts or knowledge about future events that affect choices made in the present. Decisions made under certainty, that is, when decision-makers know the outcome of selecting an alternative, use value functions for calculations. Decisions made under uncertainty, or when the outcome of selecting an alternative are unknown, use utility functions. This research uses value functions because alternative selection in the acquisition process means that alternative will proceed while alternatives not selected will not move forward. Furthermore, lack of data for this research made the use of value functions obligatory.

The assessment of HSI using VFT has not been previously applied directly to a DEW program. Uncertainty regarding changes to the DEW program will not be considered because the hierarchy can be modified to account for changes when they happen. Furthermore, utilizing VFT and its hierarchy in the first place should help keep the program on track by initially determining the importance of HSI.

This research is predicated on the assumption that the sponsor is an expert. The sponsor was used for virtually all pertinent steps in building the model. If he turned out not to be an expert, the model would be virtually useless as a defensible method for

measuring HSI. It should be noted that a different expert could, and probably would, come up with a different set of values for the model. However, the sponsor/expert used in this research is by all accounts an expert in the related fields and qualified to assist.

For this research to have a meaningful impact, the assumption was made that the military acquisition process will not depart radically from its current format in the next 10 to 20 years. The process has remained relatively stable over the years and there are no indications that this will change. The need for this assumption is directly related to the small scope this research covers, namely HSI in DEW acquisition programs. There are not many, if any, non-military uses for the specifics of the model being presented.

1.5 Preview

Chapter II covers the history of DEWs including what has been tried, what has failed, currently used DEWs, and what the military expects to use in the near future. The military acquisition process will be discussed, focusing on the general flow and how programs are evaluated from start to finish. Examples of the importance of HSI will also be discussed with an emphasis on military application. Decision analysis using VFT examples, advantages, and disadvantages will be covered. Finally, experts and knowledge will be discussed. Chapter III provides the “how-to” of the VFT model and shows why VFT can be utilized for this particular problem. It also covers knowledge elicitation techniques and choosing the right expert. Chapter IV covers the model’s hierarchy and how it would be applied. In conclusion, Chapter V discusses areas of future research and insights gained from this research.

II. Literature Review

This chapter reviews current and projected directed energy weapon (DEW) applications as well as the acquisition process and how acquisition programs are evaluated. It also covers human systems integration (HSI), positive and negative outcomes of HSI, decision analysis using value-focused thinking (VFT), and examples of VFT implementation. The end result should be an understanding of the complex and difficult process to field a DEW with the appropriate HSI principles and how VFT could be used to do so.

2.1 Directed Energy Weapons

For years, DEWs resided in the realm of science fiction. The end of the 19th century saw a type of DEW, the heat ray, introduced to the public through the novel *War of the Worlds*. Although the heat ray was a fictional weapon in a science fiction book, the general concept is pretty close to the reality of infrared lasers. It is not quite the DEW that people imagine, being invisible as opposed to a visible laser.

As noted by the Department of State (1983), the military began researching DEWs in earnest during the 1980s, after President Ronald Reagan proposed the Strategic Defense Initiative program (SDI). The announcement focused on a plan to defend the country from nuclear attack by way of a space-based missile defense program. Futuristic technology was proposed, including space-based lasers that had not yet been developed. The President's announcement raised questions as noted by Levi (1983) that are still relevant today.

- What missions might such weapons systems fulfill?
- What hurdles currently block the way to practical realization of these systems?
- What arguments are being made for and against DEW systems?

2.1.1 Missions

What missions might such weapons systems fulfill? DEWs are generally envisioned as defensive weapons. From the military's initial vision of DEWs providing protection from nuclear attack to a more recent but similar vision of countering incoming rockets, artillery, and mortars (C-RAM), the defensive capabilities have always seemed more viable than offensive ray-gun type efforts. The Air Force outlined three distinct areas of interest: forward base defense, aircraft self-protection, and precision strike (Stanley, 2018). It should be noted that the defensive capabilities of DEWs could feasibly be used in an offensive role, if desired.

2.1.2 Hurdles

What hurdles currently block the way to practical realization of these systems? Much of the technology for DEWs has matured over the last 30 years, reaching a point where it could be used by the military, given the right mission set. Previously, and to a lesser extent now, the size, weight, and power requirements of a DEW system were a hindrance to practical operational use. Ethical considerations are discussed in 2.1.4.

2.1.3 Arguments

What arguments are being made for and against DEW systems? Proponents in favor of DEW systems have not changed their selling points in any meaningful way over the years. Alexander (2008) explains the attractiveness of DEWs as scalability, speed-of-light engagement, low-cost per shot, extremely precise targeting, and unlimited

magazine. Scalability refers to the potential to dial the power up to burn through targets or dial it down to do just enough damage to cause mission failure. Adjusting power is a simplification of what the operator does to the focus of the beam by manipulating the intensity, duration, and wavelength of the beam. Scalability on its own offers a uniqueness not seen in conventional weapons. A conventional projectile has predictable behavior once it is fired. The scalability factor of a DEW allows the same weapon system to be used for multiple scenarios.

Alexander (2008) also explains what is probably the second biggest selling point of DEWs – the engagement speed. Conventional weapons take time to reach the target and depend on things like speed of jet engines or rocket propulsion, detonation of gunpowder, or ballistic velocity. DEWs, on the other hand, can hit the target almost instantaneously after acquisition. The operator can place energy on target at the speed of light, matching the speed of the other parts of the detect-to-kill chain.

The low-cost per shot of a DEW compared to a conventional weapon is explained with a Javelin missile example. Whereas the shoulder fired Javelin missile costs over \$100,000, firing a DEW at the same target has a cost only of the energy it uses. Comparatively, the DEW is magnitudes cheaper to fire than conventional weapons. Similarly, a DEW's magazine load is essentially limited by the amount of available energy or power source. The exception to both points are chemical-based lasers, which need the chemical in order to function. Finally, a DEW is extremely precise in its targeting. It is as simple as keeping the beam pointed directly on the target.

Detractors of DEW systems tell a different story. The advantages of DEWs are agreed upon, but the benefits do not paint the full picture. A DEW's speed-of-light

engagement does not mean the target will be destroyed or disabled instantaneously. It means the beam can reach the target at the speed of light. There is still time needed to have effects upon the target.

Another major negative characteristic of DEWs are their sensitivity to atmospheric conditions such as dust, moisture, and turbulence (Alexander, 2008). Anything less than an ideal atmosphere can lead to a weakening of the beam and reduction or elimination of the DEW's intended effects on the target. By virtue of DEWs being beams of energy, they are also strictly line-of-sight weapons and have no indirect fire capability. This could potentially be a problem when the operator is in a defilade or behind cover, forcing them into a less secure position for the sake of firing the DEW.

The size and weight of DEWs are also an issue. In general, a more powerful laser system will be larger and heavier than a less powerful system. This can pose problems when attempting to integrate powerful DEWs with a smaller vehicle or person. In essence, the mobility of powerful DEWs can be prohibitive. More powerful DEWs also use more power, resulting in the need for a larger power source and thus a larger platform. The issue of ricochet must also be considered. On the positive side, DEWs are extremely precise. However, lasers and other energy beams are not totally absorbed by the material they encounter. When the energy is reflected away, it must go somewhere, thus potentially causing unintended damage away from the target.

2.1.4 Ethical Concerns

Physical characteristics are not the only concerns with DEWs. As with any new weapon system, there are bound to be ethical debates and discussions on proper use. DEWs, particularly laser weapons, are addressed in the Protocol of Blinding Lasers, part

of the Protocol Additional to the Geneva Conventions of 12 August 1949. This protocol prohibits deliberate and permanent blinding by lasers on the battlefield (Backstrom & Henderson, 2012). This means lasers are permitted under law, with the only prohibition being deliberate, permanent blindness. Many militaries use lasers as range finders or may utilize optical dazzlers. These devices work well as intended, but could be used to cause blindness if operated outside the normal specifications, such as too close to a target or aiming directly into a person's eyes.

Critics envisioned DEWs being used in space and pushed for a ban on weapons in space (Levi, 1983). There are still no laws banning the use of DEWs in space, only Article IV of the 1967 Outer Space Treaty that bans nuclear or other weapons of mass destruction from orbit (Dembling & Arons, 1967). This alludes to a possible legal hurdle for DEWs: their potential for dual purpose use in armed conflict (Leins, 2016).

The advent of DEWs also brought concerns of ethical employment of such weapons. Numerous studies have been inconclusive and erred on the side of negligible effects of low-level radio frequency energy on humans (Jauchem, 2008). This includes exposure to radio-frequency energy such as cell phones, microwaves, and radio transmissions. All these exposures are inadvertent and generally unavoidable. However, DEWs would be directed at individuals for the purpose of causing an effect. Rapid changes in technology resulting from ongoing research quickly adds more complexities to the ethics debate. There are ongoing tests of optogenetics on mice that have shown light delivery technology can manipulate their brain cell function. Such a weapon would certainly have legal and ethical implications if directed against humans (Leins, 2016).

2.1.5 *Today's DEWs*

There are several weapons either currently in use or that have been tested and fielded that can be classified as DEWs. They are split between two of the most prominent directed energy technologies: high-energy lasers (HELs) and high-powered microwaves (HPMs) (Sanyal, Bevington, & Brigham, 2017). Since lasers are already used by the military for a variety of purposes, HELs emerged as leading contender for DEWs. HELs extend the capability of existing lasers by essentially increasing the power ranges to achieve more effects. The four main approaches to HELs are solid-state, fiber, chemical, and free electron (Sanyal et al., 2017), which are all infrared. HPMs, on the other hand, use microwave or radio-wave frequency ranges. These offer some of the same benefits of HELs such as active denial and other non-lethal effects. Scaled up in power, the same beam can be used in a lethal capacity (Sanyal et al., 2017).

The Active Denial System (ADS) is a non-lethal, counter-personnel, vehicle mounted system created by Raytheon. Antal (2013) describes the system as one of the first such systems fielded by the Army. Tested and shown to have a range of approximately one mile, the ADS directs a high frequency beam of 95GHz waves at a person or group of people. The energy is invisible to the target person or group and causes intense uncomfortableness within a few seconds by way of heating the skin. In this manner, targets are obliged to leave the area. Throughout rigorous testing, the system was shown to be non-lethal, but there are still doubts as to the effects over a longer time. Antal (2013) also notes the ADS's fielding in Afghanistan with the Army in 2010, even though it was never used. In a 2012 demonstration, the Marines seemed to embrace the ADS more than the Army.

A design of experiments was conducted to test the methodology for the effectiveness of non-lethal weapons in a crowd scenario. The experiment showed a long-range DEW suppressed the crowd the most. Through the breadth of the experiment, the long-range DEW showed statistically significant differences on all measures of effectiveness (Mezzacappa et al., 2017). However, the authors noted that the experiment results should not be used to draw conclusions about the effectiveness of any particular weapon type as the experiment focused on the methodology.

The Mobile Experimental High Energy Laser (MEHEL) is Stryker mounted mobile testbed to support the Army's laser programs (Pina, 2017). Pina further describes the MEHEL as a 5kW system designed to defeat small unmanned aircraft system (sUAS) threats. Its \$30 per shot cost is calculated by the amount of diesel fuel needed to power the shot. In 2017, the latest version of the MEHEL operated from a combat vehicle successfully defeated a sUAS. A potential use for the MEHEL is defeating sUAS swarms, although more testing is needed.

One DEW system has been operationalized aboard the USS Ponce in the Persian Gulf (Coffey, 2014). The Laser Weapon System (LaWS) was installed on the ship in 2014 and has been tested and used aboard ever since. The DEW was designed to be operated by a single sailor using a controller similar to the ones found on the Xbox and PlayStation game systems (Coffey, 2014). Coffey (2014) also explains how the LaWS integrates six solid-state infrared beams, which can be modified from low to high power for warning or target destruction. The system is mounted on a pre-existing Phalanx gun system, thus removing the need for an entirely new platform and tracking system (Gunzinger & Dougherty, 2012).

2.1.6 *Tomorrow's DEWs*

Other DEWs are still in the development process as engineers work to improve previous systems while learning from their failures and successes. The engineers and their military customers are working to synchronize technological feasibility with mission need. This effort goes hand-in-hand with the military's analysis of the changing threats and where they see DEWs fitting into the equation.

The HEL systems mentioned earlier are universally confined by their size, weight, and power consumption (SWaP) limitations (Coffey, 2014). In response to these limitations, a Dayton, OH based company, Optonicus, developed an optical phased array for the U.S. Defense Advanced Research Projects Agency (DARPA). This array was made specifically for DARPA's Excalibur program and featured low power requirements, long-range turbulence correction, and scalability. The system was tested and shown to compensate for atmospheric aberrations. However, the most intriguing aspect was the system's ability to do so in a package 10 times lighter and more compact than previous HELs (Coffey, 2014).

The DEW programs mentioned thus far offer warfighters capabilities different than those currently in their arsenal. However, an ongoing issue is matching those capabilities to operational requirements (Stoudt, 2012). The gap between engineers and operators often prevents DEWs from being fully utilized, even when fielded. Staying with this theme, a lack of formal requirements has created a situation where the technology is pushed by the developers rather than pulled by the operators (Stoudt, 2012).

Some of the suggested missions for DEWs have not changed much over the years. Others are being realized as well-suited for DEW. These missions include defending infrastructure such as power plants, performing non-lethal engagements like crowd control, and attacking targets in an urban environment (Zimet & Mann, 2009). As warfare evolves and the threat scenarios change, DEWs with a lower power output could possibly be used alongside conventional weapons. This is a shift from the elusive 100kWh HEL often talked about as the goal for laser DEWs (Zimet & Mann, 2009). Welch et al. (2007) suggests there is not much reason to continue trying to field high-powered lasers until the operational demands generate priorities. Likewise, they suggest that fragmented efforts in science and technology projects should move to specific research and development programs that can lead to fielded systems.

2.2 Acquisition Programs

Military acquisition is more than just purchasing an item. Acquisition is a broader term that covers the process to design, engineer, construct, test, deploy, and sustain an item (Schwartz, 2014). The entire process is sometimes described as long and arduous because it must follow statutes and regulations laid out to ensure such processes have well-defined structure and accountability. A weapon system must go through three steps: identifying a required need, establishing a budget, and acquiring the system (Schwartz, 2014). The entire acquisition process has been lambasted numerous times for being slow, overly bureaucratic, and ineffective. Despite discussions to overhaul the process, it remains essentially unchanged. Schwartz (2014) does an excellent job summarizing the acquisitions process and much of the following paragraphs are attributed to his work.

2.2.1 Identifying a Requirement

In 2003, the Joint Capabilities Integration and Development System (JCIDS) was created as a new process to identify, assess, and prioritize which capabilities the military requires. This new process was a shift in approaches from threat-based to capabilities-based. In short, needed capabilities were identified to fit priorities based on high-level strategy and guidance documents such as the National Defense Strategy. The previous process developed and fielded systems based on perceived threats to the nation. A primary reason for making the change was to develop systems that could be used jointly so unnecessary time and money was not spent on separate systems that filled the same capabilities gap.

