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MAXIMIZING WARFIGHTER CAPABILITY USING SURVEYED NECESSITY MEASUREMENT: APPLICATION TO THE USAF F-15C FLEET

John M. Colombi, David R. Jacques, and Dennis D. Strouble

Within the Department of Defense, with changing missions to counter dynamic and asymmetrical threats, the acquisition workforce strives to maximize capability for joint warfighting. How acquisition professionals measure and select capability improvements for the nation's weapon systems is a perpetual challenge, made even more complex with constrained defense budgets. This study identifies a method for determining which upgrades should be purchased (production) for which aircraft in the F-15C fleet by optimizing a capability proxy measure. Each upgrade's "necessity" for a given mission area was obtained by conducting a survey of over 250 experienced F-15C pilots. The solution presented in this article should be extensible to other weapon system capability decisions.

With the planned addition of the F-22A into the United States Air Force (USAF) inventory, the Service developed plans to draw down the F-15 fleet to 179 total aircraft (F-15 C/D models only) by 2013, eventually transitioning most aircraft to the Air National Guard (ANG). However, as a result of decisions made by the Base Realignment and Closure (BRAC) Commission (DoD, 2005) and the 2006 Quadrennial Defense Review (QDR) (DoD, 2006), as well as a reduced F-22A buy, the USAF and ANG will keep an additional number of aircraft in service through 2024. Since current plans and budgets have been based on a fleet of 179, the budgets will not support installation of all planned upgrades to a larger F-15 fleet.

This research demonstrates a method for determining the optimal mix of production upgrades for the future F-15 fleet (including C and D models, but not E models,

which are managed separately) within a constrained budget. To make this determination, the following three questions had to be answered:

- Which upgrades (modifications) are most needed for the F-15 to perform its mission(s)?
- How can these upgrades be compared on a common scale?
- Can we maximize a fleet's capability for a fixed budget authority?

The study thus seeks to provide an optimized solution for keeping a large number of aircraft beyond the 179 relevant for combat duty for one to two additional decades of service.

BACKGROUND

The F-15 is an all-weather, maneuverable tactical fighter designed to gain and maintain air supremacy over the battlefield. This superiority is achieved through a mixture of maneuverability, acceleration, range, weapons, and avionics. The weapons and flight control systems are designed so one person can safely and effectively perform air-to-air combat. But as the Advanced Tactical Fighter (ATF) program was conceived, this new aircraft was seen to be a replacement for the F-15 fleet, all A-D variants. However, as the program evolved to the F-22A, the planned buy was cut from 750 aircraft to 442 aircraft to 339 aircraft. It soon became apparent that some F-15C/Ds would need to remain in service alongside the F-22A for the foreseeable future. Prior to 2001, plans were developed to reduce the F-15 fleet size to 179 aircraft by 2013. These "long-term" aircraft, also known as "Golden Eagles," were scheduled to receive a large number of modifications and upgrades that would extend their combat relevance out to 2025 and beyond. (Due to a crash, there are now only 178 Golden Eagles.) However, in 2002, the F-22A buy was further reduced to 183 aircraft, and the results of the 2005 BRAC mandated keeping a larger ANG F-15C force size than the Air Force had planned. Further, after September of 2001 the air superiority forces of the DoD have been tasked with an additional mission of homeland defense, a mission largely abandoned after the Cold War ended in the early 1990s. This combination of factors has resulted in a need for additional F-15Cs over the next 20 years.

Since little trade space exists in the fleet size, largely mandated by BRAC, QDR, and political considerations, and given the current tightly constrained fiscal environment, some sort of decision support process was needed to choose which upgrade(s) will be purchased for which aircraft and in which year. This decision in the past would often have been made in a non-scientific manner, attempting to balance conflicting though professional recommendations by multiple stakeholders in the acquisition, budget, and operational environments. The complexity of this planning decision is daunting; a number of related factors must be considered, some of which include:

- Fleet size over time including retirement schedules
- A- and B-Model retirement plans

- Sundown Rule, restricting upgrade spending on aircraft to be retired within 5 years
- Prior upgrades (Golden Eagles already have many of these upgrades)
- Acquisition costs, including unit price per lot, startup production costs, research and development cost, installation costs, and timing, testing, and certification, etc.
- Funding profiles across Future Years Defense Plan (FYDP) and appropriation type
- Squadron-specific missions, including Deployed Combat within an Air Expeditionary Force (AEF), Homeland Security, and Training
- System upgrade interdependencies

This research was sponsored by the F-15 system program office and was focused on previously approved modifications. The 11 modifications examined have been vetted through all appropriate requirements and capability reviews. Thus, the challenge was to find the number of each modification to maximize fleet capability over time to perform the F-15 missions. A tool and method was requested to support this complex acquisition decision.

METHOD

The method used to solve this problem first started with a set of 11 upgrades, provided and currently managed by the program office, which added to F-15 capability. To establish a measure of capability improvement for all upgrades, an online survey of experienced F-15 pilots was released. The survey data were averaged, scaled, and combined with various fleet and acquisition constraints. All this was input to a linear programming model that searched for the best set of modifications and their respective production quantities, constrained primarily by budget authority.

CANDIDATE UPGRADES AND COSTS

The list and description of 11 current upgrades is shown in Table 1. The cost of each upgrade (per aircraft) is shown in Figure 1. Admittedly, there could be some variability in these costs due to variations in total quantity purchased and the quantity purchased per year, but for purposes of this study these costs are representative.

