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A Cost-Effectiveness Analysis of C-12 Variant Airborne ISR Capabilities in the Marine Corps

March 2022

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Prepared for the Naval Postgraduate School, Monterey, CA 93943

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ABSTRACT

Military strategists and technologists have welcomed the rise of remotely piloted aircraft (RPAs) in intelligence, surveillance, and reconnaissance (ISR) roles because of their persistence and expendability, which provide operational flexibility to commanders and decision makers. Furthermore, RPAs generally cost less to operate than manned systems. However, some small manned ISR aircraft have low operating costs, have been proven in operations around the world, and do not require any new spending to develop. While pursuing RPAs to gain the benefits identified, the Marine Corps may incur costs that reduce overall value to the service. In this study, I conduct a cost-effectiveness analysis of two ISR systems to determine the alternative with the best value. The representative platforms analyzed are the unmanned RQ-21A and the manned MC-12W, to determine if the Marine Corps can realize greater value from a small manned aircraft than small RPAs for ISR missions. I find that the RQ-21A is a more effective platform based on the objective hierarchy established, with a measure of overall effectiveness (MOE) score of .721. However, it is more costly than the MC-12W on a cost per flight hour (CPFH) basis with a CPFH of $18,223. The MC-12W is a less effective platform based on the objective hierarchy established, with an MOE score of .497. However, it is less costly than the RQ-21A on a per flight hour basis with a CPFH of $6,079.

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LIST OF ACRONYMS AND ABBREVIATIONS

AAV	assault amphibian vehicle
ACC	air component commander
ACE	air combat element
AFCAA	Air Force Cost Analysis Agency
AFTOC	Air Force Total Ownership Cost
ANG	Air National Guard
AoA	analysis of alternatives
ARG/MEU	Amphibious Ready Group / Marine Expeditionary Unit
ATMRS	Aviation Type Model Series Reporting
C2	command and control
CADE	Cost Assessment Data Enterprise
CAPE	Cost Assessment and Program Evaluation
CBA	cost-benefit analysis
CDD	Capability Development Document
CE ratio	cost-effectiveness ratio
CEA	cost-effectiveness analysis
CENTCOM	U.S. central command
CES	cost element structure
CMC	commandant of the marine corps
CNO	chief of naval operations
CPFH	cost per flight hour
CPI	consumer price index
CVT	consolidated VAMOSC tool
EABO	expeditionary advanced base operations
FHP	Flying-Hour Program
FMV	full-motion video
FOC	full operational capability
FVL	future vertical lift
GMTI	ground moving target indicator
GPC	great power competition

GWOT	global war on terror
HQMC	Headquarters Marine Corps
IED	improvised explosive device
IFF	Identify Friend-or-Foe
IOC	initial operational capability
ISR	intelligence, surveillance, and reconnaissance
ITEG	Integrated Trailer-ECU-Generator
KPP	Key Performance Parameters
KSA	key system attribute
MAGTF	Marine Air-Ground Task Force
MALE	Medium Altitude Long Endurance
MCAS	Marine Corps Air Station
MDS	Mission Designator Series
MEU	Marine Expeditionary Unit
MILCON	military construction
MILPERS	military personnel
MOE	Measure of Overall Effectiveness
NCCA	Naval Center for Cost Analysis
NPV	net present value
O&M	operations and maintenance
O&S	operating and support
OIE	operations in the information environment
OMB	office of management and budget
OSD	Office of the Secretary of Defense
PED	processing, exploitation, and dissemination
PMC	passengers, mail, and cargo
PPBS	planning programming budgeting system
RDT&E	research, development, test, and evaluation
RFP	Requests for Proposal
RPA	remotely piloted aircraft
SAR	synthetic aperture radar
SATCOM	satellite communication

SIGINT	signals intelligence
SRS	Sky Hook Recovery System
STUAS	small tactical unmanned aircraft system
UAS	unmanned aircraft system
UAV	unmanned aerial vehicle
VAMOSC	Navy Visibility and Management of Operating and Support Costs
VMU	unmanned aerial vehicle squadron

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I. INTRODUCTION

The U.S. Marine Corps must be prepared to fight across the range of military operations, from small wars and counterinsurgencies to major combat operations against sophisticated peer competitors with advanced weapons. While the Marine Corps is currently conducting force design based on the pacing threat, the potential for future conflict below the level of great power war will not fade. In both small wars and high-end combat operations, airborne intelligence, surveillance, and reconnaissance (ISR) is a critical enabler which provides key information to supported commanders. The joint force currently employs a mix of both manned and unmanned ISR aircraft, each with different capabilities and limitations.

In the case of the U.S. Marine Corps however, there have been no manned ISR aircraft in inventory since 1979 (Marine Corps History and Museums Division, 2002). While this is a departure from the mix of manned and unmanned systems that the other services employ, one could assume it is for good reason that the Marine Corps chooses to employ only unmanned systems in this role. One benefit of unmanned systems is generally a lower cost than comparable manned aircraft. Unmanned ISR aircraft have some of the lowest cost per flight hour (CPFH) in the DOD (Office of the Under Secretary of Defense (Comptroller) [OUSD(C)], 2021). However, the Marine Corps' most recent unmanned ISR program, the RQ-21A Blackjack was cancelled only three years after being declared a full operational capability (FOC) and less than six years after achieving initial operational capability (IOC) (Commandant of the Marine Corps, 2021). This short lifespan highlights the fact that while unmanned remotely piloted aircraft (RPAs) are generally cost effective, they are not without shortcomings. Whether the Marine Corps could have employed a manned ISR system instead of the RQ-21A and realized lower costs per flight hour remains an open question.

This paper examines whether the costs of operating the unmanned RQ-21A Blackjack are significantly different than a small manned ISR aircraft, such as the MC-12W Liberty. I analyze all life cycle cost elements of these programs, including research and development, procurement, operating and maintenance, and personnel costs. I control for time differences in the programs by determining the net present value (NPV) of each program and discounting to current year dollars. Additionally, I determine the sources of cost differences between these programs to identify major cost drivers and understand tradeoffs between manned and unmanned systems in ISR roles. Finally, I conduct a cost-effectiveness analysis (CEA) to allow for comparison of the relative costs and effects of these two airborne ISR alternatives. I find that the RQ-21A Blackjack is more expensive on a cost per flight hour (CPFH) basis that the MC-12W. However, the unique attributes of the RQ-21A result in greater overall effectiveness based on a multi-objective analysis. Decision makers must trade CPFH for effectiveness in the case of these two programs.

This paper contributes to a growing body of research on the cost differences between manned and unmanned ISR systems. Other research has focused on large, airliner-sized manned platforms such as the EP-3 Ares and P-8 Poseidon and their equally large, unmanned replacements like the MQ-4C Triton and the RQ-4 Global Hawk (Congressional Budget Office, 2021; Larkins, 2012). This paper extends the literature by analyzing cost differences between small RPAs and small manned aircraft. Cost data retrieved from the OSD Cost Assessment Data Enterprise (CADE) and Navy Visibility and Management of Operating and Support Costs (VAMOSC) databases will be primarily used to inform the analysis. The MC-12W program (FY08 to FY15) will be compared with cost data from the RQ-21A program (FY13 to FY20), including all life cycle cost elements, except disposal costs. Total flight hours by system will yield a final cost per flight hour (CPFH) for each system. Next, the NPV of each system will be computed in current year dollars to determine cost-effectiveness of each platform. Finally, the differential effectiveness of the systems will be addressed to build an understanding of the relative advantages of each program.

The remainder of the paper is structured as follows. In the next section I summarize the history of unmanned ISR aircraft in the Marine Corps and compare the operational capabilities of the RQ-21A and the MC-12W. In the third section I present the cost data for each program and describe the methodology I use for the cost-effectiveness analysis. The fourth section is a cost-effectiveness analysis of the two alternatives using a multi-objective analysis. The last section concludes the paper and provides recommendations for future extensions of this research.

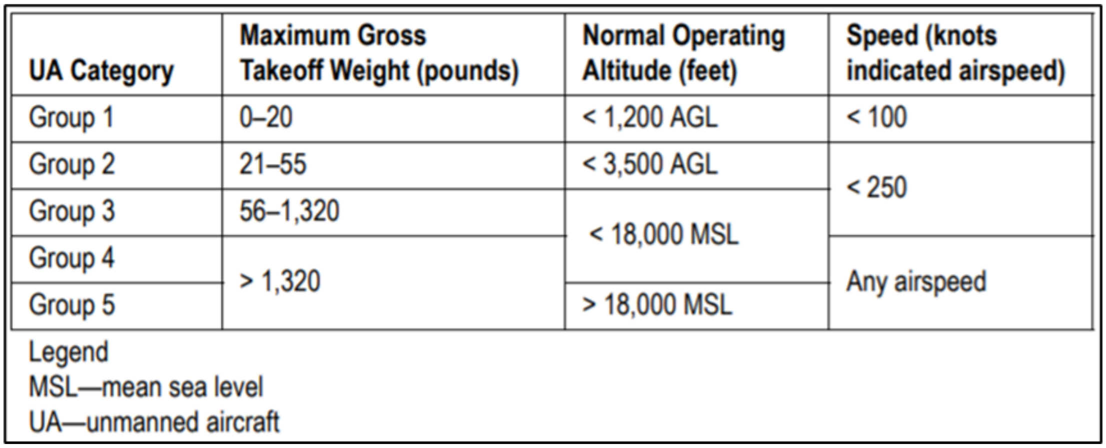
II. BACKGROUND

A. OVERVIEW

The need for commanders to conduct reconnaissance and collect intelligence information on the battlefield is a constant in warfare. The rise of modern technologies in warfighting, advancements in command and control (C2) systems, and the increased proliferation of threat actors only increases the need for this collection. The U.S. military has largely responded to this need through the acquisition of airborne ISR systems, which provide persistent real-time information about the situation on the ground. Over the course of the last two decades, piloted ISR aircraft have been steadily replaced by RPAs (Congressional Budget Office, 2021). The benefits of RPAs in ISR roles are improved persistence as compared with many manned platforms and reduced risk to force because there is no pilot or crew onboard. These favorable aspects of RPAs have led to an increasing share of ISR missions being fulfilled by unmanned aircraft, especially during the Global War on Terror (GWOT) (Smith, 2016).

There are five categories of RPA employed by the U.S. military. These are grouped by gross takeoff weight, operating altitude, and top speed as shown in Table 1.

Table 1. RPA categories and characteristics. Source: Combat Development and Integration (CD&I) (2016b).



UA Category	Maximum Gross Takeoff Weight (pounds)	Normal Operating Altitude (feet)	Speed (knots indicated airspeed)
Group 1	0–20	< 1,200 AGL	< 100
Group 2	21–55	< 3,500 AGL	< 250
Group 3	56–1,320	< 18,000 MSL	
Group 4	> 1,320		Any airspeed
Group 5		> 18,000 MSL	

Legend
MSL—mean sea level
UA—unmanned aircraft

The Marine Corps has procured three different Group 3 RPAs in its history. The RQ-2 Pioneer, the RQ-7 Shadow, and the RQ-21A Blackjack. While the United States Marine Corps has employed these unmanned airframes in an ISR role, it has not procured a dedicated manned ISR platform since 1979 (Marine Corps History and Museums Division, 2002). This contrasts with the other services, each of which has kept multiple manned ISR aircraft in inventory up to the present day. In 1987 the Marine Corps began employing its first RPA, the Group 3 RQ-2A Pioneer (Figure 1). This aircraft and its subsequent RQ-2B variant remained the Marine Corps' primary RPA until 2007 (National Air and Space Museum, 2018). During the GWOT, from 2007–2016 the Marine Corps employed the Group 3 RQ-7 Shadow as its primary RPA (Figure 2) (CD&I, 2016b).

Figure 1. RQ-2A Pioneer. Source: National Air and Space Museum (2018).

Figure 2. RQ-7 Shadow. Source: Marines (2017).

The primary RPA currently employed by the Marine Corps is the Group 3 RQ-21A Blackjack (Deputy Commandant for Aviation [DCA], 2019). The RQ-21A is similar in characteristics to its predecessors, however it has the unique capability of launching and recovering on amphibious ships at sea. This history of solely Group 3 RPA employment in the Marine Corps and lack of manned ISR aircraft demonstrates the Marine Corps' nearly 35-year commitment to unmanned systems for ISR, as well as to the operational flexibility provided by a medium-sized ISR platform in the Group 3 family.

In April of 2021, the Marine Corps announced the forthcoming divestiture of all RQ-21A RPAs and the expansion of unmanned aerial vehicle squadron (VMU) capacity to include three new Medium Altitude Long Endurance (MALE) squadrons based on the much larger Group 5 MQ-9A Reaper RPA. This shift indicates the continued Marine Corps emphasis on unmanned systems for the future battlefield and the upgrade in capability from the smaller unarmed RQ-21A to the much larger, higher-flying, and armed MQ-9A (Commandant of the Marine Corps, 2021).

While battlefield commanders require persistent ISR of the kind provided by RPAs, the same kind of intelligence information can be provided by manned aircraft. Manned ISR aircraft, while usually realizing higher cost per flight hour (CPFH) during normal operations than RPAs, may not realize higher life cycle costs, when considering the expense of development, integration, testing, SATCOM bandwidth, ground station MILCON, and pilot training (Larkins, 2012). A direct life cycle cost comparison has been conducted on larger ISR platforms in the past, but never on smaller Group 3 RPAs of the kind employed by the Marine Corps and comparable manned aircraft such as the ubiquitous and inexpensive C-12 family of utility aircraft.