2.2.2 Budgeting

The Planning, Programming, Budgeting, and Execution (PPBE) system is an annual process that aims to work within fiscal constraints to provide a mix of forces, equipment, manpower, and support. The planning stage is where the national defense strategy is laid out and priorities for programs are developed. The programming stage is where missions and objectives of weapons programs are submitted, along with a proposed budget. The budgeting stage occurs simultaneously but separately from the actual program proposals. Once a program decision is made or a budget review is conducted, the budget decision is issued. Finally, the execution stage takes place. In this stage, programs are evaluated against metrics, including funding obligations.

2.2.3 Acquisition

The Defense Acquisition System is a general framework that is intended to work with all manner of programs, from missiles, to information technology, to vehicles and

weapon systems. Program development times are not uniform and vary greatly (Van Atta, 2013). Scheduling is often overly ambitious or unrealistic given the nature of the technology within the program. DEWs fall prey to this situation due to the complex nature and employment of the technology involved. Major systems development takes an average of seven to ten years (Van Atta, 2013).

2.2.4 *Evaluation of Acquisition Programs*

All programs must meet specific requirements throughout the process to continue to the subsequent phase. These are known as Milestone A, B, and C. Milestone A happens pre-systems acquisition and initiates technology maturation and risk reduction. Milestone B happens at the end of pre-systems acquisition directly before the start of systems acquisition and initiates engineering and manufacturing development. Milestone C initiates production and deployments and occurs during systems acquisition. Acquisition is broken into five phases: materiel solution analysis, technology maturation and risk reduction, engineering and manufacturing development, production and deployment, and operations and support. Figure 3 shows the interaction between the milestones and phases.

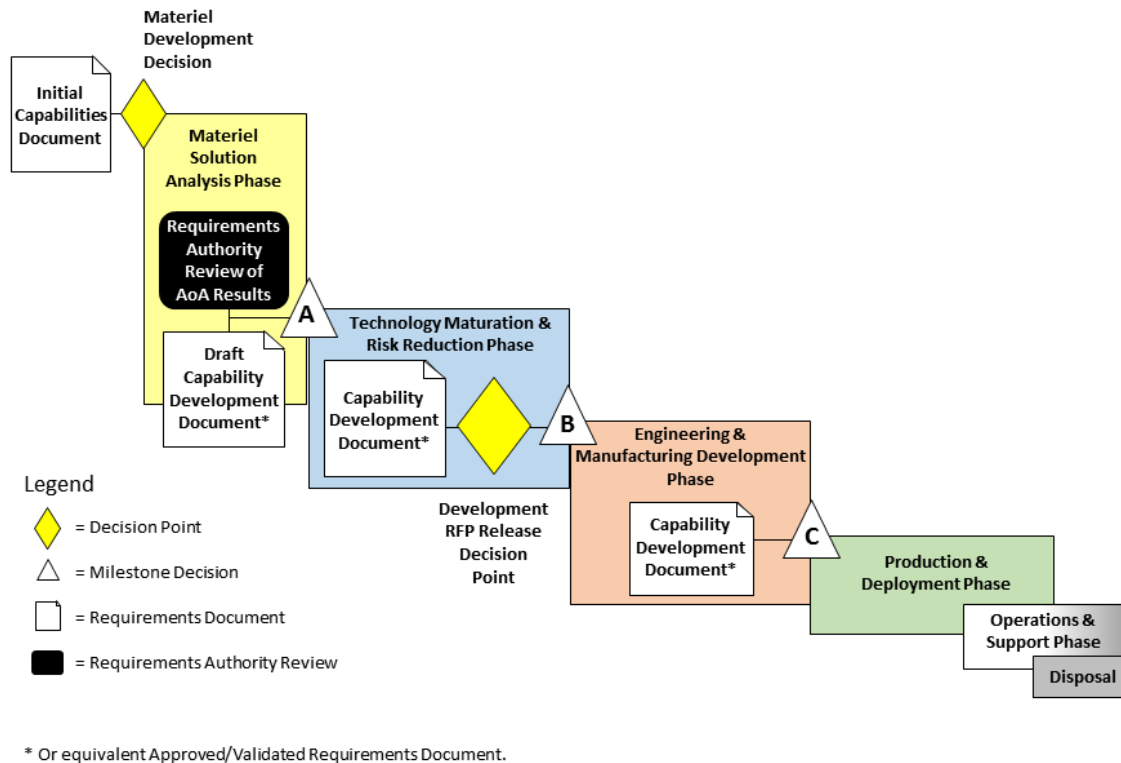


Figure 3. Acquisition Phases and Milestones (Defense Acquisition University, 2017)

The three milestones determine if a program has met the exit requirements of the current phase and can continue to the next phase. Formal evaluation standards are not spelled out due to the differing nature of unlike programs. Instead, each program manager and Milestone Decision Authority are given the brunt of the task to ensure developmental test and evaluation people have adequately evaluated their program (Defense Acquisition University, 2017). This research can be used to fill the void when looking at the HSI portion of a DEW acquisition program.

2.3 Human Systems Integration

According to the Air Force HSI Handbook, “HSI is the process by which to design and develop systems that effectively and affordably integrate human capabilities

and limitations” (Department of the Air Force, 2009). Similarly, Air Force Instruction 63-1201 defines HSI as, “A disciplined, unified, and interactive systems engineering approach to integrate human considerations into system development, design, and lifecycle management to improve total system performance and reduce costs of ownership” (Department of the Air Force, 2007). In both cases and throughout various other organizations’ definitions, HSI boils down to seamlessly meshing human and system for better performance and reduced costs. HSI covers a wide range of factors that the Air Force divides into nine domains: manpower, personnel, training (MPT), human factors engineering, environment, safety, occupational health (ESOH), survivability, and habitability. The HSI domains are defined with liberal help from the HSI Domain Guide (Carr & Greene, 2009a).

Manpower: The manpower domain addresses both the number and type of personnel required. It covers the occupational specialties (may be multiple specialties) needed to train, operate, maintain, and support the developed system. The domain ties in with other domains in its pursuit of engineering designs that optimize the use of manpower for the purpose of keeping human resource costs within reason. The determination of manpower levels and their associated positions must also account for the cognitive, physical, and physiological demands on humans. Considerations must be made for the technological impact possibilities on humans integrated into a system. Human resources is a related but not identical field.

Personnel: The personnel domain addresses all things a human is required to possess to operate, maintain, and support the system. This includes their knowledge, skills, and abilities (KSAs); experience; and aptitudes. Human aptitudes include such

things as cognitive, physical, and sensory capabilities. The domain also considers the means to recruit and retain the people. Systems requirements drive recruitment, testing, qualification, and selection. The personnel domain works by defining human performance characteristics and then determining target populations for select occupational specialties. This includes the management of said occupational specialties for career progression and assignments. The domain can impact both manpower and training. The domain can also act as a driving force for design requirements. Like the manpower domain, human resources is a related but not identical field. Human resources can be thought of an overarching domain that contains both manpower and personnel.

Training: The training domain addresses all resources and instruction required to provide personnel (identified in the personnel domain) with the KSAs to operate, maintain, and support the system. This includes both individual and collective training, as well as both qualification training and proficiency training. Emphasis should be placed on training options that enhance the population's capabilities, maintain skills, are comparatively fast, and use an optimal mix of training resources. All training systems and materials should be developed concurrently with the system. The fielding of the training system may be required prior to the actual system so personnel can operate, maintain, and support the system when it is fielded.

Human Factors Engineering (HFE, referred to in this research simply as Human Factors): The human factors domain involves the understanding and integration of human capabilities into system design. Human capabilities include cognitive, physical, sensory, and team dynamic. The integration must take place at the onset of the system design and continue through system disposal. The main goal is to effectively integrate the human-

system interfaces so system performance can be optimized. System functions should be designed with a comprehensive human factors analysis so system requirements and functions align. Human factors account for increasingly complex technology and the demands on people. Human factors increase usability for system users by minimizing design characteristics that lead to errors. The domain also helps to eliminate the need for design work-arounds.

Environment: The environment domain considers the relationships that exist between all living things and systems with water, land, air, space, cyberspace, markets, and organizations. A goal is to protect the environment from system design, manufacturing, operations, sustainment, and disposal activities. These considerations could affect the concept of operations and requirements.

Safety: The safety domain promotes design characteristics that directly affect the potential for death or injury to operators, maintainers, and support personnel in the form of reduced accidents or mishaps. In the same vein, the design characteristics reduce the potential for cascading failures within the system and in other systems. Lessons learned from previous systems are heavily utilized so design features prevent hazards where possible and minimize risk where prevention is unattainable. Redundant systems are key, as are systems that alert the user when a problem exists. Systems that assist in avoiding and recovering from errors are also part of the safety domain. A few examples of widespread issues are: factors that threaten the safe operation of the system; walking and working surfaces; pressure extremes; and control of hazardous energy releases such as mechanical, electrical, fluids under pressure, ionizing or non-ionizing radiation, fire, and explosions.

Occupational Health: The occupational health domain enhances job performance of operators, maintainers, and support personnel by promoting system design features that minimize the risk of injury, acute or chronic illness, and disability. When health hazards cannot be avoided, the domain recommends personal protective equipment, protective enclosures, or mitigation measures. Some common issues include noise, chemical exposures, atmospheric hazards like oxygen deficiency, vibration, and both ionizing and non-ionizing radiation. Additionally, there are human factors to be considered that could result in chronic disease or discomfort. An example is repetitive motion injuries.

Survivability: The survivability domain helps reduce injury and loss of the system. Any characteristic that enables the total system to be less susceptible to mission degradation or termination, injury or loss of life to users, or partial or complete loss of the system and its components is part of survivability. Some characteristics include life support, body armor, helmets, plating, egress/ejection equipment, air bags, seat belts, and electronic shielding. These concerns must be addressed with the total concept of operations in mind and for all users, operators, maintainers, and support personnel.

Habitability: The habitability domain covers system working and living conditions. Some examples are lighting, ventilation, adequate space, vibration, noise, and temperature control, as well as the availability of medical care, food and/or drink services, suitable sleeping quarters, sanitation, and personal hygiene facilities. These types of characteristics are necessary for personnel and impact recruitment and retention (personnel domain). Overall system performance is influenced by its personnel and their level of morale, motivation, quality of life, safety, health, and comfort.

2.3.1 Importance of HSI

Failure to address HSI concerns at the inception of the systems engineering process causes HSI attributes to not be deeply implemented in the systems engineering process (Bodenhamer, 2012). This may seem like a trivial point, until compared with a typical system's life-cycle cost as shown in Figure 4. As depicted, the cost to change design direction [or implement additional HSI measures] increases significantly as the process moves forward. In other words, the life-cycle cost of a system is essentially locked in early in the process, thereby making it difficult to change anything moving forward past the original design. This contrasts with the actual system costs (lower curve) that rise much slower over time. Both curves eventually meet at the end of the life-cycle, meaning much of the life-cycle cost is realized near the end of the useful life of the system. Onkham et al. (2012) recognized the need to address human factors, one of the HSI domains, to produce desired outputs on costs associated with human capability, human reliability, and decision making. Addressing these factors at the beginning of a process reduces risk, uncertainty, and total ownership cost (TOC).

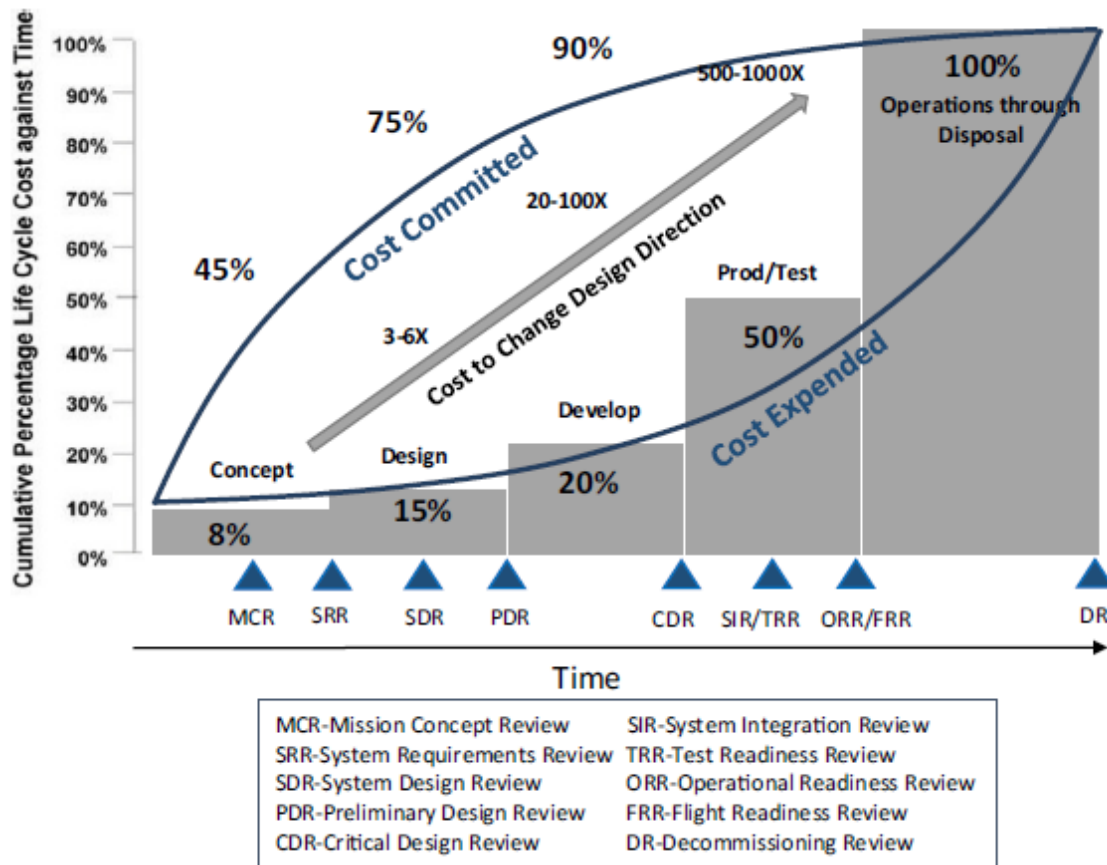


Figure 4. Life Cycle Cost Impacts from Early Phase Decision-Making (adapted) from the Systems Engineering Handbook, Volume 3.1 (as cited in Silva-Martinez, 2016)

2.3.1.1 Case Study 1: HSI Lessons Learned from UAVs

Tvaryanas et al. (2005) found that 60.2% of UAV mishaps involved human factors. The study looked at 221 UAV mishaps categorized by the DoD's mishap classifications (Department of Defense, 2011). The mishaps totaled more than \$151.5 million in damages (Feltman, Curry, & Kelley, 2018), in today's dollars. The study recognized the "tendency to consider complex systems as "technology" driven rather than "people-technology" driven. Improvement of technology generally means more complex systems, which increases the chance for failures associated with both human and

mechanical causes. They highlight a case study on UAVs that calls attention to the UAVs' high mishap rate as compared to general aviation. Comparing the 32 mishaps per 100,000 flight hours of the Air Force's RQ-1 Predator to general aviation's 1 mishap per 100,000 flight hours shows that UAV reliability is orders of magnitude worse than general aviation. It could be argued that a higher mishap rate for an unmanned vehicle is less important than a manned vehicle because of the absence of a human pilot being affected by the mishap. However, the DoD recognizes "the reliability and sustainability of UAVs is vitally important because it underlies their affordability (an acquisition issue), their mission availability (an operations and logistics issue), and their acceptance into civil airspace (a regulatory issue)" (Defense Science Board, 2004). Table 1 shows the summary of UAV mishaps by human factors taxonomies.

