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West Point, New York 10996

Comparing Organic vs. Handoff UAV Support to the Maneuver Company

OPERATIONS RESEARCH CENTER OF EXCELLENCE
TECHNICAL REPORT DSE-TR-0728
DTIC #: ADA469275

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Directed by
Lieutenant Colonel Simon R. Goerger, Ph.D.
Director, Operations Research Center of Excellence

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Abstract

The US Army has plans to deploy a dedicated Unmanned Aerial Vehicle (UAV) system at every echelon in order to provide responsive support to the battlefield commanders. However, there are disadvantages to fielding such a large number of different and separately controlled vehicles. This research addresses one key part of this issue of selecting the right mix of UAV systems: How shall a company be supported? We consider two alternatives for the company commander, loosely based on systems currently under development: (1) the "Organic" system, which consists of two vehicle-transported VTOL vehicles of ~50 kg each assigned to each company and flying missions when needed; and (2) the "Handoff" system, a 100-200 kg vehicle in the air constantly during operations, maintained and launched at the battalion level, but handed off as needed to the companies, which have Level IV control capability. We focus on performance measures that are strongly affected by the architecture and on finding closed-form approximations that allow extensive sensitivity analysis. We use high-level queuing and Markov chain models to estimate performance. We find that under some circumstances maneuver companies are better served by the "Handoff" system. We also identify performance and scenario parameters that have a strong effect on this and consequently deserve more study.

This inquiry originated as a group project given to several teams of cadets taking SE450: Project Management and System Design. Though it was originally purely an academic exercise, the methods and results of several of the teams were of great interest. The authors were inspired to develop the best of the cadets' ideas, adding their own contributions to produce this work. We include in this report some remarks on how well the project worked in helping the cadets understand how to approach a complex systems engineering problem typical of those faced by the Army.

About the Authors

Dr. Roger Chapman Burk has been on the faculty of the Department of Systems Engineering at the US Military Academy since 2000. He retired from the Air Force in 1995 after assignments in spacecraft mission control, spacecraft engineering, and mission analysis for the National Reconnaissance Office, and as director of the Graduate Space Operations program at the Air Force Institute of Technology (AFIT). He then worked in industry as a systems engineer and analyst for Science Applications International Corporation and The Aerospace Corporation before coming to USMA. He has an MS in Space Operations from AFIT and a PhD in Operations Research from the University of North Carolina at Chapel Hill. His research interests include decision analysis, space application, and unmanned vehicles. He has published technical papers in *Military Operations Research, Interfaces,* and the journals of *Algorithms, Multi-Criteria Decision Analysis,* and *Guidance, Control, and Dynamics*. In 2007-08 he was a visiting associate professor at the Center for Innovation in Engineering Education at Princeton University.

Mrs. Robin Kowalchuk Burk has taught at the US Military Academy since 2001, in the departments of Systems Engineering and of Electrical Engineering and Computer Science. Prior to coming to USMA she spent 27 years in industry as a software engineer, project manager, program manager, and senior executive in early- and mid-stage high technology companies serving both defense and commercial markets, including Intelligent Transportation Systems products. She holds an MBA from the University of North Carolina at Chapel Hill with a focus in finance and operations and is currently completing a PhD in Information Science at the University at Albany, State University of New York. Her research interests include cognitive robotics, human-robot interfaces, artificial intelligence, knowledge representation, and metrics for characterizing the performance and reliability of complex intelligent software systems, including those embedded in unmanned vehicles. Her technical books have been translated into multiple languages and include *TCP/IP Blueprints* and several editions of *UNIX Unleashed* (SAMS/Macmillan Computer Press). She has also served as technical editor of several books on communications networks.

Acknowledgements

We would like to thank thirty cadets from the USMA Class of 2007 whose enthusiasm for this project and originality in working on it inspired us to write this paper. We would also like to acknowledge that many of their ideas found their way into this paper and were the starting point for our analysis.

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Chapter 1: Problem Description

1.1 UAV Support to the Company

The purpose of this investigation was to compare two system concepts for providing support from an unmanned aerial vehicle (UAV) to an Army maneuver company. Such a company might be an infantry company of ~150 soldiers traveling in light armored vehicles and fighting mainly on foot, or a tank company with ~10 tanks. These companies are organized into battalions, which consist typically of three or four maneuver companies plus a headquarters and smaller units that provide scouting, mortars, medical care, and other support. The UAV support consists mainly of video imagery.

The two concepts we consider are: (1) a UAV system organic to the company, operated from vehicles that travel with the company commander and flying when needed at the commander's direction; and (2) a UAV system that is organic to the battalion of which the company is part, keeping one air vehicle (AV) in the air constantly during operations and assigning that AV to direct support of one of the companies as needed, the company then taking control of the AV and its payload until the period of direct support is over. We named these the "Organic" system concept and the "Handoff" system concept, respectively.

We wanted to compare these two concepts at the architectural level, rather than comparing two specific hardware designs; i.e. we wanted to identify performance criteria and other desiderata that are strongly affected by the architecture and method of operations. To the greatest extent possible, we avoided making any assumptions about implementation that were not clearly implied by the system concept.

Since we were interested in system concept exploration, we developed high-level performance models that were simple enough to evaluate in closed form but still captured all important considerations and the essential effects of the architectural choice. We used those models to generate input to a multiattribute value model and estimate the relative desirability of the two concepts. Another reason to develop simple models was that system performance was sure to depend to the technical performance of system elements (such as the AVs), which could be only roughly estimated, and on operational conditions, which might vary considerably from time to time. With high-level models, it was possible to perform a survey of relative system desirability for a wide range of estimates of performance and conditions.

This work was motivated by the Army's current design for the Future Combat System (FCS) to equip the Army starting in 2014 (Cartwright and Muilenburg, 2006). That system as currently envisioned (late 2006) has four different designs of UAVs, one each for the platoon, company, battalion, and brigade levels. We wanted to explore the idea of dispensing with the company-level UAV and using the battalion-oriented design for company support instead. However, the FCS consists of many things, of which the UAV architecture is a relatively small part. We limited our investigation to the single question of Organic vs. Handoff concepts for company support. We envision an FCS-era environment and a highly networked force, which enables the Handoff concept, but otherwise we did not assume the presence of or take into account any other FCS systems. We would be delighted if our methods and results provided useful insights for FCS development, but the scope of this work is limited to one architectural question considered more or less in isolation.

We are not proposing or recommending that the decision in FCS to field separate company- and battalion-level systems be revisited. That decision was made by individuals with more military and technical knowledge than the authors and we have no reason to question it. Our interest is rather in developing a method for making similar decisions on a firm quantitative basis. We believe questions like this will arise repeatedly as UAV systems and operations evolve. We hope to contribute a decision framework that captures all the important considerations and quantitative models that evaluate key performance measures.

There are two main points of interest in this work. The first is that it develops at least partially a value structure capturing all important aspects of a UAV system architecture decision, and such decision will inevitably be made many times in the next few years as UAV systems develop and proliferate. The second is that it develops mathematical models that provide quantitative measures of value for some of the important system criteria.

Finally, we would like to note the pedagogical value of the original cadet projects out of which this work emerged.   We believe there is substantial value in providing soon-to-be-commissioned future officers with an opportunity to wrestle with the complex operational tradeoffs associated with fielding new capabilities. We will briefly return to this point later in this report.

1.2 Academic Origin of the Investigation

This research started as a purely academic exercise, and part of our interest in it was pedagogical. The problem was posed to eight teams of three or four First Class (i.e. senior) cadets at the U.S. Military Academy taking SE450 during the academic year 2005-06, in sections taught by one of us (Robin Burk). The purpose of the course is for the cadets to integrate and apply what they have learned by working in a team on a realistic problem using a systems approach. Common practice was to have the cadets work on a real problem for a real client. Usually this has meant working on a problem for some organization at the post, such the cadet mess hall or other post service providers. Although these problems do give cadets some experience developing requirements and evaluating solutions in coordination with a real client, often the problems had to be relatively simple both because of the limited experience and expertise of the cadets and in order to bound the investment of time and effort required of the clients who contributed valuable time to work with cadet teams. We felt that such problems were often of a nature that the application of a formal systems approach was not necessary, and that as a result the cadets did not develop an appreciation of the value of the systems engineering techniques they were using.

As an experiment, we challenged two sections of cadets with the company UAV issue, a much more complex and significant problem than those typical for the course, with one of us (Roger Burk) acting as a surrogate client. (Two other sections of cadets were challenged with another issue regarding selection and deployment of advanced equipment, namely tactical high energy lasers for fixed base defense against rockets, artillery and mortar attack.) We hoped that the complexity of the UAV problem would make obvious the utility of the full systems engineering approach, and that the cadets would be engaged and motivated by the obvious significance of a problem like this to the Army. We did not expect that the cadets would have the resources to produce a definitive solution, but we thought their approaches might provide some interesting insights.

We were not disappointed. The cadets came up with a variety of interesting ways to formulate the problem and showed energy and initiative in identifying and interviewing both prior-enlisted cadets and also officers on post who had recent operational experience relevant to UAVs. There was no pattern in the conclusions the cadet teams reached: some favored an Organic system, some a Handoff system, and some developed an additional alternative that they liked better than either. This variety of approaches and conclusions, and the significance of the original problem, led us to try to consolidate everything that had been done into one best approach, taking the best features from all the cadets' work, and adding our own thoughts to it. That is what this work represents. We did limit the scope of our own analysis to the two system concepts described above, in order to have a manageable problem that could still provide some useful insights into a real Army system-level decision.

1.3 Summary of Major Results

We identified nineteen criteria to judge between the Organic and the Handoff systems. Nine of these either depended almost entirely on details of air vehicle or other system component design and not significantly on the architecture, or in some way showed equivalent performance between the two architectures, so these nine were not considered further. Six of the remainder showed a clear qualitative advantage for the Handoff system, and four of them showed at least a possible advantage, qualitative or quantitative, for the Organic system. We developed quantitative models for three of these last four, so that we could estimate what advantage, if any, the Organic system had in the four. Then we compared that result with the six qualitative criteria favoring the Handoff system, to see if we could discern an overall advantage.

We did not find a general overall advantage for either the Organic or the Handoff system concept. Instead, we found that the advantage varied with one's assumptions about the problem. The most important assumptions were: the operational requirements, especially the tempo of the operations in which the unit is engaged; the system performance characteristics of the designs, especially the ability of the Organic system to plan, set up, and launch a mission; and the relative value tradeoff between system cost on the one hand and responsiveness (i.e. time from support request to camera on target) on the other. Responsiveness was one of the most important criteria, and its measurement was very sensitive to modeling assumptions.

We found the responsiveness of the Handoff system to be sensitive to the operations tempo because of queuing delays in using the AV (though this can be ameliorated to some extent by positioning the aircraft and prioritizing users wisely). The average delay was 39 minutes in what we called our baseline scenario, but in various excursions the average was as low as 19 minutes and as high as 103. On the other hand, the responsiveness of the Organic system could be excellent, but only if there is a quick way to plan a mission and prepare and launch an AV.

That delay is the major factor in Organic responsiveness; using our model we estimated that responsiveness at 31 minutes in the baseline case, with excursions varying from 11 to 61 minutes. Thus we found that the Organic system has an arguable advantage in this very important criterion, and that the advantage is very sensitive to assumptions about operations tempo and the Organic system mission initiation performance.

If the Organic system has an advantage in responsiveness, it has to be set against other advantages of the Handoff system that we identified but did not quantify. The Handoff system has an important advantage in saving development costs, since it is already being developed as the battalion UAV, while the Organic system would have to be developed independently for the company mission. In addition, the Handoff system would save significant recurring costs because of consolidations in training, logistics, and operations, even if the direct costs to operate the Handoff and Organic systems were similar. We concluded that the relative advantage between the Organic and Handoff system turns on one's judgment of the relative importance of these cost savings compared to the probable advantage of the Organic system in responsiveness. Other criteria showed smaller advantages for one system or the other but the issues of responsiveness and system cost emerged as the most significant.

1.4 Organization

This report is organized as follows: Chapter 2 describes the setting: the Army's Future Combat System and role of UAVs in it, the five levels of control of a UAV, the currently envisioned FCS operations concept for UAV support to companies via full local control (Organic), and the proposed alternative of supporting companies via local control of the airborne AV and payload only (Handoff). Chapter 3 develops the criteria we used for the comparison between the two alternatives and describes how we dealt with them. Chapter 4 develops the additive value model to make the comparison: the quantitative measures for selected criteria, the single-dimensional value functions for the measures, and the relative swing weights to account for tradeoffs between the criteria. Chapter 5 gives the modeling results, comprising a baseline result using a set of baseline model parameters and an extensive sensitivity analysis varying all of the parameters over fairly wide ranges. Chapter 6 gives our conclusions and recommendations from the study. Chapter 7 concludes with a discussion of our pedagogical experience using this problem as a course project for systems engineering students at West Point.

Chapter 2: UAVs in the Future Combat System Maneuver Battalion

2.1 FCS and Its Four Classes of UAVs

An official Army description of the Future Combat System is available online (Cartwright & Muilenburg, 2006). The FCS comprises an integrated set of vehicle, combat, support, and information systems being developed together to equip the Army of the next decade. FCS is currently programmed to cost $122 billion; it is the Army's largest and arguably most important new system development (United States Army, 2006, "FCS Overview"). It is designed around an information network providing integrated command, communications, intelligence, logistics, and training services. This network will link all elements of the FCS together. In addition to systems for the individual soldier, the FCS will include a family of eight manned ground vehicles: an infantry carrier, a command vehicle, a tank-like "mounted combat system," cannon and mortar carriers, a scout vehicle, a medical vehicle, and a recovery and maintenance vehicle. Other weapon systems will include intelligent mines, an Armed Robotic Vehicle, and a missile launcher with a variety of missiles. There will also be an unmanned utility and logistics vehicle with three variants. Unmanned reconnaissance systems will include unmanned ground systems, a small unmanned ground vehicle, and four classes of unmanned air vehicles.