In the airborne ISR context, the shift to remotely piloted aircraft (RPA) is inexorable. RPAs provide a persistent, risk-worthy, and capable intelligence asset to their supported unit. They can dwell above a target for long durations, further increasing their value to troops on the ground (Morton, 2012). However, very capable manned ISR assets based on the ubiquitous C-12 aircraft have been flown in combat operations for over 20 years. These aircraft have provided the same type of intelligence that is provided by modern RPAs and have proved effective in countless operations across the globe (Ayre & Hough, 2012). The Marine Corps operates the UC-12 aircraft in a non-ISR role, using it to move passengers, mail, and cargo (PMC) throughout the battlespace as part of the Operational Support Airlift (OSA) program (Figure 3). The UC-12 has low operating and support (O&S) costs due to the ease of maintenance and the reliability of the airframe itself (Chase, 2000). While the Marine Corps operates the UC-12 and similar manned aircraft as part of the OSA program, these assets generally do not conduct aerial reconnaissance. While the Marine Corps publication for aviation operations states that “all aircraft units constantly perform visual air reconnaissance” there is no specific mention of aerial reconnaissance as a task for the UC-12 (Combat Development and Integration [CD&I], 2018). Furthermore, the role of OSA aircraft in the six functions of Marine aviation is stated as only assault support, with no mention of aerial reconnaissance in the OSA doctrinal publication (Combat Development and Integration [CD&I], 2016a). The same document opens with a vignette citing the OSA aircraft which flew from Bahrain during operations Desert Shield and Desert Storm in 1991. These OSA pilots conducted “nightly intelligence runs which provided aviation combat element (ACE) planners with critical bomb damage assessment intelligence for operational planning.” The intelligence gathering and aerial reconnaissance capabilities of this type of aircraft are demonstrable, but it is not employed in this role by the Marine Corps.

Figure 3. A Marine Corps UC-12W Huron in Afghanistan. Source: Marines (2012).

B. RQ-21A BLACKJACK HISTORY AND ROLE IN THE MARINE CORPS

The RQ-21A Blackjack is the current program of record for the Marine Corps for airborne ISR.

1. RQ-21A Blackjack History

The RQ-21A Blackjack was procured to be the replacement for the Marine Corps' previous Group 3 RPA, the RQ-7B Shadow. The major driver behind switching to the Blackjack was the need to be able to launch and recover the system from an amphibious warship while underway. This capability would enhance the expeditionary character of the embarked Marine Air-Ground Task Force (MAGTF) by providing real-time ISR under the control of the Marine Expeditionary Unit (MEU) commander. The first RQ-21A system was declared Initial Operations Capable (IOC) in January of 2016 (Peck, 2017). It was not until 2019 that the final system was delivered and the RQ-21A was declared a full operational capability (FOC) (Naval Technology, 2019). In April of 2021, the first Annual Update to the Marine Corps' Force Design 2030 modernization plan included language which indicated that the Marine Corps would entirely divest from the RQ-21A as a capability. The same document indicated that the Marine Corps would begin experimentation with another Group 3 RPA, the V-Bat, manufactured by Martin Aviation. Additionally, the Marine Corps would expand the number of active-duty UAS squadrons by three, all of which would be geared toward Medium-Altitude/Long Endurance (MALE) RPAs, which are normally larger Group 4 or Group 5 systems. The document specified that experimentation with the General Atomics MQ-9A Reaper RPA would be conducted for use at these squadrons (Commandant of the Marine Corps, 2021). The RQ-21A was in service for less than four years when this decision was announced.

2. RQ-21A Blackjack Role

The RQ-21A (Figure 4) is a Group 3 RPA, which can be launched and recovered without a runway, using a rail-launched takeoff system and Sky Hook Recovery System (SRS). The designation RQ-21A indicates the entire system, not just the airframe. The system is also known as the Small Tactical Unmanned Aerial Vehicle (STUAS). The system includes a total of five aircraft, one launcher, one SRS, two Integrated Trailer-ECU-Generator (ITEG), associated support equipment, and four utility trucks. The RQ-21A provides all-weather, day and night, full motion video (FMV), signals intelligence (SIGINT), and laser designator support to the ground forces commander. The RQ-21A is employed by the Marine Corps unmanned aerial vehicle squadrons (VMUs). VMU-1 is located at Marine Corps Air Station (MCAS) Yuma, Arizona, VMU-2 is located at MCAS, Cherry Point, North Carolina, VMU-3 is located at MCAS Kaneohe Bay, Hawaii, and VMU-4 is located at MCAS Camp Pendleton, California (DCA, 2019).

The RQ-21A is a capable ISR system. It carries an electro-optical camera with digital zoom, a mid-wave infrared imager, laser rangefinder, infrared marker/designator, as well as a communications suite. Some RQ-21 systems have also been outfitted with synthetic aperture radar (SAR) and ground moving target indicator (GMTI) systems. It can conduct up to 16 hours of continuous flight, at up to 20,000 ft. altitude and with a maximum speed of 90 knots. It has a range of only 50 km from the ground station, which it communicates with via a radio link. As a Group 3 RPA, it has a small wingspan of approximately 16 feet (Boeing Insitu, 2021).

Figure 4. RQ-21A Blackjack. Source: Boeing Insitu (2021).

C. MC-12W LIBERTY HISTORY AND ROLE IN THE AIR FORCE

The MC-12W Liberty is just one of many systems that the Air Force employed to conduct airborne ISR during the GWOT.

1. MC-12W Liberty History

In April of 2008, Secretary of Defense Robert Gates stood up the first ISR Task Force with the purpose of increasing the number of ISR assets available to battlefield commanders in Iraq and Afghanistan. Gates had been struggling to respond to the immediate needs of these tactical commanders in other areas as well, such as providing up-armored vehicles that were less vulnerable to improvised explosive devices (IED)s. For the

ISR Task Force, the goal was to rapidly increase the available ISR assets in theater, to augment the many RPAs that were already operating in these conflicts. The Air Force responded to the demands of the ISR Task Force by procuring 37 C-12 variant ISR aircraft, all purchased from civilian sources, and then modified each airframe to include sensors, radios, and intelligence collection equipment (Tittel, 2010). The new aircraft were designated the MC-12W Liberty (Figure 5). This effort was known as Project Liberty, in reference to the "Liberty Ships" of World War II, which were a class of low-cost, mass-produced ships manufactured by the U.S. to bolster the number of vessels available for Navy transportation needs (AFCENT, 2013). The Air Force deployed the first MC-12W systems in 2009, just over a year after the ISR Task Force was stood up. These systems provided real-time battlefield information that the commanders on the ground needed. Especially crucial was the full-motion video (FMV) and signals intelligence (SIGINT) information that the aircraft provided. The systems continued in the active-duty Air Force inventory until 2015, when they were transitioned to the Air National Guard (ANG). Today there are a total of 13 MC-12W aircraft in the ANG inventory (Air Force, 2021).

2. MC-12W Liberty Role

The MC-12W Liberty provides medium-altitude ISR support to ground commanders. It is a joint forces air component commander (ACC) asset which is deployed in support of the joint force commander. The designation MC-12W describes not just the aircraft but the ISR suite as well. This includes the processing, exploitation, and dissemination (PED) system which is integral to bringing actionable intelligence to the troops who need it. The system provides all-weather, day and night, FMV, SIGINT, and laser designator support to the ground forces commander. The MC-12W is operated by the 137th Special Operations Air Wing, Will Rogers ANG Base, Oklahoma City, Oklahoma (Air Force, 2021).

The MC-12W carries an electro-optical camera with digital zoom, a mid-wave infrared imager, laser rangefinder, infrared marker/designator, as well as a communications suite. It has the capability to add additional sensors based on mission requirements. It can conduct up to eight hours of continuous flight, at up to 35,000 ft. altitude and with a maximum speed of 312 knots. It has a range of 2,400 nautical miles. It has a wingspan of 58 feet and can accommodate up to 4,000 lbs. of cargo, sensors, and passengers (Air Force, 2021).

Figure 5. MC-12W Liberty. Source: Air Force (2021).

D. ISR IN COUNTERINSURGENCY AND THE GRAY ZONE

The rise of the MQ-1 Predator RPA in the 1990s coincided with the relative peace of the period following the end of the Cold War. After the Soviet Union collapsed, the U.S. no longer had a peer geopolitical rival on the world stage. The period of relative peace that followed may never have necessitated the employment of thousands of unmanned aircraft had it not been for the GWOT, which began when the U.S. was attacked on September 11, 2001. The U.S. launched operations in Afghanistan and later Iraq, both of which devolved into counterinsurgency struggles against determined adversaries.

Counterinsurgency refers to the actions taken by the U.S. government and its multinational partners to defeat an insurgency. A key factor in counterinsurgency operations that distinguishes it from other military operations is that the local population is understood to be a focus of effort, and that winning their trust will lead to insurgents being forced into the open where they can be engaged directly. To accomplish this goal, U.S. and allied forces must be able to patrol, live, operate, and conduct civil engagements amongst the people (Joint Chiefs of Staff, 2018). The need for long-duration, highly capable ISR aircraft has only increased as counterinsurgency operations have become a continuous part of military operations since 9/11.

The gray zone refers to competition between and among states below the level of war, but above the level of normal diplomatic relations between countries. In this competitive arena, the most exquisite military capabilities and weapons are not routinely employed, but rather a struggle for influence, access, and credibility relies on a combination of capabilities below the level of war (Hoffman, 2018). The characteristics of specific gray zone operations and the military hardware needed to carry them out is not apparent yet. However, the need to understand and sense the battlespace is enduring. The persistent ISR that commanders have grown accustomed to in Iraq, Afghanistan, Syria, and other counterinsurgency theaters around the world, will continue to be a necessity in the gray zone.

E. EABO AND MARINE CORPS FORCE DESIGN 2030

Beginning with the recognition that the return to great power competition (GPC) necessitates adapting the naval services to new paradigms, the Commandant of the Marine Corps (CMC) and the Chief of Naval Operations (CNO) approved the concept for Expeditionary Advanced Base Operations (EABO) in 2019. In 2021, the Marine Corps published the first EABO manual which "sets forth pre-doctrinal considerations for forces conducting expeditionary advanced base operations," titled Tentative Manual for Expeditionary Advanced Base Operations (TM EABO). This manual defined EABO as "a form of expeditionary warfare that involves the employment of mobile, low-signature, persistent, and relatively easy to maintain and sustain naval expeditionary forces from a series of austere, temporary locations ashore or inshore within a contested or potentially contested maritime area in order to conduct sea denial, support sea control, or enable fleet sustainment" (CD&I, 2021). The role of intelligence collection in the conduct of such operations is highlighted throughout the document, as maritime domain awareness, surveillance and reconnaissance, and operations in the information environment (OIE) are key aspects of this new operational paradigm. Furthermore, TM EABO highlights the need to shift from producing "actionable intelligence" to conducting "actions to produce intelligence," which are defined as "intelligence-led operations" (CD&I, 2021). The emphasis on intelligence is clear, and programs which support intelligence collection demand close inspection as they will contribute to this form of warfare in the future.

In the Commandant of the Marine Corps' Force Design 2030 guidance to the force, medium and long-range ISR aircraft capabilities were identified as a key shortfall for the service. Additionally, the same document indicated that the Marine Corps of the future should be "capable of successfully competing and winning in the gray zone." This recognition of a shortfall in ISR capabilities and the intent to operate in the gray zone creates many opportunities in the service. Furthermore, the Marine Corps has made drastic cuts to legacy systems such as tanks, assault amphibian vehicles (AAV)s, and towed artillery to reinvest the cost savings in modernizing the force (Commandant of the Marine Corps, 2020). In this situation where every dollar counts, the life cycle cost of the ISR aircraft that will be procured is important. Platforms that are too expensive may detract from other modernization efforts that could be undertaken. A cost-effective manned ISR solution could allow the Marine Corps to meet its objectives within budget constraints. Evaluating the life cycle costs of previous manned and unmanned ISR aircraft, especially the short-lived RQ-21A program, is essential to understanding the costs of future investments in these types of capabilities.

F. LITERATURE REVIEW

This study examines the differential costs and effects of operating the unmanned RQ-21A Blackjack and the manned MC-12W Liberty. This is accomplished by comparing the sources of cost differences between these programs and by applying a cost-effectiveness analysis (CEA). There is a significant theoretical background to the conduct of cost-effectiveness analyses on many kinds of programs and policies. For this reason, it is important to understand the background of the cost-effectiveness literature before conducting novel research. The purpose of this literature review is to highlight the applicable academic literature on CEA so that it can provide context to this research.

1. Cost-Benefit Analysis

A review of the cost-effectiveness analysis literature cannot be undertaken without first understanding cost-benefit analysis, as cost-effectiveness analysis is a derivative form of cost-benefit analysis (CBA). CBA is "a policy assessment method that quantifies in monetary terms the value of all policy consequences to all members of society" (Boardman et al., 2001). Simply stated, CBA compares the costs and benefits of a project, program, policy, or proposal in terms of dollars or another currency. The original invention of this technique is credited to Jules Dupuit, a French engineer who in 1848 theorized a method for comparing the costs of road maintenance with the benefits of improved mobility of people and goods as determined by willingness-to-pay (Ekelund, 1968). In the modern era, CBA is used extensively for public projects in various domains. There are numerous examples of CBAs in the areas of agriculture, pollution, drug abuse, housing, migration, waste disposal, medicine, transportation, and many others (Boardman et al., 2001). CBA has been required by law in the United States since 1939, when a provision of the Flood Control Act required the benefits of proposed projects to be greater than their costs. Furthermore, within the Defense Department the use of CBA was part of the Planning, Programming, Budgeting System (PPBS) in the 1960s (Guess & Farnham, 2000). Subsequent U.S. presidential administrations required more extensive use of CBA in various activities, and in the Reagan administration in particular, executive order 12291 required that all government agencies conduct CBA on all proposed regulations which would incur over $100 million in annual economic effects, to show that any new regulation would provide benefits that exceeded their costs (Shapiro, 2011). Today CBA and CEA are required by law for any analyses or estimates submitted to the Office of Management and Budget (OMB) in support of legislative and budget-programs (Office of Management and Budget, 2016)

2. Cost-Effectiveness Analysis Literature

The fundamental difference between a CBA and a CEA is that while a CBA monetizes and compares both costs and benefits, a CEA monetizes and compares costs, but for multiple reasons does not monetize and compare benefits. Instead, a CEA "compares mutually exclusive alternatives on the basis of a ratio of their costs and a single quantified but not monetized effectiveness measure" (Boardman et al., 2001).