Table 1. Summary of Prior UAV Mishap Studies Using Standardized Human Factors Taxonomies (Tvaryanas et al., 2005)

Seagle ³⁴	Ferguson ¹⁷	Manning et al. ²¹	Rogers et al. ³⁰
Navy <i>n</i> = 203	Navy <i>n</i> = 93	Army <i>n</i> = 56	Air Force, Army <i>n</i> = 48
<u>Taxonomy</u> : Taxonomy of Unsafe Acts	<u>Taxonomy</u> : Taxonomy of Unsafe Acts	<u>Taxonomy</u> : HFACS	<u>Taxonomy</u> : Human systems issues
<u>Human Factors</u> : 43%	<u>Human Factors</u> : 59%	<u>Human Factors</u> : 32%	<u>Human Factors</u> : 69%
<u>Factors</u> :* Unsafe acts (59%) Accidental acts (52%) Slips (2%) Lapses (16%) Mistakes (39%) Conscious acts (7%) Infractions (7%) Unsafe condition (46%) Aeromedical (20%) CRM (27%) Readiness violations (7%) Unsafe supervision (61%) Unforeseen (34%) Foreseen (47%)	<u>Factors</u> :* Unsafe acts (38%) Intended (17%) Mistakes (12%) Violations (7%) Unintended (20%) Slip (14%) Lapse (3%) Unsafe condition (40%) Aeromedical (10%) CRM (28%) Readiness violations (10%) Unsafe supervision (43%) Unforeseen (15%) Foreseen (12%)	<u>Factors</u> :* Unsafe acts (61%) Skill-based (22%) Decision (33%) Misperception (17%) Violations (11%) Preconditions (6%) CRM (6%) Unsafe supervision (50%) Inadequate supervision (33%) Failed to correct known problem (17%) Supervisory violations (11%) Organizational influences (44%) Organizational process (44%)	<u>Factors</u> : Training (27%) Team performance (25%) Situational awareness (18%) Interface design (16%) Cognitive & decision making (14%)

Tvaryanas et al. (2005) uses data from Table 1 combined with their own analysis to gain several insights into the role of human factors in UAV mishaps. Figure 5 uses the Human Factors Analysis and Classification System (HFACS) to display human causal factors of UAV mishaps. The highest percentage of mishaps were due to organizational influences. This could possibly be traced back to the initial phases of development when HSI could have played a role in shaping the design of and training for the system.

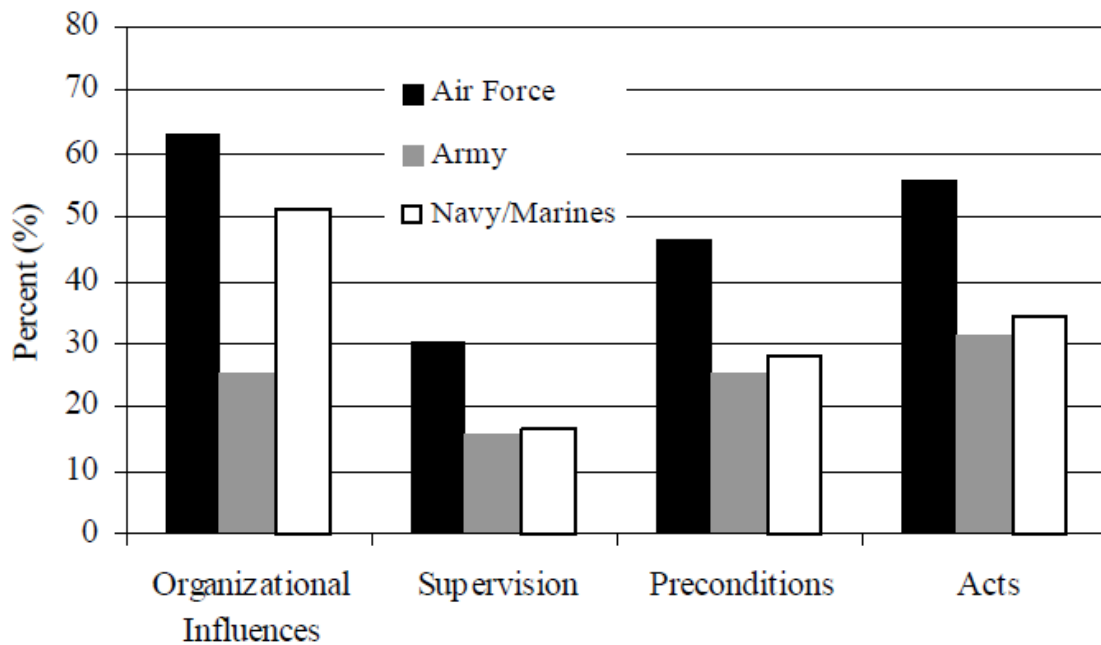


Figure 5. Top Level HFACS Human Causal Factors by Military Service as Percentage of Total Mishaps (Tvaryanas et al., 2005)

Of note, the organizational influences category includes resource/acquisition management and was the most frequent type of latent failure, present in 79.4% of human causal factors mishaps in the Air Force (Tvaryanas et al., 2005). Tvaryanas et al. (2005) “summarizes the root categories of acts as a percentage of the total acts by service” in

Figure 6, where it can be seen that the Air Force has a higher percentage (47.2%) of skill-based errors than the other services.

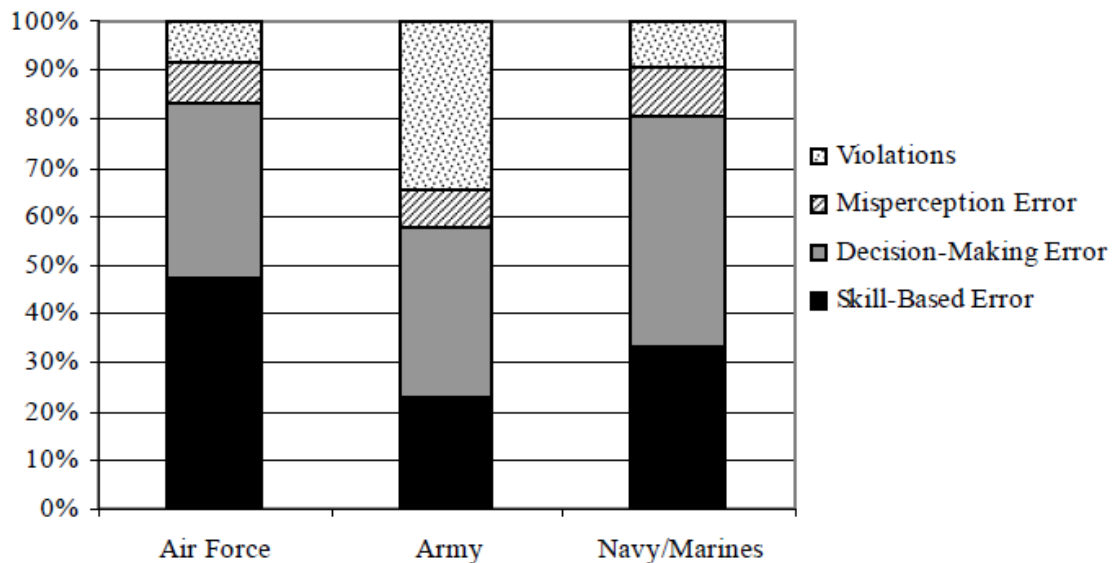


Figure 6. Root Categories of Acts as Percentage of Total Acts by Service (Tvaryanas et al., 2005)

Figure 7 shows UAV mishaps by the more familiar HSI domains. The human factors domain easily outpaced all other domains as containing the most mishaps. Within human factors, 60% of Air Force mishaps involved organizational interfaces failures (Tvaryanas et al., 2005). Tvaryanas (2005) notes the consistent findings showing a higher frequency of Air Force mishaps can be traced directly to acquisition failures tied to subsystem component reliability problems.

“The excessive numbers of mechanical failures analyzed in the UAV Reliability Study are physical manifestations of a recurring latent failure in the acquisitions process. To effectively address current UAV mishap rates and safeguard investments in future UAV systems, the investigational

spotlight must move from mechanical failures as the cause of UAV mishaps to failures in the organizational culture, management, or structure of DoD's acquisition processes for UAVs.” (Tvaryanas et al., 2005)

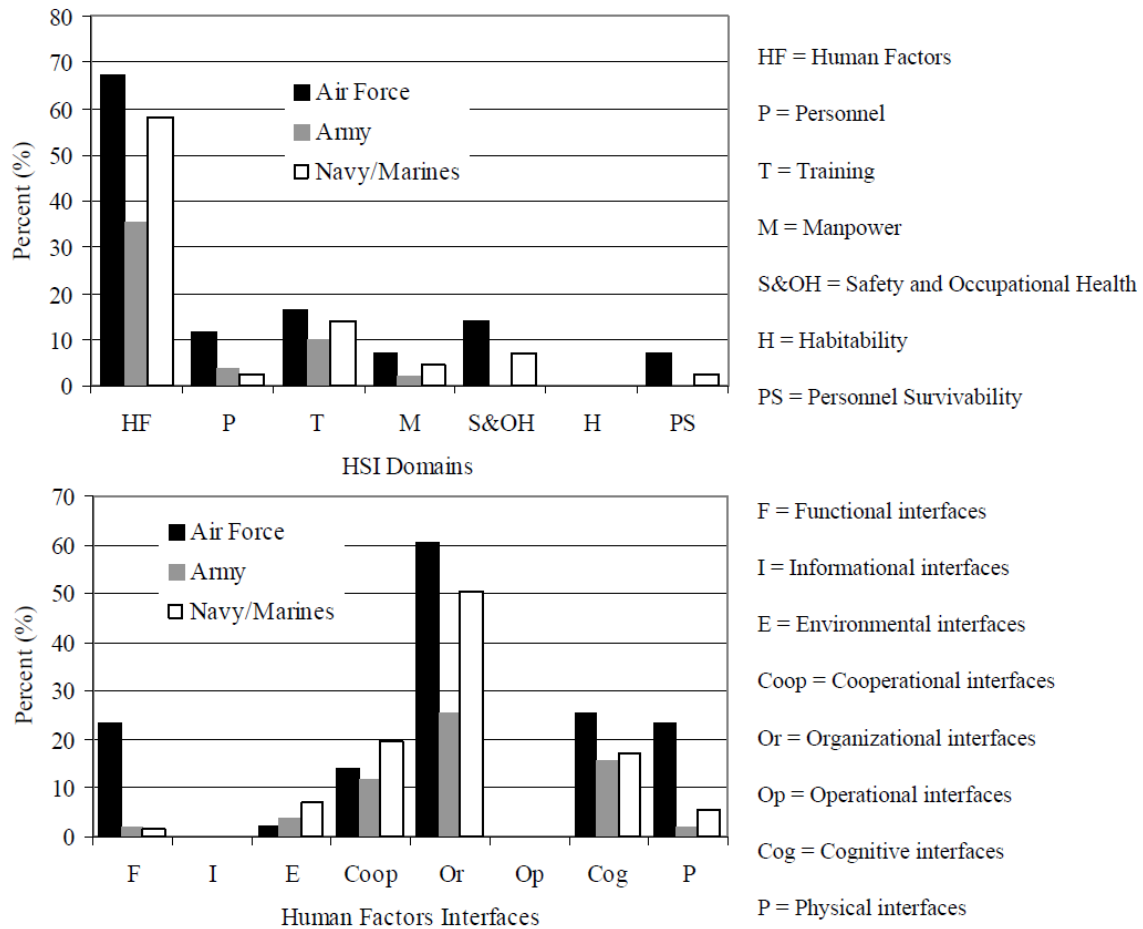


Figure 7. HSI Domains/Interfaces by Service as Percentage of Total Mishaps (Tvaryanas et al., 2005)

2.3.1.2 Case Study 2: HSI Success Story of F119 Engine

When Lockheed won the initial \$13.7 billion [in today's dollars] contract in 1991 (*Donley v. Lockheed Martin Corp*, 2010) to develop the next-generation stealth fighter, the F-22, the Secretary of the Air Force noted one reason was due to its superior engines

(Bolkcom, 2007). A reason for the increased attention to engines was the F-15's F100 engine service record. Although high performing, the F100 was prone to failure and the resulting downtime needed for maintenance (Liu et al., 2010). The Air Force subsequently implemented the Reliability, Maintainability, and Sustainability (RM&S) program in 1984, soon after work began developing the F-22. Pratt & Whitney, developers of the F119 engine, realized the importance of this program and pushed to use HSI as a way to make their engine more reliable.

Seven of the nine HSI domains were represented by organizations within Pratt & Whitney (Liu et al., 2010). The Chief Engineer of the F119, Frank Gillette, was the driving force behind the incorporation of HSI principles, which in turn led to adherence to the Air Force's RM&S program. It took constant leadership intervention and adherence to policies to move forward with development of the engine while maintaining an eye on both RM&S and HSI.

The competition between Pratt & Whitney and General Electric to develop the F-22's engine was eventually won by Pratt & Whitney. After both companies were awarded money to continue their development, Pratt & Whitney chose to devote double the test hours as General Electric, with an emphasis on meeting the RM&S guidelines. General Electric ended up developing a superior engine in terms of performance while Pratt & Whitney had a slightly less performance-based engine that more closely aligned to RM&S through the use of HSI (Liu et al., 2010).

The integration of RM&S into Pratt & Whitney's development process showed that even separate organizations working together could successfully consider and apply

HSI. Liu et al. (2010) identified three factors as key to the success of HSI within systems engineering of the F119 program:

1. Air Force policy to elevate the visibility of HSI
2. Pratt & Whitney's willingness to internalize HSI practices and enforce accountability for HSI
3. The integration of HSI and systems engineering in the early phases of the acquisition life cycle

The fact that HSI considerations were coupled with other systems engineering practices was a strength of the project. The lack of a centralized "HSI group" did not detract from the project's goal of meeting Air Force requirements of RM&S (Liu et al., 2010).

2.3.2 HSI Implementation

Airbus Defense and Space looked at their current enterprise architecture philosophy and realized it did not provide sufficient weight to the human aspects of existing architectures or to proposed changes to current products. The resulting investigation prompted integrating more HSI (areas that were not covered by their existing human view architecture) into different areas of their model based system engineering process (Sharples, 2015). A different study integrated HSI concepts, specifically human factors, in the early design stages of a nuclear main control room. It recognized the importance of correctly identifying and implementing high-level requirements early in the design to avoid continual updates (Yan, Habiyaemye, Wei, & Tran, 2017).

Looking past successful uses of integrating the human factors domain of HSI into developing better functioning systems, there have also been studies on the research-

practice gap. This is the gap that exists when practitioners or operators do not heed the recommendations of researchers on the subject. Specifically reviewing human factors, the study showed journal publications over the last 50 years have shown an increase in the number of articles that use theory. There is evidence that the research-practice gap is shrinking, yet still present (Chung & Williamson, 2017).

