Cost-Effectiveness Analysis of Autonomous Aerial Platforms and Communication Payloads

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1. Introduction

This chapter demonstrates the use of multi-criteria decision making to analyze the cost-effectiveness of autonomous aerial platforms and communication payloads for communication missions in the military. We compare the cost-effectiveness of 17 aerial platforms and 9 communication payloads across three mission scenarios.

Unmanned aerial vehicles (UAVs) can help supply the information technology connectivity that is increasingly being demanded by technology advancements on the battlefield. Autonomous vehicles are well suited for the communication mission, which is often mundane and tedious. The advent of lightweight construction materials, high energy-density lithium battery technology, and more efficient microprocessors increase UAV capability (Department of Defense 2013). The larger payload capacities and longer endurance of modern UAVs combined with communication payloads that are more capable and efficient and weigh less make them more suitable to the communications relay role than their predecessors. UAVs are also more flexible than more permanent infrastructure like relay and cellular towers, and they can be quickly repositioned to support warfighters on the move.

Scrutiny on discretionary spending in public budgets, including defense budgets, will continue to increase in many countries. Future acquisitions will need to be executed thoughtfully with a clear consideration of the value and cost. Although other studies (see Ferguson and Harbold 2001, Collier and Kacala 2008) have analyzed the costs and benefits of UAVs for different missions, no study has undertaken an extensive cost-effectiveness of the most modern UAVs and other aerial platforms that can support communication requirements for military operations in austere environments. This chapter seeks to remedy that deficiency by performing a cost-effectiveness analysis of aerial platforms and communication payloads for use as a communication relay in support of distributed military operations.

We conduct a multi-objective analysis to analyze and compare the cost-effectiveness of selected aerial platforms and communication payloads across three scenarios. This chapter considers 13 different UAVs, 4 alternative aerial platforms, and 9 communication payloads suitable for the communication relay mission. UAVs range in size from the hand-launched Raven to the Triton with its 130-foot wingspan, and communication payloads vary in weight from less than a pound to over 250 pounds. We follow the approach detailed in Chapter 8 to analyze the cost-effectiveness of these alternatives. An objectives hierarchy lists the desirable attributes for aerial platforms and communication systems, and value measures and trade-off weights lead to a numerical measure of effectiveness (MoE). The annualized life-cycle costs (LCC) are estimated for the aerial platforms, and acquisition costs are calculated for the communication payloads. Selecting the most cost-effective alternative involves consideration of the costs and MoEs. After selecting the most cost-effective aerial platforms and communication payloads for a specified scenario, we discuss whether the selected aerial platforms are compatible with the communication payloads.

Section 2 reviews a few applications of cost-effectiveness analysis in defense and discusses previous studies of UAV effectiveness. We briefly outline in Section 3 the different UAVs, alternative aerial platforms, and communication payloads. Section 4 discusses the cost-effectiveness model. An objectives hierarchy is presented for the aerial platform and for the communication payload in Section 5. After detailing the methodology for estimating costs for the aerial platforms in Section 6, we analyze the cost-effectiveness of all the alternatives for three different scenarios in Section 7, and concluding thoughts are discussed in Section 8. We rely on subject matter experts to collect and analyze data for several alternatives, and develop value measures and trade-off weights based on our own research, expertise, and experiences. Consequently, the results should not be viewed as definitive, but the analysis does provide insights into selecting the best aerial platform for different communication relay missions. Defense decision makers could incorporate their own preferences within this framework to determine the most cost-effective aerial platform and communication payload for a given scenario.

2. Literature review

Cost-effectiveness analysis seeks to evaluate costs versus the benefits of an alternative when the benefits cannot easily be measured in monetary units. The MoE can be a single numerical measure of performance if only one objective determines the effectiveness for a decision problem. Frequently, decision makers have multiple objectives, and combining several objectives into a single MoE requires a systematic process or mathematical equation. Value-focused thinking encourages decision makers to articulate their values and identify and structure their objectives (Keeney 1996). Multi-objective or multi-criteria decision making provides a framework for developing value measures over those objectives and trade-off weights among objectives in order to combine several objectives into a single MoE for a given alternative (Keeney and Raiffa 1976, Kirkwood 1997).

Some multiple objective analyses include minimizing cost as an objective and developing a multi-attribute value function over all the objectives, including cost. For example, a study to help the U.S. Army determine which bases to close develops a value function for 40 attributes, including a few cost-related attributes (Ewing, Tarantino, and Parnell 2006). The decision maker selects the set of bases to remain open that maximizes the total value subject to Army capability requirements. A cost-effectiveness analysis for the Army (Buede and Bresnick 1992) constructs MoEs for several air defense alternatives and depicts the MoE and the cost of each alternative on a two-dimensional chart. Similarly, our analysis separates the cost of each alternative from its MoE and compares the cost-effectiveness of the alternatives on a two-dimensional chart.

Several studies have analyzed the use of UAVs for different military missions, but many are financial in nature. The LCC of the the Triton UAV determines the financial implications of the U.S. Navy purchasing this system for its Broad Area Maritime Surveillance (Lawler 2010). Yilmaz (2013) compares the Reaper and the Guardian UAVs for U.S. border security and the Israeli-manufactured Heron UAV for patrolling Turkey's border but focuses primarily on the costs of the systems as opposed to their effectiveness. Some business case analyses (Thiow Yong Dennis 2007, Fry and Tutaj 2010) determine the number of UAVs of a specified type that is necessary to achieve a mission, and the decision maker should choose the UAV type that can accomplish the mission at the lowest total system cost. These approaches are similar to the second way to structure an economic evaluation of alternatives as described in Chapter 4.

A multiple objective analysis (Ferguson and Harbold 2001) compares the Global Hawk UAV, the manned research vehicle Proteus, and three solar powered aircraft that could be used for communications relay, intelligence, surveillance, and reconnaissance. A score is assessed for each platform based on the following objectives: instantaneous access area, endurance, survivability, feasibility, flexibility, responsiveness, and acquisition cost. A more recent analysis (Collier and Kacala 2008) measures the effectiveness of airships, UAVs, and tactical satellites based on a multi-objective framework across a range of operating environments and mission sets. The decision maker should select a mix of different aircraft to maximize the total fleet effectiveness subject to a budget constraint (see Chapter 4).

In this chapter, we apply the principles of multi-criteria decision making to evaluate the effectiveness of several aerial platforms, including UAVs and airships. Like Ferguson and Harbold (2001), we focus on a communication relay mission, but we use LCC for the aerial platforms as opposed to acquisition costs because LCC more accurately represents total costs. We examine more aerial platforms, which have multiplied since the Ferguson and Harbold (2001) study. A unique contribution of this chapter is the examination of the cost-effectiveness of communication payloads that can be integrated with the aerial platform. Collier and Kacala (2008) study multiple scenarios—a technique that we adopt in this chapter. Unlike Lawler (2010), Thiow Yong Dennis (2007), and Fry and Tutaj (2010), who develop models so that the benefits or effectiveness is equal across the UAV alternatives, our analysis determines unique MoEs for different aerial platforms and communication payloads and different mission scenarios.