The first CEA is credited to Arthur M. Wellington who produced The Economic Theory of the Location of Railways, in 1887 (Quade, 1971). This work introduced the concept that an engineer not only builds things, but also conserves resources while doing so and thus can improve the cost-effectiveness of projects. CEA remained a relatively little-used or researched technique apart from CBA until the 1950s when the growth of operations research and systems analysis became prominent in the defense department (Quade, 1971).

a. Early modern CEA literature

The CEA literature in the 1950s and 1960s was sparse and limited almost exclusively to the department of defense (Quade, 1971). There are some highlights from this period which characterize the scholarship of the time.

Foster and Hoeber (1955) theorized a guide for strategic decision-making using CEA as the basis for the method. They addressed the key reason for using CEA, that some elements of a problem are "simply not measurable" (Foster & Hoeber, 1955). This paper also introduced a model for decision makers to compare dissimilar weapons systems over time. McMillan (1961) applied CEA to naval warships to determine the ideal attributes for anti-submarine warfare and their accompanying costs.

(Fox, 1965) contributed substantially to the literature on CEA, again in the military context, with his *Theory of cost-effectiveness for military systems analysis*, which presents a theoretical basis for cost-effectiveness analysis. He incorporates randomness into the theory which added to the theoretical basis for CEA recommendations. Furthermore, he discusses the problems inherent in using cost effectiveness ratios and with the treatment of time periods in the analysis.

b. CEA in medicine

Cost effectiveness as an analytical tool in medicine became prominent in the 1970s because of concerns about the increasing costs of health care. The literature on CEAs especially grew during this time, and cost-effectiveness itself became more common in medical journals than in non-medical ones (Warner & Hutton, 1980). There are myriad potential uses for cost-effectiveness analysis in medicine. One can imagine these range from studying the effectiveness of routine care to major surgeries, new medications and therapeutics, and public health measures like vaccination programs for common viruses. In each of these cases, "analysts may be unwilling or unable to monetize the most important policy impact… for example many people are willing to predict the numbers of lives saved by alternative programs but unwilling to place a dollar value on a life saved" (Boardman et al., 2001).[1]

c. Multiple objective decision making

In government decision making, especially in the domain of defense and national security, it is impossible or infeasible to measure society's willingness to pay in monetary terms. Nor can security outcomes be "priced out" of a market by revealed preferences, because the government may be the only buyer in the marketplace. In these situations, where outcomes are defined vaguely as deterrence or security, a CBA is not appropriate and a CEA can be used (Wall & MacKenzie, 2015). However, defining the objectives of deterrence or security requires the acknowledgement that each of these goals has multiple facets, and decision makers face a multiple objective decision problem. This concept was first theorized by Keeney and Raiffa (1976) who developed a practical theory for analyzing decisions with multiple competing objectives. While this work did not apply specifically to military problems, the literature eventually included direct application of these ideas. Wall and MacKenzie (2015) developed a practical tool for quantitative investigation of all factors that may influence a decision, as applied to defense programs specifically. The

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[1] Some opposing research suggests that even things such as human life can be monetized. See Kniesner et al. (2015) and Rohlfs et al. (2015) for a review of that line of literature.

present research draws on the multiple objective decision making work of Wall and MacKenzie to build an objective hierarchy with quantifiable attributes.

d. Manned vs. unmanned ISR aircraft CEAs and related research

Cost-effectiveness analysis as a tool for military decision making continues to be used for a wide variety of applications in acquisitions, sustainment, operations, logistics, program budgeting, construction, and many others. In the area of remotely piloted vehicles specifically, there has been a growing body of literature on the relative advantages and disadvantages of manned and unmanned aircraft in a reconnaissance role. Kumar (1997) contributed early research into the costs and benefits of UAVs in a reconnaissance role. This research outlined the difficulties in comparing costs between the two technologies. Specifically, the problem of comparing older manned aircraft to newer unmanned systems, the multi-role nature of RPAs as compared with single-role manned aircraft, longer dwell times, cheaper construction, differential payload capacities, and the differential sortie and maintenance rates of the two technologies (Kumar, 1997).

Glade (2000) incorporated evaluation criteria for manned, unmanned, and autonomous systems in his research on the implications of unmanned aerial vehicles on military operations. Advantages and disadvantages as well as proposed roles for each were established and differentiated (Glade, 2000).

RAND published a comprehensive methodology for studying remotely piloted aircraft in multiple roles and missions in 2012. This work importantly contributed a detailed operational effectiveness model which could be used to categorize different RPAs (Figure 6). This model could be applied broadly to many types of RPAs but was tailored to airborne ISR platforms because of the focus on the capabilities of onboard sensors and the types of targets they could identify. This work also identified the problems with directly comparing the operational effectiveness of one platform against another due to reliance on other systems, the operational context, and the unknowable future of unmanned technologies (Lingel et al., 2012).

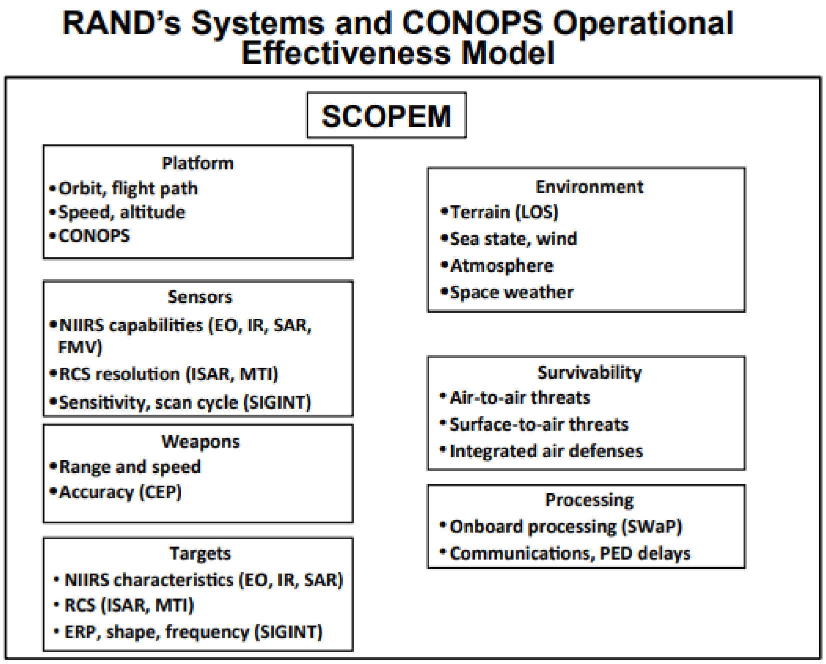


Figure 6. Operational effectiveness model for evaluating RPA's. Source: Lingel et al. (2012).

Larkins (2012) made an important contribution to the literature with the direct O&S cost comparison made between two systems which filled the same role, allowing for control of the operational factors identified in the earlier literature as complicating elements in this research. Larkins compared the O&S costs of the Navy's EP-3 Ares manned ISR aircraft and the Navy's unmanned replacement for this capability, the MQ-4 Triton. This research uncovered the granular differences between these types of programs and how they contributed to O&S cost increase. This was the first research to include costs of constructing and manning ground collection sites and purchasing increased satellite bandwidth to control RPAs. The present research draws on Larkins' cost analysis and extends the application of this technique to smaller ISR systems.

Two research teams used CEA techniques including the development of a Measure of Overall Effectiveness (MOE) to compare different attributes of unmanned systems with dissimilar designs. (Kacala & Collier, 2008) published a study of the cost-effectiveness of tactical satellites, high-altitude long-endurance airships, and RPAs in both ISR and communications roles. This study used pairwise comparison to determine the effectiveness of 15 different platforms. Everly and Limmer (2014) used a CEA with multi-objective decision making analysis to compare the costs and effectiveness of different aerial communications platforms in multiple operational environments. Their work studied RPAs, towers, and aerostats as the platform for communications equipment in the operational environment. They employed an objective hierarchy to develop the measure of overall effectiveness. Neither of these studies directly compared manned and unmanned platforms in their CEA. The present research extends Everly and Limmer's application of multi-objective decision making by applying it to ISR systems instead of only communications relay platforms.

e. Literature review summary

A review of the literature on cost-effectiveness analysis has important ramifications for the comparison of small RPAs and manned ISR aircraft. First, a measure of overall effectiveness (MOE) is an important element of previous successful CEAs on military systems. This technique can be applied to both manned and unmanned platforms. Second, important attributes of ISR systems have already been identified which set them apart from manned systems and which should be accounted for in the creation of an objective hierarchy. Lastly, cost comparison between manned and unmanned systems requires a detailed tabulation across all cost elements to uncover important differences in cost between platforms.

The present study extends the literature by completing the first CEA comparing tactical airborne ISR platforms of both manned and unmanned types. Inherent in this analysis is also a life cycle cost comparison between smaller manned and unmanned aircraft. This research develops a methodology for comparing dissimilar systems which can be used by decision makers for future analyses of other platforms.

G. BACKGROUND SUMMARY

While the Marine Corps has operated manned ISR aircraft in the past, since the 1980s the only airborne ISR assets have been unmanned aircraft in the Group 3 class. This includes the current program of record for airborne ISR, the Group 3 RQ-21A Blackjack. The RQ-21A differs from other aircraft in its class in that it can be launched and recovered from the deck of an amphibious warship. There are other options available to the Marine Corps for conducting airborne ISR in the current defense programmatic landscape. Specifically, the MC-12W and other manned ISR aircraft like it provide the same type of intelligence information as the RQ-21A. The MC-12W is a proven ISR asset that has performed during GWOT operations in deployed locations around the globe. The MC-12W is based on the ubiquitous King Air 350 transport aircraft, which the Marine Corps already operates as the UC-12 under the OSA program. The role of ISR in future operations characterized by counterinsurgency, gray zone operations, and expeditionary advanced base operations is paramount. Programs which support airborne intelligence collection within budget constraints are necessary in the future operating environment. The literature on manned and unmanned ISR aircraft includes many comparisons of systems, but there has not yet been a CEA conducted on smaller tactical systems such as the RQ-21A or the MC-12W.

III. DATA AND METHODOLOGY

A. DATA OVERVIEW

The historical record of the cost elements included in this analysis of both the RQ-21A program and the MC-12W program are available in several databases which military personnel can access with valid credentials. Additionally, these cost elements are public record and retrievable by searching the published budget documents for the respective service in each year and filtering by program name. For ease of search and retrieval and to gain the greatest fidelity on each individual element, two primary databases are used in this research. The Naval Visibility and Management of Operating and Support Costs (VAMOSC) system is used to retrieve information on the RQ-21A, as it is a Naval program. For the MC-12W, the Air Force system that provides the best information is the Air Force Total Ownership Cost (AFTOC) program. Each of these systems allows military cost analysts to run queries by specific program and subsequently analyze and visualize cost element data by year and appropriation category. In addition to these databases, a third source of information is used for data on the RQ-21A program specifically. This data is the research, development, test, and evaluation (RDT&E) spending on the RQ-21A system by year, which is directly from the program office, Navy and Marine Corps Small Tactical Unmanned Aircraft Systems Program (PMA-263) located at Patuxent River Naval Air Station, Maryland.

1. Naval VAMOSC Data

The naval system which collects and reports U.S. Navy and Marine Corps historical operating and support (O&S) costs is VAMOSC. It is managed and maintained by the Naval Center for Cost Analysis (NCCA). The RQ-21A data available in VAMOSC spans the entire life of the program, from 2013 to the present. RQ-21A cost data is retrieved by running a VAMOSC Corporate Document report using data in the Aviation Type Model Series Reporting (ATMSR) Universe. This data is reported in the expanded Cost Assessment and Program Evaluation (CAPE) 2020 cost element structure (CES), which is the standard used by the Office of the Secretary of Defense (Office of the Secretary of

Defense [OSD], 2020). RQ-21A cost data for the years 2013 to the present with all cost elements is included in this research.

2. AFTOC Data

The Air Force system which collects and reports historical operating and support (O&S) costs is AFTOC. It is managed and maintained by the Air Force Cost Analysis Agency (AFCAA). The MC-12W data available in AFTOC spans the entire life of the program, from 2008 to 2015, when the program was transferred to the Air National Guard (ANG). MC-12W cost data is retrieved by running an AFTOC Metrics Tool report using the Programmatics for Multiple Mission Designator Series (MDS) dataset and sorting by aircraft designator. This data is reported in the expanded Cost Assessment and Program Evaluation (CAPE) 2020 cost element structure (CES), which is the standard used by the Office of the Secretary of Defense (OSD) (OSD, 2020). MC-12W cost data for the years 2008 to 2015 with all cost elements is included in this research. It is noted that no RDT&E costs were reported in AFTOC for the MC-12W in any year. This is confirmed by searching the Air Force's Consolidated VAMOSC Tool (CVT), which is available through the Cost Assessment Data Enterprise (CADE) portal, which is managed by OSD's Cost Assessment and Program Evaluation (CAPE) office.

3. Other Data

In addition to the information available in Naval VAMOSC and AFTOC, some data is directly from the program office. Specifically, the RDT&E expenditures for the RQ-21A program for each year studied.