The Future Combat Systems envisions UAVs of different design organic at the platoon, company, battalion, and brigade levels. (FCS brigade-level organizations have sometimes been called "units of action" or "UAs.") These four classes are called numbered I through IV. Class I (platoon) will weigh less than 15 pounds, will be backpackable, and will have vertical takeoff and landing (VTOL) capability and a video camera payload. Class II (company) will also have VTOL capability, but it will be vehicle-mounted, have longer range and endurance, and will have target designation capability for non-line-of-sight weapons (missiles, cannon, mortars) as well as a video camera. Class III (battalion) will not necessarily be VTOL, but it will have yet longer range and endurance and will carry additional communications relay, mine detection, Chemical, Biological, Radiological and Nuclear (CBRN) detection, and meteorological survey payloads. Class IV (brigade) will have additional range, endurance, and capabilities.

Systems are currently in development for the four FCS UAV classes. *Defense Industry Daily* provides a summary of their status as of late 2005 ("Four FCS UAV Sub-Contracts Awarded (updated)," 2005). In 2006 Honeywell Defense & Space Electronic Systems received a contract to develop the Class I system based on their Micro Air Vehicle, which has a ducted fan design. First flights and prototype deliveries are planned for late 2008 ("Honeywell Lands FCS Class I UAV Contract," 2006). Class II candidates are less advanced; four contracts have been awarded to develop them. One was to Piasecki Aircraft Corporation, which will develop a dual shrouded rotor AV called the Air Scout (Piasecki, 2005). The other three are all under the Defense Advanced Research Projects Agency's (DARPA's) Organic Air Vehicle (OAV) II program ("Four FCS . . . ," 2005) and all are using ducted fan designs. One DARPA team is led by Aurora Flight Sciences; the team is developing a variant of Aurora's GoldenEye family of tilt-body vehicles. Another team is led by Honeywell International and is basing their development on Allied Aerospace's iSTAR family of vehicles, which use a ducted fan with lift augmented by the airfoil shaping of the duct. The third DARPA team is led by BAE Systems, whose design has not been published. The larger Class III UAV is also in development, with three candidates currently being worked on. AAI Corporation is proposing the Shadow III, based on the Shadow 200 UAV currently in service with the U.S. Army. Teledyne Brown Engineering (TBE) is proposing the Prospector, a variant of the German Kleinflugger Zielortung (KZO) being built by Rheinmetall DeTec for the Bundeswehr. Both the Shadow III and the Prospector use fixed-wing, catapult-launched AVs. The Shadow lands in a field using wheeled landing gear, while the Prospector will use a parachute and airbags. The third Class III competitor is a wheeled autogyro called the Air Guard that is being developed by a team led by Piasecki. The largest FCS UAV, the Class IV, has already been identified: it is the Fire Scout helicopter built by Northrop Grumman.

Our concern in this paper is with the Class II and Class III types, the two for which there are still competing types of aircraft. Table summarizes the technical characteristics of the competing designs, to the extent that they have been defined and published. For the most part these are design requirements or predictions rather than proven performance, so they should not be taken as definitive. They are provided to give a concrete impression of the type of systems we are investigating. The many blanks in the table probably reflect the fact that the data are considered proprietary by the competing companies.

Table I. Published Technical Characteristics of Class II and Class III Candidates and Related Systems

<table>
<tr><th></th><th colspan="4">Class II Types*</th><th colspan="4">Class III Types</th></tr>
<tr><th>AV Character-istics</th><th>FCS Require-ments</th><th>Air Scout</th><th>GoldenEye-100</th><th>iStar</th><th>FCS Require-ments</th><th>Shadow 200</th><th>Prospector</th><th>Air Guard</th></tr>
<tr><td>Length (ft)</td><td></td><td></td><td></td><td></td><td></td><td>11</td><td>7.5</td><td></td></tr>
<tr><td>Width/ Wingspan (ft)</td><td></td><td></td><td></td><td></td><td></td><td>14</td><td>11</td><td></td></tr>
<tr><td>Weight (lbs)</td><td><112</td><td></td><td>150</td><td></td><td>300-500</td><td>380</td><td>355</td><td></td></tr>
<tr><td>Endurance (hrs)</td><td>>2</td><td></td><td></td><td></td><td>>6</td><td>5</td><td>6</td><td></td></tr>
<tr><td>Range (km)</td><td></td><td></td><td></td><td></td><td></td><td>125</td><td>200</td><td></td></tr>
<tr><td>Max speed (knots)</td><td></td><td></td><td>160</td><td></td><td></td><td>105</td><td>120</td><td></td></tr>
<tr><td>Launch method</td><td></td><td rowspan="2">VTOL tandem shrouded rotors</td><td rowspan="2">VTOL tiltbody</td><td rowspan="2">VTOL tiltbody</td><td></td><td>Catapult</td><td>Catapult</td><td rowspan="2">STOL autogyro</td></tr>
<tr><td>Landing method</td><td></td><td></td><td>Field</td><td>Parachute/ Airbag</td></tr>
<tr><td>Support vehicles</td><td></td><td></td><td></td><td>Transporter, possibly others</td><td></td><td>Four HMMWVs, two trailers</td><td>Launcher, Maintenance, Recovery, others)</td><td>Transporter, others</td></tr>
<tr><td>Sources</td><td>FCS Program Office, 2004</td><td>Piasecki, 2005</td><td>Aurora, 2004, 2006</td><td>Allied Aerospace, no date</td><td>FCS Program Office, 2004</td><td>Fulgham, 2004</td><td>Teledyne Brown Engineering, 2005</td><td>Piasecki, 2005</td></tr>
</table>

*We have found no published description of the BAE design.

2.2 Levels of Control

A supported unit may have only limited direct control of the UAV that is supporting it. At one extreme, it may be limited to receiving data indirectly from the UAV. At the other, it may completely control all UAV operations from takeoff to landing. At intermediate levels, the supported unit may receive a direct downlink from the AV, control where the payload is pointing, or control the flight of the AV while it is supporting the unit. Five levels of control are conventionally defined as follows (United States Army, 2006, FMI 3-04.155, sections 4-110 to 4-114):

Table II. UAV Levels of Control

Level	Control
I	RECEIPT AND DISPLAY OF SECONDARY IMAGERY OR DATA.
II	RECEIPT OF IMAGERY OR DATA DIRECTLY FROM THE UNMANNED AIRCRAFT
III	CONTROL OF THE UNMANNED AIRCRAFT PAYLOAD
IV	CONTROL OF THE UNMANNED AIRCRAFT, LESS TAKEOFF AND LANDING
V	FULL FUNCTION AND CONTROL OF THE UNMANNED AIRCRAFT TO INCLUDE TAKEOFF AND LANDING

Thus, this paper compares Level IV control with Level V control for the company support mission.

The following sections describe these alternatives in more detail. The amount of detail is kept to the minimum necessary to define the concepts, since we want to arrive at general results that will apply regardless of the particular implementation.

2.3 Company Support: An Organic Class II UAV

The FCS Class II UAV is envisioned as an organic company asset with complete Level V control at the company level. Based on the requirements and prototypes described in Table , we can expect that the AV will have some sort of ducted fan propulsion and will take off and land vertically, though it could possibly tilt in the air for high-speed flight. The AV is likely to weight about 112 pounds, and it will require ground equipment for mission planning, AV data linking and flight control, communication, refueling, maintenance, and repair. The system will also need one or more soldiers trained to operate and maintain the system. We assume that the system will include at least two AVs to allow continual support and to provide redundancy in case of failure. On the other hand, we believe the Army will want to minimize the number of ground vehicles, equipment, and soldiers deployed at the company level, for reasons of logistics and operational security. Based on these considerations, we envision the Organic system as consisting of one ground vehicle carrying two soldiers, two VTOL AVs, and all the necessary equipment and supplies. A schematic drawing of the Organic operations concept is shown in Figure 1. If the actual Class II UAV system does not turn out to be exactly like this, it is likely to be similar, and we believe that the differences should have little effect on our architectural-level evaluation.

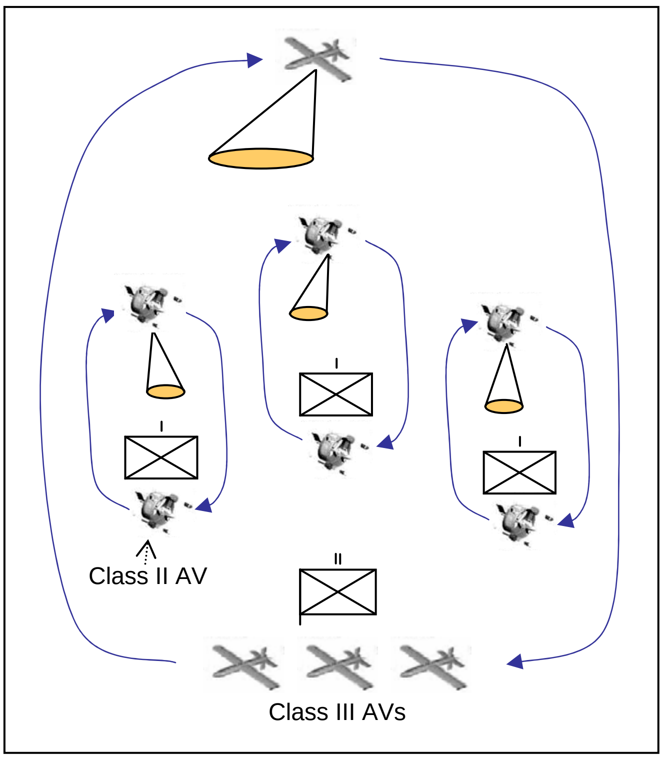

Figure 1. Organic Operations Concept

2.4 An Alternative: A Battalion-Level UAV

We evaluate an alternative operational concept in which UAV support to the company is provided by a larger Class III vehicle that is maintained and flown at the battalion level and is handed off in flight as needed to a company to control at Level IV. We call this the Handoff system. In the FCS era each battalion is expected to have a Class III UAV supporting the battalion commander; we envision a second Class III system also belonging to the battalion, but dedicated to supporting the companies. During operations, the companies' UAV would be kept on station overhead, waiting for a call. When a company requested support, the AV would be flown to their area and handed off to local control until the mission was complete, when the AV would be returned to battalion control or possibly handed off to another company. In case of competing requests, the users would wait until previous missions were completed and then receive control of the AV, unless a more urgent need gave them priority, in which case an ongoing mission would be broken off. We assume that in the FCS era such handoffs will be technologically and operationally relatively easy. We envision that an operational plan would establish which company had priority for the system, based on company mission, tactical situation, and time of request. A UAV platoon in charge of the system would coordinate the handoffs, and the battalion commander would be the ultimate arbiter in case of competing requests under unforeseen circumstances.

Our motivation for considering such an alternative was the idea that there could be substantial efficiencies from consolidating the Class II and Class III systems, and that in the highly networked FCS the required rapid handoffs would be technically practical. We also saw parallels with the Army's employment of other supporting weapon systems. Such systems can be organic at a higher echelon but dedicated to a lower-echelon unit for a shorter or longer period of time. One example of this is artillery, where a forward observer with an infantry company can in effect control the fire of a battery that is assigned at the brigade level. Other examples include mortar, engineer, and aviation units. There is also a parallel in close air support, where a forward air controller controls Air Force attack aircraft when they are hitting targets close to friendly forces. These parallels gave us hope that the Handoff system would be practical in a military sense. We were concerned whether the delays would be tolerable when there were multiple requests for the companies' UAV, but we also thought that the Handoff system would sometimes actually be faster to support, since it would have an AV on station in the air. We thought that quantitative modeling could clarify the relative advantages.

Based on the performance parameters in Table I, we envision the Handoff air vehicle as weighing about 400 lb and being probably fixed-wing, catapult-launched, and field-landed. The top speed is about 115 knots and the endurance at least six hours. The Handoff system includes four air vehicles and six to twelve ground vehicles to provide maintenance, repair, storage, transportation, launch, recovery, control, communication, and other support functions. Organizationally, it is a platoon organic to the battalion. In normal operations it operates out of an open area reasonably close to the battalion headquarters and keeps one of its AVs in the air continuously. After about four hours on station, an AV is relieved in place by another AV and returns to the landing field. These UAVs will be dedicated to supporting the company commanders and will be handed off in flight from company to company, or back the UAV platoon, as required. A second UAV platoon, identical in equipment and very likely operating out of the same field, will fly a UAV dedicated to supporting the battalion commander. A schematic of the Handoff operations concepts is shown in Figure 2.

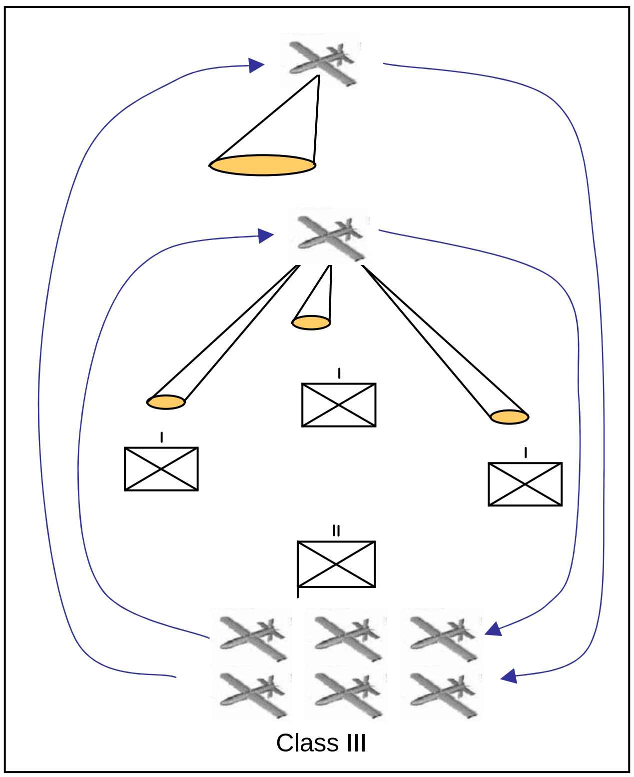

Figure 2. Handoff Operations Concept

Having described the Organic and Handoff systems and their concepts of operations for support of maneuver companies, we now turn to identifying the criteria by which the two systems should be evaluated.