3. Alternatives

Over 50 countries' militaries are developing or operating about a thousand different UAV platforms (Parsons 2013). The U.S. Department of Defense currently has approximately 11,000 UAVs in their inventory, consisting of almost 150 different platforms (American Institute of Aeronautics and Astronautics 2013). Israel, who first deployed UAVs for military operations, manufactures approximately 45 different UAV platforms (Dobbing and Cole 2014). We focus on 13 UAVs and 4 other aerial platforms that can be used for communication missions. We separately consider several communication payloads that can be fitted to these aerial platforms. Much of the information and many of the specifications for the aerial platforms come from Nicholas and Rossi (2011).

UAVs can be divided into five categories: small, medium, large, high altitude long endurance (HALE), and vertical takeoff and landing. Small UAVs are hand launched and include the Wasp III and RQ-11 Raven. Both UAVs are hand launched with ranges of 3-5 miles.

We examine two medium-size UAVs, the RQ-Shadow 2000 and the RQ-21 Blackjack. The Shadow with a wingspan of 20 ft is launched by catapult and usually lands using a runway with a hook at the bottom of the aircraft to snag a wire across the runway. The Shadow is primarily used for reconnaissance, surveillance, target acquisition, and battle damage assessment. The RQ-21 Blackjack with a 16 ft wingspan is a catapult-launched, vertically arrested UAV with multi-mission capability and 6 payload bays with power and Ethernet that can be fitted with cameras, communication capabilities, or other custom payloads.

Large UAVs have wingspans exceeding 25 ft and include the MQ-1 Predator, the MQ-1C Gray Eagle, the MQ-9 Reaper, and the X-47B Unmanned Combat Air System Air Carrier Demonstration (UCAS-D). The Predator was originally designed for intelligence, surveillance, and reconnaissance (ISR) but has been enhanced to be capable of taking on many roles to include targeting, forward air control, laser designation, weapons delivery, and bomb damage assessment (General Atomics Aeronautical 2013). The Gray Eagle is a larger version of the Predator used by the U.S. Army (General Atomics Aeronautical 2012a). The Reaper, also known as Predator B, is a hunter-killer UAV designed to eliminate time-sensitive targets via onboard 500-pound bombs and Hellfire missiles (General Atomics Aeronautical 2012b). Still in the demonstration and testing phase, the UCAS-D is designed to take off and land on aircraft carriers and to perform persistent surveillance with strike capability (Naval Air Systems Command 2014).

HALE UAVs are typically large UAVs with a maximum ceiling of approximately 60,000 feet and an endurance of 24 hours or more. The RQ-4 Global Hawk is operated by the U.S. Air Force for long-range ISR. The MQ-4C Triton is the U.S Navy's version of the Global Hawk and has deicing capability.

Vertical takeoff and landing UAVs (which can be small, medium, or large) have rotary blades. These UAVs include the MQ-8 Fire Scout, which is used on ships to provide situation awareness, targeting support, and communications relay, and the YMQ-18A Hummingbird used for ISR and carrying cargo.

Non-UAV aerial platforms considered as part of this study include rapidly erected towers and tethered balloons. Rapidly erected towers present an interesting alternative to UAVs because data link and power can be supplied via cables from the ground, which can offer near limitless endurance. Two possible towers are the Rapid Aerostat Initial Deployment (RAID) Tower System and Cerberus Tower ("Army Deploys" 2008). Tethered balloons, such as the TIF-25K and PTDS-74K aerostats, are capable of carrying power and data through the tether and can go significantly higher than towers ("US Army Aerostat-Based PTDS" 2010, Raven Aerostar 2014).

In addition to identifying the most cost-effective aerial platform, we also evaluate the cost and effectiveness of 9 communication payloads that can be used with the aerial platforms. Wave Relay is a mobile ad hoc network (MANET) solution that continuously adapts to fluctuations in terrain and the environment to maximize connectivity and communication performance (Persistent Systems 2012, 2014). We consider two Wave Relay configurations: the Wave Relay Gen4 Board and the Wave Relay Quad Radio Router. WildCat II is a tactical MANET product and can interact with two separate ground networks, bridge ground and airborne networks, or act as backhaul (TrellisWare Technologies 2014a). Ocelot is a small form module manufactured by the same company that manufactures WildCat II (TrellisWare Technologies 2014b). The Xiphos 1RU and the Xiphos 6RU radios are 4G tactical broadband solutions for mobile communication users. The radios claim a range of 5 to 7 miles on the ground and up to 62 miles via airborne deployment with clear line of sight (Oceus Networks 2014). The Falcon III RF-7800W OU440 is rated for operational uses up to 15,000 ft and includes a high level of encryption capability (Harris 2012b). The Falcon III AN/PRC-1176 is a manpack capable of UHF/VHF analog voice and digital data (Harris 2012a). Finally, the Direct Data Link is designed specifically for small UAVs and provides Internet Protocol (IP)-based communication between a ground station and the aircraft (AeroVironment 2013). The Raven UAV can come equipped with the Direct Data Link.

4. Cost-effectiveness model

The model for evaluating the effectiveness of the aerial platforms and communication payloads follows the approach described in Chapter 8, and interested readers are encouraged to read that chapter for more extensive details. Measuring effectiveness begins with the development of an objectives hierarchy, and the bottom level of the hierarchy consists of measurable attributes. If the attributes are mutually preferentially independent, an additive value function can be used to measure the effectiveness of an alternative (Kirkwood 1997). The MoE of the jth alternative $v(j)$ is calculated via the following equation:

$$v(j) = \sum_{i=1}^{M} w_i v_i (x_i (j)) \qquad (1)$$

where w_i is the global trade-off weight for attribute i, $v_i(\cdot)$ is a value function for attribute i, $x_i(j)$ is the level of attribute i for alternative j, and M is the total number of attributes. The range for $v_i(\cdot)$ is between 0 and 1, inclusive.

If the attribute is a numerical measure, we assess the value function using marginal analysis by asking what the incremental or marginal change in value is when the attribute is increased or decreased. We fit an exponential function to the assessed values for attribute i using a least-squares approach (see the Appendix for more details). If the attribute is composed of categorical ratings, such as “low,” “medium,” and “high,” we directly assign values from 0 and 1 for each category.