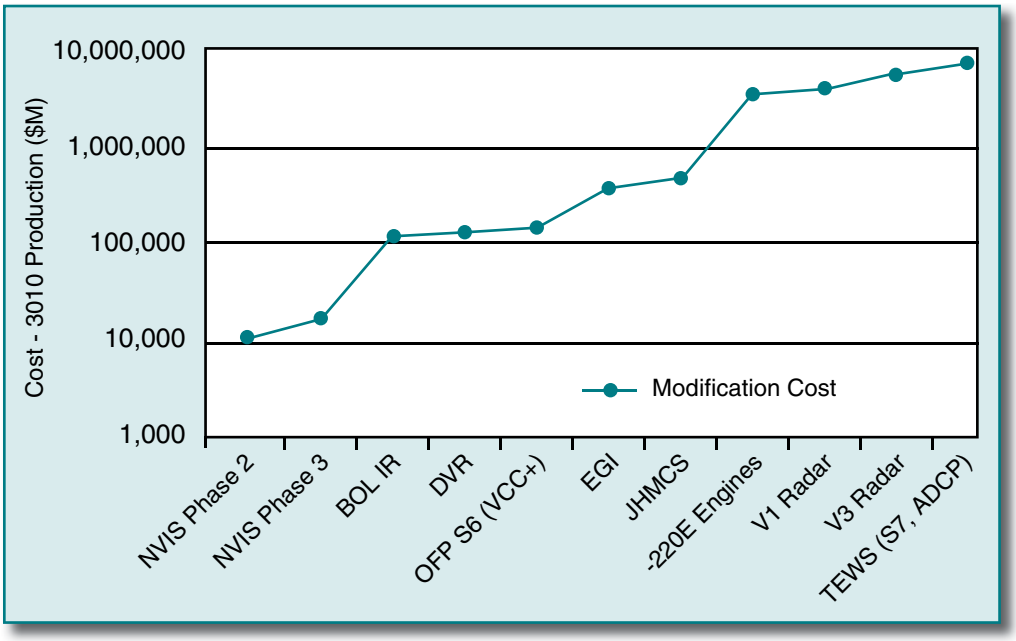
COMPARING UPGRADES ON A COMMON SCALE

A method was needed to evaluate all the candidate upgrades on a common scale that described their "value added" to the aircraft's capability. Similar techniques have been tried on other Air Force platforms, such as comparing upgrades on a "Mission Availability" improvement scale, a technique used to evaluate Air Warning and Control System (AWACS) upgrades during the Extend Sentry program. As a desired acquisition practice stemming from DoD's ongoing Capability Based Acquisition

TABLE 1. F-15 MODIFICATION/UPGRADES AND DESCRIPTION

Modification/Upgrade	Brief Description
220E Engines	Replaces the 30-year old F100-PW-100 engine's analog fuel control with a digital fuel control unit. This results in faster afterburner ignition, more power, increased reliability, and greater maintainability.
APG-63v1 Radar	Replacement of the entire air-to-air radar (except for the dish) with more advanced components, reducing the number of Line-Replaceable Units (LRU) from seven to five. Offers increased radar performance in addition to improved reliability and maintainability.
APG-63v3 Radar	Combines the new "back end" processors of the APG-63v1 radar with an active electronically scanned array (AESA) radar dish, providing vastly improved detection, identification, and target tracking ability and increased Mean Time Between Failures (MTBF).
Joint Helmet-Mounted Cueing System (JHMCS)	A helmet-mounted display and cueing system allowing the pilot to assess aircraft and weapons status while maintaining "eyes out" of the cockpit. Allows visual cueing of high-off bore sight (HOBS) weapons like the AIM-9X.
Night Vision Imaging System (NVIS) Phase II	Aircraft's interior lighting modified to be Night Vision Goggle (NVG) compatible.
Night Vision Imaging System (NVIS) Phase III	Aircraft's exterior lighting modified to be Night Vision Goggle (NVG) compatible.
Embedded GPS/INS (EGI)	Adds a Global Positioning System (GPS) receiver to the aircraft and integrates it with the aircraft's existing Inertial Navigational System (INS).
BOL IR	Defensive system providing for continuous covert employment of IR countermeasures for increased survivability in the visual arena
Digital Video Recorders (DVRs)	Upgraded recording devices that capture sensor and display parameters digitally, eliminating the unreliable 8mm recording system
Upgraded Tactical Electronic Warfare Set (TEWS)	Upgrades to the F-15's 1970s-era Radar Warning Receiver (RWR), Internal Countermeasures Set (ICS), Electronic Warfare Warning System (EWWS), and Countermeasures Dispenser (CMD) Systems.
Suite 6 Operational Flight Program (OFP)	Upgraded radar software offering improvements in target detection, weapons employment, target identification, and signal security. Suite 6 development is already funded; however, to run Suite 6 the F-15 requires an updated central computer called the Very High Speed Integrated Circuitry Central Computer Plus (VCC+). There is a unit cost for the VCC+.

FIGURE 1. F-15 UPGRADE COSTS PER AIRCRAFT (3010 PRODUCTION) ON LOGARITHMIC SCALE



initiative, the Department favors measuring all upgrades on capability delivered. However, to put the candidate upgrades on a common capability scale was difficult due to the varied performance parameters and mission applicability of each upgrade. Consider performance parameters for upgraded radar. They include search range, search volume, and target-tracking ability. But the Key Performance Parameters for an upgraded engine might include maximum thrust, fuel consumption, and spool-up time. The wide variety of parameters could not be transposed onto a common scale. Instead, the method selected evaluated candidate upgrades on a common "necessity" scale. Thus, capability improvement of a candidate upgrade is the measure of how *needed* it is to accomplish the mission.