Chapter 3: Evaluation Criteria

3.1 Criteria Generation

A set of evaluation criteria for the two operations concepts was developed by review of the current open-source literature on tactical UAV operations[*], by consideration of the needs of the various system stakeholders (**Table III**), and by informal interviews with USMA personnel who had recent operational experience either as tactical company commanders or as UAV operators. We developed nineteen criteria in six categories, as shown in **Table IV**. The six categories are:

1. Mission Operations: seven criteria relating to flight operations and getting the AV where it is needed when it is needed
2. Mission Data: three criteria regarding the quality of the EO/IR primary mission data and possible additional missions
3. Mission Support Requirements: four criteria relating to the logistics flow, training requirements, and operational footprint of the UAV system
4. Flight Coordination: two criteria on for the ease of integrating UAV operations into other flight operations in the area
5. Cost: two criteria for development and operational costs
6. System Consolidation: one criterion for the cost savings and simplifications of acquisition, training, logistics, and operations if an entire weapon system can be dropped from the inventory

When we considered how to evaluate these nineteen criteria at the architectural level, we concluded that they fell into three classes. For nine of the criteria, we could not find a convincing reason for favoring one operations concept over the other, so we considered them "even." For seven of the criteria, we could make a qualitative judgment favoring one system or the other. For the remaining three, it was not obvious where the advantage lay, so we developed quantitative models to clarify the situation. The following sections discuss these classes of criteria.

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[*] For instance, articles in *Aviation Week and Space Technology*, *Defense Industry Daily* (http://www.defenseindustrydaily.com/uavs/), and *Jane's Defence Weekly*.

Table III. Major System Stakeholders	
Stakeholder	**Primary Interests**
US Army Leadership	• Best value ops concept, considering tactical needs in current and possible future conflicts, support requirements, and life cycle costs
Tactical Unit Commanders	• Responsiveness • Reliability • Dwell time on target • Survivability • Operational flexibility • Video quality • Small tactical footprint
System Operators	• Ease of use • Reliability
Maintainers	• Low maintenance requirements (man-hours, material), especially in forward units
Logisticians	• Low strategic deployment requirements • Low logistical flow requirements (consumables, parts), especially to forward units
Air Component Commander	• Smoothly integrated Army UAV operations—low potential for air traffic conflicts

Table IV. Evaluation Criteria

Category		Criterion	Measure Type	Summary of Justification for Type Classification
1. Mission Operations	a	Responsiveness: time from when a commander requests support until a vehicle is at the target (assuming the system is operational)	**Quantitative model**	This is a very important criterion to tactical commanders, and the possible delays involved in waiting in line for support in the Handoff alternative are a major concern. This is also easy to model using standard queuing models.
	b	Reliability: probability that the system will be operational	**Quantitative model**	This is a very important criterion, but it depends largely on the individual reliabilities of the AVs and of their comm links and ground systems, which can be estimated only roughly until the systems are designed, built, and tested. However, there is also an architectural element that can be modeled: in order to be operational, the notional Organic system needs to keep one AV out of two flying, while the Handoff system needs only one out of four.
	c	Dwell Time: length of time the AV can stay on the target	*Even*	We assume that either system can maintain surveillance of a target indefinitely by handing off the mission to a newly launched AV. The Handoff system may have an advantage because its longer flight durations will require fewer handoffs. The Organic system may have an advantage from a hovering or perching capability. Overall, no advantage.
	d	Survivability: likelihood of avoiding destruction by enemy action	*Even*	Against small arms, the Handoff has an advantage because it flies too high to be easily engaged. Against radar- or infrared-guided weapons, the Organic has an advantage because it flies low enough to use terrain masking. Overall, no advantage.
	e	Flight Safety: likelihood of avoiding flying accidents	Qualitative	Handoff has an advantage because it flies farther from ground obstructions and because it is likely to land and take off under more benign conditions.

Table IV. Evaluation Criteria (continued)

Category		Criterion	Measure Type	Summary of Justification
1. Mission Operations (continued)	f	Operational Flexibility: the ease with which UAV support can be shifted to a lateral unit	Qualitative	In part, this is the result of system design, operational doctrine, and training. However, the Handoff operations concept is based on regularly shifting support from one company to another, so that system has an advantage.
	g	Usability: the ease with which soldiers can operate and maintain the system	*Even*	This depends on details of system design, not on the architectural decision.
2. Mission Data	a	Data Quality: resolution and stability of EO/IR video image	*Even*	The Handoff vehicle may carry higher-quality optics because it has a larger payload, but the Organic vehicle can fly closer to the target. We assume that these two effects cancel out.
	b	Data Handling: storage, transmission, annotation, etc.	*Even*	This depends on details of system design, not on the architectural decision.
	c	Secondary missions: capacity for payloads other than EO/IR video	Qualitative	The Handoff AV has an advantage because it has a larger carrying capacity and because its Class III design allows multiple payloads.

Table IV. Evaluation Criteria (continued)

Category		Criterion	Measure Type	Summary of Justification
3. Mission Support Requirements	a	Logistics: required flow of parts and supplies to operational units	*Even*	The Handoff system has fewer but larger systems, so without more detailed design it is impossible to say which system would produce the greater total logistical burden, if either.
	b	Personnel: number and skill level of soldiers required to operate the systems	*Even*	The Handoff system has fewer but larger systems, so without more detailed design it is impossible to say which system would require more soldiers and/or higher skills, if either.
	c	Equipment: number of vehicles and other equipment required in the field	*Even*	The Handoff system has fewer but larger systems, so without more detailed design it is impossible to say which system would require more total deployed equipment.
	d	Operational Location	Qualitative	The Handoff system has an advantage here, since flight operations (landing, takeoff, maintenance) are farther to the rear, where disruptions are fewer and supply and support easier.
4. Flight Coordination	a	Number of Vehicles in the Air	**Quantitative Model**	In the FCS era, the sky will be dark with UAVs. The system that can accomplish its mission with the fewest additional AVs in the air has an advantage.
	b	Altitude of Flight: lower flight levels have less chance of interfering with manned flights	Qualitative	The exact altitude of flight is an operational decision, but in general the Organic AV is designed to operate at a low level and the Handoff will fly higher, so the Organic has an advantage.
5. Cost	a	Development Costs	Qualitative	The Handoff system has an important advantage here, since the Handoff is already being developed for battalion-level use.
	b	Procurement, Operations, and Disposal Costs	*Even*	The Handoff system has fewer but larger systems, so without more detailed design it is impossible to say which system would be cheaper overall, if either.
6. System Consolidation			Qualitative	If the entire Organic weapon system can be eliminated, there will be huge simplifications in training, logistics, and operations.

3.2 *Even Criteria*

The nine criteria we judged to be "even" were of two types. For some criteria, the Organic and Handoff systems clearly performed differently at the architectural level, but they had countervailing advantages and overall we could identify neither a winner nor a straightforward means of analysis to reveal a winner. For the rest, system performance did not depend significantly on the architecture, but rather on lower-level design. These nine criteria were:

1c. Dwell Time: length of time the AV can stay on the target. This is a case of different performance. The Handoff system would be capable of longer mission duration (though both systems could fly out a new AV to replace one on station). The Organic system is more likely to have a hovering or perching capability, which would be valuable if it was is desired to keep the angle of view constant, as when looking into a doorway.

1d. Survivability: likelihood of avoiding destruction by enemy action. This is also a case of different performance. Against small arms, the Handoff system has an advantage because it flies too high to be easily engaged. Against radar- or infrared-guided weapons, the Organic has an advantage because it flies low enough to use terrain masking. Thus there might be an advantage to one or the based on the sophistication of the threat, but that would only hold for a given conflict.

1g. Usability: the ease with which soldiers can operate and maintain the system. This depends on the design features of the equipment, not on the architecture, and if they have similar design features the systems will be equally usable.

2a,b. Data Quality and Data Handling: resolution and stability of EO/IR video image, ease of storage, transmission, annotation, etc. For the most part these will also depend on design features. We are assuming a thoroughly networked force in the FCS era so that data can be moved with ease to wherever it is needed. The Handoff system may have a higher-quality imaging system because the AV can carry a larger payload, but the Organic system will be able to fly close to the target and achieve high resolution that way.

3a,b,c. Logistics, Personnel, and Equipment: the required flow of parts and supplies, number and skill level of soldiers, and number and size of pieces of equipment in the field. The Organic and Handoff systems will almost certainly be different in these areas, but without some detail on the system design it seems impossible to say which will be better overall. The Organic system will have more and smaller units deployed; the Handoff will have fewer and larger.

5b. Procurement, Operations, and Disposal Costs. These criteria also depend on lower-level design features, since the Organic system has a larger number of units, each smaller than the Handoff system.

3.3 Qualitative Criteria

Seven criteria had a clear *a priori* advantage for one system. These seven criteria were:

1e. Flight Safety: likelihood of avoiding flying accidents. The Handoff system has an advantage because it flies at a higher altitude, farther from ground obstructions, and because it is launched, landed, and maintained farther to the rear and thus usually under more benign conditions. Flight safety will also be affected by the soundness of the design, construction, and operation of the systems, but if these are held equal, there will still be a Handoff advantage.

1f. Operational Flexibility: the ease with which UAV support can be shifted to a lateral unit. The Handoff system has an advantage because it is designed to shift rapidly from one company to another, under the coordination of battalion staff as activities on the ground cross company areas of operations. The Organic system could also be used to support a sister company, and good doctrine and training could make this easier, but it seems unlikely that it would ever be as easy as with the Handoff system. The Organic system may have some advantage in special circumstances when the company operates independently of the battalion; we neglect such rare events.

2c. Secondary missions: capacity for payloads other than EO/IR video. The Handoff system has an advantage because it has a larger AV with more payload capacity. We are assuming that the imagery mission is by far the most important for a company-level UAV, but other missions could emerge, such as signals intelligence, communications relay, attack, or emergency supply delivery (Fulgham, 2004, describes a package delivery system for the Shadow).

3d. Operational Location. The Handoff system has an advantage, under the assumption that operations farther to the rear are easier then those in forward units, other things being equal.

4b. Altitude of Flight: lower flight levels have less chance of interfering with manned flights. Here the Organic system has an advantage because its concept of operations calls for flight typically at lower altitudes.

5a. Development Costs. The Handoff system has an advantage because its development is a sunk cost (other than possibly a new Level IV control system to be deployed with the companies), since the Handoff system is assumed to be the same type as the UAV providing battalion-level support.

6. System Consolidation. The Handoff system has an advantage. Even if the procurement, operations, and disposal costs of the two systems turn out to be the same, and the development costs of the Organic system are ignored, there will still be a valuable simplification in training, logistics, and operations if an entire weapon system can be dropped from the Army inventory.

Note that for six of these seven, the advantage is with the Handoff system. Some of these could be of minor importance, especially if the lower-level system design is good and doctrine and training appropriate. However, Development Costs (5a) and System Consolidation (6) appear to us likely to be very significant, and not dependent on lower-level design or system employment.

3.4 Quantitative Criteria

This leaves three criteria for which the performance of the Organic and Handoff systems will clearly be different, for which it is not obvious where any advantage would lie, and where a quantitative model seems likely to clarify things. These are:

1a. Responsiveness: time from when a commander requests support until a vehicle is at the target (assuming the system is operational). The Organic system might seem to have an advantage because it dedicated to the company commander and always on call. However, if the operations concept is to keep the AV on the ground until needed, there will always be a delay involved in planning, preparing, and launching a mission and flying to the point of interest. On the other hand, the Handoff system may have virtually no response delay if the AV is in the air over the target and not otherwise being tasked. The Handoff system may also have a very long delay if the AV is a long way away and has a number of tasks queued up. We used geometry and a queuing model to investigate the distribution of response times for the two systems.

1b. Reliability: probability that the system will be operational. In order to be operational, the notional Organic system needs to keep one AV out of two ready for flight, while the Handoff system needs to keep one out of four actually flying. This architectural aspect of reliability can be stochastically modeled. (Another consideration is that when the Organic system is down, it is down for one company, but when the Handoff system is down, it is down for the whole battalion, which is probably worse. On the other hand, the Handoff system might more readily be backed up by the battalion's similar UAV than an Organic system would be by the battalion or by a sister company. We neglect these complications.)

4a. Number of Vehicles in the Air. The system that can accomplish its mission with the fewest additional AVs in the air has an advantage. The Organic system would have more total aircraft in the battalion, and at any one time it could have one per company flying, but it could also have none flying. The Handoff system will always have one AV in the air, and sometimes two when one is being flown out to relieve the other. We used stochastic models to estimate the average number of vehicles in the air for the two systems.

Chapter 4: Value Model

4.1   Modeling Approach

As detailed in the previous chapter, we identified nineteen criteria for this problem, of which we assessed nine as even, six as qualitatively favoring the Handoff system, one as qualitatively favoring the Organic system, and the remaining three as calling for a quantitative evaluation to determine which system they might favor. Because of the difficulty of obtaining convincing and authoritative relative weights for all the qualitative criteria, we decided to simplify the problem as follows: we decided to look in detail only at the last four criteria mentioned, the ones that favor or possibly favor the Organic system. If an assessment based only on these four favored the Handoff system, or was approximately even, then our overall assessment would have to favor the Handoff. If an assessment based on these four favored the Organic system, then we would have the more difficult problem of comparing the Organic advantage in the four criteria with the Handoff advantage in six qualitative criteria. Thus, we developed a value model using the following four criteria:

1a. Responsiveness

1b. Reliability

4a. Number of Vehicles in the Air

4b. Altitude of Flight

We evaluated the first three of these quantitatively, the last qualitatively.