Local trade-off weights are weights assessed for all attributes within a single objective. We frequently use a swing weight procedure to assess local trade-off weights among attributes within an objective (von Winterfeldt and Edwards 1986). The swing weight procedure assumes that all attributes are at the worst level, and the decision maker is asked which attribute he or she desires to move to the best level. The selected attribute receives a score of 100 and the desirability of “swinging” the other attributes from worst to best are assessed relative to the score of 100 for the most preferred attribute and a score of 0 when all the attributes are at their worst level. Local trade-off weights for each attribute are calculated by normalizing the scores so that these weights sum to one. Multiplying the local weights by the trade-off weights for each objective higher up in the objectives hierarchy returns global weights w_i for $i = 1, \ldots, M$ for each attribute so that $\sum_{i=1}^{M} w_i = 1$.

After the MoE for each alternative is calculated via Eqs. (1) and (2), we depict the MoE and the cost of each alternative as a point on a two-dimensional chart. We analyze the cost-effectiveness of each alternative that belongs to the efficient set solutions, where the efficient set is composed of alternatives that are not dominated by another alternative. Trade-offs between the different alternatives are discussed. (See Chapter 4 for an alternative perspective.)

5. Objectives hierarchy

The first step to measure the effectiveness of an alternative is to create an objectives hierarchy describing what should be done to achieve an effective solution for the aerial platform and communication payload. The aerial platform and communication payload have separate objectives hierarchies, and the bottom level for each hierarchy consists of attributes that can be measured or observed for each alternative. In order to keep the vocabulary simple, we call the first and second levels of the hierarchy “objectives” and the bottom or third level of the hierarchy “attributes.” The hierarchies are based on our opinion after extensive research and discussions with subject matter experts.

5.1 Objectives hierarchy for aerial platform

Maximizing the mission effectiveness of the aerial platform is divided into four objectives: maximizing performance, flexibility, readiness, and survivability (Figure 1). Performance describes the capability of an aerial platform to perform the mission and is composed of five attributes. We seek to maximize range (the distance an aerial platform can travel as stated by the manufacturer), endurance (the maximum number of hours a platform can remain aloft), ceiling (the platform’s mean sea level as stated by the manufacturer), cruise speed (the highest sustained operational speed a platform can achieve), and useful load (the amount of weight a platform can carry).

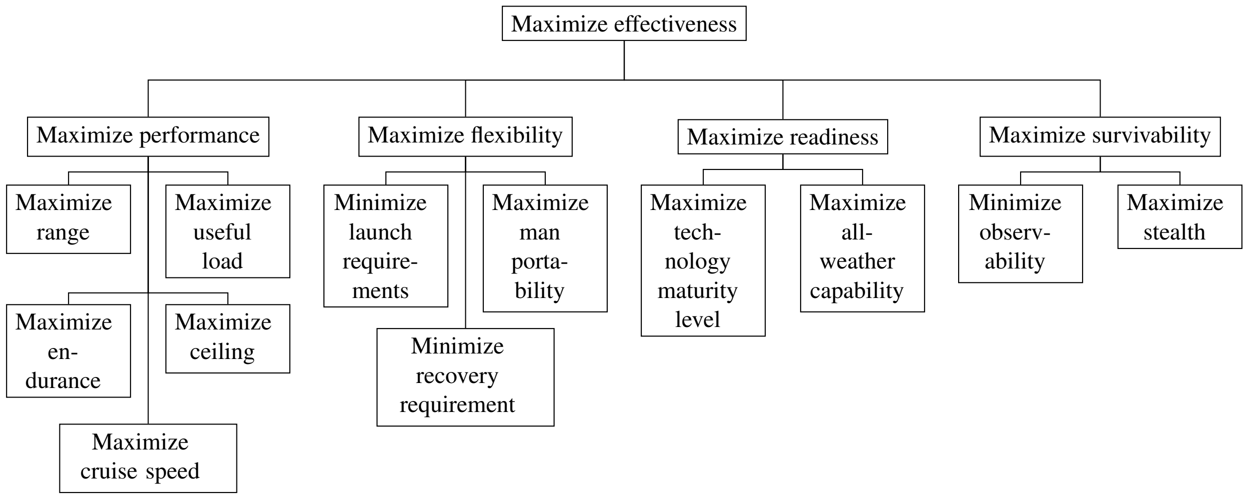

Figure 1: Objectives hierarchy for aerial platform

Flexibility describes the ability to employ the aerial platform in different conditions. Flexibility is further divided into three attributes: launch requirement, recovery requirement, and man portability. Launch requirement describes the type of launch required by the aerial platform, and aerial platforms that need less space launching are favored over assets that require more space for launch. Recovery requirement describes the type of method utilized for recovering the aerial platform, and platforms that need less space to be recovered are favored over assets that require more space for landing. Man portability is a binary attribute, and a platform that is man portable can be transported and launched by a single operator. We seek to minimize the launch and recovery requirements and maximize man portability in order to maximize flexibility.

Readiness determines how prepared an aerial platform is to support the mission. Technology maturity level and all-weather capability are the only two attributes that define readiness. Other attributes that could also be used to measure readiness include the mishap rate and availability, but data for these attributes are generally not available for the alternatives. Technology maturity level is measured by the number of years in service for the aerial platform based on initial operating capacity, and it serves as proxy measure for the reliability of a platform. Platforms with less technology maturity lack the field testing and refinement of older and more tested designs. All-weather capability is a binary attribute, and the platform must have deicing capability to be all-weather capable.

Survivability describes the ability of an aerial platform to accomplish its mission without being harmed by the enemy. We want to minimize observability and maximize stealth in order to maximize survivability. We define observability as the ability of enemy combatants to detect the aerial platform with the naked eye. Stealth is a binary attribute. If a platform uses radar absorbent materials similar to modern stealth aircraft, we consider that the platform has stealth capability.

5.2 Objectives hierarchy for communication payload

As depicted in Figure 2, the objectives of maximizing performance, flexibility, and readiness will maximize the effectiveness of a communication payload. Performance describes the ability of the communication payload to provide a communications link during optimum conditions. We seek to maximize power output and receiver sensitivity (which measure the payload's range) and to maximize throughput. Throughput measures the connection speed between the communication payload and a single user, as reported by the vendor in raw number of bits per second. Power output is measured in watts, and receiver sensitivity is measured in decibel-milliwatts.