SURVEY OF SUBJECT MATTER EXPERTS

The next step was to quantify which of the upgrades were actually needed for the F-15 to perform its mission. Admittedly, this was and is a matter of considerable debate in the F-15 community. The study required a scientific way to collect and quantify this information so that it would be accurate, useful, and defensible. The researchers decided to conduct an online survey of experienced F-15 pilots in the USAF and ANG, and use the survey results to establish the necessity of each particular upgrade.

In choosing the survey pool, the expert opinions of the most accomplished F-15 pilots in the USAF and ANG were deemed most valuable. At the same time, enough survey responses were required to be statistically valid. A survey pool was chosen consisting of only "Experienced" F-15 pilots, both current and non-current. Experienced is defined in Vol. I of Air Force Instruction (AFI) 11-2F-15 and normally

TABLE 2. SURVEY TARGET POPULATIONS

Operational Active Duty Bases	Langley AFB, VA; Mountain Home AFB, ID; Eglin AFB, FL; Elmendorf AFB, AK; Kadena AB, Japan; RAF Lakenheath, UK
Operational Air National Guard Bases	Jacksonville IAP, FL; New Orleans JRB, LA; Portland IAP, OR; Otis ANGB, MA; St. Louis IAP, MO; Hickam AFB, HI
F-15 Training Bases	Tyndall AFB, FL, Kingsley Field OR
Misc. F-15 Locations	Nellis AFB, NV; Edwards AFB, CA; Keflavik NAS, Iceland
Non-F-15 Operating Locations	Holloman AFB, NM; Sheppard AFB, TX; Moody AFB, GA; U.S. Air Force Academy
Resident PME Locations	Wright-Patterson AFB, OH; Maxwell AFB, AL; Fort Leavenworth, KS; Naval Postgraduate School, CA
Staff Locations	HQ USAF, HQ ACC, HQ PACAF, HQ USAFE, HQ AETC, HQ AFMC, 9th AF (ACC), 12th AF (ACC), 19th AF (USAFE), 7th AF (PACAF), HQ NGB, HQ JFCOM

is when a pilot reaches 500 hours in the F-15. Responses were sought from those actively flying in operational units, both Active Duty (AD) and ANG, training units (AD and ANG), and the test community. Responses were also sought from F-15 pilots currently serving on staff, in other airframes, and enrolled full-time in designated Professional Military Education (PME) schools. Additionally, responses were sought from F-15 test engineers who have worked closely with these programs. An efficient, inexpensive way to distribute the survey and collect responses was needed. A distribution method was also needed that would maximize the number of responses received and minimize the time required for a person to take part in the survey.

Excellent guidance for developing a survey and writing specific survey questions can be found in many references (Weisberg & Bowen, 1977; Meyburg & Stopher, 1979; Dillman, 2000).

All survey-related activities were conducted in accordance with AFI 36-2601, Air Force Personnel Survey Program. An Internet-based survey was developed with responses solicited via e-mail. The survey required approximately 15 minutes to complete. Survey responses were sought from the various locations, shown in Table 2.

To capture the qualifications, background, and experience of survey respondents, the first survey section collected demographics, including: rank, years flying the F-15, hours flying the F-15, current flying status, duty assignment (operational flying, Replacement Training Unit [RTU] instructor, full-time PME, etc.), AD or ANG, qualifications earned (instructor pilot, flight examiner, weapons school graduate, etc.), and combat experience. In accordance with AFI 36-2601, no attempt was made to correlate individual survey responses or demographic information specific to individuals participating in the survey.

The survey sought how necessary a particular upgrade would be for pilots to accomplish their mission. Three mission types considered were Deployed Combat, Homeland Defense, and Replacement Training Unit. The deployed combat mission correlates closely with the Concept of Operations (CONOPS) for Global Persistent Attack (Department of the Air Force, 2004a). The Homeland Defense mission correlates closely with the Homeland Security CONOPS (Department of the Air Force, 2004b). These missions were described to the survey respondents.

NECESSITY RATINGS

Survey respondents were asked to rate the necessity of each modification to accomplish each of the three missions. The upgrades considered were very diverse—some offered an increase in offensive capability (lethality), some defensive capability (survivability), while some offered both. As discussed earlier, the researchers could not find a way to rate all upgrades on a common *capability* or *utility* scale. Via the survey, the researchers were able to rate all the upgrades on a common necessity scale.

Survey respondents rated each upgrade's necessity using the following Likert psychometric scale:

0 – N/A – Don't Know – Not enough information to answer
1 – Not necessary to accomplish the mission
2 – In rare circumstances may be necessary to accomplish the mission
3 – Sometimes necessary to accomplish the mission
4 – Usually necessary to accomplish the mission
5 – Absolutely necessary to accomplish the mission

The survey respondents rated the necessity of each upgrade against each of the three mission areas—Deployed Combat, Homeland Defense, and Replacement Training Unit. Respondents were instructed to rate an upgrade with respect to its necessity only; they were to ignore the cost or perceived reliability of the upgrade. It was anticipated some survey respondents would rate many or all of the upgrades as "Absolutely Necessary" or "Usually Necessary," not providing enough stratification to accurately evaluate the necessity of those systems. For this reason, when a respondent rated multiple upgrades as "Absolutely Necessary," the respondent was asked to rank-order those upgrades in importance, and then do the same for all the upgrades ranked as "Usually Necessary." These rank orders were then used to adjust the necessity ratings.