4. Year Dollars and Inflation Indices

The costs presented in this research are in constant dollars inflated to the year 2021, for ease of understanding and comparison. Figures presented are also in constant dollars. This allows for comparisons to be made between program expenditures from different time periods. To allow for constant dollar calculations, the effect of inflation must be accounted for. There are several tools an analyst can use to adjust for inflation when calculating the cost of defense programs. For ease of understanding, this research uses the Consumer Price

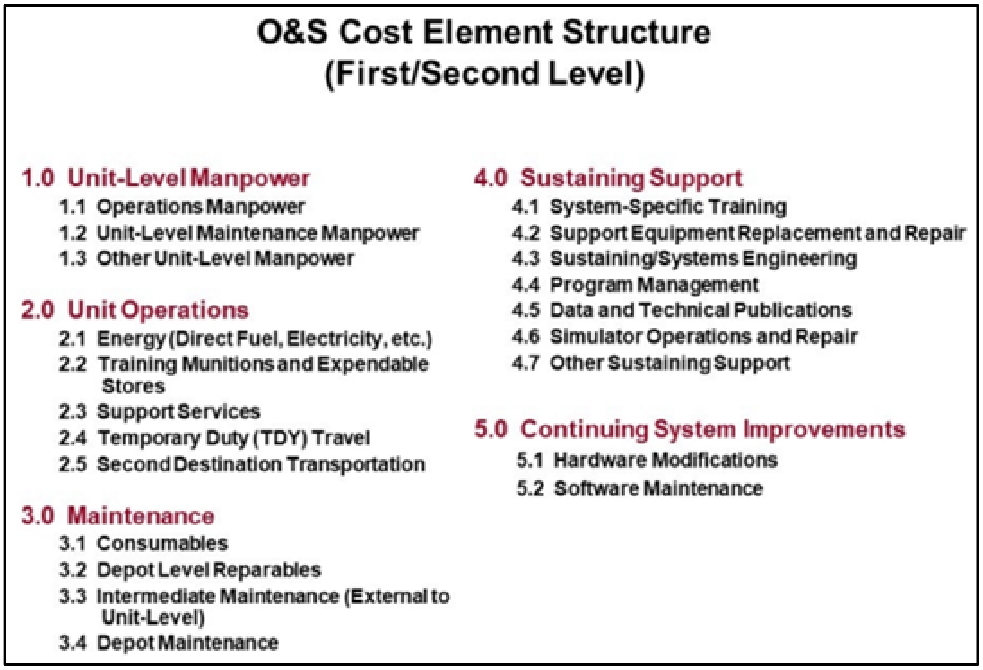
Index (CPI) to make this adjustment. Once all dollars are expressed in FY21 constant dollars, comparisons can be readily made and understood.

5. Time Period Analyzed

The two programs analyzed in this research did not run concurrently, however they will be analyzed for an equivalent length of time. The MC-12W program is analyzed for the years 2008–2015, for a total of eight years of cost data analyzed. The RQ-21A program is analyzed for the years 2013–2020, also for eight years of total cost data. As the MC-12W program began first, it will be used as the alternative to the RQ-21A in subsequent analysis of the potential cost effectiveness of the MC-12W system in the Marine Corps.

6. OSD Cost Element Structure

OSD CAPE divides cost elements for defense programs into five major categories (Figure 7). These are Unit-Level Manpower, Unit Operations, Maintenance, Sustaining Support, and Continuing System Improvements. Within each of these five categories, there are sub-levels which are organized in a hierarchy by category (OSD, 2020). Data on each of these categories was available for both programs and was aggregated at the top of the hierarchy to compare across years.


O&S Cost Element Structure
(First/Second Level)

1.0 Unit-Level Manpower
- 1.1 Operations Manpower
- 1.2 Unit-Level Maintenance Manpower
- 1.3 Other Unit-Level Manpower

2.0 Unit Operations
- 2.1 Energy (Direct Fuel, Electricity, etc.)
- 2.2 Training Munitions and Expendable Stores
- 2.3 Support Services
- 2.4 Temporary Duty (TDY) Travel
- 2.5 Second Destination Transportation

3.0 Maintenance
- 3.1 Consumables
- 3.2 Depot Level Reparables
- 3.3 Intermediate Maintenance (External to Unit-Level)
- 3.4 Depot Maintenance

4.0 Sustaining Support
- 4.1 System-Specific Training
- 4.2 Support Equipment Replacement and Repair
- 4.3 Sustaining/Systems Engineering
- 4.4 Program Management
- 4.5 Data and Technical Publications
- 4.6 Simulator Operations and Repair
- 4.7 Other Sustaining Support

5.0 Continuing System Improvements
- 5.1 Hardware Modifications
- 5.2 Software Maintenance

Figure 7. O&S CAPE cost element structure. Source: OSD (2020).

7. Cost per Flight Hour Calculation

The cost per flight hour (CPFH) is an important metric for every aircraft in the DOD inventory. There are three primary reasons why decision makers, legislators, and commanders may be interested in CPFH. First, the services use flight hours as the primary variable for Flying-Hour Program (FHP) calculations. FHP is the primary program for budgeting to maintain aircrew proficiency on various aircraft. Second, the services are regularly reimbursed for flight hours incurred by other organizations. Accurate CPFH rates allow for a per-hour charge to be applied for these flights by respective aircraft type. Lastly, CPFH can be used to compare the costs of different aircraft programs (Boito et al., 2015). This is the CPFH calculation most relevant to this research.

Comparing two or more DOD aircraft programs requires a different treatment of CPFH calculations than the other two reasons given. While the FHP and reimbursable rate calculations are most affected by costs that vary with flight hours, CPFH in the context of comparing different aircraft programs must include some fixed costs involved in the development of the program itself, as these differ between programs and cannot be ignored (Boito et al., 2015).

This research compares two aircraft from different services and in different time frames. For a complete understanding of how all costs vary with flight hours across these programs, all costs reported for the program will be included in CPFH calculations. Specifically, for the purposes of this research, CPFH will be calculated as total cost reported to CAPE across all cost element categories, plus all RDT&E spending reported by the program, divided by total flight hours reported to CAPE.

Finally, CPFH should be compared between programs only when each program is at its maturity. Comparing programs which are in their initial "ramp-up" phase with those in "steady-state" phase would be inappropriate (Boito et al., 2015). For this research, maturity will be defined as a period of at least three years in which the respective aircraft fleet is at maximum size and flying the most total hours per year.

8. Assumptions

The comparisons drawn in this research are based on the hypothetical possibility that the Marine Corps could have purchased the MC-12W manned ISR aircraft instead of the RQ-21A unmanned RPA. This comparison is relevant to the extent that certain assumptions are valid. Assumptions for this comparison include:

- The Marine Corps would not have incurred RDT&E costs if purchasing the MC-12W in 2013. The RDT&E to develop the program had already been incurred by the Air Force.
- The flight hours that the Marine Corps incurred on the RQ-21A would have been comparable to the MC-12W, had it been the airborne ISR program of record at the time.
- Costs are assumed to be reported accurately by the respective armed services to the relevant databases.
- Programs are assumed to be mature for the purposes of comparison during the period of at least three years in which the respective aircraft fleet is at maximum size and flying the most total hours per year.

- Disposal costs cannot be included in the analysis because neither program will have reached this phase by the publication of this research.
- MILPERS data is compared without regard to potential differences in flying unit composition between the services.

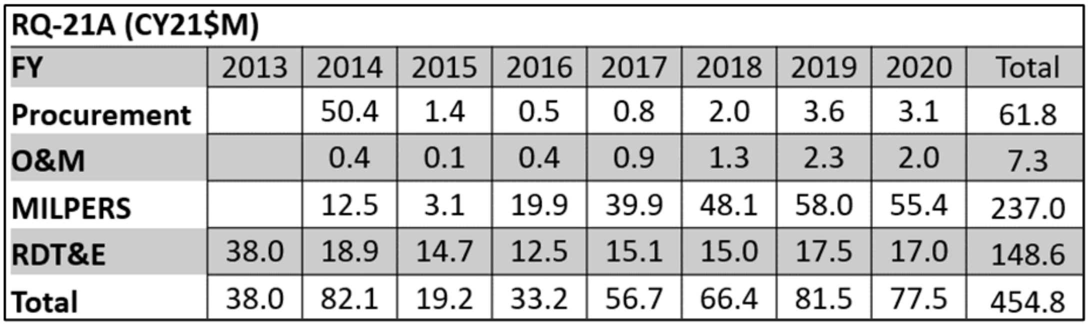
B. RQ-21A COST DATA

Cost data for the RQ-21A system is presented by appropriation type as reported to OSD. Flight hours are tabulated and used to create a CPFH calculation per year. The total size of the RQ-21A fleet is presented to indicate years of program maturity. Finally, the cost profile for the system is presented to depict how funds were spent on this program.

1. RQ-21A Costs by Appropriation

The RQ-21A program cost a total of $454.8 million in CY21 dollars. This total cost is spread over costs incurred in Procurement, O&M, military personnel (MILPERS), and RDT&E (Table 2). The only cost incurred in the initial year of the program (2013) was in RDT&E as expected. In all subsequent years, costs were incurred in all categories. Almost all the Procurement costs were incurred in year two of the program (2014), with over $50 million spent in that category in 2014 alone, representing over 81% of all procurement spending and 11% of the program's overall cost. The O&M spending on the program represented less than 2% of the total program cost, at only $7.35 million. MILPERS spending was the largest category of spending on the RQ-21A program, representing 52% of the total cost of the program at $237 million. Finally, the RDT&E spending on the RQ-21A program was significant, totaling over $148 million and representing over 32% of the total program cost (R. Aldrich, email to author, October 19, 2021).

Table 2. RQ-21A program costs by appropriation type

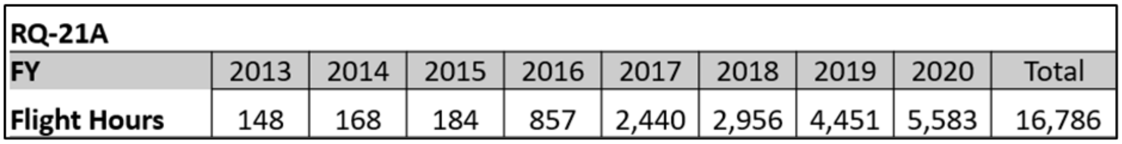


RQ-21A (CY21$M)									
FY	2013	2014	2015	2016	2017	2018	2019	2020	Total
Procurement		50.4	1.4	0.5	0.8	2.0	3.6	3.1	61.8
O&M		0.4	0.1	0.4	0.9	1.3	2.3	2.0	7.3
MILPERS		12.5	3.1	19.9	39.9	48.1	58.0	55.4	237.0
RDT&E	38.0	18.9	14.7	12.5	15.1	15.0	17.5	17.0	148.6
Total	38.0	82.1	19.2	33.2	56.7	66.4	81.5	77.5	454.8

2. RQ-21A Flight Hours

The RQ-21A program incurred a total of 16,786 flight hours between 2013 and 2020 (Table 3). This total represents all reported flight hours, including both training and operations. Flight hours notably increased beginning in 2017.

Table 3. RQ-21A flight hours

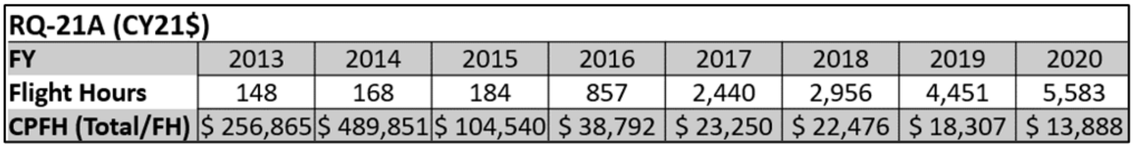


RQ-21A									
FY	2013	2014	2015	2016	2017	2018	2019	2020	Total
Flight Hours	148	168	184	857	2,440	2,956	4,451	5,583	16,786

3. RQ-21A Cost per Flight Hour (CPFH)

The CPFH calculation (Table 4) for the RQ-21A includes all costs listed above and divided by the reported flying hours per year. Notably, RQ-21A CPFH begins high, as during the ramp-up of the program both RDT&E and Procurement costs were high while flight hours were low, resulting in a high CPFH calculation. As the program continues however, CPFH declines sharply as the flight hours increase significantly over time, especially in the final three years of the program studied. In the final three years studied, CPFH declines to an average of $18,223 in 2021 dollars. By this measure, the most mature years in terms of number of flight hours are 2018, 2019, and 2020.

Table 4. RQ-21A cost per flight hour

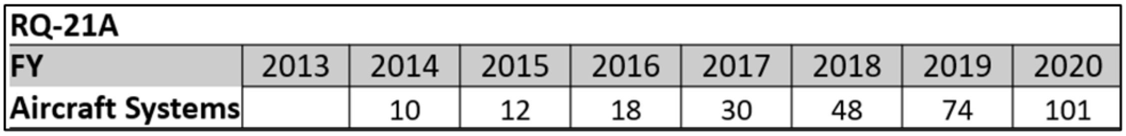


RQ-21A (CY21$)								
FY	2013	2014	2015	2016	2017	2018	2019	2020
Flight Hours	148	168	184	857	2,440	2,956	4,451	5,583
CPFH (Total/FH)	$ 256,865	$ 489,851	$ 104,540	$ 38,792	$ 23,250	$ 22,476	$ 18,307	$ 13,888

4. RQ-21A Aircraft Systems in Inventory

The total RQ-21A system inventory as reported to the Naval VAMOSC is given in Table 5. The total number of systems in inventory only grew during the period studied. By this measure, the most mature years in terms of number of aircraft in service are 2018, 2019, and 2020.

Table 5. RQ-21A aircraft systems in inventory per year



RQ-21A								
FY	2013	2014	2015	2016	2017	2018	2019	2020
Aircraft Systems		10	12	18	30	48	74	101

5. RQ-21A Program Cost Profile

The total program cost for the RQ-21A program over the years studied (2013-2020) is shown in Figure 8.