Flexibility describes the ability of the communication payload to operate in varying conditions and fulfill different mission requirements. Flexibility is composed of mesh capability, power consumption, weight, and traffic type. Mesh capability is a binary attribute because the radio can either execute a mesh topology—where nodes in the communication network can send and receive data and serve as a relay for other nodes—or not. We seek to minimize power consumption by the communication payload, which is measured in watts. Weight, measured in pounds, is based on the radio manufacturer's specifications. Traffic type is voice (VHF and UHF transmission), data (e.g., video, imagery), or

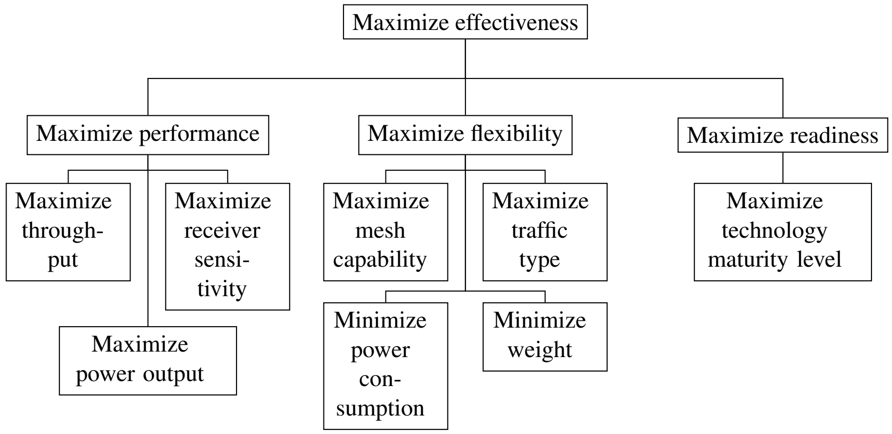

Figure 2: Objectives hierarchy for communication payload

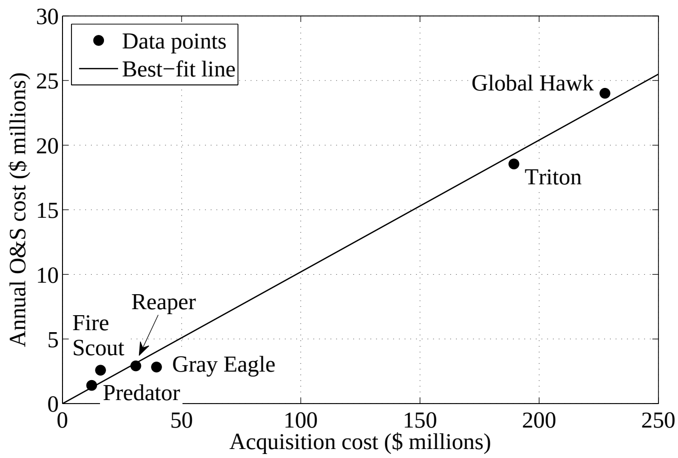

Figure 3: Annualized O&S cost as a function of acquisition cost

both.

Readiness determines how prepared a communications payload is to perform the mission. As with the aerial platforms, we use technology maturity level as a proxy measure for readiness because data on the availability of the communications payloads are not available.

6. Cost estimation

Cost-effectiveness analysis should use the LCC for each alternative, which traditionally includes research and development, acquisition, operations and sustainment (O&S), and disposal costs (see Chapter 5). The program acquisition unit cost includes research and development, procurement, and military construction costs. Disposal costs are not included in this analysis either because the aerial platforms will be used for more than 15 years or are assumed to be minimal.

We use the annualized LCC for each aerial platform where the LCC equals the program acquisition unit cost plus the annual O&S costs multiplied by the planned service life of each platform. The acquisition cost is based on a single UAV, tower, or aerostat. We are not able to differentiate the cost of the individual aerial platform from the launch and recovery equipment, ground control stations, and other support equipment. The annual O&S cost for a platforms is estimated as a linear function of the acquisition cost based on known O&S costs for six UAVs, as depicted in Figure 3. The annual O&S cost is 10.1% of the acquisition cost.

Since data on O&S costs for the communication payload alternatives are not available, we compare the costs for communication payloads only using the acquisition costs. Since O&S costs are not included for communication payloads, the costs used in this analysis underestimate the true LCCs. Even if more accurate LCCs for communication payloads were used, their costs would still be minimal compared to the costs of the aerial platforms.

7. Cost-effectiveness analysis

The aerial platforms and their communication payloads are evaluated under three different scenarios. The three scenarios are disaster relief, long range, and tactical user. Each scenario poses unique communication challenges, and a decision maker's preferences differ among the scenarios. Consequently, value functions for each attribute and the trade-off weights change under each scenario. We describe each scenario and analyze the cost-effectiveness of aerial platforms and communication payloads for each scenario.

7.1 Disaster relief scenario

Under the disaster relief scenario, we envision a situation similar to Hurricane Katrina or Typhoon Haiyan in which communication and cellular infrastructure has been rendered useless, and a nation's military is ordered to provide aid and coordinate relief efforts in the area. Communications links for rescue teams are needed for a fast and successful response. The disaster area is a circular area with a 100 nautical mile (NM) diameter. Task force headquarters is stationary and located at an airfield on the immediate perimeter of the disaster area. Throughput demand is expected to be more than 200 Mbps at various times and the number of concurrent users could be between 50 and 100. UHF, VHF, and data relay support is needed.

7.1.1 Cost-effectiveness of aerial platform

The global weights for the disaster relief scenario are presented in Table 1. We use the swing weight procedure to determine the trade-off weights among the attributes that define performance. The local weights for the performance attributes are 0.28 for ceiling, 0.22 each for useful load and endurance, 0.17 for range, and 0.11 for cruise speed. Having a sufficient ceiling is necessary to ensure coverage of the entire disaster area. Endurance is important because of the long communication requirement, and useful load is important because of the large number of first responders who need connectivity. Comparing among the objectives of performance, flexibility, readiness, and survivability, we do not assign any weight to either flexibility or survivability because the scenario assumes that headquarters is at an operational airfield and no enemy are present. We consider performance 9 times more important than readiness for this scenario. Because we assume that icing is not a problem for this scenario, technology maturity level is the only attribute within flexibility to receive a non-zero weight.

Figure 4 depicts the cost-effectiveness of each aerial platform. Ceiling and useful load account for almost half of the MoE of the most effective solutions (the Predator, Reaper, Hummingbird, and Global Hawk). The Triton, the Navy's variant of the Global Hawk, scores equally as well as those four UAVs for ceiling and useful load but is not scheduled for its first flight until 2015. Thus, the Triton performs badly on the readiness objective. If the Triton's technology maturity level equals that of the Global Hawk, its MoE would be similar to that of Global Hawk.

As can be seen from Figure 4 which depicts the annualized LCC on a logarithmic scale, the efficient solution—which eliminates any alternative that is both less effective and more expensive than another alternative—includes the Raven, Cerberus Tower, TIF-25K, Predator, Hummingbird, Reaper, and Global Hawk. The Raven's endurance of only 1.5 hours and payload of 6.5 ounces make it an ineffective platform for this scenario. The Cerberus Tower's height of 30 feet allows for approximately a 7 NM radio horizon, which is inadequate coverage for this scenario.