Our value modeling approach is based the multiple-objective decision analysis methods described by Keeney and Raiffa (1976), Keeney (1992), and Kirkwood (1996). We use an additive multiattribute value model on two grounds: (1) since we model the problem as a decision under certainty and have more than two criteria, we can be sure that there is an additive model that gives the correct preference order (Kirkwood, 1996); and (2) our knowledge of the correct preferences is too imperfect to justify any more complex model. We used the swing weight method to estimate the relative importance of the criteria because it provided a straightforward way to explicitly consider the range of possible performance in each criterion (see Clemen, 1996, pp. 547-550, for a discussion of swing weighting). Similar value modeling approaches have been used for a wide variety of problems involving multiple stakeholders and incommensurable criteria, including Air Force research project selection (Parnell et al., 2004), reconnaissance satellite selection (Burk et el., 2002), and nuclear incident response (Feng & Keller, 2006). The model was created in a Microsoft Excel spreadsheet, available from the authors, which provided a convenient way to capture all data and calculation on a series of linked worksheets, to produce graphical representations of the results, and to perform sensitivity analysis.

The rest of this chapter proceeds as follows: Section 4.2 describes the measures we selected for the three quantitative criteria in the value model and how they were calculated for the two alternatives. Section 4.3 describes how swing weights were estimated for the four criteria in the model. Section 4.4 discusses the value functions that translated the measures in the domain of value for each of the quantitative measure. Finally, Section 4.5 puts it all together and presents the complete additive value model.

4.2 Evaluation Measures

The following sections develop measures for the three quantitative criteria (la Responsiveness, 1b Reliability, and 4a Number of Vehicles in the Air) as applied to the two alternatives.

Responsiveness

We chose a direct and natural measure for responsiveness: average time from the request for support until the AV has a camera on the target. This measure captures the most important aspect of responsiveness, but not everything. The Organic system may have a lower *maximum* response time because the company commander will never have to wait for earlier support requests to be completed. This advantage is not captured by our measure. On the other hand, the Handoff system may have lower *minimum* response time because the AV may already be over the target and ready to support; furthermore, intelligent use of the system should result in this being the case for the most important requirements. Our measure does not capture this either, and we assume these two effects are of equal importance. Also, under some circumstances the Organic system might have an advantage because it can have more AVs in the air simultaneously than the Handoff system. To the extent that this is not captured by the chosen measure, we neglected it.

Responsiveness for the Organic System

For the Organic system, calculating response time is straightforward. We assume that the AV is sitting in its transporter when the company commander calls on it for a mission. The operator needs to plan the mission, prepare and launch the AV, and fly it to the target. Let

p_o = mission planning/preparation/launch time

s_o = AV dash speed

d_o = distance from transporter to target

Then

Response Time = $p_o + d_o/s_o$

Responsiveness for the Handoff System

This measure is the most complex in the value model. For the Handoff system, the time from support request to AV over the target has two components: the time required for the AV to complete any previously assigned tasks, and the time required for the AV to fly from wherever it happens to be to where it is needed.

To approximate the average required flying distance, we modeled the battalion area of operations (AO) as a rectangle of width w_h and depth d_h. We assume the AV location and the support location are uniformly and independently distributed over this rectangle. (This is conservative, since the AV is likely to be flying near the location of greatest anticipated need.) We divide the AO width and depth each into six intervals, and find the center of each of the resulting 36 cells. We find the required flying distance between each of the 36^2 cell center pairs, accounting for the fact that the Handoff vehicle flies at a higher altitude and can look obliquely, and therefore does not need to arrive exactly over the target (see Figure 3). The estimated average flying delay is then the average flying distance $\overline{F}$ divided by s_h, the dash speed of the Handoff AV.

To estimate the time to complete previous tasks, we model the Handoff system as an M/M/1 queue with a finite calling population, the server being the AV and the customers being the companies. This allows approximate average delay to be calculated with standard closed-form expressions (Hiller and Lieberman, 2001, section 17.6). It also requires several simplifying assumptions: The requests for support are assumed to arrive in a Poisson process at rate λ per company; each company has a maximum of one request outstanding at a time. The number of

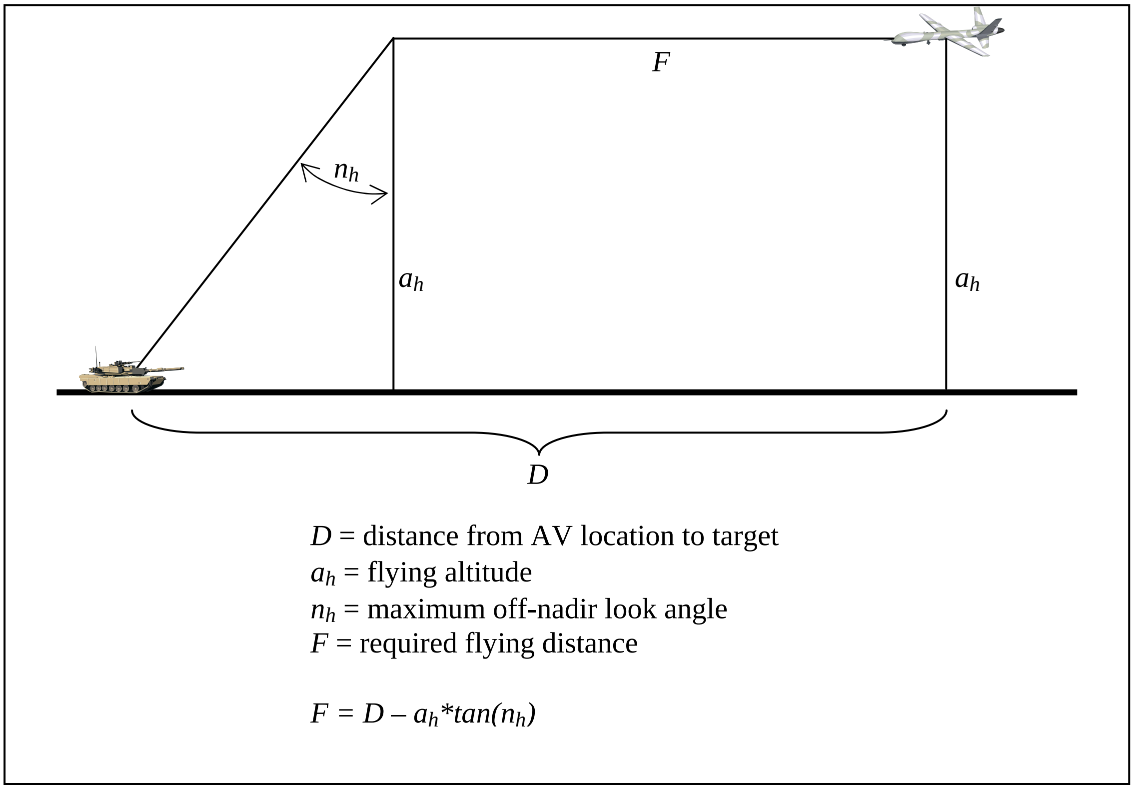


Figure 3. Flying Distance for Handoff System

companies making support requests is three, assuming that normally no more than three companies in a battalion are actively engaged. The queue service time is the sum of the flying delay calculated above and the required time on target, and we model the service times as being distributed identically, independently, and exponentially (this is a conservative approximation, since the high variance of the exponential distribution generally causes poor queue performance). The average service time is therefore $t + \overline{F} / s_h$, where t is the average required time on target, $\overline{F}$ is the average flying distance, and s_a is the speed of the AV. Under these assumptions, we can calculate W_q, the average time a company waits for its service time to begin:

$$N = \text{number of customers} = 3$$
$$\mu_h = \text{service rate} = 1/(t + \overline{F}/s_h)$$
$$P_0 = \text{probability of idle system} = \left[\sum_{n=0}^{N} \left(\frac{N!}{(N-n)!} \left(\frac{\lambda}{\mu_h} \right)^n \right) \right]^{-1}$$
$$L_q = \text{average customers waiting} = N - \frac{\lambda + \mu_h}{\lambda}(1 - P_0)$$
$$L = \text{average number of customers in system} = N - \frac{\mu_h}{\lambda}(1 - P_0)$$
$$\overline{\lambda} = \text{average customer arrival rate} = \lambda(N - L)$$
$$W_q = L_q / \overline{\lambda}$$

Since this model includes the flying delay as part of the queue service time, the company's average wait time until an AV can see the target is approximately $W_q + \overline{F}/s_h$.

Reliability

We chose a direct and natural measure for reliability: the probability that the system will be in a non-operational state, given the system's architecture and operational concept, and given mean time between failures and mean time to repair for the AV. The Organic system is operational if an AV is flying a mission or at least one AV is ready to launch on a mission. The Handoff system is operational if an AV is in the air either on a mission or on call. We continue to assume that requests for support arrive in a Poisson process at rate λ per company and we assume AV failures and repairs are independently, identically, and exponentially distributed, so that the UAV systems can be modeled with continuous time Markov chains (Hillier and Lieberman, 2001, ch. 16). We assume that AVs fail only when operating, not when on the ground. We assume that the ground and communication elements for the Organic and Handoff systems are equally reliable. Catastrophic failures involving the loss of an AV are not separately modeled; the replacement of the AV is considered a time-consuming repair.

Reliability for the Organic System

The Organic system can be in one of five states, as shown in **Table V**. The state transition diagram is in Figure 4. This model includes the following simplifying assumptions:

- The mission duration is the average required on-target time, t, plus twice the average time required to fly between the transporter and the target, d_o/s_o.
- If a mission is aborted because the flying vehicle fails while the spare is under repair, the mission cannot be resumed even when a repair is completed.
- The repair rate is constant whether one or two vehicles are under repair.

Table V. Operational States for Organic System

State	AVs Ready for Launch	AVs Flying	AVs under Repair
20	2	0	0
11	1	1	0
10	1	0	1
01	0	1	1
00	0	0	2

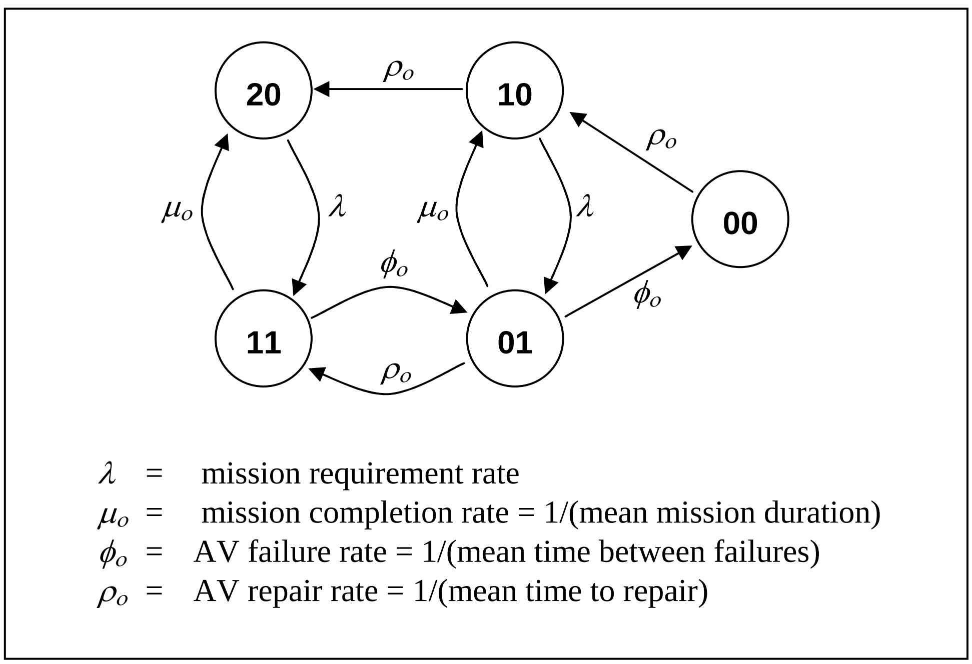


Figure 4. State Transition Diagram for Organic System

Under these assumptions, we can calculate π_{ij}, the steady-state probability that the system will be in state ij, by equating the inflow and outflow rates in each state, to get:

$$\pi_{10} = \left[\left(1+\frac{\mu_o}{\lambda}\right)\frac{\rho_o}{\phi_o} + 1 + \frac{\rho_o}{\lambda} + \frac{\rho_o+\lambda}{\mu_o+\phi_o}\left(\left(1+\frac{\mu_o}{\lambda}\right)\frac{\rho_o}{\phi_o} + 1 + \frac{\phi_o}{\rho_o} \right) \right]^{-1}$$

$$\pi_{01} = \frac{\rho_o+\lambda}{\mu_o+\phi_o}\pi_{10}$$

$$\pi_{11} = \frac{\rho_o}{\phi_o}\left(\pi_{10}+\pi_{01}\right)$$

$$\pi_{20} = \left(\rho_o\pi_{10}+\mu_o\pi_{11}\right)\frac{1}{\lambda}$$

$$\pi_{00} = \frac{\phi_o}{\rho_o}\pi_{01}$$

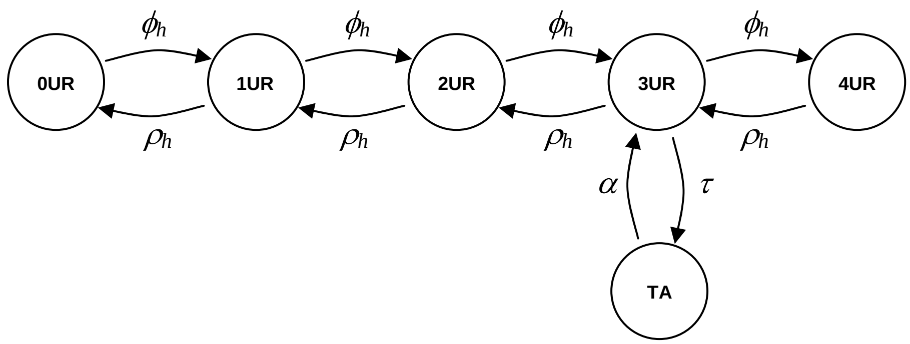
System reliability is measured by π_{00}, the probability that both AVs are under repair and neither is ready to fly a mission, and the smaller π_{00} is the better.

