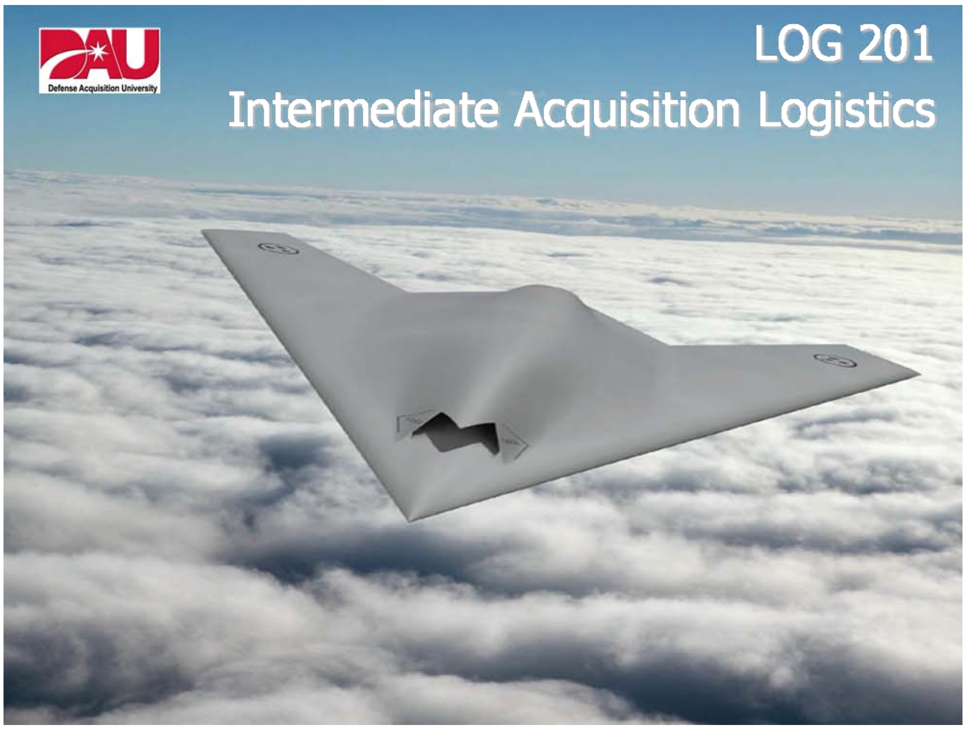
A Prognostics and Health Management System for an Unmanned Combat Aircraft System – A Defense Acquisition University Case Study

Richard A. Di Lorenzo[1] and Michael A. Bayer[2]

[1, 2] Defense Acquisition University Mid-West, Kettering, Ohio, 45420, U.S.A.

Richard.DiLorenzo@dau.mil

Michael.Bayer@dau.mil



ABSTRACT

A prognostics and health management (PHM) system is the focus of reliability improvement in the Defense Acquisition University's LOG 201 Intermediate Acquisition Logistics Part B course. LOG 201 is a one-week case-based course required for Level II certification in the Department of Defense Life-cycle Logistics career field, as required by the Defense Acquisition Workforce Improvement Act (DAWIA). In this hypothetical case, the PHM System is to be embedded in the Strike Talon Unmanned Combat Aircraft System for use by the United States Air Force and Navy.

This paper describes the Strike Talon users' requirements for a PHM system, a market investigation to determine if usable PHM monitoring equipment is already available, and

ultimate development and testing of a PHM system, which would precede a decision to produce the Strike Talon. It is the authors' intent to provide the reader with a sense of how a PHM capability may be acquired for a new unmanned combat aircraft system and how acquisition personnel could be acquainted with the impact PHM has on a system.

1. INTRODUCTION:

Department of Defense (DoD) life-cycle logisticians are required to take Defense Acquisition University's (DAU's) LOG 201 Intermediate Acquisition Logistics Part B course in order to attain Level II certification in the Life-Cycle Logistics career field. The typical student is a Logistics Management Specialist, Job Series 346. LOG 201 is a one-week case-based course, typically consisting of five rather homogenous teams of six students each. The course emphasizes the logistics-related upfront activities that lead to the acquisition of a weapon system. The weapon system used is a (hypothetical) unmanned combat aircraft system (UCAS), dubbed the Strike Talon, intended for Air Force and Navy users; although fictitious, it is based on an earlier real-life acquisition activity.

The Strike Talon Acquisition Strategy (AS) document, in the course, states that the "Strike Talon UCAS will provide extended range, long loiter, and ground attack capability to shorten the kill chain." The AS also states that "Initial Operational Capability (IOC) for the Strike Talon is defined as one squadron with 10 unmanned aircraft (UA), 2 ground control stations and sufficient support assets (technical data, training systems, spares, and support equipment)."