Because the Global Hawk's effectiveness is only slightly greater than the Reaper's MoE and it costs $30 million more per year, we prefer the Reaper to the Global Hawk. We also prefer the Predator to the Hummingbird because the Predator is only slightly less effective and costs $64,000 less per year. The Hummingbird has a faster cruising speed but less endurance than the Predator. Comparing the Predator and Reaper, we ask if annually spending $1.62 million is worth the increase in effectiveness from 0.85 (Predator) to 0.86 (Reaper). The Reaper is judged more effective than Predator because the former has a higher cruising speed, but in our opinion, the higher speed is not worth the additional cost for this scenario. We examine the trade-offs between the TIF-25K aerostat and the Predator. Although the Predator's MoE is 0.19 more than the MoE for the TIF-25K, it also costs $1.9 million more per year. The TIF-25K's endurance of 14 days surpasses that the Predator's endurance of 40 hours. Selecting either alternative can be justified. The TIF-25K offers a low cost aerial platform with long endurance and adequate payload and ceiling, and the

Table 1: Global trade-off weights for aerial platform for each scenario

Objective	Attribute	Trade-off weights for each scenario		
		Disaster relief	Long range	Tactical user
Performance	Range	0.150	0.090	0.000
	Useful load	0.200	0.090	0.155
	Endurance	0.200	0.090	0.155
	Ceiling	0.250	0.113	0.000
	Cruise speed	0.100	0.113	0.000
Flexibility	Launch requirement	0.000	0.000	0.115
	Recovery requirement	0.000	0.000	0.058
	Man portability	0.000	0.000	0.173
Readiness	Technology maturity level	0.100	0.200	0.138
	All-weather capability	0.000	0.300	0.000
Survivability	Observability	0.000	0.000	0.166
	Stealth	0.000	0.000	0.041

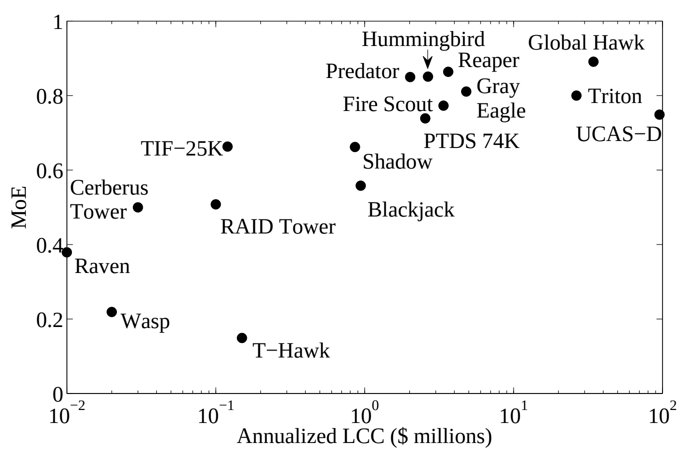

Figure 4: Cost-effectiveness of aerial platforms for disaster relief scenario

Table 2: Global trade-off weights for communication payload for each scenario

Objective	Attribute	Trade-off weights for each scenario Disaster relief	Long range	Tactical user
Performance	Throughput	0.180	0.000	0.150
	Receiver sensitivity	0.120	0.240	0.090
	Power output	0.200	0.240	0.090
Flexibility	Mesh capability	0.221	0.000	0.102
	Traffic type	0.109	0.000	0.102
	Power consumption	0.000	0.165	0.144
	Weight	0.000	0.165	0.212
Readiness	Technology maturity level	0.170	0.190	0.110

Predator offers more maneuverability and a larger coverage area, albeit at the expense of less endurance and a higher cost.

7.1.2 Cost-effectiveness of communication payload

The global trade-off weights for the communication payload attributes for disaster relief are depicted in Table 2. We use a swing weight method to determine the local trade-off weights for the three attributes (throughput, power output, and receiver sensitivity) within the performance objective. Improving power output from the worst (0 watts) to best (500 watts) level is most important and has a local trade-off weight of 0.4. Improving throughput is almost as important, and we assign a local weight of 0.36. Finally, improving receiver sensitivity is least important, and its local weight equals 0.24. Within the flexibility objective, we assess that having mesh capable technology is most important, and we judge having mesh capable technology is twice as important as having a radio that can carry both voice and data (traffic type). The payload's weight and power consumption are not important for this scenario. Comparing the objectives of performance, flexibility, and readiness, we rank performance most important, flexibility second most important, and readiness least important. We use the rank-sum method to calculate the local trade-off weights for these three objectives.[1]

As can be seen from Figure 5, the efficient solution set is comprised of the Wave Relay, Wave Relay Quad, Falcon III RF-7800W, Xiphos 1RU, and Xiphos 6RU. (Figure 5 shows the acquisition cost for each radio on a logarithmic scale to more clearly see the differences in costs.) If the decision maker places more importance on receiver sensitivity and traffic type relative to throughput, the Falcon III AN/PRC will replace the Falcon III RF-7800W as a member of the efficient solution set. Regardless, either of the Falcons is only slightly more effective than the Wave Relay Quad, and the Falcons cost $18,000 more, and we prefer the Wave Relay Quad to either of the Falcons. The Xiphos 1RU and 6RU are most effective with MoEs of 0.79 and 0.93 respectively. Both radios offer high power output, high throughput, and excellent scalability for multiple users. Their superior capabilities are worth the additional cost.

7.1.3 Solution compatibility

Both the TIF-25K and the Predator have enough useful load to carry either Xiphos radio units. However, available power for the radio units is a differentiator. The Predator has 1,800 watts available for payloads. The Xiphos 6RU's power consumption is over 3,000 watts. The Predator cannot normally support the Xiphos 6RU. The TIF-25K aerostat is capable of sending power to its payload from a ground based source up the tether. The TIF-25K should be able to power the Xiphos 6RU radio unit. This may require high voltage power sent from the ground up to the aerostat to avoid high power losses over the long transmission line of the tether, but it is feasible. If a decision maker prefers the more effective Xiphos 6RU because of its better throughput and power output, we believe the TIF-25K is the most cost-effective aerial platform. If the decision maker prefers the less expensive Xiphos 1RU, either the Predator with its greater coverage or the TIF-25K with its long endurance can serve as an effective aerial platform.

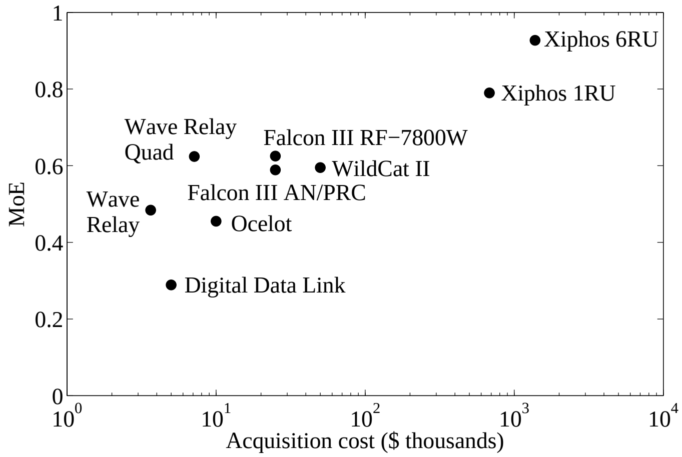

Figure 5: Cost-effectiveness of communication payloads for disaster relief scenario

7.2 Long-range scenario

In the long-range scenario, the military leadership at headquarters needs to establish UHF (voice) communications with a ship 340 NM away. The ship has lost its satellite communication capability, and we assume that headquarters is based at a large airfield near the coast. No enemy resistance is expected. The weather is cloudy with the possibility of icing conditions at higher altitudes. We assume that headquarters will need to communicate with the ship for approximately four hours.