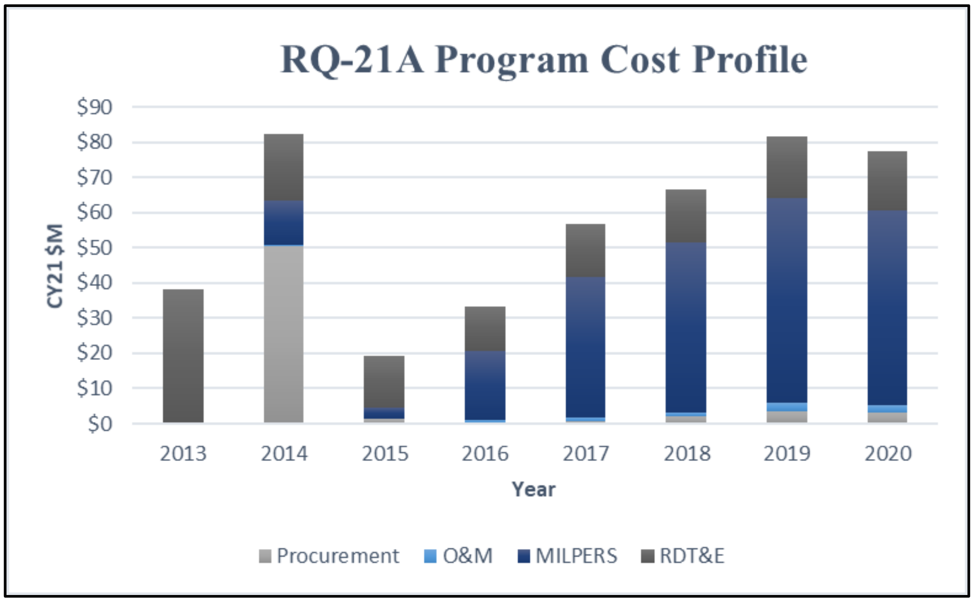


Figure 8. RQ-21A program cost profile

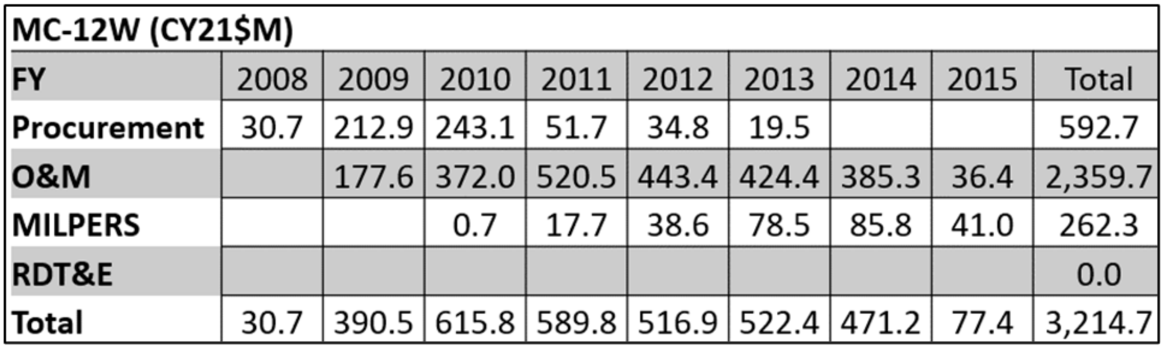
C. MC-12W COST DATA

Cost data for the MC-12W system is presented by appropriation type as reported to OSD. Flight hours are tabulated and used to create a CPFH calculation per year. The total size of the MC-12W fleet is presented to indicate years of program maturity. Finally, the cost profile for the system is presented to depict how funds were spent on this program.

1. MC-12W Costs by Appropriation

The MC-12W program cost a total of $3,214 million in CY21 dollars. This total cost is spread over costs incurred in Procurement, O&M, and MILPERS (Table 6). There were no RDT&E costs incurred on this program as reported to CAPE. The only cost incurred in the initial year of the program (2008) was in Procurement as expected. In all subsequent years, costs were incurred in all other categories. Almost all the Procurement costs were incurred in years two and three of the program (2009 and 2010), with over $456 million spent in that category in those years alone. In total, Procurement spending represented 18% of the program cost at $592 million. O&M spending was the largest category of spending on the MC-12W program. The O&M spending on the program represented more than 73% of the total program cost, at over $2,359 million. MILPERS spending was the smallest category of spending on the MC-12W program, representing just 8% of the total cost of the program at $262 million.

Table 6. MC-12W program costs by appropriation type

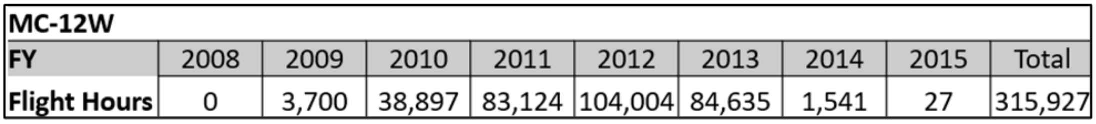


MC-12W (CY21$M)									
FY	2008	2009	2010	2011	2012	2013	2014	2015	Total
Procurement	30.7	212.9	243.1	51.7	34.8	19.5			592.7
O&M		177.6	372.0	520.5	443.4	424.4	385.3	36.4	2,359.7
MILPERS			0.7	17.7	38.6	78.5	85.8	41.0	262.3
RDT&E									0.0
Total	30.7	390.5	615.8	589.8	516.9	522.4	471.2	77.4	3,214.7

2. MC-12W Flight Hours

The MC-12W program incurred a total of 315,927 flight hours between 2008 and 2015 (Table 7). This total represents all reported flight hours, including both training and operations. Flight hours notably increased beginning in 2010.

Table 7. MC-12W flight hours



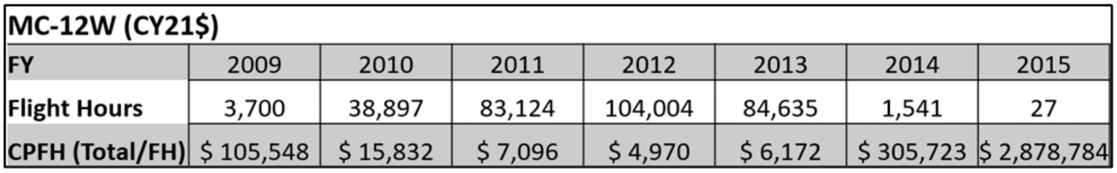
MC-12W									
FY	2008	2009	2010	2011	2012	2013	2014	2015	Total
Flight Hours	0	3,700	38,897	83,124	104,004	84,635	1,541	27	315,927

3. MC-12W Cost per Flight Hour (CPFH)

The CPFH calculation for the MC-12W includes all costs listed above and divided by the reported flying hours per year (Table 8). Notably, MC-12W CPFH begins high, as during the ramp-up of the program Procurement costs were high while flight hours were low, resulting in a high CPFH calculation. As the program continues however, CPFH declines sharply as the flight hours increase significantly over time, especially in the years

2011, 2012, and 2013. In these years, CPFH declines to an average of $6,079 in 2021 dollars. At the end of the program, in years 2014 and 215, flight hours dropped sharply and resulted in a very high CPFH before the program ended. By this measure, the most mature years in terms of number of flight hours are 2011, 2012, and 2013.

Table 8. MC-12W cost per flight hour

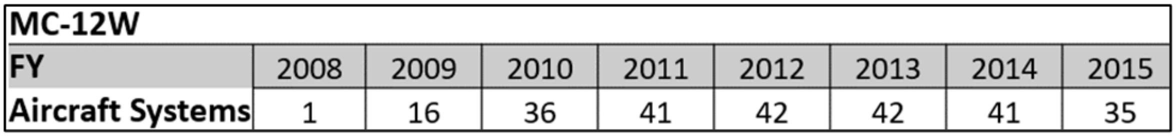


MC-12W (CY21$)							
FY	2009	2010	2011	2012	2013	2014	2015
Flight Hours	3,700	38,897	83,124	104,004	84,635	1,541	27
CPFH (Total/FH)	$ 105,548	$ 15,832	$ 7,096	$ 4,970	$ 6,172	$ 305,723	$ 2,878,784

4. MC-12W Aircraft in Inventory

The total MC-12W inventory as reported to AFTOC is given in Table 9. The total number of systems in inventory grew during the period studied until 2014, at which point it declined slightly. By this measure, the most mature years in terms of number of aircraft in service are 2011, 2012, and 2013.

Table 9. MC-12W aircraft systems in inventory per year



MC-12W								
FY	2008	2009	2010	2011	2012	2013	2014	2015
Aircraft Systems	1	16	36	41	42	42	41	35

5. MC-12W Program Cost Profile

The total program cost for the RQ-21A program over the years studied (2013-2020) is shown in Figure 9.

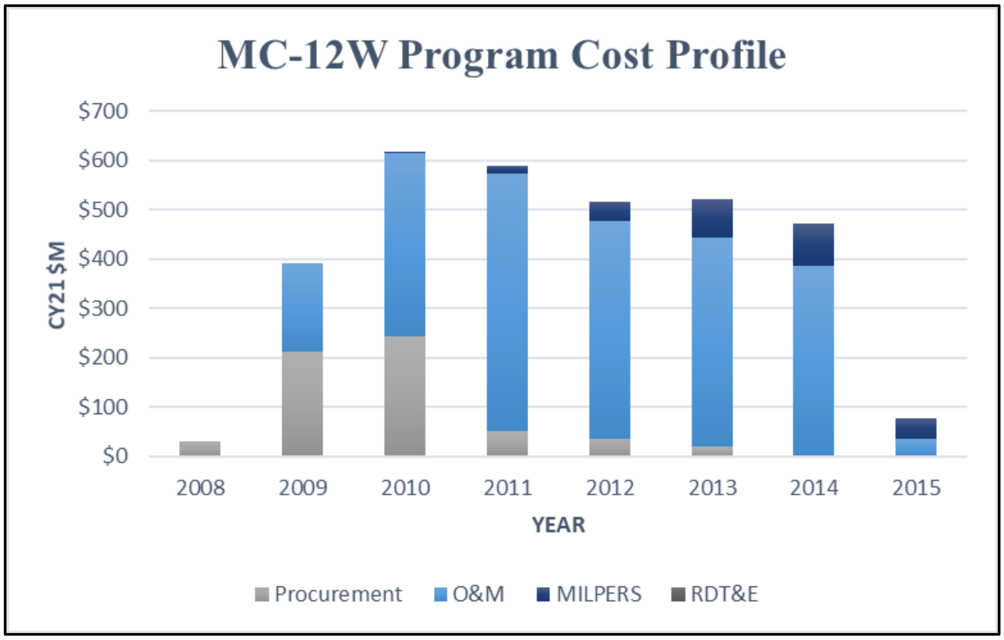


Figure 9. MC-12W program cost profile

D. EFFECTIVENESS

The costs of the two ISR systems is only one aspect of their significance to the DOD. The effectiveness of each system must also be considered.

1. RQ-21A Program Effectiveness

The RQ-21A Blackjack program has several key benefits that can be qualitatively analyzed to provide a comparison with other ISR aircraft programs. First, the program is unmanned and therefore less risky to operate. Second, the program has very low operations and maintenance (O&M) costs. This allows commanders to employ the capability with very little regard to variable costs such as fuel, maintenance, and repairs. Third, the RQ-21A has a long dwell time, allowing supported commanders the ability to loiter their ISR asset over a target for up to 16 continuous hours. Fourth, and perhaps most importantly, the RQ-21A can be transported, launched, and recovered from the deck of an amphibious ship (NAVAIR, 2021).

a. Unmanned

The RQ-21A provides benefits to the supported commander because it is an unmanned platform. The commander does not have to risk the life of a pilot or aircrew to employ this aircraft, and therefore may choose to employ it in more risky or dangerous situations. This expands the number and types of situations for which ISR aircraft can be employed for the commander.

b. Dwell time

The RQ-21A boasts a dwell of time of up to 16 hours. More dwell time over a target can improve the situational awareness of the commander. More time overhead can reduce uncertainty about a target and improve the accuracy of intelligence reports. Furthermore, a long dwell time allows for the flight deck of an amphibious warship to be reconfigured from launching the RQ-21A to launching and recovering other types of aircraft while the RQ-21A remains over the target, before finally recovering the RQ-21A itself.

c. Amphibious launch and recovery

Perhaps the most important benefit of the RQ-21A aircraft is that while it can be employed from expeditionary airfields or airports on land it can also be launched and recovered from the deck of all three types of amphibious warships common to the Amphibious Ready Group / Marine Expeditionary Unit (ARG/MEU). This flexibility allows a commander to employ all forces from amphibious shipping, without committing any Marines or Sailors ashore into potentially hostile situations to launch an ISR aircraft. Amphibious ships allow commanders to rapidly maneuver on the sea to gain a position of advantage or surprise off the coast of a given country or in vicinity of contested waterways. The RQ-21A provides a distinct benefit to the commander by being able to be launched and recovered from these types of ships, as compared to other ISR aircraft which must be launched and recovered from airfields on land.

2. MC-12W Program Effectiveness

The MC-12W Liberty program has several key benefits that can be qualitatively analyzed to provide a comparison with other ISR aircraft programs. First, the aircraft has a distinct range advantage over small unmanned systems. Second, the MC-12W has a pilot and crew on board, who can fly the aircraft and operate its sensors, regardless of whether they have communications with a ground station. Third, and perhaps most importantly, the MC-12W is based on a commercially available airframe that is readily available in the civilian aircraft marketplace, making it fast and simple to procure.

a. Range

The MC-12W boasts a 2,400 nautical mile range (Air Force, 2021). This is far greater than the RQ-21A range of approximately 50km (27 nautical miles). The difference is driven by the line-of-sight communications link required for the operation of the RQ-21A unmanned aircraft. The MC-12W has no such requirement, and as a relatively fuel-efficient and lightweight aircraft, great distances can be covered in a single mission. The benefit of this extended range to the commander is obvious. The commander can access many potential targets from the airfield of origin, without relocating to a closer airfield or risking landing in potentially hostile locations.

b. Manned

The MC-12W has a qualitative benefit in its on-board pilot and crew. A pilot and crew onboard the aircraft can make real-time adjustments to the mission, sensors, and flight plan, without a communications link with a ground station. This allows for increased flexibility and adaptability to the situation, as well as increased reliability, because if communications are lost the mission can still proceed as planned.

c. Commercial availability

The MC-12W is based on the Hawker Beechcraft Super King Air 350 and Super King 350ER aircraft. At the time of its initial fielding in 2008, it was "the fastest weapons system delivered from concept to combat since the P-51 Mustang in World War II." According to Lt. Gen. David A. Deptula, then deputy chief of staff for Intelligence, Surveillance and Reconnaissance at Headquarters Air Force (Petcoff, 2010). The reason for this speed in fielding was largely due to the use of commercial aircraft already in production to form the basis of the program. Each airframe was then subsequently modified into its ISR configuration (Turpin, 2017). This factor helped to increase the speed of delivery of the system and reduce the overall cost of development as the main system component was already commercially developed.