The part of the Strike Talon weapon system that gets the most attention (reliability improvement) in LOG 201 is the prognostics and health management (PHM) system. An aircraft PHM system can provide reliability and maintainability data in near real-time to war planners and maintenance folks on the ground. This should result in less aircraft down time, thereby increasing its operational availability and fleet readiness.

2. STRIKE TALON PHM REQUIREMENTS (IN USER JARGON)

In LOG 201, the U.S. Air Force and Navy desire the Strike Talon to feature a PHM system. As prescribed by the DoD, PHM and other user requirements are to be documented in the users' Capability Development Document (CDD), a living document describing not only capability requirements, but also operational parameters. The Strike Talon PHM requirements are as follows:

- The Strike Talon UCAS shall have a Prognostics and Health Management System (PHM) that will track the current health and condition of the Strike Talon UCAS through the use of health monitoring, diagnostics and prognostics. Rationale: Safety of flight, operational flexibility, mission accomplishment and SA (situational awareness).

- The PHM sub-systems will have a Mean Flight Hours Between Failures (Design Controllable) threshold of ≥ 6 Hours with an objective of ≥ 13 Hours.

- The PHM sub-systems will have a Mean Flight Hours between Abort (Design Controllable) threshold of ≥100 Hours with an objective of ≥ 220 Hours.

- The Main Operating Base (MOB) Mission Control System (MCS) shall monitor health and status of all unmanned aircraft (UA) under its control.

- MOB and FOB (Forward Operating Base) MCS shall conduct pre-flight and in-flight diagnostics and functional verification of mission avionics via Line of Sight (LOS) data links.

- The MOB MCS shall provide Beyond Line of Sight (BLOS) communications for UA Command and Control (C2), voice communications, mission data, Air Traffic Control (ATC) data and PHM data.

- The FOB MCS shall provide LOS communications for UA C2, voice communications, ATC data and PHM data.

- PHM status and maintenance required shall be displayed in a format that does not require technical interpretation.

- The UCAS prognostics shall detect trends and provide warning of incipient flight critical failures.

- The UCAS prognostics shall track the life usage accumulation on life-limited UCAS components in order to predict remaining life.

- The UCAS prognostics shall predict premature failures on life-limited components to enable part replacement within 10 percent remaining life.

- The PHM sub-systems will have a Mean Time to Repair threshold of ≤ 2 Hours with an objective of ≤ 1.3 Hours.

- The PHM sub-systems will have a Mean Corrective Maintenance Time Abort threshold of ≤ 2.5 Hours with an objective of ≤ 1.7 Hours.

- The PHM sub-systems will have a Maximum Corrective Maintenance Time (MMAXC at the 95th percentile) threshold of ≤ 4.5 Hours with an objective of ≤3 Hours.

- The PHM sub-systems will have a Direct Maintenance Man-hours per Flight Hour threshold of ≤ 9.5 Hours with an objective of ≤ 6 Hours.

- The UCAS design shall enable performance of all post-maintenance UA functional checks while the MCS is simultaneously controlling its maximum number of airborne UA.

- The PHM sub-systems should be capable of a BIT (Built-in Test) Fault Detection Rate coverage (FDet coverage) of all system failures with a minimum threshold ≥ 85%.

- The PHM sub-systems should be capable of a BIT Fault Detection Rate Flight Safety Critical of all flight safety critical failures that impact operational performance with a minimum threshold of ≥ 95%.

- The PHM sub-systems should be capable of a BIT Fault Detection Rate Functional of all mission systems functional failures impacting operational performance ≥ 95%.

- The PHM sub-systems should be capable of a BIT Fault Detection Accuracy of all system BIT detectable failures with a minimum threshold of ≥ 98%.

- The PHM sub-systems should be capable of a BIT Fault Isolation Rate (FIsolation) capability to isolate detected failures to an ambiguity group of one Weapon Replaceable Assembly (WRA) minimum threshold of ≥ 85%.

- The PHM sub-systems should be capable of maximizing Mean Flight Hours between False Alarms (MFHBFA) to a minimum threshold of ≥ 300 Hours with an objective of ≥ 2000 Hours.

- The UCAS diagnostics shall continue to operate while other PHM functions are being exercised.

- The PHM sub-system should be capable of maximizing Mean Time Between Operational Mission Failure to a minimum threshold of > 40 Hours with an objective of > 90 Hours.