NECESSITY COEFFICIENTS (N_C)

The survey necessity ratings needed to be converted to numeric Necessity Coefficients (N_C). A simple method would be to simply use the numerical Likert scale and average the results. In his book *The Engineering Design of Systems*, Buede cites the work of Craig Kirkwood that found exponential functions are most commonly used to approximate the value functions of stakeholders (Buede, 2000). In other words, when user preferences are stated, their highest preferences are preferred many times over to their lower preferences. In some cases, the highest preferences can be orders of magnitude greater in desirability than the lowest preferences. For these reasons,

an exponential function was used to both adjust each person's Necessity Ratings for the rank order and then convert the Adjusted Necessity Ratings to numeric Necessity Coefficients. Table 3 summarizes the conversion of survey data.

For example, if a respondent rated three upgrades as "Absolutely Necessary," the survey then asked the respondent to rank-order those as No. 1, No. 2, and No. 3. The study used these *rank orders* to further stratify the upgrades by necessity. The upgrade ranked as No. 1 necessity would be given a higher Adjusted Necessity Rating than the upgrade ranked No. 2, which would have a higher Adjusted Necessity Rating than the upgrade the respondent ranked No. 3. Assuming an exponential user preference, the Necessity Rating was adjusted for rank using the following formulas:

Adjusted Necessity Rating = $4.5 + [e / e^{(\text{rank}/2)}]$, for a Necessity Rating of "5"
Adjusted Necessity Rating = $3.5 + 0.5[e / e^{(\text{rank}/2)}]$, for a Necessity Rating of "4"
Adjusted Necessity Rating = 3, for a Necessity Rating of "3"
Adjusted Necessity Rating = 2, for a Necessity Rating of "2"
Adjusted Necessity Rating = 1, for a Necessity Rating of "1"

So the Adjusted Necessity Rating is scaled *upward* on an upgrade for which a respondent ranked first, second, or third. Conversely, the Adjusted Necessity Rating is scaled *downward* for upgrades a respondent ranked fourth, fifth, or lower. For upgrades a respondent rated as 1, 2, or 3, the respondent was not asked to rank order them, thus the Adjusted Necessity Rating is simply the same as the Necessity Rating. From there, the Necessity Coefficient was calculated for each response on an exponential scale. The exponential function used was:

If Adjusted Necessity Rating = 1, Necessity Coefficient = 0
If Adjusted Necessity Rating > 1, Necessity Coefficient = $e^{(\text{Adjusted Necessity Rating})}$

Table 3 summarizes the conversion of survey data.

TABLE 3. USER SURVEY RATING CONVERSION TO NECESSITY COEFFICIENT

Original Survey Rating	Conversion	Necessity Coefficient
0 – N/A, Don't Know	Thrown Out	N/A
1 – Not Necessary	Set to Zero	0
2 – Rarely Necessary	$e^{(\text{Rating})}$	7.39
3 – Sometimes Necessary	$e^{(\text{Rating})}$	20.08
4 – Usually Necessary	$e^{(\text{Adjusted Rating \& rank})}$	33.16 - 75.52
5 – Absolutely Necessary	$e^{(\text{Adjusted Rating \& rank})}$	90.24 - 468.12

CAPABILITY OPTIMIZATION AND CONSTRAINTS

The study merged Necessity Coefficients (derived from survey responses), costs, and many other limiting factors involved in purchasing the upgrades. Linear Programming was the method chosen based on its applicability, simplicity, and modeling

assumptions (Ragsdale, 2004). The solution used a Simplex algorithm with two-sided bounds on all variables (Frontline, 2006). The algorithm moves up and down the bounds of a feasible region defined by an optimization objective, manipulating the value of the variables, until it reaches its maximum or minimum value subject to any defined constraints. The objective function, J, used in this research was the summation of all modifications to all aircraft weighted by the modification's Necessity Coefficient.

$$\max J = \Sigma_{i=1}^{M} N_{C_i} X_i \qquad \text{(Eq. 1)}$$

where: M is the number of different types of modifications

X is the number of modifications, of type i, chosen to buy

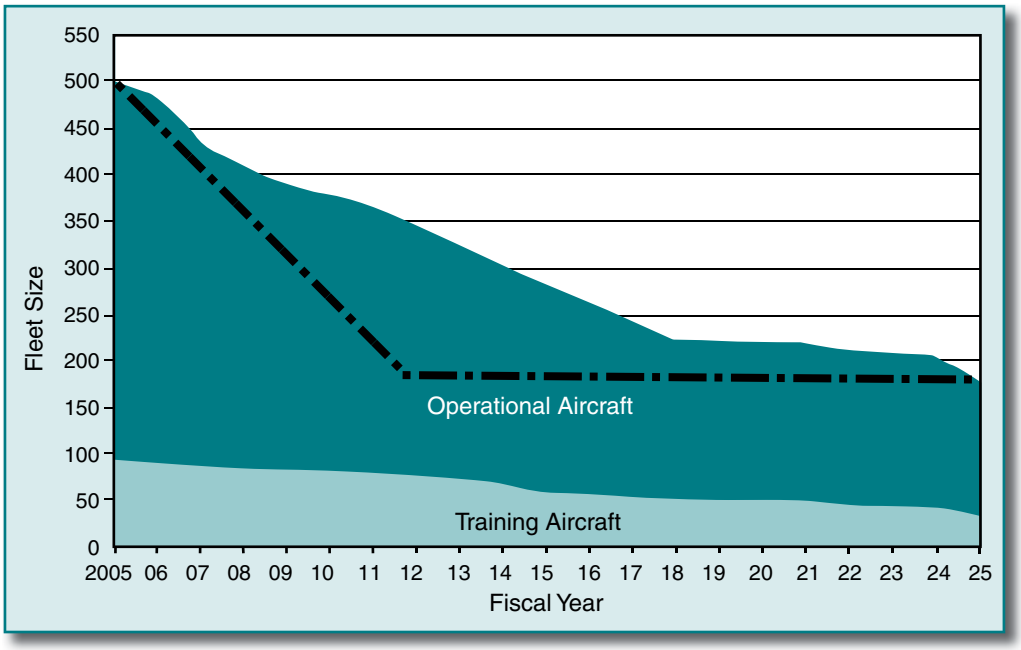
N_{C_i} is the Adjusted Necessity Coefficient for the *ith* modification.