2.4 Decision Analysis Using VFT

Parnell et al. (2013) introduces, defines, and explains decision analysis and VFT in depth within *Handbook of Decision Analysis*. At its core, they state that decision analysis is “a philosophy and social-technical process to create value for decision-makers and stakeholders facing difficult decisions involving multiple stakeholders, multiple (possibly conflicting) objectives, complex alternatives, important uncertainties, and significant consequences.” They continue by saying that VFT is a “philosophical approach to the analysis of decisions” that creates decision-making opportunities by using the value to generate better alternatives. Keeney (1992) refers to VFT as thinking that focuses first on values and later on alternatives that might achieve them. This is in contrast to alternative-focused thinking (AFT), which compares available alternatives. Parnell et al. (2013) notes that a decision is “an irrevocable allocation of resources.” From the stated definitions, it can be seen that VFT can be used by decision-makers to allocate resources effectively.

Although not utilized in this research, a key component of VFT allows decision-makers to generate alternatives, as opposed to only comparing pre-existing alternatives. For example, a decision-maker would be able to choose the best alternative given A, B, and C. However, if A, B, and C are the only choices, the decision-maker can never do

better than the best of those choices. VFT lets the decision-maker see those alternatives and analyze hybrids of those alternatives to generate new alternatives. Now, given A, B, C, and D, the decision-maker could choose D, whereas before that was not an option.

Kirkwood (1996) defines decision analysis slightly differently. A decision implies the existence of alternatives. Significant decisions result in differing outcomes and the more diverse the outcomes, the more complex the analysis (Kirkwood, 1996). Decision analysis is a process used to create value for decision-makers (DM) faced with difficult decisions that have complex alternatives, more than one objective, and substantial consequences. It must be noted that good decisions can have bad outcomes. Even a decision made logically and consistent with the DM's preferences may have a bad outcome, just like a poor decision process can sometimes lead to a good outcome (Parnell et al., 2013). One way to conduct decision analysis is through the use of VFT.

The VFT approach uses quantitative measures to give each alternative a score. In this way, alternatives can be numerically ranked against each other. A value hierarchy is used to organize evaluation considerations. These areas of concern are structured in such a way so they feed into each other from bottom to top.

The 10-step process summarized in Figure 8 is usually employed to use VFT (Shoviak, 2001). Step 1, problem identification, involves clearly defining the problem within the correct frame, perspective, and scope. Step 2, identify and structure objectives, is where the DM's values are represented in the value hierarchy. This information can come directly from the DM (platinum standard), official documents (gold standard), or from representatives of the DM (silver standard). Platinum standard is preferred over gold, which is preferred over silver. Step 3, measure the achievement of objectives, is the

process of creating evaluation measures to garner a raw score. Step 4, single attribute value function (SAVF), uses the evaluation measures of step 3 to define a function that converts raw numbers to a value score. Step 5, multi attribute value function (MAVF), adds a weight to each evaluation measure so it can be compared with every other evaluation measure with the DM's corresponding preferences. Step 6, alternative generation and screening, finds or generates alternatives that will be scored in step 7, alternative scoring. Alternative scores are computed by multiplying value scores by their weight. Step 8, deterministic analysis, and step 9, sensitivity analysis, are used to evaluate each alternative's results. Lastly, step 10, communicating results, allows the analyst to share the results with the DM.

- | |
|--|
| <p>Step 1. Problem Identification
Step 2. Identify & Structure Objectives
Step 3. Measure the Achievement of Objectives
Step 4. Single Attribute Value Function
Step 5. Multi Attribute Value Function
Step 6. Alternative Generation
Step 7. Alternative Scoring
Step 8. Deterministic Analysis
Step 9. Sensitivity Analysis
Step 10. Communicating Results</p> |
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Figure 8. VFT Steps (Shoviak, 2001)

2.4.1 Case Study: Foundations 2025

In the late 1990s, a study was directed by the Air Force Chief of Staff called *Air Force 2025*. The more than year-long study's goal was to identify system concepts and technologies for the United States Air Force to achieve air and space dominance by the

year 2025. A VFT model named *Foundations 2025* was used successfully to score 43 system concepts (Parnell, Conley, Jackson, Lehmkuhl, & Andrew, 1998).

Parnell et al.'s (1998) study was split into four phases: preparation, idea generation, assimilation, and operations analysis. An introduction to VFT and its uses was provided to all the study participants during the preparation phase. Idea generation brought system concepts and assimilation identified requirements for the concepts and determined which concepts met those requirements. The final phase was conducted concurrently with the previous three phases. The model itself was used to evaluate the final system concepts.

The search for gold standard documents proved insufficient in detail to create a value hierarchy so the silver standard approach was used instead. The investigating team asked participants to identify tasks needed to provide air and space dominance by 2025. Affinity diagrams were used to group similar verbs (tasks), which were then structured further. Using the affinity diagram, tasks were sorted separately by participants. Next, tasks were analyzed to determine duplicates, combined when needed, and further categorized into subtasks, tasks, and functions.

Parnell et al.'s (1998) team spent considerable time determining attributes and evaluation measures for each subtask. The attributes described a system's ability to accomplish a subtask while the evaluation measures quantified system performance. Operational experts were used to develop the SAVFs and determine weights. The study itself also identified six alternate futures of the state of the Earth to take into account differing possible requirements in the future. To account for this in the model, the teams involved in the study independently submitted weights for each alternate future. The

average weight for each future was used in the model. Operational analysis and technology teams then scored each system concept, which resulted in a full list of concept systems ranked against one another.

The model successfully used VFT as a methodology and proved to be effective for a large scale, complex, and long-term planning horizon problem. The five tier, 134 evaluation measure model objectively analyzed future system concepts and avoided institutional bias. It proves VFT can be used for concept systems or programs.

2.4.2 Experts

This research for this thesis relied heavily on experts, who are different than novices and other nonexperts. Experts do not necessarily have more ability than a novice; they simply have more specialized knowledge (Proctor & Van Zandt, 2008). An expert can be described as someone who has special knowledge of a specific domain such as HSI or DEWs. Chi et al. (1981) details expert characteristics in Table 2. As detailed in the table, experts are not shown to have greater abilities than a novice. Instead, they are able to draw upon their specific knowledge of a subject and perform better when working with subject specific problems or tasks.

Table 2. Characteristics of Expert Performance (Chi et al., 1981)

1.	Experts excel mainly in their domains.
2.	Experts perceive large meaningful patterns in their domain.
3.	Experts are fast; they are faster than novices at performing the skills of their domain, and they quickly solve problems with little error.
4.	Experts have superior short-term and long-term memory for material in their domain.
5.	Experts see and represent a problem in their domain at a deeper (more principled) level than novices; novices tend to represent a problem at a superficial level.
6.	Experts spend a great deal of time analyzing a problem qualitatively.
7.	Experts have more accurate self-monitoring skills.
8.	Experts are good at selecting the most appropriate strategies to use in a situation.

2.4.3 Tacit Knowledge

Another aspect of experts is their tacit knowledge. Objective knowledge can be thought of as knowledge that can be readily communicated and understood. Tacit knowledge is the opposite, and it is often difficult or impossible to communicate. Other characteristics of tacit knowledge are that it is highly individualized, practical, and specific (Ambrosini & Bowman, 2001). For the expert possessing tacit knowledge, their thought process goes through steps that the expert themselves may be unable to articulate. It is such an engrained piece of knowledge that the expert is unable to completely define or articulate their thought process, thus meeting the definition of tacit knowledge. Tacit knowledge is not restricted to experts only; novices and anyone in between possess it (Balu & Anchalia, 2015).

2.4.4 Value Hierarchy as a Knowledge Repository

There are different ways to store knowledge for subsequent use. A value hierarchy created from the first two steps of the VFT process is a way to store domain-specific knowledge. Knowledge management is a central aspect to many firms' long-term competitive strategies and the same goes for the military. Improved overall performance and utilization of competitive advantages are two benefits of good knowledge management. Defined as "the explicit and systematic management of vital knowledge – and its associated processes of creation, organization, diffusion, use and exploitation" (Skyrme, 2001), a knowledge base is inherently linked to knowledge management. A value hierarchy essentially acts as a repository for knowledge that can assist experts and non-experts alike in making good decisions about a particular issue. The tacit knowledge

contained in a value hierarchy “can be a source of advantage because it is unique, imperfectly mobile, imperfectly imitable and non-substitutable” (López-Nicolás & Meroño-Cerdán, 2011).

Multiple examples of HSI in various acquisition programs were discussed in the literature review. The need for innovation and DEWs as a part of the military’s strategic plan and the acquisition process were also covered. Decision analysis using VFT was recommended as a way to transfer knowledge specific to an HSI and DEW expert to a non-expert. The expert’s knowledge can then be used without the expert being present and a DEW acquisition program can be evaluated in terms of HSI content. This enables a new team member or person unfamiliar with the inner workings of such a system to step in and use the model as a tool to evaluate their input to the program.

III. Methodology

It is evident that program managers and the human systems integration (HSI) experts themselves face a challenge in balancing total system costs, capabilities, and functionality. While the HSI expert is not necessarily responsible for cost, they are not excluded from finding reasonable solutions to incorporate the needed HSI aspects into the system. Logically, too high a cost without the added benefit will result in certain HSI aspects not being incorporated into the system. The result would be at best, degraded performance, or at worst, a system that did not function properly due to human and machine not working together appropriately. Value-focused thinking (VFT) is a suitable methodology to evaluate this multi-criteria decision analysis problem because it is good with complex, multi-faceted problems.

This chapter will discuss VFT, the types of knowledge gathered, how to choose an expert, elicitation techniques, and interactions with the expert. Next, the how-to of the VFT process will be discussed as it relates to DEW acquisition programs and HSI. The primary focus of the chapter is knowledge elicitation methods and the application of decision analysis (DA) techniques.

3.1 Value Focused Thinking

Multi-objective decision analysis combines multiple objectives and values and scores alternatives against each other, giving decision-makers (DMs) the opportunity to evaluate each alternative objectively. The core of VFT is first understanding your objectives and then figuring out how to achieve them (Keeney, 1992). Much of the

information contained within a hierarchy comes from an expert or a decision-maker. The process of eliciting values and objectives from the decision-maker is a key part of VFT.

A primary reason for using VFT is the allowance for alternative creation by using trade-offs between value and weights. The allowance for alternative creation can come in especially handy when faced with specific problems that may have limited scope to begin with. This research is on HSI within DEW acquisition programs, which can immediately be constrained by a size component. For example, a DEW system needs space not only for the weapon system, but the operator as well. The whole system must be examined to determine which platforms could be viable candidates to host such a system. In any case, there is a minimum amount of space needed for the weapon system as well as operator area. The value hierarchy was built with this kind of constraint in mind.

Works by both Keeney (1992) and Parnell (2013) were used to explain the remainder of this section. Initially, identifying or framing the problem is the key to moving forward with the model. Incorrect framing can lead to answering the wrong question or otherwise overlooking key aspects of the problem. This in turn makes it harder for a decision-maker to make a good decision based on the model. Upon determining the correct frame, objectives are structured into the value hierarchy, which is essentially the heart of VFT. Decision-makers and any other stakeholders must agree in principal on the hierarchy as it is the basis for the scoring of alternatives and the end decision. The visualization of the model through the hierarchy is another benefit of VFT. Like a pyramid or tree, the strategic objective is the uppermost tier and branching out below it are the fundamental objectives, or lower tiers. Finally, the fundamental objectives are broken down until the objective can be measured.

Generally, the VFT process goes sequentially through the 10-step process beginning with problem identification and ending with analysis and recommendations. The methodology used here was modified based on lack of an actual DEW acquisition program to use as inputs. Steps 6-10 were not completed as a result.

3.2 Knowledge Elicitation

The VFT process does not work without a strong knowledge source. Whether it be the platinum, gold, or silver standard, something must provide the basis for the creation of the value hierarchy. The model created used almost exclusively platinum and gold sources, lending to its validity. This research used one primary decision-maker who was also the subject matter expert (SME). The SME was knowledgeable on the inner workings of DEWs, the acquisition process, and HSI. There were some small gaps in knowledge as the SME was more familiar with some domains of HSI and slightly less familiar with others. The combination of DEW, HSI, and acquisition process expertise proved vital to the research. Having a single source for the three knowledge sets helped later in the process to determine what was important. A second SME was brought in midway through the research to provide additional input and perspective. The second SME shared the same knowledge base, albeit from a different background. As such, the two SMEs provided varying perspectives while fundamentally agreeing on all major aspects of the research.

3.2.1 *Tacit vs Explicit Knowledge*

Obtaining explicit knowledge, or the kind of knowledge that can be codified and written down, is inherently easier than obtaining tacit knowledge. By its very definition, tacit knowledge cannot be easily obtained or written down. The collection and

codification of tacit knowledge essentially transforms the knowledge from tacit to explicit.

In the context of the research, explicit knowledge was the primary source of information. However, the SMEs had years of experience that in and of itself lent credence to the assertion that the SMEs possessed tacit knowledge. Bad or otherwise incomplete knowledge can significantly affect the ability of the VFT model to function properly and provide useful results.

3.2.2 Choosing the Expert

This research was developed by a sponsoring agency, the 711th Human Performance Wing (HPW), with an individual in mind to act as the lead. While often times the decision-maker is chosen by virtue of their position within the organization, this is not always the case with experts. The primary sponsor of this research also served as decision-maker and expert. Pace (as cited in Lavin et al., 2007) uses the Department of Defense's definition to describe a subject matter expert (SME) as "an individual who, by virtue of position, education, training, or experience, is expected to have greater-than-normal expertise or insight relative to a particular technical or operational discipline, system, or process, and who has been selected or appointed to participate in development, verification, validation, accreditation, or use of a model or simulation." The sponsor fits this definition by virtue of all four descriptors in the Department of Defense's definition. He is a retired Air Force Colonel (O-6) currently working in a Scientist & Engineer position at an O-5 equivalent level as a Human Systems Integration Consultant. His education includes a Doctor of Optometry, PhD in Physiological Optics, and an HSI certificate. He served 22 years on active duty with various positions relating to

optometry, lasers, vision, and HSI. In total, he has 18+ years working on HSI issues with five years having a direct influence on acquisition programs. The various assignments, education, and skills gained over the years have given him more than enough pedigree to be called an expert.

3.2.3 Knowledge Elicitation Technique

There are many methods to eliciting knowledge, each with their own advantages and disadvantages (Proctor & Van Zandt, 2008). Although all the methods are too numerous to discuss here, several were considered for use. Interviews, case studies, protocols, observation, sorting, and document analysis were all considered as viable approaches. However, observation was ruled out due to time constraints and lack of a specific ongoing DEW acquisition program to observe. Case studies were ruled out due to lack of published literature on the specific subject. Finally, the well-known and popular technique of expert interviews was chosen as the primary knowledge elicitation technique.

Related to interviews is the verbal protocol analysis method, which differs from interviews in that the expert reports their thought process for a particular task instead of answering a series of questions. Hoffman et al. (2006) conducted a series of studies that showed both think-aloud problem solving combined with protocol analysis and unstructured interviews were time consuming and had a low yield of less than one informative proposition per minute. The most efficient methods yielded between one and two informative propositions per minute and included structured interviews, a constrained processing task, and analysis of tough cases.

The interview technique was chosen as the knowledge elicitation approach because the SMEs were busy working their jobs and had limited time. Also, the small number of participants in the research (one person, later doubled to two people) ruled out other elicitation techniques such as focus groups. A survey, although feasible for portions of developing the model, was deemed too restrictive. Surveys tend to confine answers to a narrow scope and a wider lens was needed to gather the needed information. The interview process worked well when combined partially with other techniques like sorting and document analysis.