- The PHM sub-system should be capable of minimizing Mean Corrective Maintenance Time Operational Mission Failure to a maximum threshold of < 3 Hours with an objective of < 2 Hours.

3. STRIKE TALON PHM MARKET INVESTIGATION: CAN EXISTING PRODUCTS MEET THE NEED?

To determine the extent to which PHM requirements could be cost-effectively satisfied by existing products, the Strike Talon officials conducted a PHM market investigation prior to the Milestone A decision point (exiting from the Materiel Solution phase and entering the Technology Development phase of acquisition). More precisely, the market investigation was structured to determine whether commercial-off-the-shelf (COTS) or non-developmental items (NDI) could be incorporated into the PHM system to provide performance monitoring data on the following Strike Talon systems identified as mission critical: engine; oil system; hydraulic system; airframe and airframe structural components; aviation electronics (i.e., avionics), specifically the radar and flight control systems; and tires. To the extent that COTS/NDI are suitable, a Technology Development phase would not be required for the Strike Talon PHM. If required, a Technology Demonstration Strategy would need to be developed and approved at Milestone A.

The market investigation revealed that there are at least three vendors (Kildare, Slate, and Spacely) with performance monitoring products in various stages of technology maturation for the following ten Strike Talon-relevant areas:

1. Engine Life Usage: A system for monitoring critical engine performance parameters such as temperature, vibration, thrust, etc.

2. Oil Monitoring: A system for monitoring cooling and lubricating oil parameters such as temperature, pressure, viscosity, metal content, etc.

3. Hydraulic Contamination: A system to monitor and detect hydraulic system condition based upon pressure, temperature, and presence of foreign objects, e.g. metal chips.

4. Corrosion: A system designed to detect the presence of corrosion in internal aircraft spaces and structural components. Various products can measure corrosion propagation and predict corrosion induced failure.

5. Flight Load: A system to monitor dynamic g-force loads on an aircraft fuselage, wings, and flight control surfaces. These products provide a method for monitoring the loads experienced by airframe components to determine service life degradation, identify the need for conditional inspections, or the need to perform a maintenance action to prevent failure.

6. Radar Integrity: A system to monitor and detect anomalies in the radar system's performance; measures such parameters as radar coolant temperature, radar component temperature, accuracy, etc. Various products provide data that notifies operators of radar system readiness, capabilities, and associated system and component performance data to determine component life usage. Scheduled maintenance may become event based versus calendar based.

7. Flight Control: A system to measure the performance and health of flight control components such as processors, auto pilots, and servos.

8. Carbon Stress: Products that employ nano-tube sensors embedded in carbon fiber structures that can be used to detect strain, measure loads, detect cracks and crack propagation, and in some instances, "heal" microscopic stress anomalies before they can become stress cracks. The product provides a method for measuring life degradation based on actual usage and allows scheduled maintenance to be based on the material condition of the structure rather than on a time-based schedule.

9. Tire Condition: Much like the tire pressure monitoring systems available in many cars today, this system monitors tire conditions such as pressure, temperature, and tread thickness.

10. Flight Computer: Monitoring product that uses feedback loops to ascertain flight surface compliance with flight computer guidance.

Data from the three PHM-related vendors are summarized in Table 1.

Vendor / Monitoring Product	Kildare			Slate			Spacely			Suitability Index
	TRL	Perf.	Cost ($K)	TRL	Perf.	Cost ($K)	TRL	Perf.	Cost ($K)	
Engine Life Usage	9	.85	$27	8	.73	$36	9	.91	$24	
Oil Monitoring	7	.60	$16	8	.70	$21	8	.73	$36	
Hydraulic Contamination	5	.53	$35	5	.67	$37	5	.72	$42	
Corrosion	5	.33	$57	6	.46	$79	5	.45	$63	
Flight Load	3	N/A	N/A	5	.67	$87	5	.71	$81	
Radar Integrity	4	.37	$58	4	.5.	$47	5	.61	$63	
Flight Control	6	.65	$74	6	.62	$54	7	.77	$85	
Carbon Stress	2	N/A	$5,000	1	N/A	N/A	2	.91	$3,000	
Tire Condition	9	.95	$23	9	.94	$31	9	.90	$37	
Flight Computer	5	.55	$76	4	.84	$49	3	N/A	N/A	

Table 1 PHM-Related Vendor-Supplied Data

After being presented with this data, LOG 201 student teams are tasked to fill out the last column, Suitability Index (based only on TRL – Technology Readiness Level), with a "1" to indicate "suitable for use"; a "2" for "worthy of a deeper look"; or a " 3", meaning "not suitable for use". A TRL of at least 6 is required at Milestone B (exit from the Technology Development phase and entrance into the Engineering and Manufacturing Development phase of acquisition). Therefore, the Engine Life Usage monitoring product, as an example, would seem to merit a Suitability Index of 1 because the TRLs associated with all three vendors are at least 6 (each is a 9). Any PHM monitoring product that earns a "1", or possibly a "2", are considered worthy for use in the Strike Talon PHM system.