The objective function was then constrained in several ways. The most obvious and primary constraint was a fixed budget authority, but other constraints included budget appropriations, the designated combat fleet size, designated training fleet size, upgrade interdependencies, and upgrade purchase limitations.

Like the program budget, the overall F-15 fleet size is subject to changes based on USAF, DoD, BRAC, or QDR directives. Current plans call for the F-15 fleet to gradually draw down from the current level of over 480 aircraft over the next 20 years. The total planned fleet size (broken into operational and training components) by fiscal year is shown in Figure 2.

The potential upgrades sometimes can not be installed on their own—they require other upgrades to be installed prior to or concurrently with the upgrade in question.

FIGURE 2. F-15 FLEET SIZE NOW EXCEEDS EARLIER DOWNSIZING PLANS (DASHED LINE) FOR THE NEXT 20 YEARS



This adds cost and further constrains the solution. One example is the APG-63v3 radar dish: it requires the "back-end" processors of the APG-63v1 radar.

The number of upgrades is also constrained by several other factors. First, we have already outfitted part of the fleet with some of these upgrades. An example is Embedded Global Positioning System/Inertial Navigation System (EGI). The USAF has already purchased EGI for 232 F-15s, so no money needs to be spent on EGI until the Service decides to upgrade the 233rd aircraft with EGI. Table 4 shows the current number of aircraft in the fleet already possessing a candidate upgrade.

TABLE 4. NUMBER OF AIRCRAFT CURRENTLY UPGRADED

Upgrade	Number of Aircraft
220E Engines	282
V1 Radar	178
V3 Radar	18
JHMCS	200
NVIS Phase II	178
NVIS Phase III	0
EGI	232
BOL-IR	114
OFP S6 (VCC+)	232
DVR	0
TEWS (S7, ADCP)	0

Another funding constraint occurred in cases where Research and Development (R&D) was not completed (or perhaps not even started) on a particular upgrade. In these cases, *3600 money* (R&D dollars) must be spent before *3010 money* (aircraft production dollars) can be spent. If a decision is made to buy a quantity of an upgrade, no matter how small, all associated 3600 money required to get that system ready for production must also be allocated.

Two other constraints applied were purely mathematical in nature: integer and non-negative constraints. Integer constraints applied to this F-15 problem ensure the solution can not buy a fraction of an upgrade—i.e., half of a new radar. Upgrades are only bought in integer quantities. Also, non-negative constraints ensured the algorithm would not try to "sell" certain upgrades to fund purchases of different ones—a mathematical solution but not a practical one in reality.

Since F-15s are being retired each year, there was a need to check the number of years left in a particular aircraft's life when deciding what upgrades to purchase for that aircraft. Obviously, spending a lot of money to upgrade a jet that may only have a couple years until retirement is undesirable. That money could otherwise be spent on an aircraft that will remain in service for 20 more years. The study decided

TABLE 5. MAXIMUM MODIFIABLE FLEET SIZES OVER TIME

	Short-Term (2007-11)	Mid-Term (2012-16)	Long-Term (2017-21)
Operational Fleet Size	282	204	169
Training (RTU) Fleet Size	81	56	48

to split the retirement and optimization plan into five-year blocks. Thus, the FY07 President's Budget provides an estimate of the upgrade budget available for the first five-year period of FY07–FY11. Budget estimates for subsequent five-year periods are current-year estimates based on the first five-year period. The fleet size in the optimization is thus divided into three parts: aircraft that will be around through the first five-year period, aircraft that will be around for the second five-year period, and finally aircraft that will be around for the third five-year period and beyond. Aircraft that will be retired in the next five years are not considered for upgrades. Modifiable aircraft numbers used are shown in Table 5.

All the above constraints were then added to the optimization model, resulting in the following:

$$\max J = \sum_{i=1}^{M} N_{Ci} X_i \qquad \text{(Eq. 2)}$$

such that:

$X_i \le CA_i(\text{period})$, (number $\le$ max number F-15 Combat Aircraft at end of period)

$X_i \le TA_i(\text{period})$, (number $\le$ max number F-15 Training Aircraft at end of period)

$X_i \le M_i$, (i.e. number $\le$ max number of Mods needed - many already installed)

$X_i \ge 0$, (number of mods selected is a non-negative number)

$X_i \in$ Integer

$\sum_{i=1}^{M} Cost_{3600}(X_i) \le BA_{3600}(\text{period})$, (one time R&D Cost $\le$ 3600 Budget Authority in period)

$\sum_{i=1}^{M} Cost_{3010}(X_i) \le BA_{3010}(\text{period})$, (one time Production Cost $\le$ 3010 BudgetAuthority in period)

$\sum_{i=1}^{M} Cost_{3010}(i) \cdot X_i \le BA_{3010}(\text{period})$, (total Production Costs $\le$ 3010 BudgetAuthority by period)

$X_i = X_j$, if modification i requires (enabled by) modification j

In general, this study did not investigate the cost or feasibility of moving upgraded systems from aircraft to aircraft as jets are retired. The added cost and logistic requirements are prohibitive in many cases. In some cases, upgraded systems on retired aircraft will re-enter the fleet as spare parts. Further, Air Force planners assumed that as the combat fleet is reduced in size, aircraft with many upgrades installed will be transferred to the training fleet, and the trainer aircraft with fewer upgrades will be the ones actually removed from service. Lastly, no attempts were made to include Operations and Sustainment costs to this model.