E. METHODOLOGY

The methodology in this study is a cost-effectiveness analysis wherein costs are expressed in CPFH, and effectiveness is expressed as a measure of overall effectiveness (MOE) score.

1. CPFH during Program Maturity

The MC-12W and RQ-21A programs are not of equivalent size. To compare costs, the programs should be compared on a per-flying hour basis. During the three years of RQ-21A program maturity, the program recorded a total CPFH of $22,476, $18,307, and $13,888 in 2018, 2019, and 2020 respectively, for an average CPFH during maturity of $18,223. Alternatively, during the three years of MC-12W program maturity, the program recorded a total CPFH of $7,096, $4,970, and $6,172 in 2011, 2012, and 2013 respectively, for an average CPFH during program maturity of $6,079.

2. Cost per Aircraft during Program Maturity

Another way to analyze the costs of the programs considering their different sizes, is to compare costs per aircraft in 2021 dollars. During program maturity, the RQ-21A had an average cost per aircraft system of $1.08 million over the years 2018–2020. Alternatively, during program maturity, the MC-12W had an average cost per aircraft system of $13.03 million over the years 2011–2013.

3. Flight Hours per Aircraft during Program Maturity

Given the average CPFH and average cost per aircraft reported above, it is important to understand the differential flight hours per aircraft during program maturity. During 2018–2020, the RQ-21A averaged only 59 flight hours per aircraft system. During 2011–2013, the MC-12W averaged 2,171 flight hours per aircraft system. This difference in average flight hours per aircraft largely explains why the CPFH is lower for the MC-

12W and the cost per aircraft is lower for the RQ-21A. Simply stated, the MC-12W flew far more flight hours during the three years of program maturity than in the comparable years for the RQ-21A.

4. O&M vs. MILPERS Spending

The RQ-21A and MC-12W programs have different life cycle funding profiles. Most notably, each platform has one spending category that is the bulk of all program spending. For the RQ-21A, MILPERS spending accounts for over 52% of all program spending while O&M spending accounts for less than 2% of spending. Conversely, MILPERS spending makes up only 8% of MC-12W spending, while O&M spending makes up over 73% of all program spending. While the programs can be compared with one another, they are fundamentally different from a cost perspective because the RQ-21A requires almost no O&M funding. While low O&M costs are appealing in any program, they still do not reduce the CPFH of the RQ-21A to the levels of the MC-12W.

5. Comparison with Published Reimbursable Rates

The DOD publishes reimbursable rates for aircraft annually. This publication is a reference for outside agencies, foreign governments, and other users of military aircraft for the cost per flight hour they will be billed for the respective aircraft used. A comparison of reimbursable rates listed for each of these aircraft is possible if costs are adjusted for inflation and compared in constant year dollars. In 2012, the reimbursable rate for the MC-12W for other federal agency use was $3,638. This was to be paid as $3,376 in O&M and $262 in MILPERS (OUSD(C), 2011). In 2022, (the only year reimbursable data was published by OSD) the RQ-21A reimbursable rate for other federal agency use was $4,392. This was to be paid as $4,299 in O&M and $92 in MILPERS (OUSD(C), 2021). Adjusted to 2021 dollars, this is $4,312 per hour for the MC-12W and $4,450.25 for the RQ-21A. These published rates indicate that OSD recognizes that the CPFH for the RQ-21A is higher than for the MC-12W, even considering that these reimbursable rates likely do not include the fixed costs of the programs.

6. Cost-Effectiveness Analysis

When it is difficult or infeasible to monetize the benefits of a policy or program, a cost-effectiveness analysis (CEA) can be used as an alternative to a traditional cost-benefit analysis (CBA) (Boardman et al., 2001). In a CBA all costs and benefits are monetized, discounted to present dollars, and costs are subtracted from benefits to arrive at the net present value (NPV) of each alternative. The alterative with the highest NPV is preferred. In CEA on the other hand, costs are monetized and discounted to present values, but benefits are not. Instead, a CEA compares alternatives as a ratio of their costs and a single quantified effectiveness measure. This cost-effectiveness ratio (CE ratio) can then be used to rank alternative policies or programs (Boardman et al., 2001).

If the CE ratio is only based on one type of effectiveness measure, in the case of ISR aircraft perhaps a single measure could be dwell time over target, or accuracy of the onboard camera sensor, then the CEA is very simple. This is because it would be relatively uncomplicated to make a ratio between cost and a single measure like one of the two mentioned. However, in most analyses there are multiple measures of effectiveness of different alternatives. This complicates the development of a CE ratio. To overcome these difficulties, the multi-objective analysis method is employed to allow for comparisons between alternatives with more than one attribute of effectiveness or with dissimilar attributes. The overall effectiveness and cost of each alternative can then be used to rank alternatives (Everly & Limmer, 2014).

This research uses multi-objective analysis to compare the two dissimilar ISR aircraft and create a CE ratio for each. First, an objective hierarchy is developed based on the Key Performance Parameters (KPPs) that the Marine Corps documented before acquiring the RQ-21A. Next, value functions are developed based on my own research and judgment. The value functions give each objective a normalized score between zero and one. Next, each objective is assigned an importance weight so that comparisons can be drawn between dissimilar effectiveness attributes. Finally, each alternative is assigned a Measure of Overall Effectiveness (MOE) score based on the value function and importance weight of its attributes (Everly & Limmer, 2014).

Importantly, the MOE score is heavily influenced by the value function and importance wights assigned to the effectiveness attributes of each system. In a CEA, these judgments are made by the decision maker responsible for the outcome by choosing one alternative over another. In this research, I serve as the decision maker who makes these judgments. To apply this method to future scenarios, decision makers would have to use their own judgments in these key areas to arrive at an MOE score for each alternative (Everly & Limmer, 2014).

7. Objectives Hierarchy

The first step in creating an MOE for the alternative ISR aircraft is to determine what matters to decision makers when choosing which aircraft to procure. This will reveal the important attributes which can be represented by objectives. To determine all the relevant objectives, it is useful to create a hierarchy with the MOE at the top and the attributes that make up the MOE listed in hierarchical fashion below (Figure 10). Each subsequent level down in the hierarchy is a narrower and more detailed attribute of each system which comprise overall effectiveness (Wall & MacKenzie, 2015).

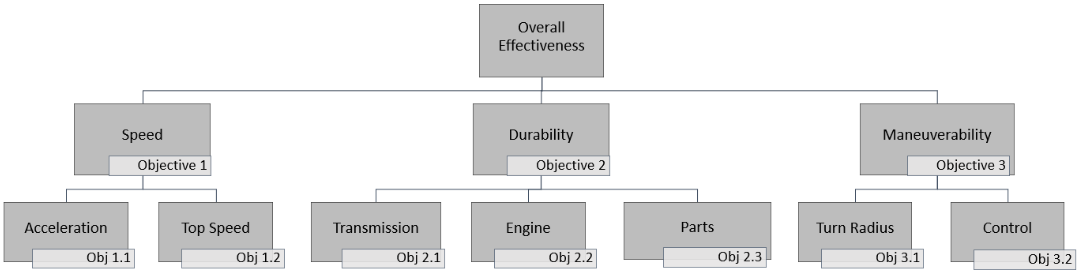


Figure 10. An example objective hierarchy for a sports car

Creating this hierarchy through subjective judgments is of course possible, and an experienced decision maker could likely create an operational hierarchy without referencing existing definitions of effectiveness. However, this research will rest the creation of the hierarchy on a published requirements document which lists the performance attributes of the system to be procured. The requirements document is the Capability Development Document (CDD) for the Tier II Unmanned Aircraft System/

Small Tactical UAS (Tier II STUAS CDD) which was published in 2008 (S. Zickert, email to author, January 6, 2022), and which forms the basis upon which the Marine Corps eventually acquired the RQ-21A in 2013. According to the Defense Acquisition University, a CDD "specifies capability requirements in terms of developmental Key Performance Parameters (KPPs)… and other related information necessary to support development of one or more increments of a materiel capability solution" (Defense Acquisition University, 2022). The CDD is a key step which is completed before the program can progress to sending out Requests for Proposal (RFPs) to industry or establish and acquisition strategy (Defense Acquisition University, 2022).

8. Value Functions

At the very bottom of the objective hierarchy, each attribute must be assigned a value between 0 and 1, to allow for comparisons between attributes that are dissimilar in type and unit of measurement. Decision makers use a value scale to assign this number. The value scale does not need to reflect linear variation between the value and a unit of measure such as dwell time measured in hours or camera resolution measured in megapixels. Instead, the decision maker can reflect marginal differences in each attribute by assigning values in a non-linear fashion (Everly & Limmer, 2014). For instance, dwell times under four hours may provide very little benefit to the decision maker, but dwell times between four and eight hours may be beneficial, and each hour between four and eight could be much more impactful than the last. Additionally, dwell times above 16 hours may not have the same marginal benefit as those between four and eight, because the ability to launch and recover the aircraft and continue with a second platform while conducting maintenance on the first may be more beneficial to the overall mission.

To develop this value function with marginal differences in attributes accounted for, the incremental value of each attribute must be determined and then divided by the cumulative value of all the attributes to arrive at a value between zero and one for each as shown in Table 10.

Table 10. Example incremental values for aircraft dwell time

Dwell Time	Incremental Value
0-4 hours	2
4-6 hours	6
6-8 hours	8
8-10 hours	9
10-12 hours	7
12-16 hours	5
16+ hours	4

The value function for this attribute could then be calculated by dividing the cumulative value of all incremental values by the individual cumulative value at each value level of attribute assigned as indicated:

$$Sum: 2+6+8+9+7+5+4=41$$

The dwell time cumulative values would then be assigned as shown in Table 11.

Table 11. Example cumulative values for aircraft dwell time

Dwell Time	Cumulative Value	Value
0-3 hours	2	2/41 = .049
4-5 hours	2+6 = 8	8/41 = .195
6-7 hours	2+6+8 = 16	16/41 = .390
8-9 hours	2+6+8+9 = 25	25/41 = .610
10-11 hours	2+6+8+9+7 = 32	32/41 = .780
12-15 hours	2+6+8+9+7+5 =37	37/41 = .902
16+ hours	2+6+8+9+7+5+4 =41	41/41 = 1

In this example, an aircraft with a dwell time over 16 hours would receive a perfect score. However, an aircraft with a dwell time of 10 hours would only see a reduction of 22% (Figure 11). This allows a decision maker to influence the comparative valuation and to answer the question: “how much is too little?” or “how much is too much?” (Everly & Limmer, 2014), (Wall & MacKenzie, 2015).

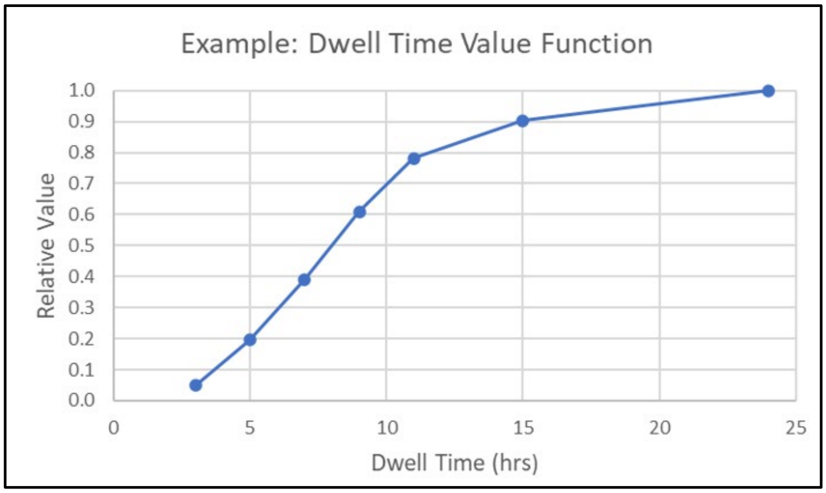


Figure 11. Dwell time value function

For other measures of attribute effectiveness, it is more difficult to directly compare across systems because the attributes are not countable in units like hours, miles per gallon, range, etc. In these instances, the decision maker must use a constructed measure, which is assessed to be between 0 and 1 based on judgment and experience (Wall & MacKenzie, 2015). For instance, many aircraft have an Identify Friend-or-Foe (IFF) radio module, which prevents mishaps and collisions between friendly aircraft in the same airspace. Without this attribute the aircraft may not meet the minimum specifications to operate alongside other aircraft in the same squadron. For this attribute, those alternatives that possess an IFF module would have a value of 1, while those that do not would have a value of 0.

9. Importance Weights

Once value functions have been assigned for each bottom-level attribute on the objective hierarchy, each objective is assigned an importance weight so that comparisons can be drawn between dissimilar effectiveness attributes. The importance weight assigns a relative value to each attribute between 0 and 1, based on the decision maker's assessment of the relative importance of each attribute to overall system effectiveness. If each attribute was equally important to the decision maker, then the importance weight would be 1-N, where N is the total number of alternatives to be weighted. However, if the decision maker values some attributes more than others, those alternatives must be given more weight and the others less. For this analysis, a rank-sum approach to importance weights will be used. The first attribute will be given a weight of N, where N is the total number of attributes. The next attributes will be given a weight of N-1, then N-2, etc., until the final attribute is given a weight of 1. The normalized weight is then simply the weight assigned divided by the sum of all weights (Everly & Limmer, 2014).

10. MOE Score

Finally, with value functions and importance weights assigned, the decision maker can calculate a single collective measure of value, called the MOE. The MOE reflects the extent to which one set of attributes contained in an alternative is preferred to another set of attributes contained in another alternative. (Wall & MacKenzie, 2015) MOE is simply the sum of the product of value functions and their corresponding importance weights as depicted:

$$v(j) = w_1 * v_1(x_1(j)) + w_2 * v_2(x_2(j)) + \ldots + w_n * v_n(x_n(j))$$

where $v(j)$ represents the MOE for alternative j, $w1$ is the importance weight for the 1st attribute, $v1(.)$ is the value function for the 1st attribute, and $x1(j)$ is the raw value for the 1st attribute for alternative j (Everly & Limmer, 2014).