A semi-structured interview was used for knowledge elicitation from the experts. The semi-structured interview was chosen in part due to Hoffman's (2006) assertion that structured provides better results than unstructured. This technique allowed for more varied responses and avoids close-ended questions. In this particular case, the experts also happened to be the decision-makers, which was another reason the semi-structured approach was used. In many instances, decision-makers may be managers or supervisors who work exclusively in the role of overseeing others. They may not hold a high degree of knowledge on the particular subject and often rely on the expertise of others. This was not the case in this research, and it helped speed the process of creating the value hierarchy.

The semi-structured approach worked because multiple, identical interviews did not need to be conducted over time as in a structured interview. Likewise, having no questions prepared in advance did not make sense as in an unstructured interview. The semi-structured interview was a good balance between the two. It allowed for a partially

formalized interaction between researcher and SME where a few constructed questions could generate further discussion on a subject.

3.2.4 *Expert Interactions*

Research into DEWs and the acquisition process was conducted before ever meeting with the expert. This was a vital piece of the pre-interview process to obtain credibility as a researcher and provide a base from which to formulate questions and guide the discussion. Five scheduled interviews were conducted over the course of the research, which lasted approximately seven months total. Each meeting was scheduled for one hour and opened with an explanation of the reason for the interview. Care was taken during each interview to distinguish between facts, opinions, and assumptions. In working through a semi-structured interview process, four to six questions were prepared beforehand with additional questions asked based on the answers. This technique led to open discussions and allowed for the free flow of information and knowledge.

The first meeting happened early on and was meant as a “meet and greet” between researcher and expert. It served as a starting point for reconciling scholarly research and expert knowledge. Subsequent interviews progressed through the VFT steps. Interviews four and five saw the inclusion of a second expert. The combined knowledge and inputs of both SMEs enhanced the information being provided. Although the lack of a larger group of stakeholders could be thought of as detrimental to the process, it actually provided an opportunity to quickly come to decisions regarding the creation of the hierarchy. Lack of access to the decision-maker was not a problem throughout the hierarchy construction.

It should be noted that in the context of this research that the experts and decision-makers were one and the same. Applied to an actual DEW acquisition program, the experts have authority to make limited decisions about HSI in the program. Other stakeholders and decision-makers make important decisions throughout over which the experts have little control. The experts are essentially the advocates for HSI within the program and could use the model to support their suggestions.

3.3 VFT Process

3.3.1 Step 1: Problem Identification

The VFT steps shown in Figure 8 were used, starting with step 1. An incorrectly framed problem leads to the wrong problem being solved. This failure will inevitably lead to a poor decision because the decision will not be based on relevant analysis. Framing the decision specifies three key aspects of the decision: purpose, perspective, and scope (Parnell et al., 2013).

Purpose: Arguably the most important part of the problem is defining the purpose. Sometimes the purpose is obvious and other times there might be a less obvious definition. The question that needs to be answered in the “why.” In this research the “why” was to measure the HSI in a DEW acquisition program.

Perspective: Questions such as “is this going to save money” or “how can we increase the effectiveness” are examples of different views of the same problem. Coming at the problem from different angles can be beneficial, but framing helps identify the key issues and who should be making decisions.

Scope: The scope of the decision sets the boundary from which the problem will be assembled. Areas outside the scope will not be examined and are deemed irrelevant to

the problem at hand. This research focused specifically on the HSI in DEWs as opposed to all weapon systems or other acquisition programs.

The first two meetings with the decision-maker confirmed the need for an objective, defensible means to conduct HSI on a DEW acquisition program. The HSI/DEW expert had many years of experience and knowledge and the current situation had no standardized process for measuring the application of HSI. Too often, the supervisor would let the expert know when enough was enough. Importantly, the process was not necessarily repeatable from one DEW acquisition program to the next.

To better meet the needs of the acquisition program and thus support the DEW system being developed, the many domains of HSI must be applied early and deliberately. The alternatives can then be analyzed to see how HSI was applied to the acquisition program. The Air Force states that the “goal of HSI is to maximize total system performance, understanding that the human element is an integral part of systems, while minimizing total ownership costs” (Carr & Greene, 2009a). Thus, the strategic values remain constant across the board of acquisition programs. This gives a clear indication of how HSI should be viewed during the acquisition process.

3.3.2 Step 2: Identify & Structure Objectives

The objectives definition phase went through several iterations after being discussed during the first few interviews. At first, a strawman hierarchy was developed through gold standard documents. After the first interactions and discussion, the hierarchy was updated with the new platinum standard information. The decision-makers agreed that the objective was to have a measurable way to fulfil their mandate of including HSI in the acquisition process while also satisfying their own internal objective

to “ensure weapons systems are designed, developed, or adapted with human capabilities and limitations in mind” (Department of the Air Force, 2018). The goal was to determine what was valued to achieve the fundamental objective and subsequently organize the values from general to more specific, in hierarchal format. Keywords, concepts, ideas, and values were recorded throughout each interview, sorted, and then grouped into logical bunches. This led to the basis for the model’s first hierarchy.

The initial proposal had “Improve System Performance” as the fundamental objective and the nine HSI domains as the Tier 1 objectives. Further discussion revealed the initial fundamental objective was off the mark and missed addressing the identified problem. Although “Improve System Performance” is a part of the objective, it is not the primary objective. It was changed to “Integrate Human with DEW System” to capture the essence of what VFT would do for this problem. This top-down method first identified what is most important to the decision-maker and allowed the further breakdown of important objectives. The nine HSI domains originally used as tier 1 objectives were modified to their oft used combinations of Human Factors, MPT, ESOH, and Abilities (comprised of Survivability and Habitability). The second tier is comprised of more specific definitions of the nine HSI domains (first tier objectives). The third tier shows the most important and relevant values from the second tier. Finally, the measures make up the last tier and show the degree of attainment for the values in the previous tier. The value hierarchy shell is shown in Figure 9 and depicts the three distinct tiers (the final measures tier is not pictured). There are four tier 1 objectives, 11 tier 2, and 22 tier 3.

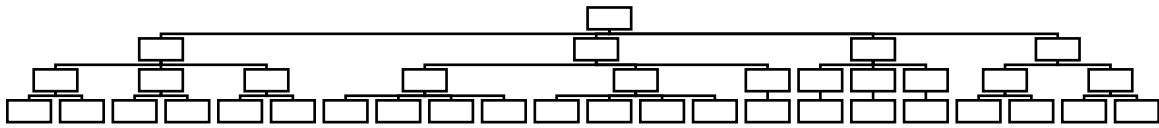


Figure 9. Value Hierarchy

The first-tier objectives represent the same nine definitions previously covered in Chapter II. The relationship between the nine HSI domains and the fundamental objective represents a clear, logical way to view HSI in a given DEW program that results in a mutually exclusive, collectively exhaustive value hierarchy. There are some inherent overlaps with the nine domains as they are originally structured. For example, survivability and habitability can be argued to be sub-domains of human factors. The challenges with some similarities and potential for cross-contamination between objectives were overcome with second and third tier objectives that clearly defined how they fit into the hierarchy. This still allowed for trade-offs to be made between objectives while staying mutually exclusive. The first tier is shown in Figure 10 with the fundamental objective on top. Each of the four branches are ordered by how the HSI domains are normally addressed, but the order itself has no bearing on the problem. Each branch is broken down further in Chapter IV. Definitions of the four tier 1 objectives are shown in Table 3.

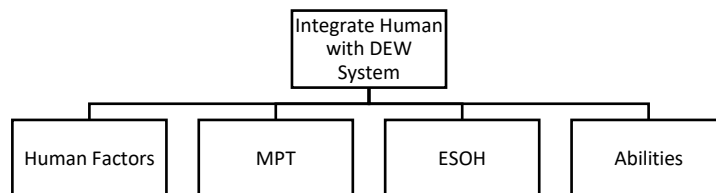


Figure 10. Tier 1

Table 3. Abbreviated Definitions for Tier 1 (Drillings, Knapp, & Shattuck, 2015)

Human Factors	The integration of human characteristics into system definition, design, development, and evaluation to provide for effective human-machine performance under operational conditions.
MPT	Manpower: The number of people needed to operate, maintain, train, and support a system; includes military, civilians, and contractors.
	Personnel: The performance-related characteristics of people needed to operate, maintain, and support the system. This includes the cognitive and physical capabilities required to train for, operate, maintain, and sustain materiel and information systems.
	Training: The process of designing and delivering a managed set of experiences so that people have the knowledge, skills, and attitudes that will enhance user capabilities, maintain skill proficiencies, and decrease individual and collective training costs.
ESOH	Environment: Those system design characteristics that serve to minimize the impact of the system on the water, air, and land and the interrelationship that exists among water, air, land, and all living things. Prevalent issues include the prevention of pollution of the environment by reducing the use of hazardous materials and the release of pollutants into the environment.
	Safety: The design features and operating characteristics of a system that serve to minimize the risk of illness, disability, or death to users, operators, and maintainers.
	Occupational Health: Design features and operating characteristics of a system that create significant risks of bodily injury or death. Prominent sources of health hazards include acoustics energy, chemical substances, biological substances, temperature extremes, radiation energy, oxygen deficiency, shock (not electrical), trauma, and vibration
Abilities	Survivability: Ability of personnel to exist and function during and following exposure to hostile situations or environments; includes combat weapons-induced injuries, enemy or friendly casualties, hazards inherent to personnel during threat or combat conditions, and inherent hazards of military equipment to include egress when system is damaged or destroyed.
	Habitability: Those living and working conditions that are necessary to sustain the morale, safety, health, and comfort of the user population. These conditions directly contribute to personnel effectiveness and mission accomplishment, and they often are related to recruitment and retention problems.

3.3.3 Step 3: Measure the Achievement of Objectives

HSI practices can be measured in numerous ways. Cognitive workload, for example, has entire papers devoted to different methods of measurement. The practice used in this model to obtain measurements focused on obtainability and sensibility. A measure is of no use if the data cannot be obtained. Likewise, measurements that do not encapsulate the correct attribute are of no use. Measures were obtained through interviews with the decision-makers to ensure subject matter expertise was engrained into the model. Chapter IV shows measures for the lowest tier objectives. This research did not reach an in-depth conclusion regarding measures and instead provides proposals of what could be used Chapter IV.

3.3.4 Step 4: Single Attribute Value Function

Single attribute value functions were not fully developed for this research. Like step 3, only the method is explained. An example of a possible value function is mentioned in Chapter 4.1.5.

Single attribute value functions (SAVFs) are used to standardize the measures across the hierarchy. Exponential, linear (including piecewise linear), categorical/discrete functions are the most common methods used (Kirkwood, 1996). The piecewise linear function contains line segments of varying slopes. A generic example of categorical data would be yes/no or low/medium/high options. With categorical data, each category (or choice) is assigned a number representing the capability. The lowest acceptable threshold was given a value of 0 while the best was given a score of 1. In the yes/no example, no would have a score of 0 while yes would score 1. In a low/medium/high example, the medium could possibly have a score of 0.5 or anywhere else between 0 and 1 based on

the decision-maker's preference. Exponential functions of increasing preference signify that small inputs results in small outputs while large inputs result in large outputs. Larger numbers are preferred in these cases because they add more value. The value function is shown in Equation (1). The opposite is true for exponential functions of decreasing preference shown in Equation (2).

$$v(x) = \begin{cases} \frac{1 - \exp[-(x - Low)/\rho]}{1 - \exp[-(High - Low)/\rho]}, & \rho \neq \text{infinity} \\ \frac{x - Low}{High - Low}, & \text{otherwise} \end{cases} \quad (1)$$

$$v(x) = \begin{cases} \frac{1 - \exp[-(High - x)/\rho]}{1 - \exp[-(High - Low)/\rho]}, & \rho \neq \text{infinity} \\ \frac{High - x}{High - Low}, & \text{otherwise} \end{cases} \quad (2)$$

3.3.5 Step 5: Multi Attribute Value Function (Weights)

Appropriately applying weights to each attribute is a major part of the VFT process. The weights signify the importance of each attribute and account for differing scores for attributes with the same values. However, importance does not convey everything about weights. Keeney (1992) says, “if the value trade-offs are done properly and address the question of how much of one specific attribute is worth how much of another specific attribute, the insights from the analysis are greatly increased and the likelihood of misuse of those judgments is greatly decreased.” Local weights are those within the same branch and tier, that when summed equal 1. Figure 11 shows an example

of local weights. Attribute 1's weight of 0.75 and Attribute's 2 weight of 0.25 summed together equal 1. Likewise, Sub 1A's 0.20 and Sub 1B's 0.80 equal 1.

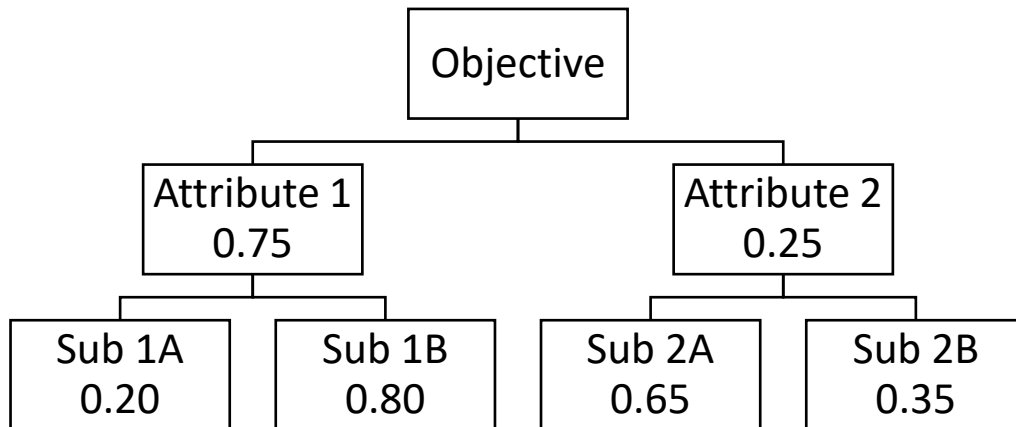


Figure 11. Local Weights

Global weights are similar except they sum to 1 across each row as shown by the numbers enclosed in parenthesis in Figure 12. Global weights can be viewed as each attribute's max contribution to the overall score. Global weights can be determined either hierarchical or non-hierarchical. The hierarchical approach views each objective as it appears in the hierarchy and can be completed either top-down or bottom-up. The non-hierarchical approach views only the lowest tier objectives. Once weights are determined, the upper-tier weights are calculated.