RESULTS

SURVEY RESULTS

A total of 278 F-15 pilots participated in the survey. A significant number of survey responses were received from all facets of the F-15 community including operational pilots (both AD and ANG), RTU instructors, the test community, and F-15 pilots serving on staffs and at full-time PME. A demographic summary of the survey participants is shown in Table 6.

Figure 3 shows the necessity coefficients that were derived from the survey results using the formulas discussed above for two missions. Of note, the scores for a given upgrade in the Combat mission are generally much higher than for Training, representing the higher necessity of most of the listed systems to do that mission. Also, while the Homeland Defense survey results were collected, it was decided that a separate Homeland Defense F-15 configuration would not be feasible to implement,

TABLE 6. F-15 USER SURVEY—RESPONDENT DEMOGRAPHICS

Average number of years flying F-15C	8.4
Average number of hours flying F-15C	1362
Number of respondents currently performing flying duties	222
Number of respondents currently performing other duties	54
Number currently operationally flying with the active duty Air Force	108
Number currently operationally flying with the Air National Guard	37
Number of respondents who were/are Training (RTU) instructors	92

FIGURE 3. NECESSITY COEFFICIENTS *(N_C)* PER MODIFICATION FOR COMBAT AND TRAINING MISSIONS

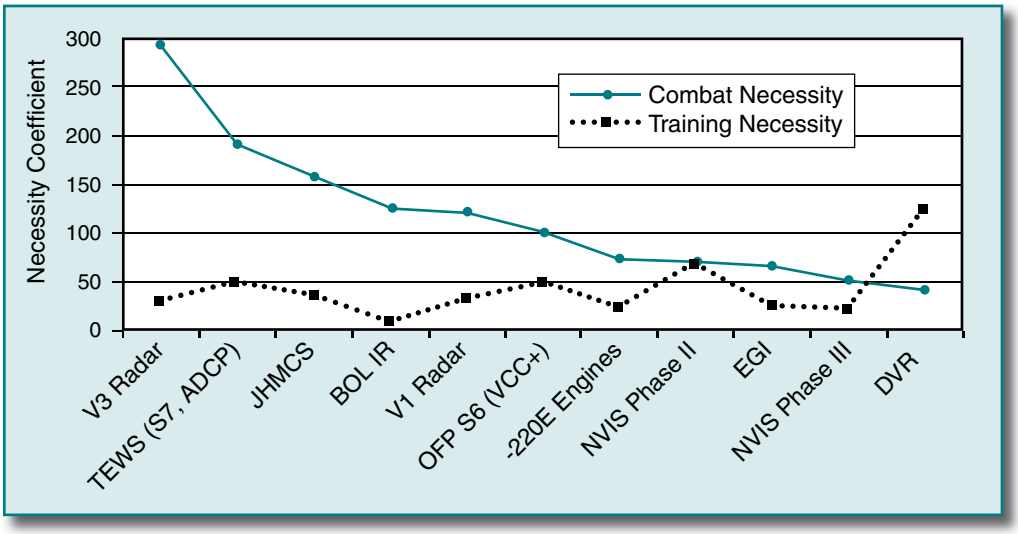


TABLE 7. TIME PHASED OPTIMIZATION SOLUTION

	Short-Term		Mid-Term		Long-Term		Total
Upgrades	Number to Buy (Combat)	Number to Buy (RTU)	Number to Buy (Combat)	Number to Buy (RTU)	Number to Buy (Combat)	Number to Buy (RTU)	Number to Buy
220E Engines	0	0	0	0	0	0	0
v1 Radar	0	0	0	0	0	0	0
v3 Radar	0	0	1	0	14	0	15
JHMCS	26	0	0	34	0	0	60
NVIS Phase II	104	81	0	0	0	0	185
NVIS Phase III	282	81	0	0	0	0	363
EGI	0	0	26	56	0	0	82
BOL-IR	168	0	0	0	0	0	162
OFP S6(VCC+)	104	0	0	0	0	0	104
DVR	0	81	179	0	0	0	260
TEWS (S7, ADCP)	0	0	0	0	0	0	0

so the optimization program eliminated this option and focused on the two remaining missions—Combat and Training.

OPTIMIZATION RESULTS

The optimization was run with the best current estimates of fleet size, budget authority, and upgrade-specific cost. The model was test-run for several different scenarios to check its validity and also to evaluate its sensitivity to some of the assumptions made earlier. Due to the funding environment today, the recommendations are based on a fairly constrained budget across each of the next three FYDPs. Table 7 shows the purchase recommendations of the model for the short-, mid-, and long-terms using a modest budget and having only two configurations—Combat and Training.

OPTIMIZATION OBSERVATIONS

At first glance, the optimization results generated one major question: Why isn't the model recommending immediate purchase of the item(s) rated as most necessary in the survey? As a specific example, why do the results recommend immediately buying Digital Video Recorder (DVR) and Night Vision Goggles (NVG)-compatible interior and exterior lights for the fleet instead of the APG-63v3 radar when the radar

ranked so highly on the survey? Perhaps the reader will think it is because of the *relative cost* of the items. The v3 radar certainly has a much higher Necessity Coefficient than DVR (7 times), but it also has a per-unit cost over 450 times that of the Night Vision Imaging Sensor (NVIS) Phase II. Several striking examples of relative cost can be calculated. For the price of only four v3 radars, it would be possible to upgrade all the remaining combat-coded jets in the short-term fleet (168 aircraft) with BOL-IR; and for the price of equipping three aircraft with the Joint Helmet Mounted Cueing System (JHMCS), it would be possible to install NVIS Phase II lighting in the 104 aircraft remaining in the short-term fleet without it. Recall that the optimization is trying to maximize capability for the entire fleet, not just an individual aircraft.