7.2.1 Cost-effectiveness of aerial platform

Table 1 displays the global trade-off weights for the long-range scenario. As with the disaster relief scenario, the objectives for flexibility and survivability receive zero weight because the military is operating from a large airfield and enemies are not present. Within the performance objective, we believe it is most important to improve cruising speed, and cruising speed receives a local weight equal to 0.24. Improving the ceiling is only slightly less important, and the local trade-off weight for ceiling equals 0.23. Useful load, endurance, and range each receive local weights equal to 0.18. Within the readiness objective, the deicing capability may be crucial, and we assess local weights of 0.6 for all-weather capability and 0.4 for technology maturity level. The attributes that determine performance (useful load, ceiling, endurance, range, and cruising speed) have value functions in which the value of 0 corresponds to satisfactory requirements to complete the communication mission. Consequently, we are willing to trade off more performance in favor of readiness than we were in the disaster relief scenario. Both the performance and readiness objectives receive a trade-off weight equal to 0.5.

The long-range scenario requires that aerial platforms satisfy a minimum ceiling of 19,102 ft. This number is calculated as a function of the 340 NM distance between the ship and military headquarters. The Shadow, Raven, Wasp, and T-Hawk UAVs, the TIF-25K aerostat, and the RAID and Cerberus Towers are excluded from this analysis because their ceilings do not meet this requirement. The Blackjack's ceiling is 19,500 ft, but its range of 55 NM is so small that it would need a much higher ceiling to be effective for this scenario. Consequently, the Blackjack is not feasible for this scenario.

The efficient solution set for the long-range scenario consists of the Predator, Reaper, and Triton (Figure 6). The Triton and UCAS-D are the most effective because of their deicing capability. Since the first flight for the UCAS-D is scheduled for 2019, its technology maturity level performs poorly, but even if it had the same technology maturity level as the Triton, the latter would still be more effective because the Triton has a higher ceiling than the UCAS-D. We estimate the annualized LCC of the UCAS-D at $95 million, but its price point may come down to that of the Triton as the technology becomes more mature. If the UCAS-D's LCC is closer to that of the Triton, the UCAS-D could be a cost-effective alternative for the long-range scenario.

The Triton is annually $23-25 million more expensive than the Reaper and Predator, but the Triton's MoE is 0.21 greater than that of the Reaper and 0.30 greater than that of the Predator. This gap in effectiveness is primarily due

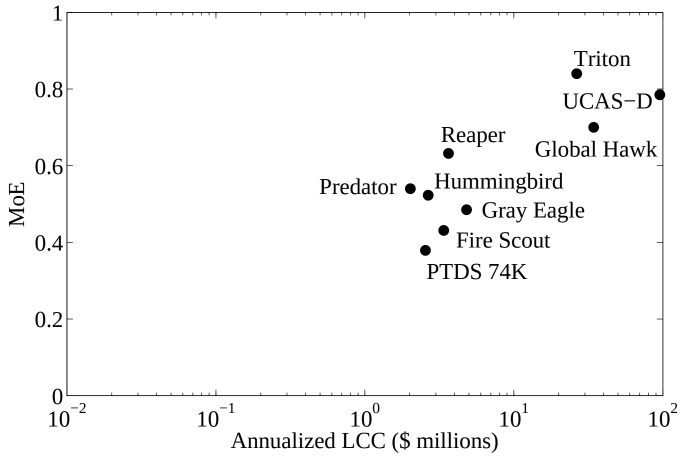

Figure 6: Cost-effectiveness of aerial platforms for long-range scenario

to the Triton's deicing capability. If icing conditions are not a factor, we prefer the Reaper to the Triton. The Reaper costs $1.6 million more than the Predator, but its MoE is 0.09 greater than that of the Predator. All three UAVs will be evaluated for compatibility with the most cost-effective communication payloads.

7.2.2 Cost-effectiveness for communication payload

Since the headquarters needs to be able to talk with the ship, the communication payload must support voice transmission. Given this requirement, the Falcon III AN/PRC and the Wildcat II are the only feasible alternatives. Within the flexibility objective, we are indifferent between trading off between power consumption and weight, and the traffic type receives no importance because the two feasible alternatives can support both voice and data transmission (Table 2). We are also indifferent between trading off between power output and receiver sensitivity, and throughput is not important for this scenario. When comparing among the higher-level objectives, we prefer to increase performance, then to increase flexibility, and finally to improve readiness. We assign local weights of 0.48, 0.33, and 0.19 to those three objectives, respectively.

Figure 7 depicts the cost-effectiveness of the two feasible radio units. The Falcon III AN/PRC and the Wildcat II are about equally effective according to our preferences, and we prefer the less expensive Falcon III AN/PRC. If a decision maker is unwilling to trade off as much flexibility for performance as we are, the Wildcat II will be rated more effective than the Falcon III AN/PRC. A decision maker may prefer the lighter Wildcat II that consumes less power than the Falcon III AN/PRC. The cost difference between the two communication payloads is about $25,000, which may not be an important discriminator when the annual cost of the UAV is $2 million or more.

7.2.3 Solution compatibility

The three identified cost-effective aerial platforms for the long range scenario are the Predator, Reaper, and Triton UAVs. The Predator offers an effective low cost option. The Reaper offers twice the ceiling of the Predator and a turbine engine for a reasonable increase in cost over the Predator. The Triton offers unparalleled mission effectiveness but is also the most expensive of the three options by several orders of magnitude. Budget considerations as discussed in Chapters 4 and 7 may influence which UAV is selected. All three UAVs can easily support the Falcon III AN/PRC, which is a 12-pound, 55-watt 117G radio. Because these UAVs can easily support the Falcon III AN/PRC, a decision maker may not want to purchase the more expensive Wildcat II for this scenario.