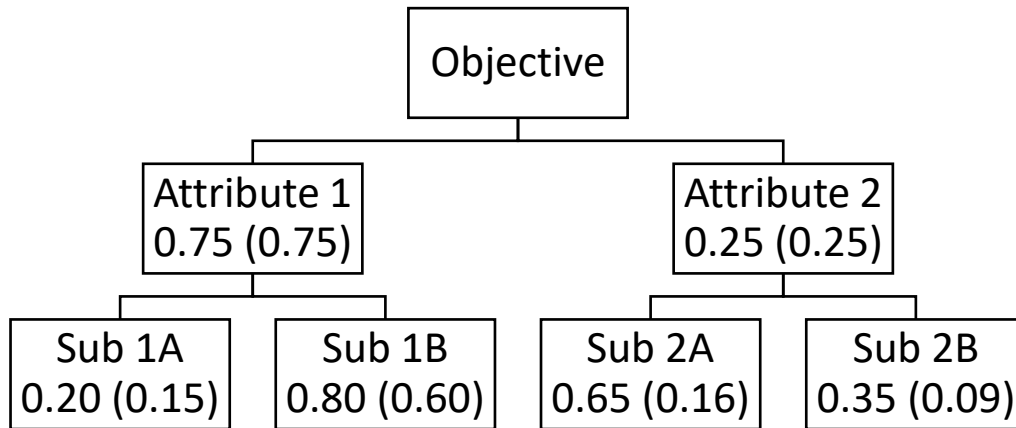


Figure 12. Global Weights

The decision-makers used a direct weighting method (100-ball) to determine all weights. This method entails the decision-maker ranking each attribute on a scale of 1 to 100. As explained in the preceding paragraphs, local weights across tiers and within branches will sum to 1, or 100 in the context of this method. Likewise, global weights will also sum to 100 across rows. The decision-maker pictured having 100 balls to allocate to attributes. After distributing the balls to each attribute, the decision-maker reviewed his allocations with the understanding that an attribute assigned a weight of 50 indicated it was twice as important as one assigned a 25.

A baseline estimation was provided to them based on previous discussions and they both made adjustments as needed. Using the top-down approach, they started with tier 1 and worked their way down to the lowest tier. At the conclusion of that session, the weights were verified to represent the importance of each attribute. Final weights will be discussed in Chapter IV.

The 100-ball method was used because of incomplete measures and value functions. This method is a type of importance weight, that is, weights are assigned to

measures independent of the variation of the measure range. A more widely accepted method for determining weights is known as swing-weighting. In this method, both importance and variation of the scales of value measures are taken into account (Keeney, 1992). For example, if we reduce the range of one of the measure scales while holding all other measure ranges constant, the measure's relative weight decreases while all other weights increase. A swing-weight matrix is proposed by Parnell (2009) as a tool for decision-makers to assess swing weights.

3.3.6 Step 6: Alternative Generation

The timing can greatly affect the alternative generation process, given the nature of the acquisition process and when the HSI practitioners are first called upon for input. Pre Milestone A input would be different than later in the process. Sometimes there may be pre-existing alternatives in which case plugging in the numbers provides an easy comparison. The model can also be used to determine which trade-offs give the most benefit. The realization of trade-offs is one of the cornerstones of a VFT model. Taking away functionality in one area may lead to improved functionality elsewhere, resulting in a better overall system.

3.3.7 Step 7: Alternative Scoring

Scoring is completed by inputting the appropriate values into the model. A best practice is to have the decision-maker, or whoever is completing the scoring portion, to not review the weights or value functions prior to categorizing or assigning the appropriate value. This prevents the person from changing the value based on how they think the score may change due to its weight or particulars of it

3.3.8 Step 8: Deterministic Analysis

Deterministic analysis examines the results of the model. Different ways of visualizing the alternatives are used to gain insights into the results. Two popular examples are the value breakout and cost vs value charts. The value breakout chart displays each alternative in a bar chart where it is easy to see how much each attribute contributes to the total score. The cost vs value chart depicts each alternative in relation to its cost (x-axis) and value (y-axis). Both charts, and others, can help uncover information within the model that may not be apparent at first glance.

3.3.9 Step 9: Sensitivity Analysis

Sensitivity analysis examines whether different assumptions lead to different scores and consequently, a reordering of the ranked alternatives. The most common aspect to change is the weights. For example, if a weight equaled 50% of the overall model, reducing it to 25% could have an impact on the alternatives' ranks.

3.4 Summary and Preview

This chapter discussed the methods and procedures used to build the value hierarchy. The primary methods used were a series of in-depth interviews with the decision-makers, who were also subject matter experts in the applicable disciplines. The foundational input from both the experts and the Air Force's HSI Handbook resulted in a credible and defensible value hierarchy. Chapter IV will cover the nuances of each branch including objective definitions and associated measures.

IV. Results

The conclusion of interviews with the decision-makers resulted in a value hierarchy for use on DEW acquisition programs. Each branch of the hierarchy will be decomposed by objective. The objectives will be defined and proposed measures outlined. Finally, proposed weights are discussed. As explained more in Chapter V, the hierarchy needs some additional refinement before it could be used effectively. Figure 13 shows the first tier of the hierarchy.

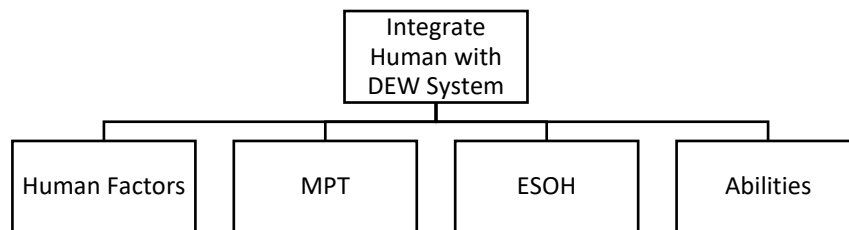


Figure 13. Tier 1 (repeated)

4.1 Decomposition of Branches

Each branch (Human Factors, MPT, ESOH, and Abilities) will be explained with a visual representation, objective definitions to the lowest tier, and summary of measures. A branch-by-branch review was chosen over a step-by-step summary to offer a holistic view of each branch. The weighting portion is covered separately in the chapter to build a complete picture of the hierarchy.

4.1.1 Human Factors Branch

The human factors branch is an important part of HSI and is often mistaken as being the only HSI domain. This is probably because even without knowing it, people associate “human systems integration” with the directly human aspects found in human factors. The human factors branch, shown in Figure 14 and defined in Table 4, consists of three tier-2 objectives, each with two tier-3 objectives for a total of six lowest level objectives. With human factors as the overarching principle, a summary of the measures is shown in Table 5 and defined in Table 6.

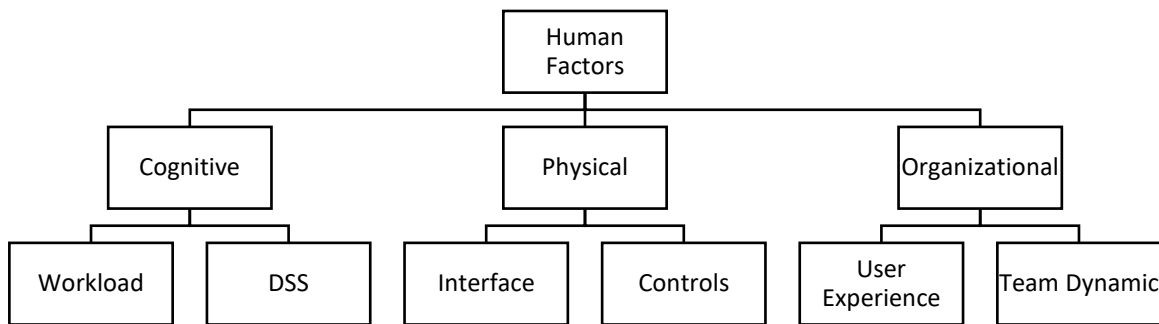


Figure 14. Human Factors Branch

Table 4. Definitions of Human Factors Branch

Human Factors		Suitable integration of human characteristics into system.
Cognitive		Psychological processes of decision making and problem solving.
	Workload	Level of mental effort put forth.
	Decision Support System	Whether a decision support system (DSS) can assist.
Physical		Relation of human interactions with the world.
	Interface	Whether the point of interaction between human and system
	Controls	Appropriate placement of touchpoints.
Organizational		Connections between user, encompassing system, and other crew.
	User Experience	Satisfaction of user while operating system.
	Team Dynamic	Whether relationship between crew members affects functionality.

Table 5. Summary of Measures for Human Factors Branch

	Lowest-Tier Hierarchy Value	Associated Measure	Lower Bound	Upper Bound
Cognitive	Workload	Speed of Kill Chain	Slower	Faster
	Decision Support System	Error Rate	5%	0%
Physical	Interface	Ease of Use	Various	
	Controls	Reachability	Hard	Easy
Organizational	User Experience	Satisfaction Level	Low	High
	Team Dynamic	Task Dependencies	100%	0%

Table 6. Definitions of Human Factors Measures

Measure	Definition
Speed of Kill Chain (workload)	The speed at which the operator can complete the kill chain, i.e. faster or slower than opposing force.
Error Rate	How often the DSS provides inaccurate information.
Ease of Use	The ease at which an operator can interact with the system.
Reachability	How difficult it is for the operator to reach controls.
Satisfaction Level	Whether an operator experiences fulfillment from operating the system.
Task Dependencies	The operator's reliance on other crew members to operate effectively.

4.1.2 MPT Branch

The MPT branch, shown in Figure 15 and defined in Table 7, consists of three tier-2 objectives and a total of nine lowest level objectives. The reader may notice the “personnel” in MPT is represented in the hierarchy as Knowledge, Skills, and Attributes (KSAs). This distinction is due to KSAs being the primary personnel factor to consider for this research. The four lowest-level objectives for both Manpower and KSAs are identical. This is because the type of manpower to consider are the same people who need to possess the requisite KSAs. With MPT as the overarching principle, a summary of the measures is shown in Table 8 and defined in Table 9.

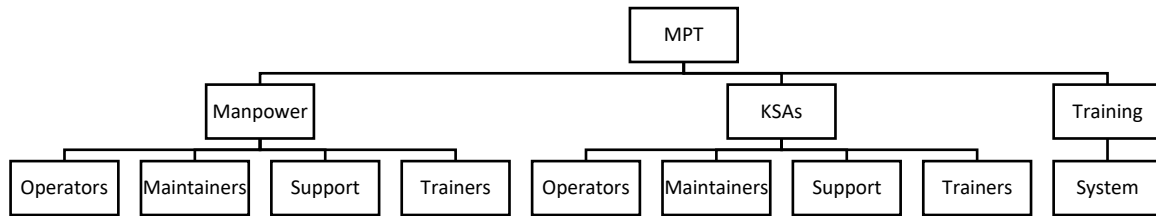


Figure 15. MPT Branch

Table 7. Definitions of MPT Branch

MPT		
Manpower		The number of people needed to employ system.
	Operators	People who operate the system.
	Maintainers	People who maintain the system.
	Support Personnel	People who support the system.
	Trainers	People who provide training for the operation, maintenance, and support of the system.
KSAs		Knowledge, skills, and abilities pertinent to employment of the system.
	Operators	People who operate the system.
	Maintainers	People who maintain the system.
	Support Personnel	People who support the system.
	Trainers	People who provide training for the operation, maintenance, and support of the system.
Training		The experiences and tools used to teach system users what they need to know.
	System	Classes, instructions, manuals, aids, and anything else that is used to provide training.

Table 8. Summary of Measures for MPT Branch

	Lowest-Tier Hierarchy Value	Associated Measure	Lower Bound	Upper Bound
Manpower	Operators	Personnel Required Relative to Legacy System	More	Less
	Maintainers			
	Support			
	Trainers			
KSAs	Operators	ASVAB Score	High	Low
	Maintainers			
	Support			
	Trainers			
Training	System	Course Length (wks)	12	1

Table 9. Definitions of MPT Measures

Measure	Definition
Personnel Required Relative to Legacy System	The number of personnel required compared to the legacy system. This includes operators, maintainers, support personnel, and trainers.
ASVAB Score	The Armed Services Vocational Aptitude Battery score.
Length (wks)	The length of formal training for operators.

4.1.3 ESOH Branch

The ESOH branch, shown in Figure 16 and defined in Table 10, consists of three tier 2 objectives and an equal number of lowest level objectives. They are, in essence, proxy attributes to the tier-2 objectives. As noted in the next section, the equal number of tier-2 and tier-3 objectives result in both tiers having the same weights. The reason for the further decomposition is to clarify what objective is actually being measured. It also makes more sense when paired with the remainder of the hierarchy so each branch has a similar number of tiers. With ESOH as the overarching principle, a summary of the measures is shown in Table 10 and defined in Table 11.

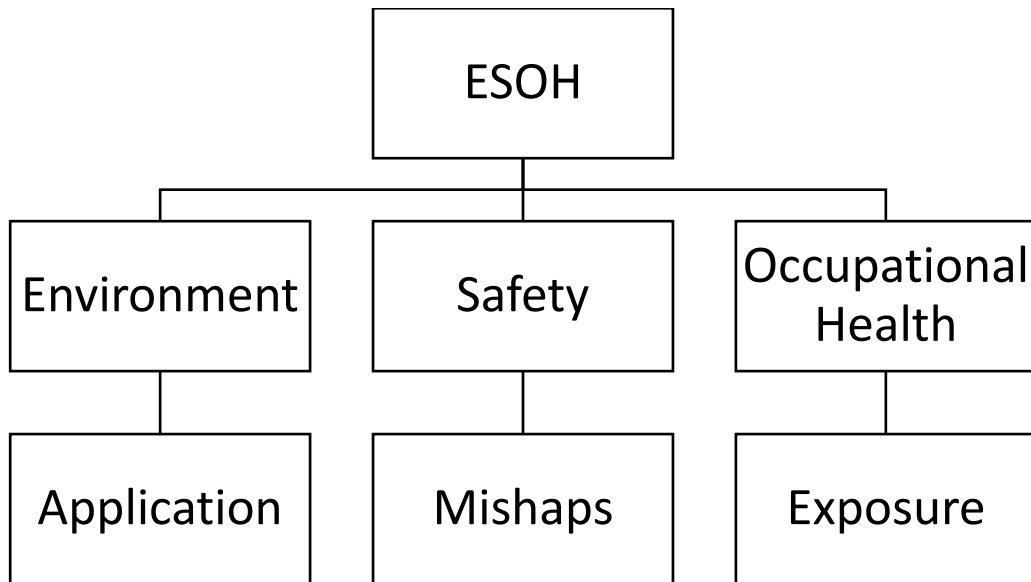


Figure 16. ESOH Branch

Table 10. Definitions of ESOH Branch

ESOH		
Environment		Characteristics that minimize the impact of the system on the world around it.
	Application	Whether methods of smart employment are known.
Safety		Characteristics that minimize risk of injury.
	Mishaps	Any unplanned event that results in personal injury or property damage.
Occupational Health		Risks from the system itself.
	Exposure	Whether effects can be controlled to minimize accidental exposure to persons other than targets.

Table 11. Summary of Measures for ESOH Branch

	Lowest-Tier Hierarchy Value	Associated Measure	Lower Bound	Upper Bound
Environment	Application	Do operational plans include methods/reasons for employment?	No	Yes
Safety	Mishaps	Incident Rate by Class	A	0%
			B	
			C	
			D	
Occupational Health	Exposure	Likelihood of Accidental Exposure	10%	0%

Table 12. Definitions of ESOH Measures

Measure	Definition
Do operational plans include methods/reasons for employment?	Planning guidance taking into account DEWs. Do leaders and operators possess the know-how of when to employ the weapon?
Incident Rate by Class	The DoD categorizes into four classes: A - >\$2M in damages B - >\$500,000 in damages C - >\$50,000 in damages D - >\$20,000 in damages
Likelihood of Accidental Exposure	Chance of non-target being exposed to the weapon's beam.

4.1.4 Abilities Branch

The Abilities branch, shown in Figure 17 and defined in Table 13, consists of two tier-2 objectives, each with two lowest level objectives, for a total of four lowest-level objectives. With Abilities as the overarching principle, a summary of the measures is shown in Table 12 and defined in Table 13.