11. Cost-Effective Solution

Once an MOE is determined for each alternative, the comparison with cost can be made and presented graphically. For the purposes of this research, cost is given in CPFH, to control for the differences in program size. The MOE assigned for each alternative will be plotted on the y-axis against the CPFH plotted on the x-axis. A decision maker will be able to determine whether a superior, efficient, or satisficing solution has been arrived at. Superior solutions exist when one alternative has both highest MOE and lowest cost. Efficient solutions are those that are not dominated by other alternatives. In this usage, ‘dominate’ means that an efficient solution must be more effective and cost less than other solutions, rendering others pointless. Since this research compares only two alternatives, efficient solutions will not apply. A satisficing solution occurs when a decision maker has a known cost or MOE that meets the minimum requirements and selects that alternative nearest to that minimum point. This solution type will not apply to this research either (Wall & MacKenzie, 2015). For the purposes of this research, a CE ratio defined as the MOE divided by the CPFH, will be used to determine the solution, if a superior solution does not exist.

F. DATA AND METHODOLOGY SUMMARY

Cost data on both the RQ-21A and the MC-12W are available in DOD databases for users to access and analyze. These data are organized in the OSD CAPE cost element structure. The most mature years of the RQ-21A program were 2018–2020, and the most mature years of the MC-12W program were 2011–2013. Maturity is determined by the years with the most flight hours and the largest number of aircraft in service. The CPFH for the RQ-21A system during program maturity is $18,223 in 2021 dollars. The CPFH for the MC-12W system is $6,079 in 2021 dollars. These calculations relate the cost of the two systems, but to conduct a CEA there must be an accounting of the effectiveness of each system as well. An objective hierarchy and a multi-objective analysis form the basis of the effectiveness methodology in this study. Value functions and importance weights are assigned to the attributes identified in the objective hierarchy to create a CE ratio for each system consisting of effectiveness divided by cost. The CE ratios are then compared to determine which system is most effective.

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IV. RESULTS

A. OVERVIEW

This chapter contains a CEA of the RQ-21A and the MC-12W as outlined in the methodology section. First, the objective hierarchy based on the KPPs contained in the relevant CDD is presented and explained. Next, the value functions for each bottom-level attribute are presented. Next, the importance weights are applied to the attributes. Finally, an MOE score for each alternative is calculated and a CEA solution is assigned.

B. OBJECTIVE HIERARCHY

The objective hierarchy is based on the KPPs in the CDD of the Tier II Unmanned Aircraft System. This requirements document represents the validated need which the Marine Corps eventually satisfied by procuring the RQ-21A. The KPPs of the proposed system are based on additional performance attributes. These KPPs and performance attributes form the second and third tiers of the objective hierarchy. The top level of the hierarchy is "overall effectiveness." The subsequent objectives and attributes are as follows.

1. Objectives

Below the top-level objective of "overall effectiveness," there are four objectives which combine to produce overall effectiveness. These are derived from the KPPs in the Tier II STUAS CDD. The KPPs are listed as:

- networked/interoperable
- net-ready
- resilient
- materiel availability
- precise

- day sensor
- night sensor
- expeditionary
- operates from navy ships
- transportable by CH-53
- transportable by Expanded Capacity Vehicle (ECV)
- adaptable
- modular/interchangeable payloads
- persistent
- air vehicle endurance

Additionally, three key system attributes (KSAs) are listed for the system:

- materiel reliability
- ownership costs
- sensor operating environment (OE)

These KPPs and KSAs can be refined and recombined into four simpler objectives. First, we can discard the first KPP (networked/interoperable). This KPP does not differ amongst alternatives as defined in this CEA. Both the RQ-21A and the MC-12W meet the net-ready requirement defined in the KPP. Next, resilience narrowly defined as materiel availability of system components can be expanded to include material reliability, one of the KSA's. These can be recombined into the objective "reliability." Next, the KPP "precise," which examines the precision of the onboard sensors, can be combined with the "adaptable" KPP and "sensor operating environment" KSA, as these all deal with the onboard sensor capabilities. It can also be expanded to include SIGINT sensor attributes found in the CDD. These requirements are combined into the objective “sensors.” Next, the expeditionary KPP can be directly added to the hierarchy, as it is both important to the system requirements in the CDD and differs amongst alternatives. This objective is “expeditionary.” Finally, the “persistent” KPP can be expanded from simply the endurance of the air vehicle to include air vehicle range as well. This new objective is “access.” Figure 12 depicts these objectives in the hierarchy.

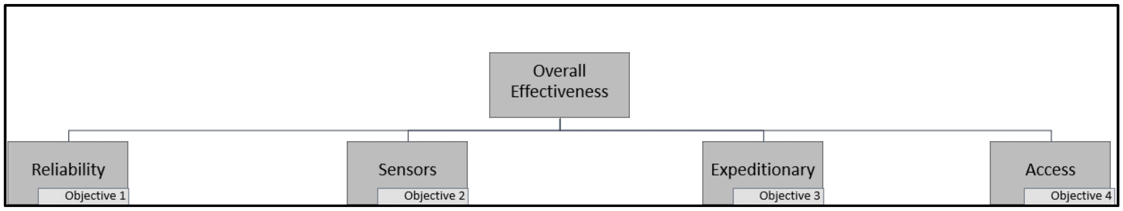

Figure 12. Objective hierarchy second-level objectives depicted

2. Sub-objectives and Attributes

These objectives can be further divided into sub-objectives and attributes. First, the reliability objective can be defined by mission capable rate (MC rate).

Next, the sensor objective is derived from the KPPs and further defined into the attribute useful load. Useful load is defined as the payload weight available after accounting for fuel and personnel. Useful load is used as the attribute because sensor technology improves over time, and differences between two systems should not be based on the sensor available at the time it was fielded, which can be easily upgraded as technology advances. Instead, the total capacity to carry sensors of any type, measured in pounds, is a simpler metric to allow for comparison between systems. This metric has been used in relevant research on aerial platforms by Everly and Limmer, in the study *Cost-effectiveness analysis of aerial platforms*, 2014.

Next, the expeditionary objective can be further divided into ability to operate from Navy ships and ability to be transported within the vehicles listed in the KPP. These are the attributes of the expeditionary objective.

Lastly, the access objective can be further divided into both aircraft dwell time over the target as well as total range of the aircraft. These are the attributes of the access objective.

The objective hierarchy now has attributes at the bottom level that can be measured (Figure 13). The structure of the hierarchy has been refined to the point where the question, "what do you mean by that?" can be answered for each objective (Wall & MacKenzie, 2015).

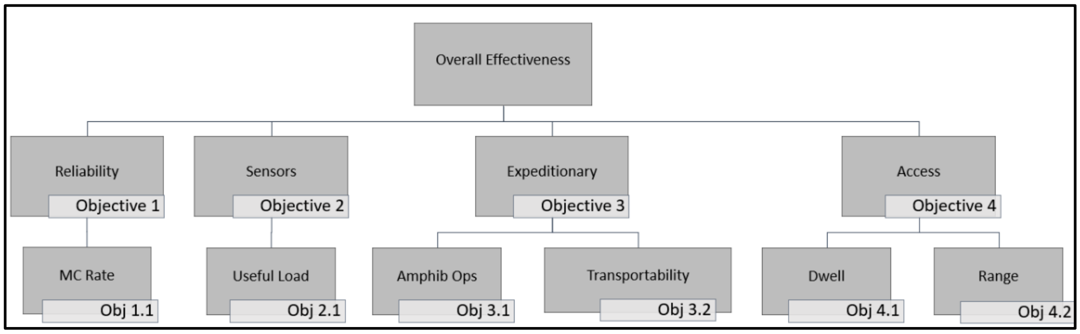

Figure 13. Objective hierarchy for RQ-21A and MC-12W CEA

C. VALUE FUNCTIONS

At the bottom level of this objective hierarchy, I assign each attribute a value between 0 and 1, which allows comparisons to be drawn between dissimilar attributes. The value function requires that the incremental value of each attribute be determined based on the natural measure (physically measured or countable), or constructed measure (not physically measured, simply the degree to which an objective is achieved), for each attribute. The attributes are addressed individually across the bottom level of the objective hierarchy and the reasons for each value function assignment explained. The value functions for each attribute produce a cumulative value which can be plotted for each attribute, and which contributes to the MOE calculation.

1. Objective 1 – Reliability

I derive the reliability objective from the KPPs and use the attribute MC rate to quantify it. MC rate represents the percentage of time an aircraft is available while it is under the control of a unit (Chapa, 2013). For each aircraft, this number can be compared to arrive at the value function (Table 12).

For the RQ-21A, the MC rate achieved during the most programmatically mature year (2020) was 82.4%. The operational goal was 80% (D. Higgins, email to author, January 20, 2022). In the case of the RQ-21A, the MC rate is largely driven by system components other than the air vehicle itself, especially the STUAS Launch System (SLS) and the STUAS Recovery System (SRS). These components allow the aircraft to take off and land, and without them the entire system is down for maintenance. With only one SLS and one SRS per system, it is the most common limiting factor for the RQ-21A MC rate according to PMA-263, the program office for the RQ-21A system (D. Higgins, personal communication, January 24, 2022).

The MC-12W is based on the ubiquitous Hawker Beechcraft King Air 350 aircraft. This airframe is in use in the U.S. Air Force, Army, Navy, and Marine Corps in various configurations. The MC-12W MC rate was 100% in 2018 and 100% in 2019 (Wood, 2021). Furthermore, the modern Marine Corps C-12 variant aircraft, the UC-12W, has an average MC rate over the years 2017–2021 of 94.4%, (D. Higgins, email to author, January 20, 2022) reflecting a high MC rate within the Marine Corps' maintenance system. The MC rate used for this attribute is the average of these two measures weighted by their respective fleet sizes, 97.8%.

Table 12. Incremental values for MC rate

MC rate (%)	Incremental Value
0-50	5
51-60	4
61-70	3
71-80	2
81-90	1
91-100	1

The cumulative values for this attribute are assigned as depicted in Table 13.

Table 13. Cumulative values for MC rate

MC rate (%)	Cumulative Value	Value
0-50	5	.313
51-60	5+4 = 9	.563
61-70	5+4+3 = 12	.750
71-80	5+4+3+2 = 14	.875
81-90	5+4+3+2+1 = 15	.938
91-100	5+4+3+2+1+1 = 16	1

This cumulative value calculation produces the function in Figure 14.

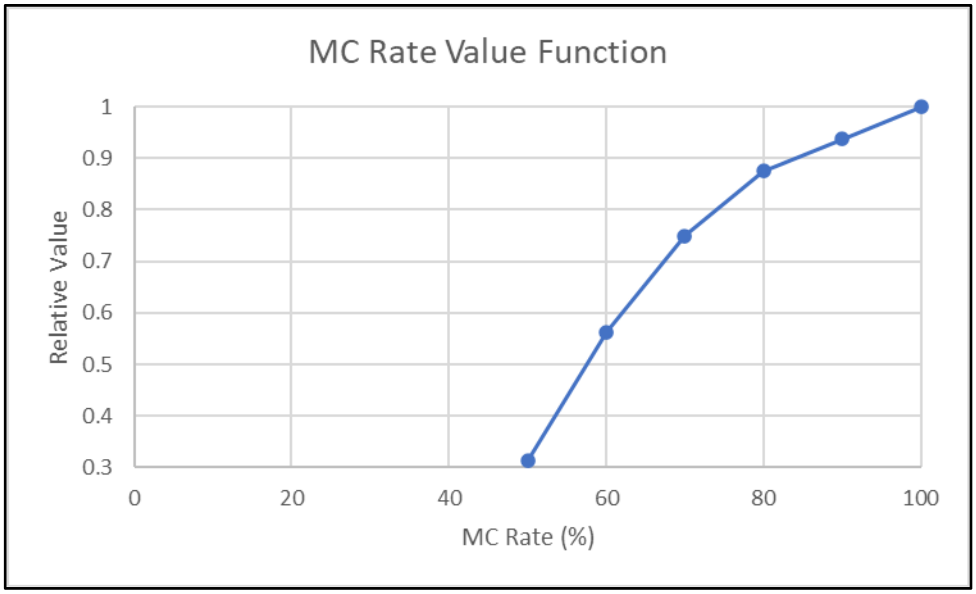

Figure 14. MC rate value function

2. Objective 2 – Sensors

I derive the sensors objective from the KPPs and use the attribute useful load to quantify it. Useful load is the payload weight available after accounting for fuel and personnel. The useful load of the RQ-21A is 39lbs (NAVAIR, 2021). The useful load of the MC-12W is 1,670 lbs. (Headquarters Air Combat Command, 2009). This attribute is assigned incremental values as depicted in Table 14.

Table 14. Incremental values for useful load

Useful Load (pounds)	Incremental Value
0-9	1
10-19	2
20-49	4
50-99	5
100-499	9
500-999	5
1000-1999	3
2000+	1

The cumulative values for this attribute are assigned as depicted in Table 15.

Table 15. Cumulative values for useful load

Useful Load (pounds)	Cumulative Value	Value
0-9	1	.033
10-19	1+2 = 3	.1
20-49	1+2+4 = 7	.233
50-99	1+2+4+5 = 12	.4
100-499	1+2+4+5+9 = 21	.7
500-999	1+2+4+5+9+5 = 26	.867
1000-1999	1+2+4+5+9+5+3 =29	.967
2000+	1+2+4+5+9+5+3+1 = 30	1

This cumulative value calculation produces the function in Figure 15.