7.3 Tactical user scenario

This tactical user scenario involves a small special operations team or a single soldier trying to establish communications with higher command to coordinate extract. The tactical user is close to completing his mission and needs to

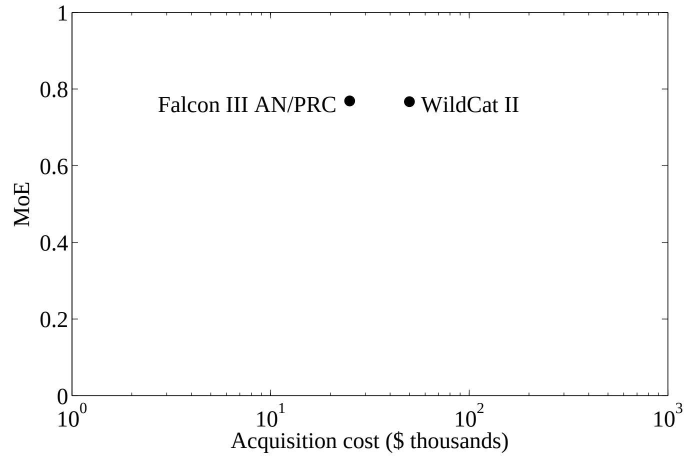

Figure 7: Cost-effectiveness of communication payloads for long-range scenario

radio back to base to arrange a helicopter extract. The tactical user is about 10 NM away from the base, and a 500 ft mountain is blocking radio signals back to base. The tactical user lacks satellite communication capability. No extraction plans or time of next contact were established during the last contact between the base and the tactical user more than 24 hours ago. Only a small number of end users need to be supported. Although the primary method of communications is UHF/VHF, video may also be necessary. Additionally, the enemy is believed to be in the vicinity. The tactical user prefers to have possession and control of the aerial platform.

7.3.1 Cost-effectiveness of aerial platform

If the 500 ft mountain is located midway between the user and headquarters, the tactical user scenario requires a minimum ceiling of 1,000 ft for the aerial platform. This requirement eliminates the T-Hawk, RAID Tower, and Cerberus Tower as feasible alternatives. After meeting this requirement, an aerial platform with a higher ceiling will not necessarily perform better, and we assign a trade-off weight equal to 0 to the ceiling attribute. The attributes range and cruising speed are not important for this scenario and also receive a weight of 0. We determine an equal preference for trading off between useful load and endurance, and each attribute receives a local weight of 0.5 within performance. Within the objective of flexibility, we use the rank-sum method to assign local weights after determining that man portability is the most important, launch method is the second most important, and recovery method is the least important. We determine that observability is much more important than stealth because the enemy is relatively low tech and decreasing observability is four times as important as moving from no stealth to stealth capability. This scenario has good weather, and deicing capability is unimportant, and technology maturity level has a local weight of 1.0.

The global weights for the attributes for the tactical user scenario is depicted in Table 1. We use a swing weight procedure to determine the relative importance of performance, flexibility, readiness, and survivability. Improving the flexibility of the aerial platform so that the platform can be carried and launched by a single individual is slightly more important than improving the performance (increasing the useful load and ceiling). Less important is improving the survivability (decreasing the observability), and least important is increasing the readiness (improving the technology maturity level).

The Raven is the superior solution for the tactical user scenario because it is the most effective and least expensive alternative (Figure 8). The Raven's small size allows it to be carried by a single individual. It can only remain in the air for 1.5 hours, but that should be enough to allow the user to communicate with higher command. If man portability is a requirement, the only other feasible platform is the Wasp. The Wasp's smaller size and less weight may make it more portable than the Raven, but the Raven has more endurance and range. In our opinion, having more endurance is more important than the smaller size, and we select the Raven as the most cost-effective platform for this scenario.

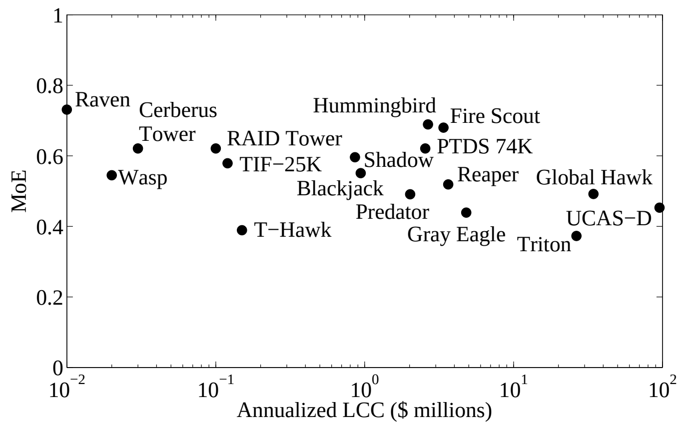

Figure 8: Cost-effectiveness of aerial platforms for tactical user scenario

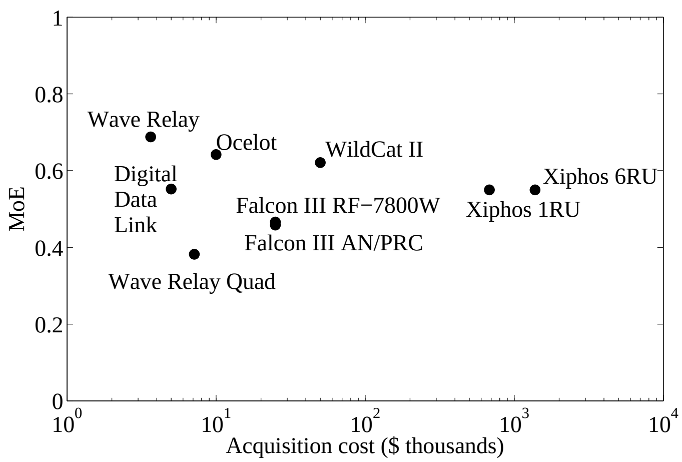

Figure 9: Cost-effectiveness of communication payloads for tactical user scenario

7.3.2 Cost-effectiveness of communication payload

Because we are selecting a UAV that can be carried by a single user, we place a lot of importance of maximizing flexibility, as depicted in Table 2. Using a swing weight procedure, we assign trade-off weights of 0.56 for flexibility, 0.33 for performance, and 0.11 for readiness. Within the flexibility objective, we believe it is important to minimize the weight of the radio, followed by minimizing power consumption. The attribute for weight has a local trade-off weight of 0.38, and power consumption has a local weight of 0.26. Mesh capability and traffic type each have local weights of 0.18. For the performance objective, increasing throughput is the most important attribute in order to allow the tactical user to transmit some video. The local weight for throughput is 0.45, and the both of the local weights for power output and receiver sensitivity are 0.27.

Figure 9 displays the cost-effectiveness for the communication payloads. The Wave Relay radio is the most effective and the least expensive alternative. The Wave Relay's MoE is the largest because of the radio's small weight and relatively high throughput. If a decision maker places more importance on power consumption and receiver sensitivity relative to throughput, the Ocelot will become more effective than the Wave Relay although the former costs almost three times as much as the Wave Relay. Both communication payloads weigh less than 0.2 lbs. If a decision maker is unwilling to trade off as much performance in favor of flexibility than in our assessment, the WildCat II may be the most effective. The WildCat II weighs 3.4 lbs, which likely makes it too heavy for the small UAVs.