After reviewing the PHM market investigation data (emphasizing technology maturity) and refining the Strike Talon PHM requirements, program officials decided to require only the following six PHM monitoring products:

1. Engine Life Usage Processor (ELUP)
2. Hydraulic Health Sub-unit
3. Flight Stress Computer
4. Health Management System Signal Processor
5. Data Download System
6. Vehicle Management System.

The next major PHM-related step in the acquisition of Strike Talon was to write contractually-binding technical requirements for the PHM system.

4. SELECTED STRIKE TALON PHM REQUIREMENTS (IN CONTRACTUAL JARGON)

Contractual technical requirements for Strike Talon are contained in its Performance Based System Specification (PBSS), which is derived from the latest approved version of the CDD. The Strike Talon PBSS Diagnostics includes the following requirements for the PHM (all of which are covered in the next and following sections):

1. The UCAS shall achieve a BIT FDet coverage of 85 percent of all system faults excluding structural and mechanical equipment where the design does not allow for BIT integration.

2. The UCAS shall incorporate a BIT FIsolation Rate capability to isolate not less than 85 percent of detected faults to an ambiguity group of one WRA.

3. The UCAS shall incorporate a BIT FIsolation capability to isolate not less than 90 percent of detected faults to an ambiguity group of two WRAs. Fault isolation can be through manual, semi-automatic, or automatic means, with manual or semi-automatic isolation performed in accordance with approved technical documentation.

4. The UCAS, excluding the Support System, Mean Flight Hours Between False Alarms (MFHBFA) shall be greater than or equal to 300 hours (Threshold) and 2000 hours (Objective).

Relevant to these PBSS requirements, the following explanations are provided:

- Number of False Alarms: This is the number of False BIT indications associated with a specific PHM WRA.

- Total Number of Faults: This is the total number of faults associated with a specific PHM WRA.

- Number of BIT Detectable Faults: This is the total number of faults associated with a specific PHM WRA for which there is a BIT function available to detect.

- Fault Detection Rate (Coverage): The total number of BIT detectable failures divided by the total number of failures. This excludes structural and mechanical equipment where the design does not allow for BIT integration. The minimum requirement is 85%.

- Fault Isolation Rate: A percentage of detected failure that identifies the correct faulty Weapons Replaceable Assembly (WRA) either directly or through the use of prescribed maintenance procedures. The Fault Isolation rate is the total number of failures correctly isolated to a specified WRA ambiguity group divided by the total number of detected failures (not including false alarms) then multiplied by 100 to express the quotient.

- BIT Isolation 1: This is the total number of faults associated with a specific PHM WRA for which the BIT was able to correctly isolate the fault to one specific WRA being monitored.

- BIT Isolation 2: This is the total number of faults associated with a specific PHM WRA for which the BIT was able to correctly isolate the fault to two possible WRAs being monitored.

5. STRIKE TALON PHM DEVELOPMENTAL TESTING

Next in the Strike Talon case study comes PHM Developmental Testing (DT). DT provides assurance that the requirements stated in the PBSS have been met. The Strike Talon logged 4,750 hours of DT. Test data for the six PHM monitoring products was as follows:

1. The Engine Life Usage Processor experienced 150 faults during the test period with 111 BIT detectable failures, 109 correct BIT indications, and 3 false alarms. The ELUP also had 64 BIT Isolation 1 and 84 BIT Isolation 2 events.

2. The Hydraulic Health Sub-Unit had 75 faults with 50 being BIT detectable faults and 45 correct BIT indications; there were also 2 false alarms. There were 34 BIT Isolation 1 and 43 BIT Isolation 2 occurrences.

3. The Flight Stress Computer had 199 BIT detectable faults out of 290 total faults. There were 170 correct BIT indications. There were 121 BIT Isolation 1 and 129 BIT Isolation 2 occurrences. 2 false alarms were recorded.

4. The Health Management System (HMS) Signal Processor had 155 total faults with 2 false alarms during the test period. There were 130 BIT detectable faults with 71 BIT Isolation 1 and 82 BIT Isolation 2 occurrences. 89 correct BIT indications were recorded.