Reliability for the Handoff System

We model the Handoff system similarly and with a similar set of assumptions, the differences coming from the different operations concept. The Handoff system keeps an AV in the air and on call if at least one of its four AVs is operable; the AV on station is replaced in the air without a break in support unless it is the only one operable, in which case there is a break while it return for refueling and any necessary servicing. The states of the Handoff system are shown in **Table VI** and the state transition diagram is in Figure 5**.**

Table VI. Operational States for Handoff System

State	AVs Ready	AVs on Station	AVs under Repair	AVs in Turn-around
0UR	3	1	0	0
1UR	2	1	1	0
2UR	1	1	2	0
3UR	0	1	3	0
TA	0	0	3	1
4UR	0	0	4	0



τ = time-on-station rate = 1/(mean time on station)
α = mission turnaround rate = 1/(mean turnaround time)
ϕ_h = AV failure rate = 1/(mean time between failures)
ρ_h = AV repair rate = 1/(mean time to repair)

Figure 5. State Transition Diagram for Handoff System

Under these assumptions, the steady-state probabilities that the system will be in each state are:

$$\pi_{1UR} = \left[1 + \frac{\rho_h}{\phi_h} + \frac{\phi_h}{\rho_h} + \left(1 + \frac{\tau}{\alpha}\right)\frac{\phi_h^{\,2}}{\rho_h^{\,2}} + \frac{\phi_h^{\,3}}{\rho_h^{\,3}}\right]^{-1}$$

$$\pi_{0UR} = \frac{\rho_h}{\phi_h}\pi_{1UR}$$

$$\pi_{2UR} = \frac{\phi_h}{\rho_h}\pi_{1UR}$$

$$\pi_{3UR} = \frac{\phi_h^{\,2}}{\rho_h^{\,2}}\pi_{1UR}$$

$$\pi_{TA} = \frac{\tau}{\alpha}\pi_{3UR}$$

$$\pi_{4UR} = \frac{\phi_h}{\rho_h}\pi_{3UR}$$

System reliability is measured by $\pi_{TA} + \pi_{4UR}$, the probability that no AV is on station because three are under repair and the fourth is either in turnaround or also under repair.

Number of Vehicles in the Air

This criterion is its own measure. The Handoff system will always have one AV in the air when operating normally, aside from the short periods when one AV is relieving another on station. The Organic system can have none in the air, or as many as one per engaged company.

Number of Vehicles in the Air for the Organic System

We make the assumptions necessary to model the Organic system as an M/M/3 queue with a finite calling population of three. The average number of AVs in the air is then *L*, the average number of customers in the system, which can be calculated as follows, using standard queuing formulas (Hillier and Lieberman, 2001, section 17.6):

t = average time required over target (as before)

d_o = average distance from transporter to target (as before)

s_o = AV dash speed (as before)

$$\nu = \text{service rate} = \left(t + 2\frac{d_o}{s_o} \right)^{-1}$$

λ = arrival rate of support requests per company (as before)

N = calling population = number of companies engaged = 3

s = number of servers = 3

$$P_0 = \left[\sum_{n=0}^{N} \frac{N!}{(N-n)!n!} \left(\frac{\lambda}{\nu} \right)^n \right]^{-1}$$

$$P_n = \frac{N!}{(N-n)!n!} \left(\frac{\lambda}{\nu} \right)^n P_0 \quad \text{for } n = 1,2,3$$

L_q = number of customers waiting for service = 0

$$L = \sum_{n=0}^{s-1} nP_n + L_q + s\left(1 - \sum_{n=0}^{s-1} P_n \right)$$

Number of Vehicles in the Air for the Handoff System

Under normal operational conditions, the Handoff system will have one AV in the air constantly, and it will have two AVs in the air when a replacement is being flown out to relieve an AV on station and the relieved AV is flying back to base. Above we calculated $\overline{F} / s_h$, the average to fly to or from a randomly selected station in the battalion AO. If o_h is the average time on station, then the fraction of time with two AVs in the air is $2(\overline{F}/s_h)/o_h$ and the average number of AVs in the air is $1+2(\overline{F}/s_h)/o_h$.

4.3 Measure Weights

The swing weight assigned to each of these measures depends on the possible range of variation of the measures. In the sensitivity analysis excursions we performed (see section 5.3), we found that the measures fell within the limits shown in **Table VII**. Note that the range for Responsiveness was very significant: 6 minutes to 108 minutes. For a company commander in action this could easily be a vital difference. On the other hand, the swings in the other measures seem much less important. All scores in Reliability were quite good (system operable more than 96% of the time), so the swing is not so important. The measures for Traffic Density and Flight Altitude are of yet lower importance because they address the Flight Coordination area, which is surely secondary. Furthermore, the swing in scores for Average AVs in the Air (one vehicle per battalion) seems small considering the number of manned and unmanned aircraft that will be flying around anyway. For these reasons, we assigned swing weight to the four measures in the ratio 100:15:2:2, as shown in the table, along with the resulting swing weights. There are not definitive weights, being based on our judgment after a review of the literature on UAV use and interviews with soldiers who had recent operational experience. However, we believe they are a reasonable starting place for this exploratory study.

Table VII. Measure Swing Weights

	Criterion	Measure	Lower Limit	Higher Limit	Relative Importance of Difference	Swing Weight
1a	Responsiveness	Avg Time to Target (hours)	0.1	1.8	100	0.840
1b	Reliability	Fraction of Time System Inoperative	0	0.04	15	0.126
4a	Traffic Density	Avg AVs in Air	0.2	1.2	2	0.017
4b	Flight Altitude	Flight Region	Low	High	2	0.017

4.4 Returns to Scale and Value Functions

All four measures are of the “less is better” type, but only Responsiveness seems to require a careful consideration of how value accumulates as one moves from larger raw scores to lower. We evaluate Flight Altitude qualitatively and only at the extreme values, so we do not need to consider return to scale. We could see no reason for other than a linear return to scale for Reliability and Traffic Density, and in any case those swings are of relatively small importance. However, the swing for Responsiveness is very important, and we could easily see that most of the value could be lost quickly as response time increased, so we developed a nonlinear value curve for Average Time to Target. This is shown in Figure 6. We assume that half the value is lost after 30 minutes and 80% of the value is lost after one hour. Again, this curve is not definitive, but we believe it is a reasonable approximation of actual value to company commanders.

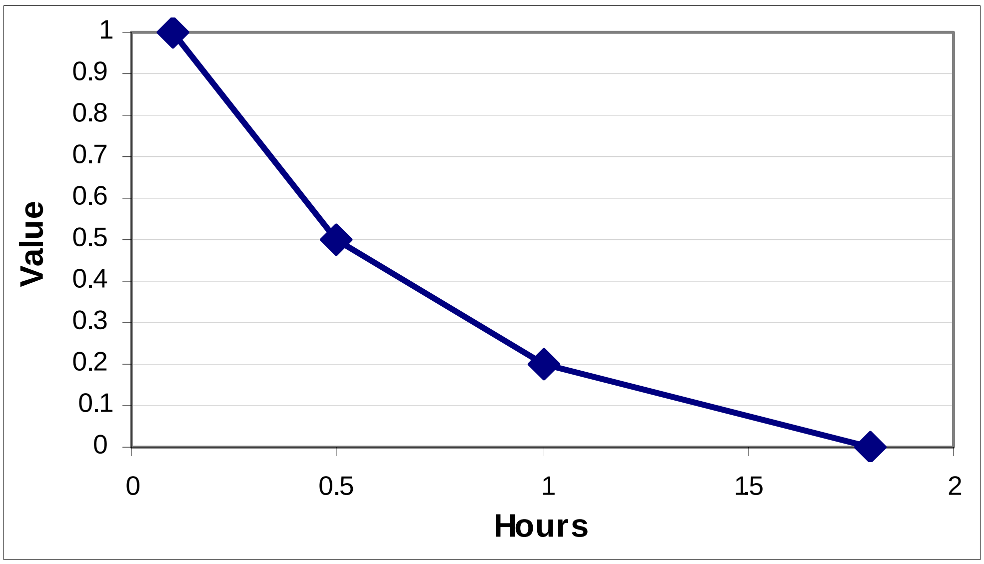


Figure 6. Value Function for Average Time to Target

4.5 Summary of the Value Model

The value model is summarized in Figure 7. Recall that the model includes only those criteria from **Table IV** that favor or possibly favor the Organic system.

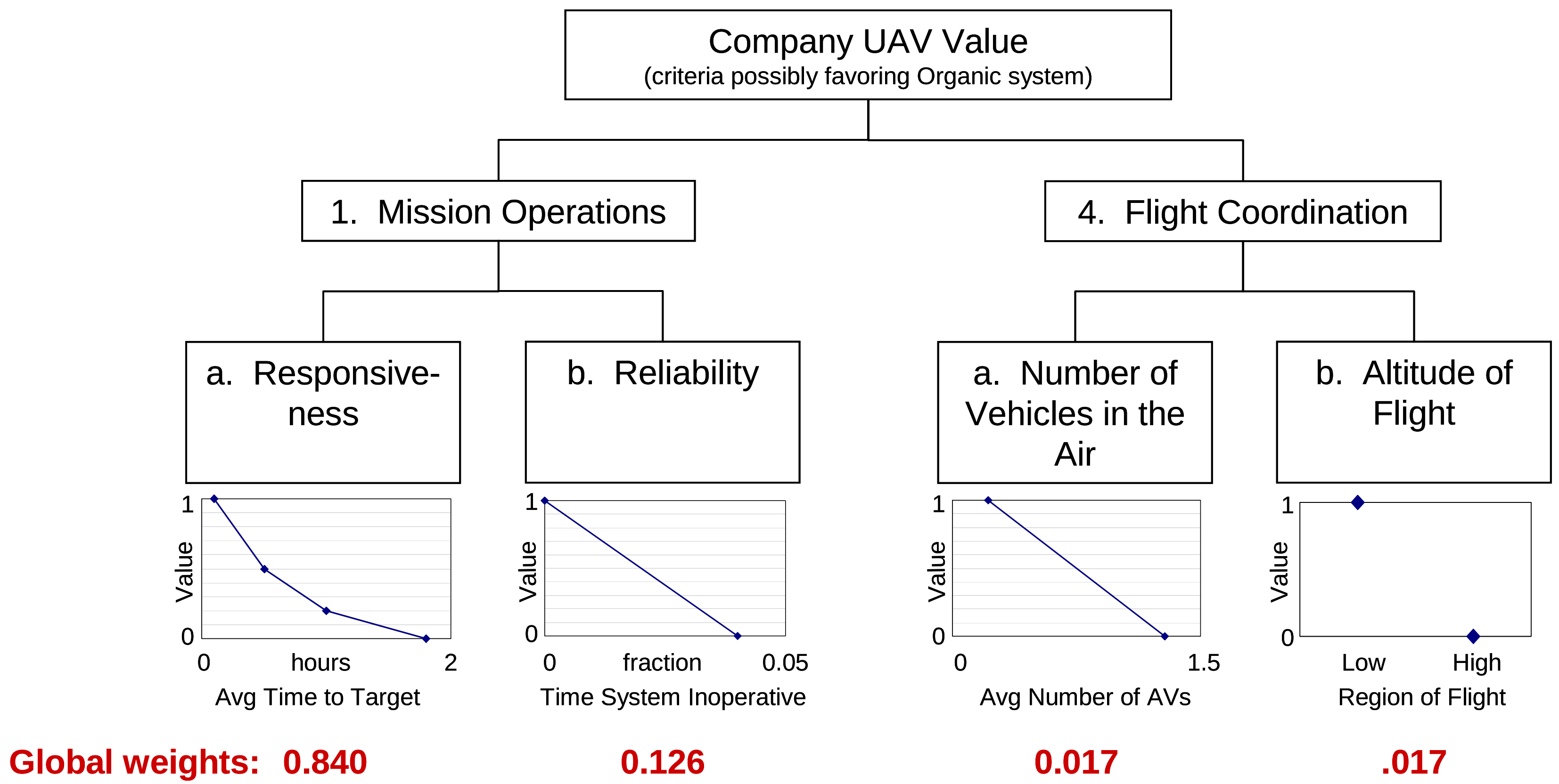


Figure 7. Value Model

Chapter 5: Results

5.1 Parameters of the Model

The model calculates value from 20 parameters that the analyst can set as desired. These parameters are shown in **Table VIII**, along with the baseline or base values we used for this study and the high and low values we used for sensitivity analysis.

Table VIII. Model Parameters

	Symbol	Parameter	Units	Base	Low	High
REQUIRE-MENTS	λ	Rate of Mission Requirements	per hr per co	0.208	0.104	0.417
	t	Average Required On-Target Time	hrs	1	0.5	2
ORGANIC SYSTEM	p_o	Org Setup/Mission Planning/Launch Time	hrs	0.5	0.167	1
	s_o	Org AV Speed	knots	160	50	200
	d_o	Org Average Distance to Fly	km	4	2	10
	f_o	Org Average Time Between Failures	flying hrs	4	2	8
	r_o	Org Average Time To Repair	hrs	2	1	4
HANDOFF SYSTEM	w_h	BN AO Width	km	80	40	160
	d_h	BN AO Depth	km	40	20	80
	s_h	HO AV Dash Speed	knots	115	100	230
	a_h	HO AV Altitude	ft	5000	3000	10000
	n_h	HO AV Off-Nadir Look Angle	deg	45	30	60
	o_h	HO AV Average Time-on-Station	hrs	4	2	8
	t_h	HO AV Average Turnaround Time	hrs	1	0.5	2
	f_h	HO Average Time Between Failures	flying hrs	8	4	16
	r_h	HO Average Time To repair	hrs	1.5	0.75	3
WEIGHTS		Responsiveness Measure Weight		0.84	0.7	1
		Reliability Measure Weight		0.126	0	0.3
		Traffic Density Measure Weight		0.017	0	0.1
		Flight Altitude Measure Weight		0.017	0	0.1

The rest of this section gives a brief account of how the base and extreme values were selected. Some were based on published performance values for UAV systems in operation or under development; others were purely notional, being reasonable assumptions based on information available to us and to the cadets who developed earlier versions of the model. Unless otherwise stated, the low and high values were half and twice the base, respectively.

Rate of Mission Requirements. The base value is five per company per 24 hours, figuring two missions in the morning, two in the afternoon, and one at night.