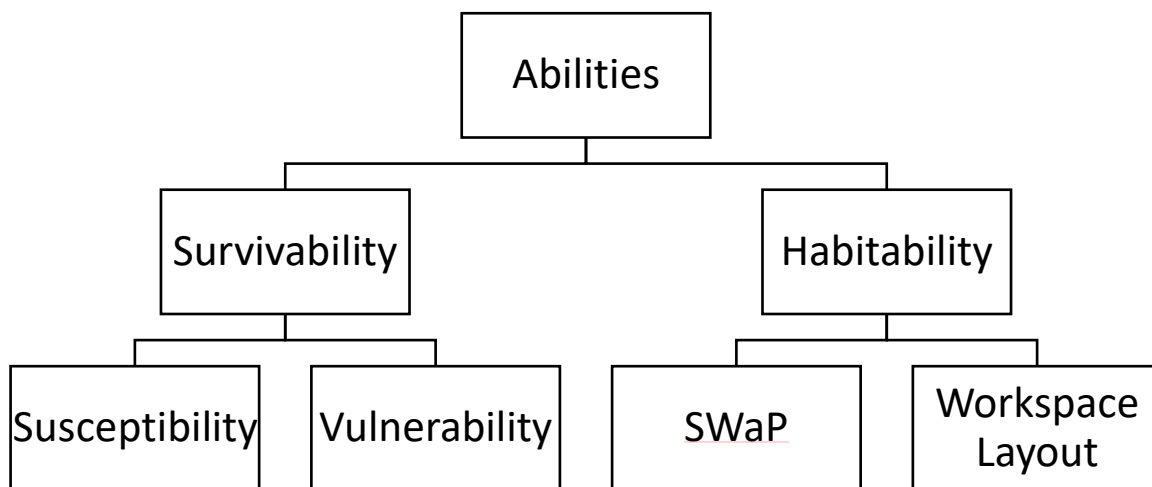


Figure 17. Abilities Branch

Table 13. Definitions of Abilities Branch

Abilities		
Survivability		Ability to function in hostile situations or environments.
	Susceptibility	Inability to avoid threats.
	Vulnerability	Inability to withstand hits.
Habitability		Living and working conditions to sustain users of the system.
	SWaP	Reasonable size, weight, and power for system.
	Workspace Layout	Characteristics of the workspace such as temperature and lighting conditions.

Table 14. Summary of Measures for Abilities Branch

	Lowest-Tier Hierarchy Value	Associated Measure	Lower Bound	Upper Bound
Survivability	Susceptibility	Probability of DEW Hit	100%	0%
	Vulnerability	Probability of DEW Kill	100%	0%
Habitability	SWaP	Dimensions	Varies by System Enclosing the DEW System	
		Weight (lbs)		
		Power Used (kW)		
	Workspace Layout	Lighting (fc)	30	50
		HVAC	Worst	Best

Table 15. Definitions of Abilities Measures

Measure	Definition
Probability of DEW Hit	How likely the DEW system is to take a hit.
Probability of DEW Kill	How likely the DEW system is to cease functioning after a hit.
Dimensions	Total size of the system in length, width, height.
Weight (lbs)	How much the system weighs.
Power Used (kW)	How much power the system uses.
Lighting (fc)	The amount of lighting in the workspace.
HVAC	The heating, ventilation, and air conditioning of the workspace.

4.1.5 Example SAVFs

Two example SAVFs are shown in Figures Figure 18 and Figure 19. Figure 18 shows a possible SAVF for the length of training in weeks. If the length of training were one week, it would receive a score of 1, the highest possible score. A length of 12 weeks would result in a score of 0, the lowest possible value. The midvalue of four weeks would receive a score of 0.5. When determining SAVFs, the midvalue can change based on the decision-maker's discretion. Whereas some may keep the midvalue exactly in the middle of the range, others could feel the midvalue was closer to the extremes, changing the value in the process.

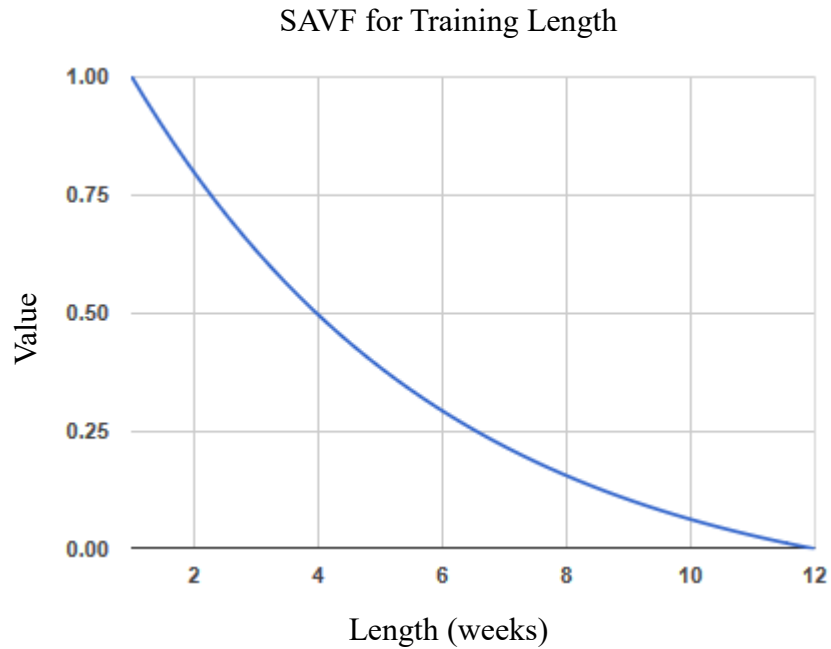


Figure 18. Example Exponential SAVF

Figure 19 shows a possible SAVF for illuminance of the workspace as measured in foot candles (fc). An illuminance equal to 30 fc would score 0, the lowest possible value. An illuminance equal to 50 fc would score 1, the highest possible value. An illuminance equal to 40 fc would score 0.5, the mid-value.

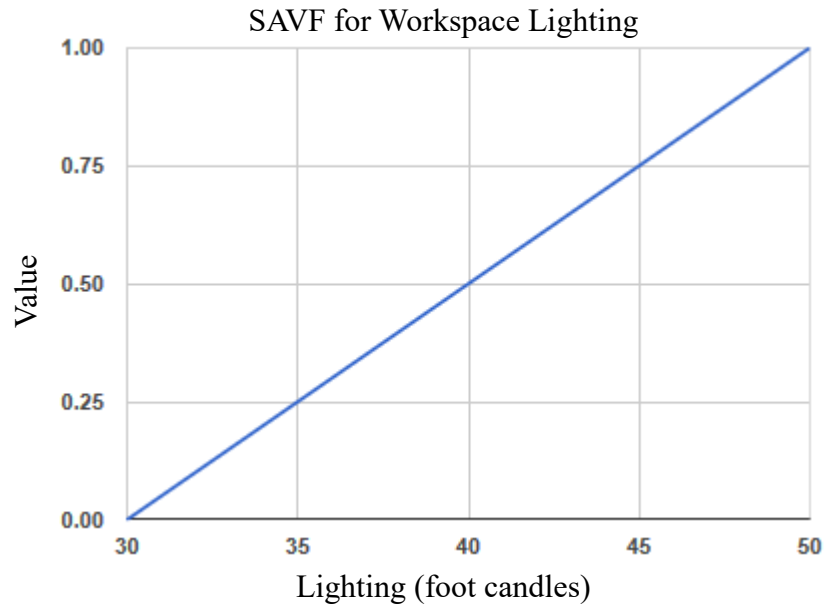


Figure 19. Example Linear SAVF

4.2 Hierarchy Weights

Weights across tiers will be displayed in the same manner as discussed in the previous chapter, with global weights enclosed in parenthesis. The tier-1 weights are shown in Figure 20 and Figure 21. The tier-1 weights have equal local and global weights. It was determined that the MPT branch was the most important and thus deserved a weight of 0.55, the highest of any objective. The relatively high importance stems from the fact that most costs over the life of a system come from the people involved with said system. Second most important was Human Factors at 0.20, followed by ESOH at 0.15 and Abilities at 0.10. The decision-makers were careful not to discount any particular objective and weighted them appropriately based on their observance of practiced procedures and sentiments.

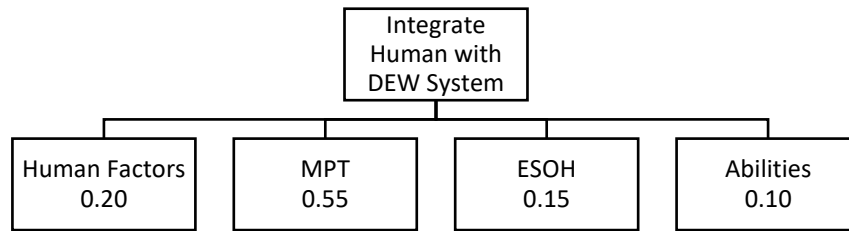


Figure 20. Tier 1 Weights

A graph of the weight distribution is shown in Figure 21. As mentioned in the previous paragraph, MPT holds the highest weight and thus is the most important to the decision-maker. As visualized below, it is almost three times more important than the next highest attribute, Human Factors. To put how much more weight MPT has than the other attributes in perspective, it is about 3.5 times more than ESOH and 4.5 times more than Abilities. Likewise, the 0.20 weight for Human Factors is twice as big as Abilities' 0.10 weight. The remainder of the hierarchy is broken down in the following sections.

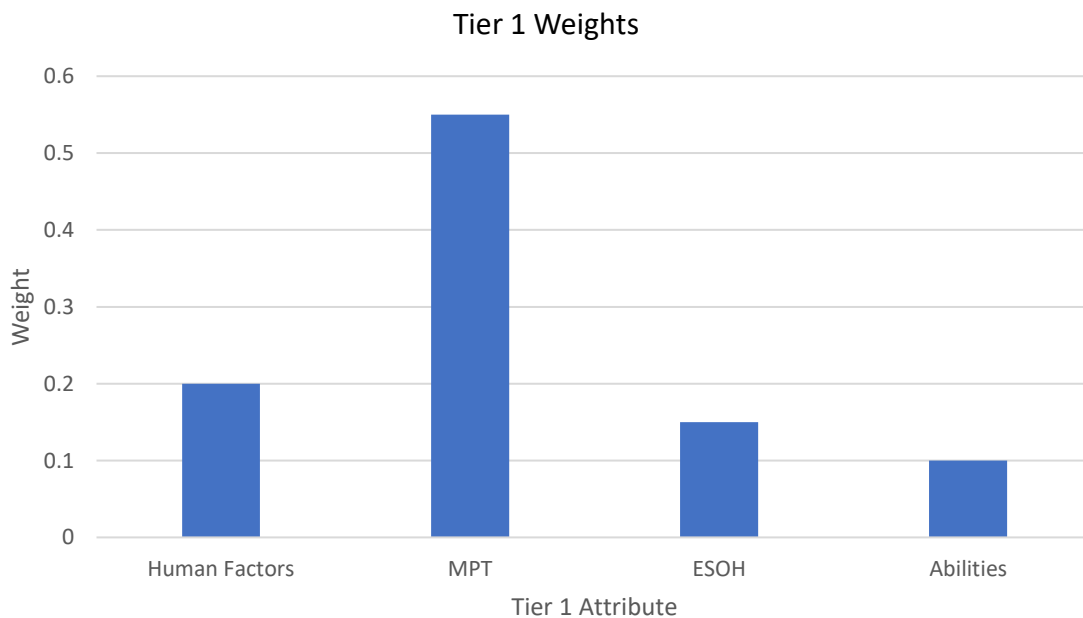


Figure 21. Tier 1 Weights Chart

4.2.1 Human Factors Weights

Human Factors was broken down into three tier-2 objectives, with each of those being broken into two tier-3 objectives (shown in Figure 22). Cognitive, Physical, and Organizational have local weights of 0.55, 0.35, and 0.10, respectively. The global weights are 0.11, 0.07, and 0.02. Global weights have meaning in the overall hierarchy discussion. Out of the entire 20% weight Human Factors has in the hierarchy, Cognitive is 11%, Physical 7%, and Organizational 2%. If each category was given the maximum score, it would equal 20% of the total score.

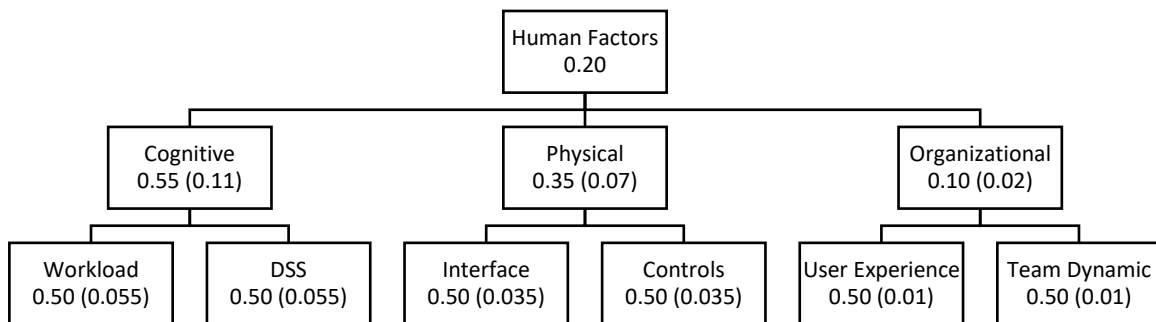


Figure 22. Human Factors Weights

Cognitive: The cognitive objective had the highest weight among the three tier-2 objectives. This is due to the assertion that operating a DEW is mostly mental as opposed to a physical toll on the body. The tier-3 objectives of Workload and DSS were given equal local weights of 0.50, resulting in identical global weights of 0.055. The global weights indicate a top score in each category would result in 11% of the total score, at 5.5% each.

Physical: The physical objective had the second highest weight of 0.35 and like cognitive, had two tier-3 objectives. The Interface and Controls were locally weighted evenly at 0.50, resulting in global weights of 0.035. The global weights indicate a top score in each category would result in 7% of the total score, at 3.5% each.

Organizational: The organizational objective was deemed the least important with a weight of 0.10. Again, two tier-3 objectives of User Experience a Team Dynamic were used. The local weights were 0.50 and global 0.01. The global weights indicate a top score in each category would result in 2% of the total score, at 1% each.

4.2.2 MPT Weights

MPT was broken down into three tier-2 objectives and a total of nine tier-3 objectives (shown in Figure 23). Manpower, KSAs, and Training have local weights of 0.30, 0.50, and 0.20, respectively. The global weights are 0.165, 0.275, and 0.11. This branch has the highest weights of all the branches, signifying the importance of manpower, personnel, and training. KSAs are the most important objective in the hierarchy, accounting for 27.5% of the total score. Second most important is Manpower at 16.5% followed by Training at 11%. Cognitive, from the Human Factors branch, also comprises 11% of the total score. MPT and Human Factors combine to account for 75% of the total potential score.