5. The Data Download System had 63 total faults with 54 being BIT detectable. There were 47 correct BIT indications. The DDS had 3 false alarms, 33 BIT Isolation 1, and 37 BIT Isolation 2.

6. The Vehicle Management System had 187 BIT detectable faults out of 225 total faults. There were 122 BIT Isolation 1 and 122 BIT Isolation 2 occurrences. There were also 3 false alarms and 160 correct BIT indications.

6. EVALUATION OF STRIKE TALON PHM DEVELOPMENTAL TEST DATA

The student teams are then tasked to evaluate the test data. To facilitate this, they are given the PHM Developmental Test Data Template as shown in Table 2. Table 3 shows the data resulting from PHM Developmental Testing.

Nomenclature	Test Hours	# False Alarms	Total # of Faults	# of BIT Detectable Faults	# of BIT indications correct	# BIT Isolation 1	# BIT Isolation 2
Prognostic & Health Management System	0	0	0	0	0	0	0
Engine Life Usage Processor (ELUP)	0	0	0	0	0	0	0
Hydraulic Health Sub-unit	0	0	0	0	0	0	0
Flight Stress Computer	0	0	0	0	0	0	0
Health Management System (HMS) Signal Processor	0	0	0	0	0	0	0
Data Download System	0	0	0	0	0	0	0
Vehicle Management System	0	0	0	0	0	0	0

Table 2 PHM Developmental Test Data Template

Nomenclature	Test Hours	# False Alarms	Total # of Faults	# of BIT Detectable Faults	# of BIT indications correct	# BIT Isolation 1	# BIT Isolation 2
Prognostic & Health Management System	4750	15	958	731	620	445	497
Engine Life Usage Processor (ELUP)	4750	3	150	111	109	64	84
Hydraulic Health Sub-unit	4750	2	75	50	45	34	43
Flight Stress Computer	4750	2	290	199	170	121	129
Health Management System (HMS) Signal Processor	4750	2	155	130	89	71	82
Data Download System	4750	3	63	54	47	33	37
Vehicle Management System	4750	3	225	187	160	122	122

Table 3 PHM Developmental Test Results

This data is linked to the following PHM Developmental Test Data spreadsheet (figure 1), which the students are asked to analyze:

Nomenclature	TYPE	MFHBFA			$F_{Det\ coverage}$		$F_{Isolation}$	
		Allocated		Actual	Min Rqmt	Actual	Min Rqmt	Actual
		T	O					
Strike Talon		20	300				**.85 to 1 WRA**	**0.72**
Unmanned Aircraft		60	400				**.9 to 2 WRA**	**0.80**
Prognostic & Health Management System		300	2000	**316.67**	**0.85**	**0.76**		
Engine Life Usage Processor (ELUP)	**WRA**					0.74		
Hydraulic Health Sub-unit	**WRA**					0.67		
Flight Stress Computer	**WRA**					0.69		
Health Management System (HMS) Signal Processor	**WRA**					0.84		
Data Download System	**WRA**					0.86		
Vehicle Management System	**WRA**					0.83		

Figure 1 PHM Developmental Test Data Computations

An example of an acceptable evaluation of the data for the four PHM diagnostics requirements is:

BIT FDet coverage: <u>does not meet the specification</u> since the computed value, .76, is smaller than the minimum acceptable value of .85.

BIT FIsolation to an ambiguity group of **one** WRA: <u>does not meet the specification</u> since the computed value, .72, is less than the minimum acceptable value of .85.

BIT FIsolation to an ambiguity group of **two** WRA: <u>does not meet the specification</u> since the computed value, .80, is less than the minimum acceptable value of .90.

MFHBFA: <u>meets the specification</u> because the computed value, 316.67 hours exceeds the minimum acceptable value of 300 hours.

7. STRIKE TALON PROGRAM OFFICE RESPONSE TO FAILED PHM DEVELOPMENTAL TESTING

Since the PHM system met only one of its four requirements, the Strike Talon program office asked the contractor for a get-well plan in preparation for another cycle of DT. The contractor develops and submits engineering change proposals (ECPs), planned design (reliability) improvements for each of the six monitoring products in the PHM system. Implementation of these ECPS will affect funding needed to acquire and support Strike Talon as well its expected operational availability (as affected by inherent availability of the PHM system). Those effects are explicitly addressed in the following spreadsheet (figure 2.):

Student Instructions:

1. Read the scenarios located in LOG 201 M3-1 Exercise Student Workbook.
2. Under the WRA located below, select whether to accept the scenario to be incorporated or not.
3. As each scenario is selected, the impact is displayed below (Negative # implies improvement).
4. Procurement Cost is capped at Not-to-Exceed (NTE) $55M.
5. Repair & Non-Recurring Costs is capped at NTE $170M.
6. Field/Fleet Cost is capped at NTE $35M
7. Field/Fleet LFp Cost is capped at NTE $10M.