7.3.3 Solution compatibility

The Raven and Wasp III UAVs have useful loads of 0.41 and 0.2 lbs, respectively, which excludes use of the WildCat II radio. The Wasp III would also have trouble carrying either radio. The Raven can easily accept the weight of the Ocelot and the Wave Relay card at 96 grams. However, with additional wiring, dedicated battery and antenna, either the Ocelot or Wave Relay could exceed the Raven's useful load, which could result in degraded performance of the airframe. Even though both communication payloads possess a small form factor, the payload compartment of the Raven may not be able to support either radio. A previous study (Menjivar 2012) tested a Raven with a Wave Relay payload. The Wave Relay radio had to be taped onto the outside of the UAV instead of being secured inside the payload compartment, which is not ideal for performance of the UAV or the communication link.

One communication payload that would work with the Raven is AeroVironment's Digital Data Link. AeroVironment offers the Digital Data Link with the Raven UAV from the factory. Digital Data Link's price is positioned between the Wave Relay and the Ocelot at $5,000, but it has a slightly lower MoE than either one at 0.55. However, compatibility between the Digital Data Link and the Raven is assured, whereas the Ocelot and the Wave Relay units needs further testing to ensure compatibility.

8. Conclusions

This chapter demonstrates the use of multi-criteria decision making to analyze the cost-effectiveness of aerial platforms and communication payloads for communication missions in the military. We compared the cost-effectiveness of 17 aerial platforms and 9 communication payloads across three mission scenarios.

The first scenario requires long endurance and high bandwidth capability to complete a disaster relief mission. The most cost-effective aerial platforms are the TIF-25K aerostat and the Predator UAV. The TIF-25K combines endurance measured in weeks and a high useful load with a moderate ceiling. Additionally, the TIF-25K can utilize a tether to power its payloads from the ground. The Predator is a very capable UAV platform with a relatively long endurance, long range, and reasonable cost of ownership. The most cost-effective communication payloads are the two configurations of the Oceus Networks Xiphos (1RU and 6RU) due to their high throughput, power output, and excellent scalability. The Xiphos radios can be relatively heavy (78 lbs to 276 lbs depending on configuration) and power hungry (855 to 3,275 watts depending on configuration). We select either a TIF-25K aerostat with a Xiphos 6RU connected to ground power or a Predator with a Xiphos 1RU configuration.

In the second scenario, a long-range relay is needed to connect users across a 340 NM range, which requires a minimum altitude of 19,102 ft due to radio horizon and UHF capability. The most cost-effective aerial platforms are the Predator, Reaper, and Triton. Due to its UHF capability, sensitivity, and power output, the Falcon III AN/PRC is the most cost-effective communication payload. Each of the three aerial platforms could be the best choice, depending on the decision maker's preference for price (Predator), better altitude and performance (Reaper), or outstanding performance and deicing capability (Triton). The extra performance and capability of the Triton comes with a much higher ownership cost than the Predator or Reaper.

A covert, tactical situation where portability is preferred is the final scenario. The most cost-effective aerial platform is the Raven, which combines man portability and adequate range and endurance with the lowest cost of any aerial platform in this study. The Wave Relay is the most cost-effective communication payload for this scenario because it weighs very little and possesses a relatively high throughput for its small form factor. However, compatibility between the Raven and Wave Relay cannot be confirmed at this time. The slightly less effective and more expensive Digital Data Link is compatible with the Raven and can be an acceptable solution in the interim until more compatibility testing can be completed between the Raven and the Wave Relay communication payload.

As with any analysis, our cost-effectiveness analysis relies on a number of assumptions, which can motivate future research. We assess compatibility between the most cost-effective aerial platforms and communication payloads within each scenario based primarily on the manufacturer's provided specifications. Actual field testing would provide a proof of concept and help validate the findings of this chapter. Since complete, transparent, and reliable cost data was not always available, further research of the fully captured LCCs for UAVs, military towers, and aerostats will enable a more accurate and detailed analysis. Other missions, such as ISR, may present an interesting and useful subject for future research, and other aerial platforms currently under development could be considered. Finally, other decision makers may have different objectives, value functions, and trade-off weights, which would change the alternatives' MoEs and the cost-effectiveness analysis.

This chapter offers a framework for comparing the cost-effectiveness of dissimilar aerial platforms and communication payloads across different mission sets. Several militaries around the world currently operate UAVs, and their use for communication will likely grow in the future. This research develops value functions and weighting parameters that change based upon mission requirements and are easily adapted to other mission sets including the traditional ISR mission. Our analysis demonstrates that the cost-effectiveness of an alternative depends on the mission requirements, and the military should continue to purchase a wide array of aerial platforms and communication payloads that can be used for different missions.

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We would like to thank Glen Cook and John Gibson of the Naval Postgraduate School for their advice and feedback during this research and for sharing their expertise in communication systems. Copies of the spreadsheets used to analyze the cost-effectiveness of the aerial platforms and communication payloads can be downloaded and altered to meet a decision maker's own preferences from Cameron MacKenzie's web page at https://faculty.nps.edu/camacken/ under the tab "Thesis Supervision."

Appendix

Exponential value functions are used for the numerical attributes. The value of attribute i at a given level x_i can be calculated based on whether the decision maker prefers "more" or "less" of an attribute:

$$v_i(x_i) = \begin{cases} \dfrac{1-\exp\left(a\left[x_i - x_{\min}\right]^b\right)}{K} & \text{if more is preferred} \\ \dfrac{1-\exp\left(a\left[x_{\max} - x_i\right]^b\right)}{K} & \text{if less is preferred} \end{cases} \tag{2}$$

where $K = 1-\exp\left(a\left[x_{\max} - x_{\min}\right]^b\right)$ is a normalizing constant, $x_{\min}$ is the attribute level for which $v(x_{\min}) = 0$ if more is preferred and $v(x_{\min}) = 1$ if less is preferred, $x_{\max}$ is the attribute level for which $v(x_{\max}) = 1$ if more is preferred and $v(x_{\max}) = 1$ if less is preferred, and $a \in \mathbb{R}$ and $b > 0$ are parameters selected to minimize the sum of the squared distances between $v_i(x_i)$ and the assessed values.

In order for the value function to be defined over the domain of the attribute and so that $0 \leq v_i(x_i) \leq 1$, we require that $v_i(x_i) = 0$ for all $x_i \leq x_{\min}$ and $v_i(x_i) = 1$ for all $x_i \geq x_{\max}$ if more is preferred and require that $v_i(x_i) = 0$ for all $x_i \geq x_{\max}$ and $v_i(x_i) = 1$ for all $x_i \leq x_{\min}$ if less is preferred.

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Notes

[1]The rank-sum only requires the decision maker to rank the objectives rather than determining the exact trade-off between multiple objectives. For three objectives, the most important objective receives an unnormalized weight of 3, the second most important receives a 2, and the least important receives a 1. Dividing each weight by the sum of these weights returns normalized weights of $\frac{1}{2}$, $\frac{1}{3}$, and $\frac{1}{6}$ for the first, second, and third objectives, respectively.