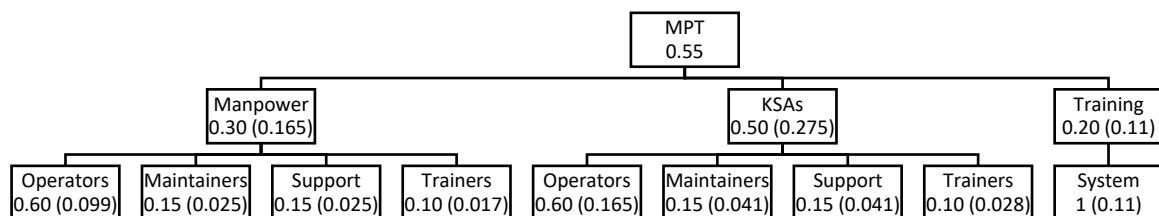


Figure 23. MPT Weights

Manpower: The manpower objective was deemed second most important of the MPT branch with a weight of 0.30. Four tier-3 objectives of Operators, Maintainers, Support, and Trainers were used. The Operators objective was deemed most important with a local weight of 0.60 and global weight of 0.099. Maintainers and Support share equal importance with local weights of 0.15 and global weights of 0.025. Least important was Trainers at 0.10 and 0.017. The global weights indicate a top score in each category would result in 16.5% of the total score, with 9.9% allocated to Operators, 2.5% each to Maintainers and Support, and 1.7% to Trainers.

KSAs: The KSAs objective was deemed most important of the MPT branch, which also made it the most important objective to the hierarchy. The four tier-3 objectives are identical to those in the Manpower objective and share the same local weights of Operators – 0.60, Maintainers – 0.15, Support – 0.15, and Trainers – 0.10. However, due to the increased weight of the tier-2 KSAs objective, the global weights are larger at 0.165, 0.041, 0.041, and 0.028, respectively. The global weights indicate a top score in each category would result in 27.5% of the total score, with 16.5% allocated to Operators, 4.1% each to Maintainers and Support, and 2.8% to Trainers.

Training: The Training objective was deemed the least important with a weight of 0.20. The one tier-3 objective of System has a local weight of 1 and global weight of 0.11. The global weight indicates a top score in System would result in 11% of the total score.

4.2.3 ESOH Weights

ESOH was broken down into three tier-2 objectives, each with only one tier-3 objective (shown in Figure 24). Environment, Safety, and Occupational Health have local

weights of 0.20, 0.60, and 0.20, respectively. The global weights are 0.03, 0.09, and 0.03. A large drop in importance can be seen in the weights for the three tier-2 objectives. Environment and Occupational Health account for 6% of the total score at 3% each while Safety is 9%. To add context, the KSAs of Trainers in the MPT branch account for 2.8% of the total score, which is almost the same as both Environment and Occupational Health individually. Each of the three tier 2 objectives only had one tier 3 objective, meaning global weights in both tiers were identical. To add context, the Manpower of Operators in the MPT branch equal 9.9%, about 1% more than the Mishaps weight.

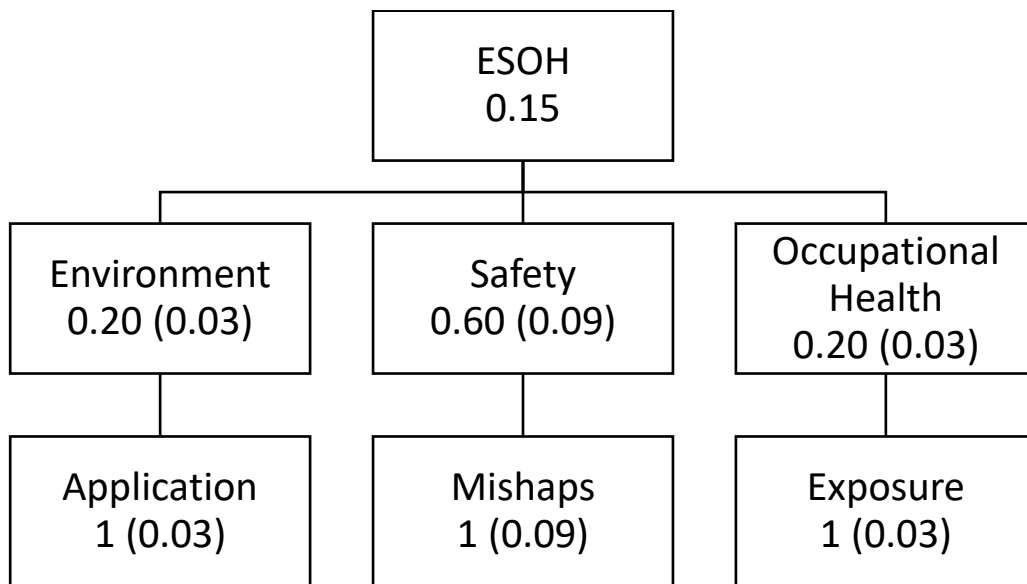


Figure 24. ESOH Weights

4.2.4 Abilities Weights

Abilities was broken down into two tier-2 objectives, each with two tier-3 objectives (shown in Figure 25). Survivability and Habitability have local weights of 0.30 and 0.70, respectively. The global weights are 0.03 and 0.07. They indicate a top score in

each category would result in 10% of the total score, with 3% allocated to Survivability and 7% to Habitability.

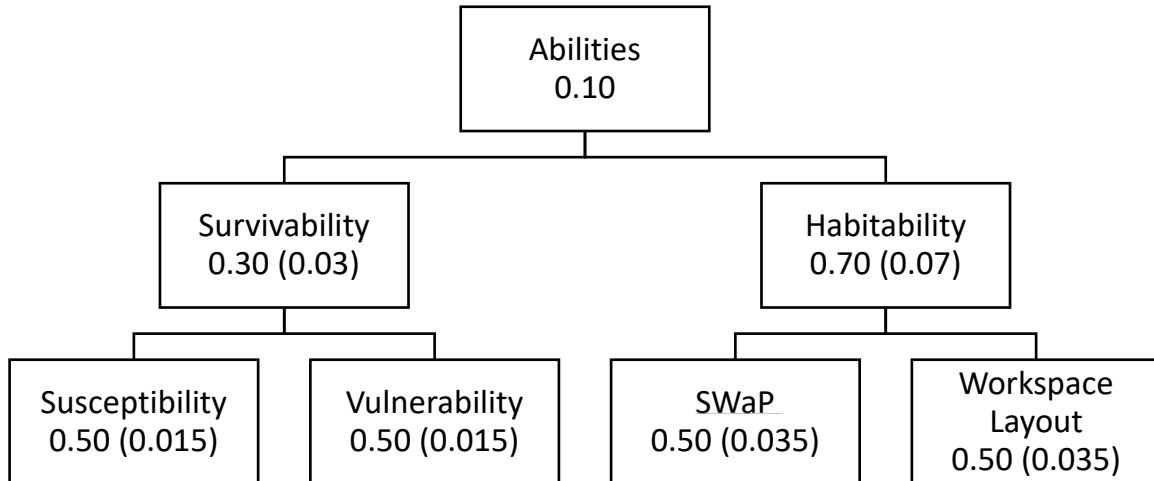


Figure 25. Abilities Weights

Both tier-2 attributes of Survivability and Habitability have two tier 3 attributes. Survivability is divided into Susceptibility at 0.50 local and Vulnerability at 0.50 local. Their global weights are both 0.015. Habitability is divided into SWaP at 0.50 local and Workspace Layout at 0.50 local. Both global weights are 0.035. The global weights of Susceptibility and Vulnerability are 1.5%, the lowest in the entire hierarchy. This is not to say these attributes are unimportant. Rather, it says they are the least important when compared to all other attributes.

4.3 Steps 6-9: Alternative Generation, Scoring, and Analysis

These steps were not applicable to the problem because there were no ongoing, accessible DEW acquisition projects from which to garner data. This does not invalidate

the method because VFT is already proven as a method to solve these types of problems, i.e. complex, significant consequences, and multiple objectives.

4.4 Step 10: Communicating Results

Results can be communicated in various ways and tailored to specific audiences or decision-makers. Recommendations can be made and it is important to note that the highest scoring alternative may not always be the best choice given certain assumptions of other influencers to the problem.

4.5 Usefulness of Hierarchy

A decision-maker should be able to use this hierarchy as a starting point for recognizing what is important when applying HSI principles to a DEW acquisition program. The hierarchy itself will not produce any output. Three possible options for inputting data are The Perduco Group's web-based VFT Tool, the Microsoft Excel version developed by Dr. Weir at AFIT, or the "DecisionAnalysis" package developed by Deehr (2018) located on the Comprehensive R Archive Network (CRAN) website, written in the programming language R. All packages will perform the same calculations and output identical values. Once the values are input and scores are calculated, alternatives can be compared against each other. Then adjustments can be made to certain values to generate new alternatives that may not have previously been options.

V. Conclusion

This chapter reiterates the complex nature of military acquisition and the need to incorporate human systems integration (HSI) early in the process. To effectively combat future threats to the accomplishment of the Air Force's mission, game-changing technologies are needed. One such technology is a directed energy weapon (DEW). An issue with DEW acquisition is the lack of a formal measurement of HSI in the acquisition process. Since the incorporation of HSI can result in substantial cost savings and a better overall weapon system, a value-focused thinking (VFT) is proposed to measure the effectiveness of HSI. However, future work is needed to transform this model into a useful tool for HSI practitioners.

5.1 Conclusion

The military's acquisition process is a long, complex process that becomes even more complex with efforts to procure weapons that will provide superiority on the battlefield for years to come. These types of weapons are often more expensive due to the technological advances over their predecessors. Directed energy weapons have proved costly to develop over time, are technologically advanced, and require a specific skillset and knowledge to be utilized properly. All factors combined, this research shows how knowledge can be obtained from a DEW and HSI expert and converted into a value hierarchy using VFT. The value hierarchy can then be used in subsequent DEW procurements to focus effort on specific HSI components.

Through the use of multi-domain expert knowledge and a codified process, organizations such as the Air Force can use VFT and its value hierarchy multiple times with minimal additional time and work investment. The value hierarchy contains all objectives important to the organization (or at least the decision-maker) and attributes that allow the measurement of each objective. After inputting applicable values, VFT provides a score for each alternative. This allows decision-makers to compare alternatives not just by rank, but by degree of objective achievement. VFT's strengths of repeatability, alternative generation, sensitivity analysis, and alternative scoring make it a good fit for evaluating HSI practices within a DEW acquisition program.

The hierarchy shows the majority of time and effort should be spent on the Manpower, Personnel, and Training HSI domains, as evidenced by the 55% weighting of the MPT objective. One reason for the overwhelming importance of MPT is due to cost. Over the life-cycle of a DEW system, or any acquisition program, the majority of costs occur in the operations and support phase (Schwartz, 2014). In this phase, much of the cost inevitably pertains to manpower, personnel, and training. Therefore, correctly ascertaining the optimal mix of operators, maintainers, support personnel, and trainers for the new system will help accurately forecast lifecycle costs. Getting the number of personnel right is just one aspect. Correctly training and employing all personnel is another factor to consider and is not covered within the model. Training length is included in the model to account for the benefit of less training time. Likewise, requiring less personnel to run the new system can only be seen as beneficial. Selecting the right personnel is also important. Personnel with a higher ASVAB score would require less training time and be better suited initially to run the system. However, higher scoring

personnel would be harder to obtain due to their demand elsewhere. This in turn could lead to higher recruiting costs or a possible shortage of needed personnel. The HSI domains of manpower, personnel, and training are vitally important to acquisition programs and weapon systems. If nothing else, a user of this model should focus their efforts on these three HSI domains to influence the acquisition effort and development of the system.

The next area of focus should be the HSI domain of Human Factors. As mentioned previously, many people only think of human factors when thinking of HSI. This is due in part to the very physical relation between the human and the machine, which is enveloped within the human factors domain. The real link between human and machine grabs peoples' attention and causes them to forget about the other HSI domains. However, this model weights the Human Factors objective at 20%, a full 35% lower than the 55% of the MPT objective. Together, the top two weighted objectives account for 75% of the model. The remaining 25% is still important, just not as central to DEW system characteristics.

This research successfully answered the first investigative question of whether an expert's knowledge of the HSI domains could be represented in a value hierarchy. Although this is only one possible solution, this model proves that the nine HSI domains can be represented in a value hierarchy. Other than simple pasting the titles of the nine domains into a hierarchal format, the beauty of a value hierarchy is the knowledge it contains. The weights are telling figures that demonstrate the relative importance of the nine domains as they relate to a DEW system. The attributes further reveal aspects of HSI that make a difference in DEW systems.

Knowledge was captured from an HSI expert and transferred via the creation of the value hierarchy. The hierarchy itself serves as a repository for the knowledge and indicates what a person should focus on when conducting HSI assessments of a DEW acquisition program. A fully produced model could improve a DEW acquisition program by providing insight into areas of concern. For example, if the model produced a score of 20 out of 55 for the MPT objective, that tells the decision-maker the particular DEW acquisition program is not doing well in manpower, personnel, or training. Further investigation would reveal a more precise reason for the low score. This knowledge by itself could provide insight into ways to change or otherwise improve the DEW program. It could also be combined with other methods such as cost estimation to provide further insight.

5.2 Future Work

There are four primary ways to develop this model into a useful tool given more time, data, and organizational involvement. First, refining the measures of each attribute would allow the input of data when it becomes available. As they stand, the measures are proposed and do not have value functions to back them up. The decision was made to not use the sponsor's time developing value measures that would not be used at this time. While still useful, the model needs to be fully flushed out and applied before it can be proven to be a viable method of assessing HSI within a DEW acquisition program.

Second, fully developing and using the VFT model on a real dataset would put the model to use and allow the sponsoring organization to see if results were helpful. The absence of real-world data resulted in a premature stopping point in the development of the model. As a result, the model lacks the ability to produce some of the more insightful

aspects of VFT analysis, notably deterministic and sensitivity analysis. Once steps 3 & 4 are fully completed, swing-weighting should be used to reassess weights. This would be a more complete approach to determining weights by accounting for both importance and variation in measures.

Third, additional expert elicitation on HSI would bring more perspective and ideas to the table. At the beginning of the decision analysis process, ideas and brainstorming act as the foundation for building the hierarchy. More ideas at the start of the process could lead to a more comprehensive hierarchy by not omitting something that a single expert may have overlooked. At the very least, a discussion could take place involving multiple personalities to gain new perspectives. Care must be taken to ask experts questions from their field of expertise.

Finally, additional VFT models could be developed to account for differences in the acquisition phases. Some measures may not be applicable in the early phases and could paint an inaccurate picture of the state of alternatives. It is also possible to evaluate alternatives based on estimations and projections and then refining the estimates into quantifiable data as it becomes available.

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14. ABSTRACT Directed energy weapons (DEW) are of interest to the armed forces as they search for more effective ways to deal with evolving threats. The development of these weapons has been ongoing for almost 40 years, despite only one operational fielding by the U.S. Navy in 2014. Some reasons for DEW's lack of adoption by the services include cost overruns and unclear requirements. Early adoption of human systems integration (HSI) in the military's acquisition process is shown to provide substantial cost savings over the life of the system. Quantifying the application of HSI within a DEW acquisition program is addressed through decision analysis using value-focused thinking (VFT). The VFT model helps program managers and HSI practitioners balance total system performance and cost of ownership. Knowledge gathered from expert elicitation was used to create the decision model consisting of objectives in a hierarchal format. The proposed VFT model is a beginning step that allows for an objective analysis of HSI efforts in a DEW acquisition program. Further work is required to make the model practical for use.						
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