The Strike Talon UCAS Threshold - Ao at IOT&E≥75%, since the PHM system is critical to overall aircraft availability
The PHM system must met an Ai (System Availability) of ≥ 90% to ensure the Aircraft Ao meets Threshold.

Current PHM Ai is: 41%

Table 1

PHM Sub-System Summary Cost Table

			Accept Scenario?	PHM Sub-System	Procurement Cost ($k)	Repair & Non-recurring Costs ($k)	Field/Fleet Cost ($k)	Field/Fleet LFp ft³ ($k)	Original Ai	Improved Ai
				Current as is LCC$:	$ 52,275	$ 390,766	$ 82,144	$ 76,230		
Wal Mart	80-77602-102	Engine Life Usage Processor (ELUP)	No		$ 10,403	$ 121,253	$ 19,281	$ 21,770	5.71%	5.71%
				Negative # Implies Improvement:	$ -	$ -	$ -	$ -		
John Deer	80-77602-103	Hydraulic Health Sub-unit (HHSU)	No		$ 8,161	$ 55,034	$ 13,417	$ 11,235	5.21%	5.21%
				Negative # Implies Improvement:	$ -	$ -	$ -	$ -		
Banner	80-77602-104	Flight Stress Computer (FSC)	No		$ 6,463	$ 55,269	$ 9,424	$ 3,990	8.51%	8.51%
				Negative # Implies Improvement:	$ -	$ -	$ -	$ -		
Kildare	80-77602-105	Health Management System (HMS) Signal Processor	No		$ 7,707	$ 43,366	$ 20,810	$ 25,515	7.51%	7.51%
				Negative # Implies Improvement:	$ -	$ -	$ -	$ -		
Slate	80-77602-106	Data Download System (DDS)	No		$ 6,292	$ 78,780	$ 4,404	$ 1,120	5.33%	5.33%
				Negative # Implies Improvement:	$ -	$ -	$ -	$ -		
Spacely	80-77602-107	Vehicle Management System (VMS)	No		$ 13,249	$ 37,063	$ 14,808	$ 12,600	8.80%	8.80%
				Negative # Implies Improvement:	$ -	$ -	$ -	$ -		
							PHM cumlative impact to Ai is:		41.07%	41.07%
				Engine Life Usage Processor (ELUP)	$ -	$ -	$ -	$ -		
				Hydraulic Health Sub-unit	$ -	$ -	$ -	$ -		
				Flight Stress Computer	$ -	$ -	$ -	$ -		
				Health Management System (HMS) Signal Processor	$ -	$ -	$ -	$ -		
				Data Download System	$ -	$ -	$ -	$ -		
				Vehicle Management System	$ -	$ -	$ -	$ -		
				Cumlative Impact:	$ -	$ -	$ -	$ -		
				Improved LCC$:	$ 52,275	$ 390,766	$ 82,144	$ 76,230		

Figure 2 Effects of Proposed PHM Design Improvements

The student teams are tasked to work this spreadsheet and answer the question "Which, if any, of the six ECPs should we fund?" They do this by changing "No" to "Yes" in the "Accept Scenario?" column. The word "Scenario" here means ECP. The spreadsheet computes cost impacts (four columns) which the student must compare to the four funding limitations (items 4-7 in the Student Instructions above the spreadsheet). The spreadsheet also computes the impact on Ai (inherent availability) of each PHM product monitoring, where the "total" should reach 90%. The solution that comes **closest** to satisfying the constraints is to buy every ECP except for the Data Download System (DDS). This solution is shown in the following spreadsheet (figure 3):

Student Instructions:

1. Read the scenarios located in LOG 201 M3-1 Exercise Student Workbook.
2. Under the WRA located below, select whether to accept the scenario to be incorporated or not.
3. As each scenario is selected, the impact is displayed below (Negative # implies improvement).
4. Procurement Cost is capped at Not-to-Exceed (NTE) $55M.
5. Repair & Non-Recurring Costs is capped at NTE $170M.
6. Field/Fleet Cost is capped at NTE $35M
7. Field/Fleet LFp Cost is capped at NTE $10M.

The Strike Talon UCAS Threshold - Ao at IOT&E≥75%, since the PHM system is critical to overall aircraft availability
The PHM system must met an Ai (System Availability) of ≥ 90% to ensure the Aircraft Ao meets Threshold.