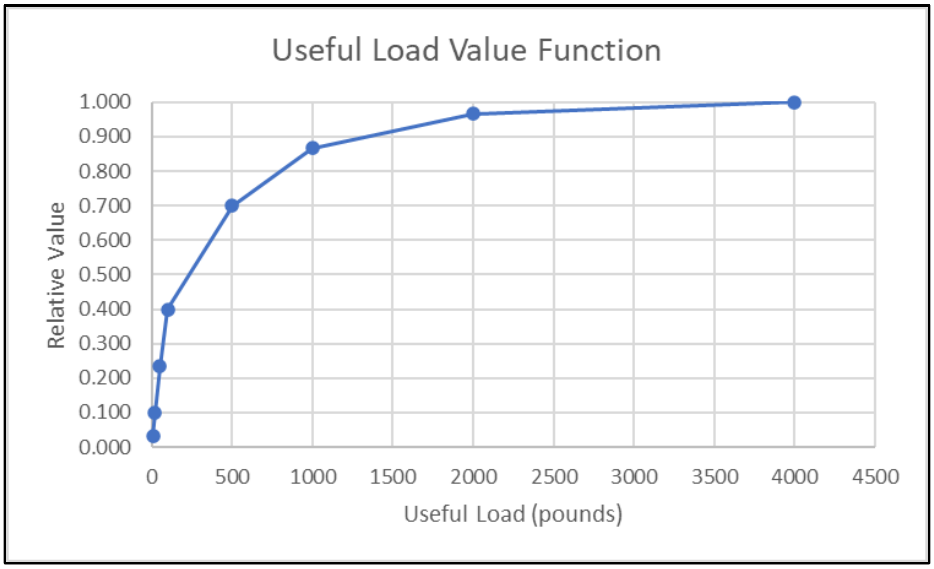

Figure 15. Useful load value function

3. Objective 3 – Expeditionary

I derive the expeditionary objective from the KPPs and use the attributes amphibious operations and transportability to quantify it. When considering amphibious operations, all three classes of amphibious warship commonly employed by the ARG/MEU are considered as one category. Likewise, transportation via CH-53 and ECV will be considered one category. These attributes are assigned as depicted in Table 16 and 17.

Table 16. Constructed values for amphibious operations

Amphib Ops	Assigned Value
No	0
Yes	1

Table 17. Constructed values for transportability

Transportability	Assigned Value
No	0
Yes	1

4. Objective 4 – Access

The access objective is derived from the KPP's and further defined by the attributes dwell and range. Dwell is the maximum time the aircraft can stay aloft over a target and range is the maximum distance the aircraft can travel before refueling. The RQ-21A has a dwell time of 16 hours and a range of 27 nautical miles. The MC-12W has a dwell time of eight hours and a range of 2,400 nautical miles. The dwell and range attributes are assigned as depicted in Tables 18 and 19.

Table 18. Incremental values for aircraft dwell time

Dwell Time (hours)	Incremental Value
0-3	2
4-5	5
6-7	6
8-9	7
10-15	9
16-23	6
24+	5

Table 19. Incremental values for aircraft range

Range (nautical miles)	Incremental Value
0-9	1
10-99	2
100-499	4
500-999	8
1000-1999	7
2000-4999	6
5000+	5

The cumulative values for each of the attributes are assigned as depicted in Tables 20 and 21.

Table 20. Cumulative values for aircraft dwell time

Dwell Time (hours)	Cumulative Value	Value
0-3	2	.05
4-5	2+5 = 7	.175
6-7	2+5+6 = 13	.325
8-9	2+5+6+7 = 20	.5
10-15	2+5+6+7+9 = 29	.725
16-23	2+5+6+7+9+6 = 35	.875
24+	2+5+6+7+9+6+5 = 40	1

Table 21. Cumulative values for aircraft range

Range (nautical miles)	Cumulative Value	Value
0-9	1	.030
10-99	1+2 = 3	.091
100-499	1+2+4 = 7	.212
500-999	1+2+4+8 = 15	.455
1000-1999	1+2+4+8+7 = 22	.667
2000-4999	1+2+4+8+7+6 = 28	.848
5000+	1+2+4+8+7+6+5 = 33	1

These cumulative value calculations produce the functions in Figures 16 and 17.

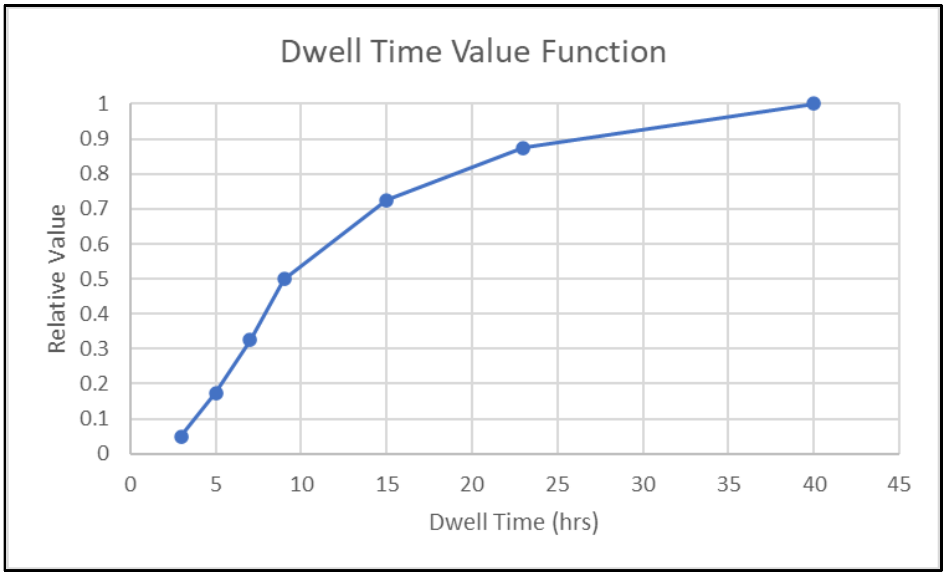

Figure 16. Dwell time value function

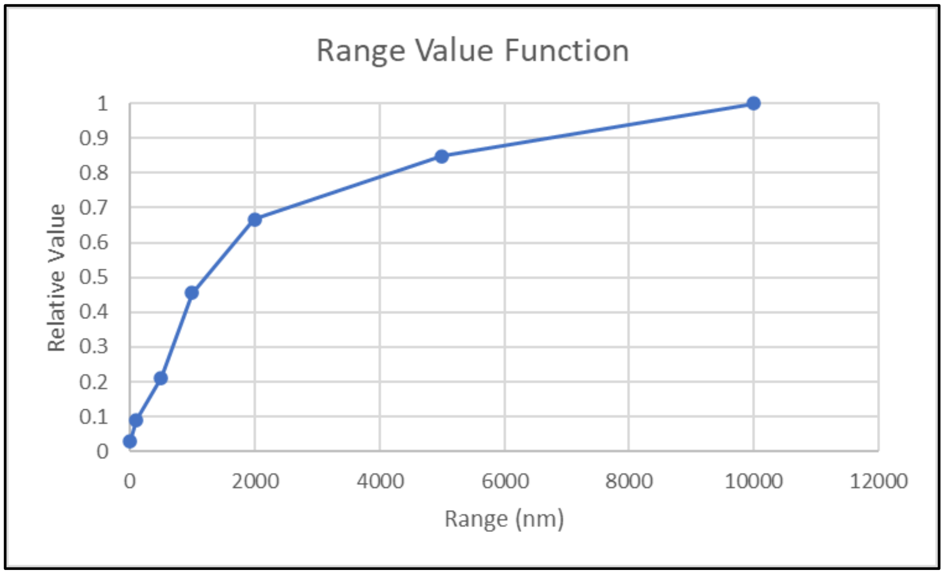

Figure 17. Range value function

D. IMPORTANCE WEIGHTS

Importance weights are assigned as depicted in Table 22.

Table 22. Importance weights by attribute

Attribute	Importance Weight
MC Rate	0.15
Useful Load	0.15
Amphib Ops	0.2
Transportability	0.2
Dwell	0.15
Range	0.15

E. MOE SCORE AND COST-EFFECTIVE SOLUTION

The MOE is given by the sum of the products of the value functions and their corresponding importance weights as given in Table 23.

Table 23. MOE score calculation

Attribute	Importance Weight	RQ-21A	MC-12W
mc rate	0.15	0.938	1
useful load	0.15	0.233	0.967
amphib ops	0.2	1	0
transportability	0.2	1	0
dwell	0.15	0.875	0.5
range	0.15	0.091	0.848
sum product		0.721	0.497

The MOE vs. CPFH graph displays the CE ratio for each ISR platform (Figure 18). This allows a direct comparison of both costs and benefits. The MOE score for the RQ-21A is .721 and the MOE score for the MC-12W is .497. There is no superior solution. A decision maker must trade-off cost for effectiveness in this situation. If there is a known CPFH limit, a satisficing solution may apply.

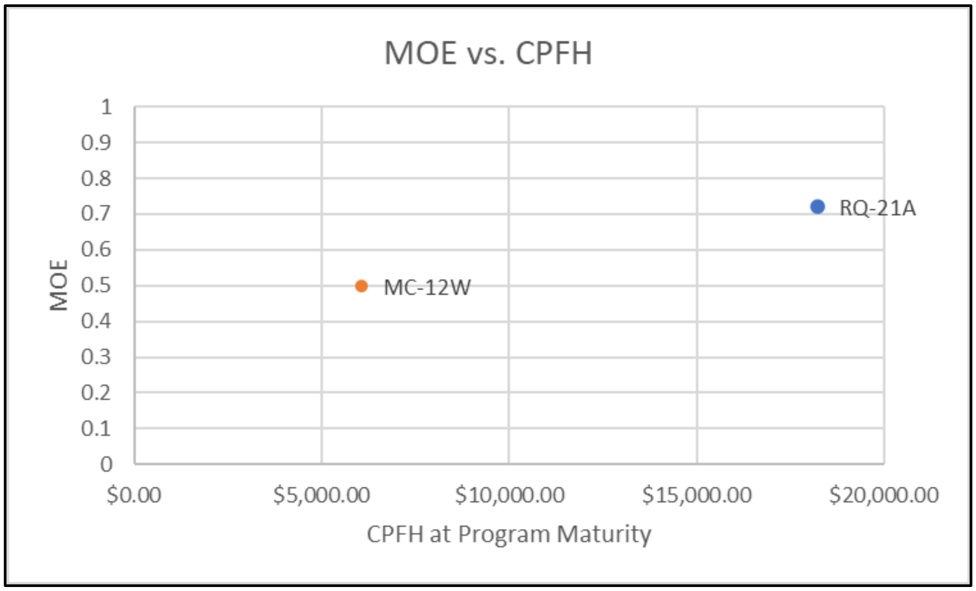

Figure 18. MOE vs. CPFH (RQ-21A & MC-12W)

F. RESULTS SUMMARY

The CEA finds that while the MC-12W is cheaper on a CPFH basis than the RQ-21A, the RQ-21A is more effective than the MC-12W as measured by the MOE score. Decision makers must trade-off cost for effectiveness in this situation. The CEA is built on an objective hierarchy which can be changed and adapted for future analyses by changing the attributes as required. Similarly, the value functions for each bottom-level attribute and their importance weights can be varied by analysts to conduct future analyses.

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V. CONCLUSION

A. SUMMARY OF FINDINGS

Methods of comparing costs and benefits in public projects in which benefits are difficult or inappropriate to quantify requires the use of a cost-effectiveness analysis (CEA). The CEA presented here thoroughly determines the costs by appropriation category for each airborne ISR program and derives a CPFH for each during the years of program maturity. Furthermore, the cost categories which are the major drivers of overall life cycle cost are identified for each program. Finally, a measure of overall effectiveness (MOE) for each platform is constructed utilizing multi-objective analysis, based on an objective hierarchy and specified attributes, and this MOE is used to determine a cost-effectiveness ratio for each platform.

The CEA found that the RQ-21A is a more effective platform based on the objective hierarchy established. However, it is more costly than the MC-12W on a CPFH basis. The RQ-21A MOE score is .721. The MC-12W is a less effective platform based on the objective hierarchy established. However, it is less costly than the RQ-21A on a CPFH basis. The MC-12W MOE score is .497.

The Marine Corps should consider the potential benefits of small manned ISR aircraft to future operations. Specifically, in future analysis of alternatives (AoA) comparisons, small manned ISR aircraft should be included alongside small unmanned ISR aircraft. While the RQ-21A may be more effective than a C-12 variant aircraft based on the requirements listed in the CDD, future requirements may change this paradigm. The low CPFH, high useful load, and long range of a small manned ISR aircraft, like the MC-12W, make it a compelling platform for the future ISR needs of the Marine Corps.

B. FUTURE RESEARCH

Future research into the differences between other manned and unmanned aircraft, especially in their differential costs, would extend this research and be useful to decision makers in acquisitions, program analysis, and operations. Specifically, trade-offs between manned ISR systems and unmanned ISR systems in the Group 4 and Group 5 categories such as the MQ-9 Reaper and XQ-58 Valkyrie.

Future research could also focus on the benefit gained by launching and recovering airborne ISR assets from amphibious ships, instead of transporting these systems to land-based airfields and operating in support of the naval campaign from land. While there are advantages to launching and recovering ISR assets from ships, there are also disadvantages. The number of airfields in vicinity of coastal areas which can support manned or unmanned airborne ISR platforms is considerable and may make launching and recovering ISR assets from amphibious ships less effective than the alternative.

Future research should focus on the differential training costs between manned and unmanned systems. Both manned ISR aircraft and RPAs have pilots, but their training is not equivalent, nor does it cost the same amount. Additionally, the cost to train other operators of unmanned systems, for instance intelligence personnel, may be different from the manned aircraft as well. All training costs should be analyzed to get clearer picture of the differences in manpower costs between these two modes of operation.

Future research could also focus on manned rotary wing platforms such as the UH-1Y and AH-1Z and future unmanned systems with comparable roles. Rotary wing comparisons between assault support airframes could also be conducted comparing the MV-22 and CH-53 with the future vertical lift (FVL) unmanned program.

Future research could also determine the extent to which differential flying unit composition between the services may contribute to differences in MILPERS spending reported to OSD.

C. RESEARCH CONTRIBUTIONS

This research applies a multi-objective analysis to compare the cost-effectiveness of dissimilar ISR assets, one manned and one unmanned. While CEAs of this sort have been made on other platforms, this study examines relatively low-cost, small, and tactically oriented ISR assets. The relative advantages and disadvantages of manned and unmanned airborne ISR assets will likely continue to be important in programmatic decision making in the DOD. This research provides a method of comparison that considers these relative differences on a cost per flight hour basis, to allow decision makers to determine the benefit for each dollar spent conducting operations.

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