Average Required On-Target Time. Notional value.

Org Setup/Mission Planning/Launch Time. Notional value. The low estimate was ten minutes.

Org AV Speed. The base value is 160 knots, the advertised top speed of Aurora Flight System's tiltbody GoldenEye-100, currently under development for the Defense Advanced Research Projects Agency (DARPA) and one of the candidates for the FCS Class II UAV (Aurora, 2006). The low value is approximately the top speed of AeroVironment's Raven backpackable UAV, currently in Army service ("Raven UAV Draws Raves From The Field," 2005). The base value is quite high for UAVs in this weight class, so the high value was limited to 200 knots.

Org Average Distance to Fly. Notional value. The high value is somewhat more than twice the base on the grounds that in the FCS area companies may operate over much larger distances than is common now.

Org Average Time Between Failures. Notional value.

Org Average Time To Repair. Notional value.

BN AO Width. Notional value.

BN AO Depth. Notional value.

HO AV Dash Speed. The base value of 115 knots is the speed of AAI's Shadow 200, the closest thing to this class of vehicle in the current Army inventory (AAI, 2006). This is relatively slow for this class of vehicle, so the low value was put at 100 knots, only slightly slower.

HO AV Altitude. The base value of 5000 feet is typical of current Shadow 200 operations, based on informal interviews. For reasons of survivability, quietness, and field of regard, this type of UAV does not usually fly at low altitudes, so the low value was set somewhat higher than half the base.

HO AV Off-Nadir Look Angle. Notional value.

HO AV Average Time-on-Station. The FCS Class III AV is planned to have an endurance of six hours (United States Army, 2006, "Class III Unmanned Aerial Vehicle (UAV)"). In order to allow time for flyout and return, the base time on station for the Handoff system was put at four hours.

HO AV Average Turnaround Time. Notional value to fly an AV from station to base, refuel and service it, and return it to its station.

HO Average Time Between Failures. Notional value. Our assumption is that the Handoff vehicle is likely to be a simpler vehicle (fixed wing rather than rotary) and maintained and operated under more favorable conditions, so we used a longer time between failures for it.

HO Average Time To Repair. Notional value. We gave the Handoff vehicle a shorter time to repair than the Organic, on the grounds that it would be a simpler AV.

Measure Weights (Responsiveness, Reliability, Traffic Density, Flight Altitude). The rationale for the base swing weights is given in section 4.3. A common rule of thumb is to consider a range of +/10% for weights. However, our weights for this exploratory study came from the judgment of the analysts rather than from that of subject matter experts, so we used a somewhat larger range of variation.

5.2 Results Using Baseline Evaluation Parameters

The model results using the baseline parameters are shown in **Table IX** and in Figure 8. The figure shows stacked bars representing weighted value in each criterion and comparing the Organic and Handoff alternatives to a hypothetical "Ideal" alternative that would achieve maximum value in the four measures (i.e. it would average 10 minute responsiveness, have perfect reliability, keep an average of 0.2 AVs in the air, and fly at a low level). Using this model, the Organic system achieves about 53% of the Ideal value, and the Handoff system achieves about 47%. The Organic system thus shows more value than the Handoff, but the difference is not great.

Table IX. Results Using Base Parameters

	Scores			Values		Swing Wts	Weighted Values	
Criterion	**Organic**	**Handoff**	**Units**	**Organic**	**Handoff**		**Organic**	**Handoff**
Responsiveness	0.513	0.646	hrs	0.492	0.412	0.840	0.413	0.346
Reliability	0.013	0.002	fraction	0.674	0.941	0.126	0.085	0.119
Traffic Density	0.529	1.071	AVs	0.671	0.129	0.017	0.011	0.002
Flight Altitude	Low	High	N/A	1	0	0.017	0.017	0.000
						TOTAL UAV SYSTEM VALUE:	**0.526**	**0.467**

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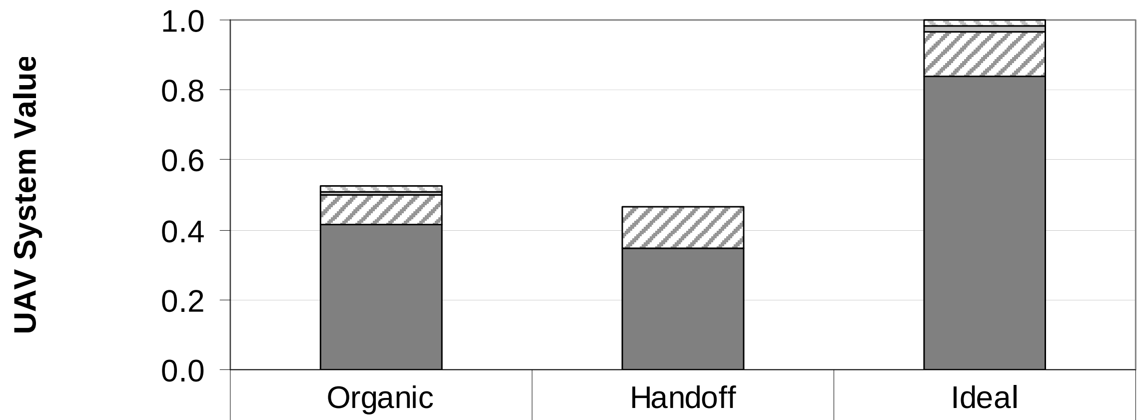

	Organic	Handoff	Ideal
Flight Altitude	0.017	0.000	0.017
Traffic Density	0.011	0.002	0.017
Reliability	0.085	0.119	0.126
Responsiveness	0.413	0.346	0.840

Figure 8. Results Using Base Parameters

The Ideal column in Figure 8 illustrates that the bulk of the value in this model is in the Responsiveness criterion. This is because of both the significance of that criterion and the wide swing in its measure (6 minutes to 108 minutes time to target). Reliability is also significant, but the swing was relative small. Traffic Density and Flight Altitude are secondary criteria with moderate swings, so they are of little importance in this model.

In the Average Time to Target measure for Responsiveness, the Organic system was modeled at about 31 minutes and the Handoff system at about 39 minutes. As described above, Organic time to target consisted of planning/preparation/launch time plus time to fly to the target. In the baseline values, the former was 30 minutes and the latter only about 1 minute, because of the assumed high speed of the vehicle and short distance involved. Thus in this model, Organic time to target is essentially constant and consists primarily of the planning/ preparation/launch time. On the other hand, the Handoff time to target shows a lot of variation. As described above, this measure consists of time to complete previously assigned tasks plus time to fly to the new task. We found in our queuing model that the former averaged 30 minutes, but that about 47% of the time the queue was empty so it would be 0 minutes. The fly-to time averaged 9 minutes, but it could be as low as 0 minutes or as high as 21 minutes. We believe these estimates are conservative, given the baseline values, because in real operations the more critical needs would receive priority in the queue, and the Handoff AV would be more likely to be flying in the area of need rather than the opposite side of the battalion AO.

Our model showed a better Reliability measure for the Handoff system than for the Organic: system inoperable 0.2% of the time vs. 1.3%. However, both figures are quite good so the difference in weighted value is small. The difference is due to the assumption that the Organic vehicle will have less time between failures and take longer to repair, and to the fact that the Organic system has to maintain one vehicle out of two operational, while the Handoff system has to maintain only one out of four. These effects appear to us to be real phenomena arising from the different operations concepts, but the extent of the difference will depend on the details of the reliability and reparability of the two AVs.

5.3 Sensitivity Analysis

Because so many of the model parameters are notional estimates only, we elected to do a complete sensitivity analysis exploring the calculated value for both systems and using the high and low values for all parameters as listed in **Table VIII**. Because of the large number of parameters, we did not attempt a two-way sensitivity analysis.

Sensitivity Analysis for the Organic System

The results of the sensitivity analysis for Organic system, varying the 11 parameters from **Table VIII** that affect its total weighted value, are shown in **Table X** and in the tornado diagram in Figure 9. By far the most important parameter was the Setup/Mission Planning/Launch Time for the system, which induced a swing in value from 0.278 to 0.869. This parameter dominated the high-weight measure of Responsiveness, accounting for the swing. At this parameter's low value of 10 minutes, Responsiveness is about 11 minutes, yielding 90% of ideal value for this measure; when the parameter is at its high value of 60 minutes, Responsiveness is about 61 minutes, yielding only 20% of ideal value. The only other parameter that induced a swing of more than 0.1 was the Average Time Between Failures. This influenced the measure of Reliability. At its low value of 2 hours, the fraction of time inoperable was calculated at 0.038, for only 6% of ideal value; at its high value of 8 hours this fraction was 0.004, for 90% of ideal value. The parameter Average Time to Repair also induced a fairly large swing in Organic system value (0.095), for a similar reason. These wide swings indicate that the value of the Organic system is strongly dependent on the AV's reliability and reparability and on a quick procedure for mission preparation and launch.

Table X. Organic System Sensitivity Analysis

	Organic System Total Weighted Value		
Parameter	**Using Low Parameter Value**	**Using High Parameter Value**	**Absolute Difference**
Org Setup/Mission Planning/Launch Time	0.869	0.278	0.591
Org Average Time Between Failures	0.449	0.555	0.106
Org Average Time To Repair	0.553	0.458	0.095
Average Required On-Target Time	0.555	0.478	0.077
Responsiveness Measure Weight	0.557	0.492	0.065
Reliability Measure Weight	0.505	0.556	0.051
Flight Altitude Measure Weight	0.518	0.566	0.048
Rate of Mission Requirements	0.551	0.526	0.024
Org AV Speed	0.508	0.528	0.020
Org Average Distance to Fly	0.531	0.514	0.017
Traffic Density Measure Weight	0.524	0.539	0.015

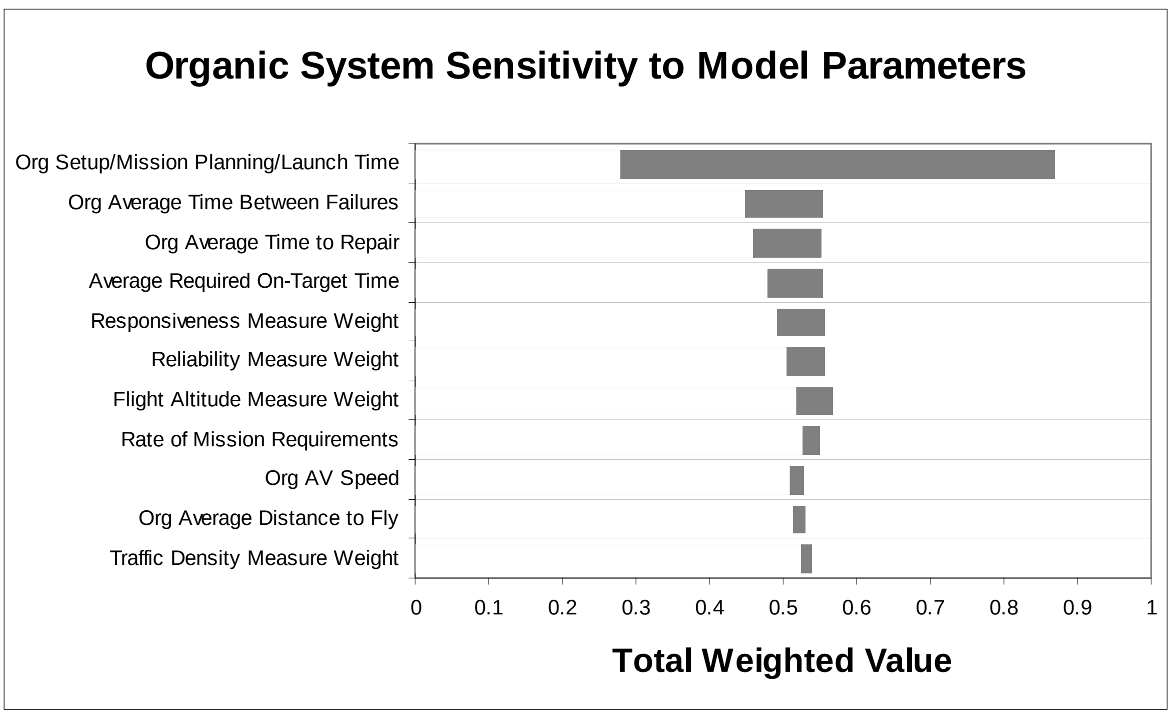

Figure 9. Organic System Sensitivity Analysis

Sensitivity Analysis for the Handoff System

The results of the sensitivity analysis for Handoff system, varying the 15 parameters from **Table VIII** that affect its total weighted value, are shown in **Table XI** and in the tornado diagram in Figure 10. By far the largest effect is from Average Required On-Target Time. If the average time required at a target is as low as 30 minutes, then our queuing model predicts that the average wait time while previous tasks are completed is only about 10 minutes, and that 66% of the time there is no wait at all. Since the fly-to time remains at about 9 minutes, the average total wait is 19 minutes, for 74% of ideal value in this high-weight measure. On the other hand, if the average time required at a target is as much as 2 hours, the average queuing wait is about 103 minutes (and no wait only 25% of the time), giving a total wait of 112 minutes, for 2% of ideal value. **Table XII** shows a summary of the effect on responsiveness of this parameter and four others. The operations tempo (as reflected in the Average Required On-Target Time and the Rate of Mission Requirements) has a dramatic effect on Handoff system responsiveness. The size of the battalion AO that the Handoff system has to cover has a smaller but still significant effect. A larger AO increases the fly-to time, and because that increases the total service time for each customer it also increases the queue wait time somewhat. Similarly, HO AV Dash Speed has an effect on the fly-to time and indirectly on the queue wait time.

Besides those in **Table XII**, only two other parameters cause a swing of more than 0.1: Reliability Measure Weight and Responsiveness Measure Weight. The relatively high score in Reliability value (0.94) resulted in changes of this magnitude in total system weighted value when measure weights were changed as described in section 5.1.