Current PHM Ai is: 89%

Table 1

PHM Sub-System Summary Cost Table

			Accept Scenario?	PHM Sub-System	Procurement Cost ($k)	Repair & Non-recurring Costs ($k)	Field/Fleet Cost ($k)	Field/Fleet LFp ft^3 ($k)	Original Ai	Improved Ai
				Current as is LCC$:	$ 52,275	$ 390,766	$ 82,144	$ 76,230		
Wal Mart	80-77602-102	Engine Life Usage Processor (ELUP)	Yes		$ 10,403	$ 121,253	$ 19,281	$ 21,770	5.71%	13.91%
				Negative # Implies Improvement:	$ 617	$ (92,621)	$ (13,277)	$ (19,705)		
John Deer	80-77602-103	Hydraulic Health Sub-unit (HHSU)	Yes		$ 8,161	$ 55,034	$ 13,417	$ 11,235	5.21%	10.86%
				Negative # Implies Improvement:	$ 704	$ (36,924)	$ (8,276)	$ (9,170)		
Banner	80-77602-104	Flight Stress Computer (FSC)	Yes		$ 6,463	$ 55,269	$ 9,424	$ 3,990	8.51%	12.16%
				Negative # Implies Improvement:	$ 391	$ (34,010)	$ (5,450)	$ (2,590)		
Kildare	80-77602-105	Health Management System (HMS) Signal Processor	Yes		$ 7,707	$ 43,366	$ 20,810	$ 25,515	7.51%	26.39%
				Negative # Implies Improvement:	$ 322	$ (34,432)	$ (16,795)	$ (24,640)		
Slate	80-77602-106	Data Download System (DDS)	No		$ 6,292	$ 78,780	$ 4,404	$ 1,120	5.33%	5.33%
				Negative # Implies Improvement:	$ -	$ -	$ -	$ -		
Spacely	80-77602-107	Vehicle Management System (VMS)	Yes		$ 13,249	$ 37,063	$ 14,808	$ 12,600	8.80%	20.79%
				Negative # Implies Improvement:	$ 611	$ (22,433)	$ (7,766)	$ (10,710)		
								PHM cumlative impact to Ai is:	41.07%	89.44%
				Engine Life Usage Processor (ELUP)	$ 617	$ (92,621)	$ (13,277)	$ (19,705)		
				Hydraulic Health Sub-unit	$ 704	$ (36,924)	$ (8,276)	$ (9,170)		
				Flight Stress Computer	$ 391	$ (34,010)	$ (5,450)	$ (2,590)		
				Health Management System (HMS) Signal Processor	$ 322	$ (34,432)	$ (16,795)	$ (24,640)		
				Data Download System	$ -	$ -	$ -	$ -		
				Vehicle Management System	$ 611	$ (22,433)	$ (7,766)	$ (10,710)		
				Cumlative Impact:	$ 2,645	$ (220,421)	$ (51,564)	$ (66,815)		
				Improved LCC$:	$ 54,920	$ 170,345	$ 30,580	$ 9,415		

Figure 3 Results of Accepting PHM Design Improvements

Note that the improved PHM Ai of 89% is a bit less than the 90% that was sought. And that one of the cost constraints (Repair and Non-recurring Costs) is a bit over the funding cap ($170.345M vs. $170.000M), but these are considered so close that further improvement is not necessary.

Next the contractor implements the design improvements to the PHM monitoring products (except the DDS) and subjects the improved PHM to 2375 hours of additional Developmental Test. Data are collected and calculations are made as before. The results are shown in Table 4.

Updated Testing after Reliablity Improvements incorporated in M3-1 Exercise 1							
Nomenclature	Test Hours	# False Alarms	Total # of Faults	# of BIT Detectable Faults	# of BIT indications correct	# BIT Isolation 1	# BIT Isolation 2
Prognostic & Health Management System	2375	1	875	835	676	579	621
Engine Life Usage Processor (ELUP)	2375	0	130	119	118	99	110
Hydraulic Health Sub-unit	2375	0	52	52	47	36	45
Flight Stress Computer	2375	0	270	250	177	150	160
Health Management System (HMS) Signal Processor	2375	0	149	149	106	95	98
Data Download System	2375	1	63	54	47	33	33
Vehicle Management System	2375	0	211	211	181	166	175

Table 4 Results of Additional Developmental Testing

The resulting data analysis for the improved PHM system is shown in Figure 4.