EXAMINATION OF OPTIMIZATION METHOD

Is this a flaw with the model—maximize fleet capability constrained by budget? Initially, assume that the approach is correct. Each modification made to an aircraft provides a measurable (through exercises, simulation or survey) increase in capability. So how does the model, using Linear Programming, search for a solution? To illustrate this, we limit the problem to only 2 of the 11 modifications, for example NVIS III and -220 Engines. This will allow a two-dimensional examination of the objective curves and constraint lines. For this simplified example, looking at one time period and one type of appropriation, the optimization model becomes:

$$\max J = \sum_{i=1}^{2} N_{Ci} X_i$$

such that:

$$\sum_{i=1}^{2} Cost_{3010}(X_i) \leq BA$$

Cast as a linear combination of modifications:

$$\max J = N_{C1} X_1 + N_{C2} X_2$$

such that:

$$Cost_1 X_1 + Cost_2 X_2 \leq BA$$

While J is typically the dependent variable, we can rearrange and write as the number of modifications of Engines, X_2, with respect to J and the number of NVIS III modifications (external lighting), X_1. Putting in actual necessity coefficients from the survey and cost (3010 $) values, the number of Engines can be written as:

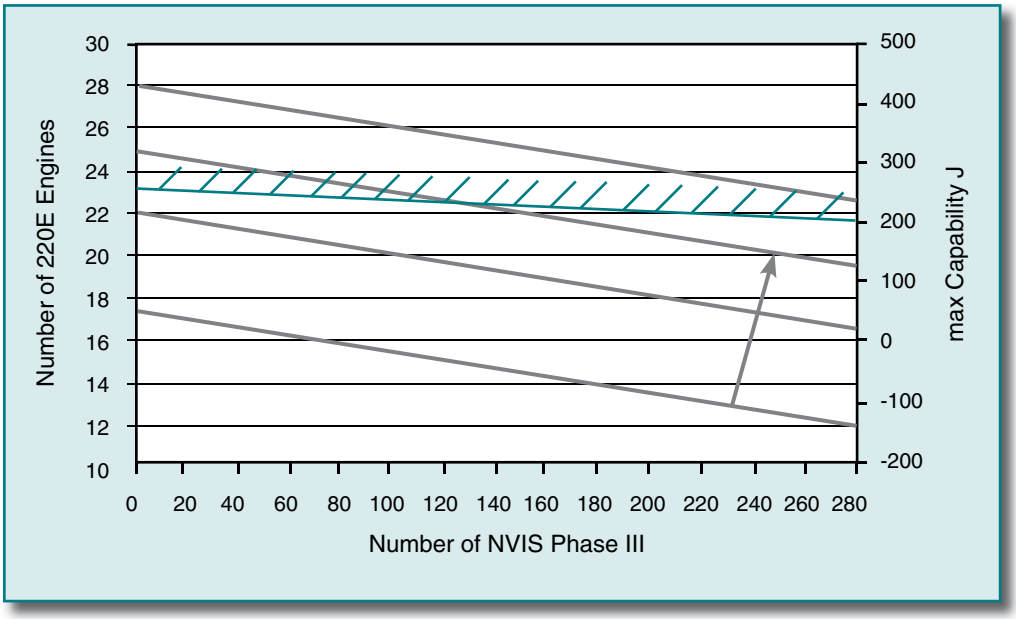
$$X_2 = -(N_{C1} / N_{C2}) X_1 + (J / N_{C2}) = -(74.2 / 51.2) X_1 + (J / 51.2)$$

such that (when the constraint is active),

$$X_2 = -(Cost_1 / Cost_2) X_1 + (BA / Cost_2) = -(\$17K / \$3.34M) X_1 + (\$77M / \$3.34M)$$

This can be graphically portrayed for varying maximums, J. In Figure 4, note that the cost constraint has a slope (with crosshatch), while the optimization of capability

FIGURE 4. OPTIMIZATION MODEL



Note: The cost constraint slope (blue with crosshatch) is a function of the cost ratios. Likewise, the objective function has a slope, a function of necessity coefficient ratios.

provides a series increasing objective lines with a second slope. To maximize *J*, the optimization algorithm will search for changes in X_2 and X_1, which increase *J*. Visually, the algorithm moves from the lowest *J* isoline up to higher contours. When the algorithm meets a constraint, it will move along it until reaching another constraint or finding a vertex (circle in figure). In this example, the design point moves toward the right (increasing NVIS) until the side constraint is reached, indicating that no more NVIS upgrades are feasible.

This type of behavior is well understood (Hazelrigg, 1996) and linear programming problems of this type will either find one optimal solution, may not find any solution if the parameters are unbounded, or find an infinite number of equally valid solutions. For the first solution to exist, it will occur at a vertex of constraint lines. The second solution is not applicable for this research, as all parameters are bounded based on maximum number of F-15 combat and training aircraft in a particular time period, as well as further constrained by budget authority and number of modifications already installed. The last solution, an infinite number of valid solutions, will be true if the active constraint line and the objective have exactly the same slope.