Table XI. Handoff System Sensitivity Analysis

Parameter	Handoff System Total Weighted Value: Using Low Parameter Value	Using High Parameter Value	Absolute Difference
Average Required On-Target Time	0.742	0.138	0.605
Rate of Mission Requirements	0.638	0.410	0.229
Reliability Measure Weight	0.399	0.562	0.163
BN AO Width	0.516	0.359	0.157
Responsiveness Measure Weight	0.516	0.412	0.103
HO AV Dash Speed	0.447	0.533	0.085
HO Average Time Between Failures	0.410	0.474	0.064
HO Average time to repair	0.474	0.410	0.064
BN AO Depth	0.483	0.426	0.057
Flight Altitude Measure Weight	0.475	0.428	0.048
Traffic Density Measure Weight	0.473	0.439	0.034
HO AV Altitude	0.465	0.474	0.009
HO AV Average Time-on-Station	0.462	0.470	0.008
HO AV Off-Nadir Look Angle	0.465	0.472	0.007
HO AV Average Turnaround Time	0.469	0.463	0.006

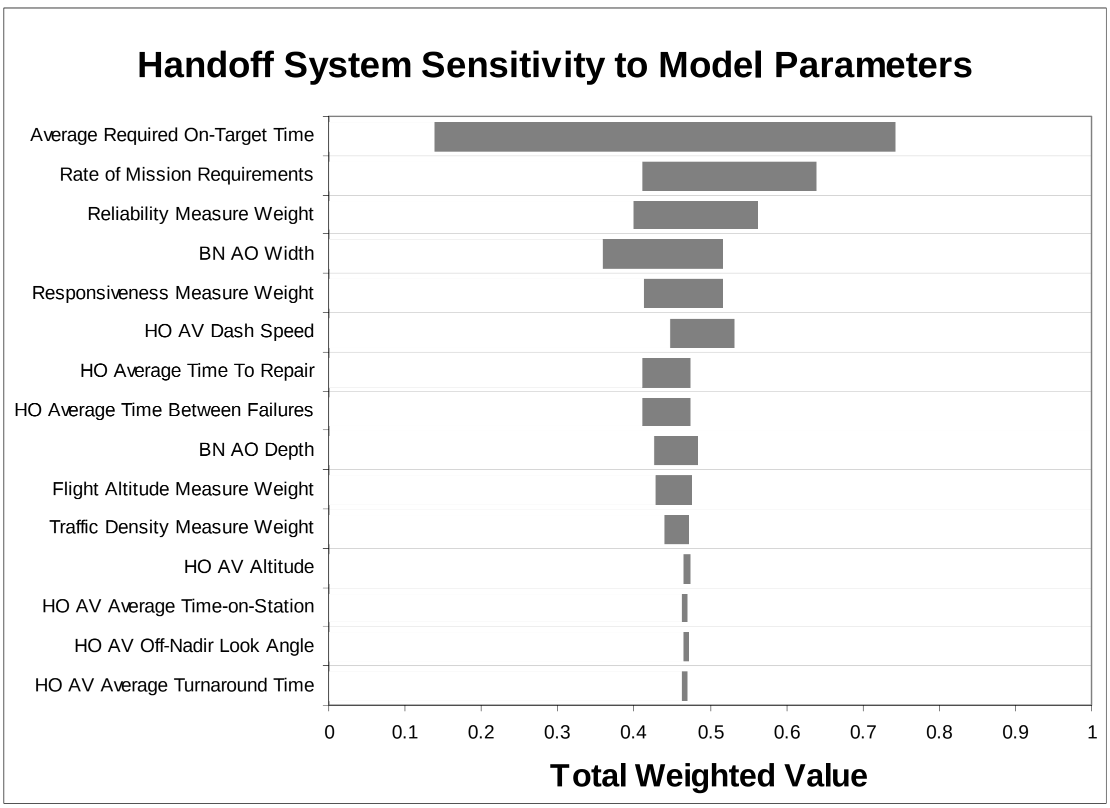

Figure 10. Handoff System Sensitivity Analysis

Table XII. Effects of Selected Parameters on Handoff System Responsiveness

Parameter	Units	Level		Probability of No Queuing Wait	Average Queuing Wait (min)	Average Fly-to Time (min)	Total Avg Delay (min)	Measure Value (0.0-1.0)
Average Required On-Target Time	hours	Low	0.5	0.66	10	9	19	0.74
		Base	1	0.47	30	9	39	0.41
		High	2	0.25	95	9	103	0.02
Rate of Mission Requirements	missions per day per co	Low	2.5	0.69	16	9	24	0.62
		Base	5	0.47	30	9	39	0.41
		High	10	0.23	53	9	61	0.19
BN AO Width	km	Low	40	0.49	28	5	33	0.47
		Base	80	0.47	30	9	39	0.41
		High	160	0.43	36	15	52	0.28
HO AV Dash Speed	knots	Low	100	0.46	31	10	41	0.39
		Base	115	0.47	30	9	39	0.41
		High	230	0.49	27	4	31	0.49
BN AO Depth	km	Low	20	0.47	29	7	37	0.43
		Base	40	0.47	30	9	39	0.41
		High	80	0.46	32	11	44	0.36

Comparing the Sensitivity Analyses

The Organic system is most sensitive to changes in UAV system performance: Setup/ Mission Planning/Launch Time, Average Time Between Failures, and Average Time To Repair. On the other hand, the Handoff system is most sensitive to changes in the operational scenario: Average Required On-Target Time, Rate of Mission Requirements, and battalion AO size. This seems to indicate that Organic system value is more critically dependent on the nature and quality of the design than the Handoff system. The Handoff system shows relatively small swings in value from changes in system design (the largest being a swing of 0.085 for AV Dash Speed), but its performance is particularly sensitive to the operations tempo (i.e Average Required On-Target Time and Rate of Mission Requirements).

The Handoff system is somewhat more sensitive to changes in the measure weights than the Organic. Since the Handoff system has a significantly higher Reliability value score (0.94

vs. 0.67), the swings in Reliability measure weight affect it more. The two Responsiveness value scores are closer (0.41 for Handoff, 0.49 for Organic), but changes in Responsiveness weight still affect the Handoff system more because of the indirect effect on Reliability weight.

It is useful to look at sensitivity of the difference in scores of the two systems. Figure 11 presents a tornado diagram showing the effect of all 20 model parameters on Organic minus Handoff total weighted system value. Here some parameters, such as Responsiveness Measure Weight, have less effect than they do for the individual system scores because they tend to move the two scores in the same direction. Others, such as Flight Altitude Measure Weight, show a greater effect here because they move the scores in opposite directions. However, the largest effects (>0.1) are still parameters that showed up at the top of Figure 9 and Figure 10. These include the following:

- Two Organic system capabilities: Org Setup/ Mission Planning/Launch Time and Org Average Time Between Failures. The first dominates Responsiveness for this system, and the second at its low value results in a relatively low Reliability score.
- Three parameters relating to scenario operations tempo and area: Average Required On-Target Time, Rate of Mission Requirements, and BN AO Width, all of which have a strong effect on Handoff system Responsiveness. The first two directly affect the utilization factor (service time over interarrival time) for the queue of reconnaissance tasks. When this factor is high the average queue wait time becomes long and Responsiveness suffers. High BN AO Width affects both queue service times and fly-to times, thus also affecting Responsiveness.
- Reliability Measure Weight. High weight on this measure emphasizes the Handoff system's advantage, which comes from the larger number of AVs and from the assumed greater vehicle reliability.

It is also noteworthy that seven of the parameters have enough effect to make the Handoff system appear to be preferable to the Organic in the value model measures. These comprise five of the six above (excluding BN AO Width) plus these two:

- Org Average Time to Repair, which affects Responsiveness like Org Average Time Between Failures
- HO AV Dash Speed, where a high speed improves the utilization factor for the Handoff mission queue and thus improves Responsiveness score.

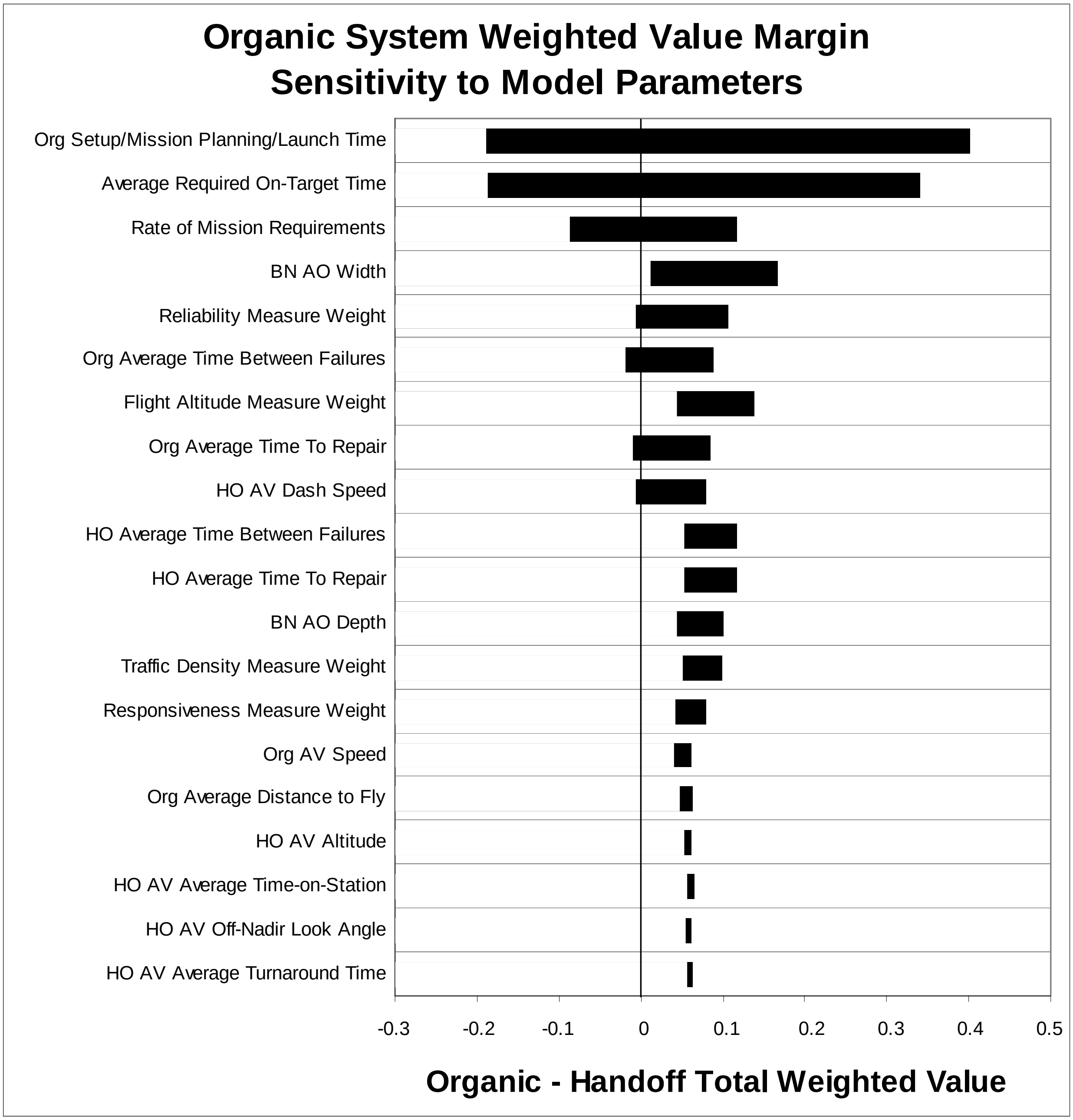

Figure 11. Sensitivity of Difference in System Values

Chapter 6: Conclusions

6.1 Overall Comparison of the Organic vs. the Handoff System

Review of Approach and Problem Formulation

The purpose of this inquiry was to find insight into the relative value of two different operations concepts for UAV support to maneuver companies, to the degree that such value would be the result of the concepts themselves and not of their particular implementation. Our evaluation of system desiderata produced a list of nineteen criteria in six categories (**Table IV**). In an initial analysis, we found no reason to prefer one operations concept to the other in nine of the criteria. The Handoff system appeared to have a qualitative advantage in another six of the criteria, which for convenience are consolidated below in **Table XIII**. That left four criteria (listed in section 4.2) in which the Organic system had an advantage or a possible advantage. Our approach was to develop a value model for those four criteria to see if they added up to enough value to outweigh the evident advantages of the Handoff system. Measure evaluation was done either qualitatively or through high-level abstract models that enabled closed-form evaluation and rapid sensitivity analysis, while still capturing the essential features of the system architectures.

Findings

We did find a moderately higher overall value for the Organic system when considering the four criteria of Responsiveness, Reliability, Traffic Density, and Flight Altitude, as shown in Figure 8. Almost all of the difference was due to the Organic system's better Responsiveness score: average 31 minutes time to target, as opposed to average 39 minutes for the Handoff system. This difference (8 minutes, 26%) could be very important in some tactical situations, but to us it is doubtful whether overall it is sufficient to outweigh Handoff advantages in **Table XIII**.

It is probably more important to look at variations in time to target than at the relatively close averages. In the operational concept we modeled, Organic time to target is relatively fixed and consists almost entirely of the time required to plan a mission and prepare and launch the

Table XIII. Qualitative Criteria with Handoff System Advantage

	Criterion	Justification of Advantage
1e	Flight Safety: likelihood of avoiding flying accidents	Handoff may have an advantage because it flies farther from ground obstructions, and because it is likely to land and take off under more benign conditions.
1f	Operational Flexibility: the ease with which UAV support can be shifted to a lateral unit	In part, this is the result of system design, operational doctrine, and training. However, the Handoff operations concept is based on regularly shifting support from one company to another, so that system has an advantage.
2c	Secondary missions: capacity for payloads other than EO/IR video	The Handoff AV has an advantage because it has a larger payload.
3d	Operational Location	The Handoff system has an advantage here, since flight operations (landing, takeoff, maintenance) are farther to the rear.
5a	Development Costs	The Handoff system has an important advantage here, since the Handoff is already being developed for battalion-level use.
6	System Consolidation	If the entire Organic weapon system can be eliminated, there will be huge simplifications in training, logistics, and operations.