Nomenclature	TYPE	MFBFA			$F_{Det\ coverage}$		$F_{Isolation}$	
		Allocated		Actual	Min Rqmt	Actual	Min Rqmt	Actual
		T	O					
Strike Talon		45	300				.85 to 1 WRA	0.86
Unmanned Aircraft		60	400				.9 to 2 WRA	0.92
Prognostic & Health Management System		300	2000	2375.00	0.85	0.95		
Engine Life Usage Processor (ELUP)	WRA					0.92		
Hydraulic Health Sub-unit	WRA					1.00		
Flight Stress Computer	WRA					0.93		
Health Management System (HMS) Signal Processor	WRA					1.00		
Data Download System	WRA					0.86		
Vehicle Management System	WRA					1.00		

Figure 4 Additional Developmental Test Data Computations

All the PHM-related requirements are now satisfied!

CONCLUSION

This paper discussed the early PHM-related activities in the acquisition of a hypothetical UCAS for the Air Force and Navy, the Strike Talon, as discussed in DAU's LOG 201 course. LOG 201 does a lot more than discussed here, but the sub-system that gets the most treatment in LOG 201 is the PHM because of its relevance to the logistics support community.

This paper provided the users' PHM requirements; covered a market research for available PHM products; and discussed contractual PHM requirements and their verification via Developmental Testing. Since the initial DT was not satisfactory, the contractor was funded to re-design and perform additional DT. This time, the PHM passed.

NOMENCLATURE:

Ai	Inherent Availability
AS	Acquisition Strategy
ATC	Air Traffic Control
BLOS	Beyond Line of Sight
C2	Command and Control
CDD	Capability Development Document
COTS	Commercial-off-the-Shelf
DAWIA	Defense Acquisition Workforce Improvement Act
DDS	Data Download System
DoD	Department of Defense
DT	Developmental Testing
DAU	Defense Acquisition University
ECP	Engineering Change Proposal
ELUP	Engine Life Usage Processor
FDet	Fault Detection
FOB	Forward Operating Base
HMS	Health Management System
IOC	Initial Operational Capability
LOG	Logistics
LOS	Line-of-sight
MFHBFA	Mean Flight Hours between False Alarms
MOB	Main Operating Base
MCS	Mission Control System
NDI	Non-developmental Item
NTE	Not-to-exceed
PBSS	Performance Based System Specification
SA	Situational Awareness
TRL	Technology Readiness Level
UA	Unmanned Aircraft
UCAS	Unmanned Combat Aircraft System

WRA	Weapon Replaceable Assembly

REFERENCE:

Instructor Support Guide, LOG 201 Intermediate Acquisition Logistics, course (2009), Defense Acquisition University, Fort Belvoir, Virginia

Richard A. Di Lorenzo is a Professor of Systems Engineering Management at the Defense Acquisition University (DAU) Mid-West Campus in Kettering, Ohio. He is an instructor of the LOG 201 Intermediate Acquisition Logistics course. He also teaches additional DAU courses in logistics and production/quality/manufacturing at DAU. He formerly taught at the Air Force Institute of Technology's School of Systems and Logistics at Wright-Patterson AFB, Ohio. There he served as course director of several R&M (reliability and maintainability) and quality courses, including design of experiments and statistical process control.

He holds the following degrees:

B.S., Mechanical Engineering, University of Notre Dame, South Bend Indiana, 1968;
MBA, Ohio State University, Columbus, Ohio, 1971;
M.S. in Aerospace Engineering, University of Dayton, 1978.

He is a graduate of the Defense Systems Management College Program Manager course and has worked as a program manager, aerospace engineer, mechanical engineer, and aerospace technical intelligence officer. He is an ASQ (American Society for Quality) Certified Reliability Engineer and Quality Engineer. He is a licensed Professional Engineer in Ohio, an Air Force Quality Facilitator and a Goldratt Theory of Constraints Jonah. He won a Best Paper Award at an ISPA (International Society of Parametric Analysts) Conference.

Michael A. Bayer is a Professor of Life Cycle Logistics at the Defense Acquisition University, Mid West Campus, Kettering, Ohio. He teaches an array of Logistic courses spanning the acquisition and sustainment areas. He was born in Sacramento, California on May 8th, 1965. He earned a Bachelor of Science in the field of Aeronautical Science from Embry Riddle Aeronautical University, Daytona Beach, Florida, U.S.A., in 1995. He later earned a Master of Science in Logistics Management from the Air Force Institute of Technology, Dayton, Ohio, U.S.A., in 2003. He served in the United States Air Force for 23 years. Additionally, he provided consultation services prior to beginning his tenure at the Defense Acquisition University. He is a the recipient of the International Society of Logistics Jerome G. Peppers, Outstanding Student Research Award