Thus, the behavior can be understood completely, for these two modifications, by the examination of the two slopes. The first is the slope of the Cost (constraint) line of $Cost_2/Cost_1$, or $Cost_{ENGINE}/Cost_{NVIS}$. The second is the slope of the Objective (necessity) line of N_{C2}/N_{C1}, or $N_{C\text{-}ENGINE}/N_{C\text{-}NVIS}$. The decision to buy more (all) NVIS modifications will occur if the slope of the necessity ratio is less than the slope of the cost ratio.

$$N_{C\text{-}ENGINE}/N_{C\text{-}NVIS} < Cost_{ENGINE}/Cost_{NVIS}.$$

TABLE 8. BALANCING COST BY EXAMINING SCALE OF NECESSITY COEFFICIENTS. FIRST QUANTITY REFERS TO OPTIMIZATION SOLUTION WITH α=100. SECOND QUANTITY USES A MORE BALANCED α=50

	Short-Term		Mid-Term		Long-Term		Total
Upgrades	Number to Buy (Combat)	Number to Buy (RTU)	Number to Buy (Combat)	Number to Buy (RTU)	Number to Buy (Combat)	Number to Buy (RTU)	Number to Buy
220E Engines	0	0	0	0	0	0	0
v1 Radar	0	0	0	0	0	0	0
v3 Radar	10/0	0	11/1	0	14/14	0	34/15
JHMCS	0/26	0	0/ 0	0/34	0	0	0/60
NVIS Phase II	0/104	0/81	0	0	0	0	0/185
NVIS Phase III	0/282	0/81	0	0	0	0	0/363
EGI	0	0	0/26	0/56	0	0	0/82
BOL IR	0/168	0	0	0	0	0	0/168
OFP S6(VCC+)	0/104	0	0	0	0	0	0/104
DVR	0/55	0/81	0/179	0	0	0	0/315
TEWS (S7, ADCP)	1/0	0	1/0	0	0	0	2/0

Another observation of these ratios can be made by examining the extremes across the set of 11 modifications. By examining the largest ratio of necessity coefficients and the corresponding cost values, one can see that the v3 radar and the DVR have the following relationship:

$$6.94 = N_{C\text{-}V3\ RADAR}/N_{C\text{-}DVR} < Cost_{V3\ RADAR}/Cost_{DVR} = 40.7. \qquad \text{(Eq. 3)}$$

This would indicate that linear programming would choose buying DVR to maximize capability.

Likewise, by examining the largest ratio of cost coefficients and the corresponding necessity values, the Tactical Electronic Warfare Set (TEWS) and NVIS II have this relationship.

$$2.78 = N_{C\text{-}TEWS}/N_{C\text{-}NVIS}\ II < Cost_{TEWS}/Cost_{NVIS}\ II = 630. \qquad \text{(Eq. 4)}$$

This would indicate that the optimization would tend to buy NVIS II modifications.

To remedy this situation of always buying low-cost, lease-capable modifications, one should examine the spread of Necessity Coefficients, N_C, and their relation to the spread of cost and budget authority. While the cost scale and constraints must remain on a linear scale, the Necessity Coefficients could be further spread, using a larger base. Recall the current scale of N_C uses $e^{\text{(Adjusted Rating \& rank)}}$. One could better balance cost using $\alpha^{\text{(Adjusted Rating \& rank)}}$, where α is chosen in the range that satisfies both Equations 3 and 4. For example, using an α of 100 and 50, the following results comparable to Table 7 are produced in Table 8.

CONCLUSIONS

This article documents an effective approach to compare system modifications in terms of capability provided, through the use of surveying experienced pilots and extracting their assessment of upgrade "necessity" to successfully conduct various missions. Necessity proved to be a novel way to compare, on a common scale, candidate upgrades with widely different system parameters. Additionally, scaling necessity on an exponential scale should better represent a user's true relative preferences. While a linear programming model can combine cost and necessity (capability), incorporating a myriad of complex constraints and relationships, one must understand the limitations of these models. In particular, one should balance scales of necessity and cost by examining point ratio extremes. These ratios (slopes) guide the search algorithms in linear programming to solutions. Results provide recommended modification purchases for the USAF F-15 fleet for combat and training aircraft across three FYDPs. This approach should be extensible across DoD programs, to extract quantitative measures of capability, constrained by budget authority, to provide those capabilities.

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Lt Col John Colombi, USAF (Ret.), is an assistant professor of Electrical Engineering at the Air Force Institute of Technology (AFIT). He holds a Ph.D. in Electrical Engineering from AFIT. Currently, he teaches graduate courses and leads sponsored research in support of the Systems Engineering program. Dr. Colombi led Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance systems integration activities, including systems engineering for the Airborne Warning and Control System at Hanscom AFB, MA.

(E-mail address: john.colombi@afit.edu)

Lt Col David Jacques, USAF (Ret.), is an assistant professor of Aerospace Engineering on the faculty of the Air Force Institute of Technology (AFIT). He holds a Ph.D. in Aeronautical Engineering from AFIT. Dr. Jacques is currently curriculum chair of the Graduate Systems Engineering Program. His research interests are in the areas of concept definition and evaluation, architecture modeling, and optimal system design. Dr. Jacques led the activation of the Air Force Center for Systems Engineering.

(E-mail address: David.Jacques@afit.edu)

Dr. Dennis Strouble is an assistant professor of Systems Engineering Management at the Air Force Institute of Technology. He holds a Ph.D. in Management and a J.D. from Texas Tech University. Currently, he teaches graduate courses in Systems Engineering Management, Information Resource Management and Law, and leads sponsored research in support of the Systems Engineering and Information Research Management programs. Dr. Strouble has taught at several universities, has remained active in the practice of law, and has founded and managed several businesses.

(E-mail address: dennis.strouble@afit.edu)

AUTHOR **BIOGRAPHY**

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