AV. Unless the system design allows this time to be short, the Organic system's Responsiveness advantage from proximity and on-call status will be nullified. On the other hand, time to target with the Handoff ops concept would vary widely depending on the tactical situation. The time could be nearly zero of the AV was already overhead and not otherwise occupied; it could be hours if the AV had to complete other long missions first and then fly a long way. In the baseline scenario, there was no queuing wait almost half the time and fly-to time averaged 9 minutes (**Table XII**); the variation in fly-to time given the baseline AO size was 0 to 21 minutes. In real operations, the battalion commander would give priority to the main effort, so the best times (nearly zero) would be realized for the most critical missions. We feel it is an open question which of these two patterns of variation is better overall.

It is also important to look at the effect on average time to target of the ops tempo assumptions in our baseline scenario, the parameters Rate of Mission Requirements and Average Required On-Target Time. The Organic system's Responsiveness is not affected by these, but the Handoff system is profoundly affected. **Table XII** shows total average time to target varying from 19 to 108 minutes as these are varied individually. If both are set to the lowest values we used (**Table VIII**), our model gives an average time to target as low as 14 minutes, and if both are high, it gives an average time of 154 minutes. This extreme sensitivity to the scenario ops temp is an important disadvantage of the Handoff system. However, if our baseline scenario assumptions turn out to be too pessimistic, the average responsiveness could be much better than the Organic system.

Our findings on the issues of overall system value, system responsiveness, system costs, and other matters are as follows:

1. We did not find a general overall advantage for either the Handoff or the Organic system concept. Instead, the advantage varies with one's assumptions about the operational requirements (especially ops tempo), the system performance characteristics (especially Organic planning/setup/launch time), and the tradeoff between system cost and Responsiveness.
2. The responsiveness of the Organic system can be excellent if there is a quick way to plan a mission and prepare and launch an AV.
3. The responsiveness of the Handoff system is very sensitive to the operations tempo because of queuing delays in using the AV, but the bad effect of this can be ameliorated to some extent by prioritizing users and pre-positioning the aircraft.
4. At the architecture level, the reliability of the Handoff system (in terms of probability of putting an AV in the air when needed) should be somewhat better because the system is likely to have more spare AVs, the AVs are likely to be less complex, and they will be launched, landed, and maintained under more favorable conditions.
5. The Handoff system has an important advantage in saving development costs, since it is already being developed as the battalion UAV, while the Organic system has to be developed independently for the company mission. The Handoff system would also save significant recurring costs because of consolidations in training, logistics, and operations. However, we did not attempt to quantify these savings.

6. The Handoff system operations concept also has other lesser qualitative advantages in flight safety, operational flexibility, secondary missions, and operational location (tables **Table IV** and Table **XIII**, lines 1e, 1f, 2c, and 3d).
7. We quantified the relative advantages on the two systems in the category of Flight Coordination (Table IV, line 4), and found them to be very small compared to the relative advantages we found in other categories.
8. We identified a number of criteria in which at the architectural level we found no reason to recommend either system over the other. These included Dwell Time, Survivability, Usability, Data Quality, Data Handling, Logistics, Personnel, Equipment, and Procurement, Operations, and Disposal Costs (Table IV, lines 1c, 1d, 1g, 2a, 2b, 3a, 3b, 3c, and 5b). Of course, particular designs of these systems could result in significant differences in these criteria.

6.2 Recommendations

In an exploratory high-level study such as this, we are reluctant to make firm recommendations other than for more detailed studies. Both the Organic and the Handoff concepts offer strong advantages. However, we have enough insight to recommend the areas that need the most study to clarify the choice between the two operations concepts. We can also identify some performance parameters that are critical to system performance and that therefore should be emphasized during system development. Finally, the insight from this study can help develop additional alternatives to provided company-level UAV support.

We found that the operations tempo (length of missions and time between missions) was a critical parameter for evaluating the relative value of the two systems. This is a very difficult thing to predict and can vary widely from one conflict or peacetime operation to another. We would recommend developing the best possible data and the best possible estimates of how this tempo is likely to vary under different conditions. Analysis of such estimates would provide a great deal of insight into the conditions under which each concept has better responsiveness and into which concept is preferable overall. Another area that should be studied to shed light on the effect of ops tempo is how a Handoff system would actually be used in the dynamics of actual operations. Our model made the simple and conservative assumptions that the system would act as a server in a first-come-first-serve queue and that successive missions would be independently and uniformly distributed over the battalion AO. We would like to develop better understanding of how command decisions on priorities and AV positioning would lessen the impact of the Handoff system's queuing delays.

We found that Organic Mission Planning/Setup/Launch Time was by far the most important system performance parameter in determining relative system value (Figure 11). Systems are now being developed to meet the FCS Class II requirement using an Organic operations concept (see section 2.1). In these developments, we recommend that a great deal of attention should be given to shortening the timeline to plan a mission, prepare an AV, and launch it under field conditions. A short timeline in this process is critical to realizing an Organic system's foremost advantage, i.e. its responsiveness.

Our final recommendation relates to the generation of additional alternatives based on what we found to be the driving factors in this study. We found that the primary advantage of the Organic system was its responsiveness (at least in many plausible scenarios), and that the primary advantage of the Handoff system was its cost savings (in development and system consolidation). There may be creative alternatives that realize both these advantages. For instance, there could be a Handoff system for company support, and each company could also have a backpackable Class I UAV such as is envisioned for use at the platoon level. That would realize most of the cost savings of the Handoff system, while also giving the company commander the responsiveness of an Organic UAV. The disadvantages would be the limited performance of the Class I UAV compared to the Class II it would be partially replacing, and the increased cost of having two systems (Handoff and Class I) supporting the company. We feel that an alternative like this is worth studying, and we recommend the development and exploration of this and other additional alternatives to address the need for company-level UAV support.

6.3 Limitations of This Work

At this point it is appropriate to review the scope and other limitations of this study in order to put our conclusions into the proper perspective. This investigation started as an academic exercise addressing a realistic but hypothetical problem. It was not sponsored research. It was based on the technical and operational information concerning tactical UAVs that could be found in unclassified published sources and in interviews with a group of soldiers with recent operational experience. Where professional judgments were called for, they were those of West Point cadets and faculty.

The scope of inquiry was limited to two operations concepts for providing EO/IR UAV support to maneuver companies. The envisioned systems were loosely based on actual systems in use or in development, but we tried to assume no more detailed definition on the systems than what was implied by the concepts. We envisioned systems operating in the FCS era, but we did not address the overall system-of-systems design of the FCS, only the issue of the UAV platforms that might be used for company-level support. We assumed that the Handoff operational concept would be practical from a vehicle control point of view. We did not attempt to develop other alternatives to meet the mission requirement, but confined our inquiry to comparing the two we started with.

We developed a list of nineteen criteria relevant to selecting a company UAV system, but only dealt with four of them in detail. For nine of the criteria we assessed the two systems as equal at the architectural level, and for six of the criteria we went no farther than assessing the Handoff system as having some advantage, probably significant in some cases.

We developed high-level models to allow assessment of measures in closed-form measures, in order to facilitate rapid sensitivity analysis and exploration of alternatives. These models required a number of formal assumptions about the distribution and independence of various random variables, and other simplifying assumptions about how the systems would operate. It's not clear how well these assumptions would hold in real life. Nevertheless, the models provided real insight into how these systems would function, in part because of the models' very simplicity. We believe our findings are relatively robust and unlikely to change if more modeling detail is added.

6.4 Future Work

This was originally no more than an academic exercise, and we have no plans to continue it on any other basis. If we were to continue it as a serious investigation, these are the areas we would work on first, roughly in order of importance:

- We would seek more expert judgment on how systems like these would really be used by company and battalion commanders in various types of conflicts, possibly from human-in-the-loop simulations.

- We would try to quantify the Handoff system advantages in development cost and system consolidation, since these seem to be possibly very significant.
- We would look more closely at how time-to-target would vary for different systems in different scenarios, looking at the distribution of times as well as at the means.
- We would develop and evaluate other alternatives, such as the Handoff-plus-backpackable-UAV option.
- We would take a closer look at the nine criteria we judged as “even” to see a significant advantage for one system or the other could be found and quantified.

Chapter 7: Pedagogical Experience

7.1 Initial Cadet Response

The cadets taking the SE450 course were not engineering majors. They were a cross-section of the Academy, majoring in history, leadership, foreign language, and many other things. It is not surprising that individual cadets and cadet teams varied in their initial response to being assigned this more challenging and complex problem. Some found the problem to be intimidating from the start or expressed concern at the likely time commitment it required. A larger percentage of the cadets, however, initially underestimated rather than overestimated the complexity of tradeoffs involved and the difficulty of the analysis required to address this problem. A significant number of cadets expressed enthusiasm for a course problem that appeared to them to be directly relevant to ongoing Army operations and in which they could envision themselves being involved after graduation and deployment as officers. At the end of the course, one typical comment was, "I didn't expect to work this hard in SE450, but it was worth it."

7.2 The UAV Problem as an Integrative Opportunity

The UAV problem was more complex and difficult than most that are assigned in SE450. However, we were pleased to find that it did provide (as we'd hoped) a fruitful opportunity for the cadets to integrate the skills they had learned in the prior systems engineering courses of their engineering sequence, and also skills and knowledge from the rest of their USMA academic curriculum and in particular from their military training as future commanders. Predictably, most of the cadets started out with a company-commander-centric view of the problem and were inclined to believe that it was "obvious" that the Organic option best suited those commanders. As the analysis progressed, this assumption tended to give way to a more sophisticated understanding of the factors that might affect the company commanders' satisfaction with each of the alternative architectures.

Cadets were also encouraged to broaden their perspective to consider the concerns and impact of the UAV architecture options on soldier-operators, battalion staffs, battalion commanders, logistics and support units, US Army Training and Doctrine Command, and the

R&D community. As they began to see the complex set of tradeoffs inherent in the problem, many expressed greater understanding of the need for analytic tools to address important decisions involving multiple objectives which might be in contention with one another.   As an added benefit, the cadets were exposed to new-to-them online and print sources of information about military R&D efforts and FCS programs.

7.3 Opportunities for Excellence

One outcome of assigning the UAV problem to SE450 cadets was that the problem's scope and complexity offered an opportunity for cadets to go beyond course requirements and to excel. From a faculty perspective, SE450 can be a challenging course to teach and mentor, in part due to the wide variation in academic majors and quantitative skills among sequencers. In the case of this UAV problem one team, composed of three economics majors and one cadet studying Military Arts, were (correctly) dissatisfied with their queuing model for AV operation, refueling and repair. In response one of us (Roger Burk) offered that team the opportunity to learn more advanced modeling techniques (continuous time Markov chains), an opportunity they embraced. Once they grasped the basics, the team invested significant time and effort in creating and interpreting a more sophisticated model for AV operations, resulting in an excellent and insightful project that was presented at an end-of-term competition and won first prize in its track.

7.4 Conclusions

Based on two terms during which the UAV project was assigned to multiple cadet teams, we feel this pedagogical experiment successfully met our main goals. On average, cadets were significantly more involved and invested in the UAV problem (and in the tactical high energy laser problem of similar difficulty) as compared with other problems which we have overseen for this and similar courses at USMA. Many of the cadets grappled with this as a military concern as well as an analytic assignment, gaining greater insight into issues associated with the selection and fielding of important new systems for battlefield use. In addition, this problem provided an opportunity for the cadets to familiarize themselves with UAVs and their recent use in Iraq and Afghanistan, including conducting interviews with cadets who had been UAV operators and officers with operational experience in those theaters. As a result, we believe that this problem enhanced the integrative impact of SE450 on the cadets involved with the UAV problem and deepened both their systems engineering skills and their appreciation for the value of these disciplines while contributing to their preparation as future Army officers.

We would encourage SE450 course directors to seek out similar projects for future terms. Our experience should also apply to other courses at other schools where the goal is to give experience in applying systems engineering to complex problems, especially where the students are not engineering majors. However, we note that the success of the UAV issue as an SE450 problem was due in part to the pre-existing interest of one of us (Roger Burk) in the issue, resulting in a willingness to serve as proxy client, and the interest of the other of us (Robin Burk) in offering a more integrative, challenging problem as compared to others executed under her leadership in the same course. Moreover, care must be taken to ensure that such problems are suitably scoped to challenge but not overwhelm cadets. Overall, however, we believe that the extra effort paid off handsomely and was well worth the additional time and energy we each invested in offering this problem to our cadet teams.

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Appendix A: List of Abbreviations*

A	
AAI	AAI Corporation (no expansion)
AO	Area of Operations
AV	Air Vehicle
B	
BN	Battalion
D	
DARPA	Defense Advanced Research Projects Agency
DTIC	Defense Technical Information Center
E	
EO	Electro-Optical
F	
FCS	Future Combat System
H	
HMMWV	High Mobility Multipurpose Wheeled Vehicle
HO	Handoff
I	
IR	Infrared
K	
KZO	Kleinflugger Zielortung
N	
n.d.	no date
O	
ops	operations
ORCEN	Operations Research Center
Org	Organic
R	
R&D	Research and Development
S	
SE	Systems Engineering
STOL	Short Take Off and Landing
T	
TBE	Teledyne Brown Engineering
U	
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
US	United States
USMA	United States Military Academy
V	
VTOL	Vertical Take Off and Landing

*This table is sorted alphabetically

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14. ABSTRACT
This research addresses one part of this issue of selecting the right mix of UAV systems: How shall a company be supported? We consider two alternatives: (1) the "Organic" system, which consists of two vehicle-transported VTOL vehicles assigned to each company; and (2) the "Handoff" system, a larger air vehicle in the air constantly during operations, maintained and launched at the battalion level. We focus on performance measures that are strongly affected by the architecture, and on finding closed-form approximations that allow extensive sensitivity analysis. We find that under some circumstances maneuver companies are better served by the "Handoff" system. We also identify performance and scenario parameters that have a strong effect on this, and consequently deserve more study. This inquiry originated as a cadet group design project; this report includes some remarks on how the project worked in helping the cadets understand how to approach a complex systems engineering problem.

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