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Risk Assessment of Readiness and Life Cycle Cost for Weapon Systems

7 December 2012

by

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Abstract

Given an acceptable level of military performance, arguably the two most important criteria for weapon systems performance are readiness (operational availability, or Ao) and life cycle cost (LCC). These two criteria are in conflict: one may maximize Ao by increasing LCC or minimize LCC by degrading Ao. In this paper, we develop a model to analyze risk factors associated with this bi-criterion problem. To analyze the impact of input factors on risk, or variance in the outcome criteria, we conduct Monte Carlo simulation. We then apply design of experiments methodologies to identify risk factors by analyzing quantiles of these criteria in which we examine the probability that cost will exceed a certain threshold dollar amount and the probability that readiness falls below a certain threshold.

Keywords: weapon systems performance, readiness, life cycle cost, risk factors, Monte Carlo simulation

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I. Introduction

The life cycle cost (LCC) of a weapon system is the cost of acquiring, operating, and supporting that weapon system. The careful management of LCC will be increasingly important as defense budgets come under pressure in the next few years because of the U.S. Federal Government debt and deficit. There is a trade-off between LCC and deployed performance of a weapon system because investments in support -- e.g., spare inventory, repair capacity, etc. are expensive. Since these expenditures are to some degree discretionary, program managers will be under increasing pressure to reduce deployed support investments. The intent of such pressure will be to reduce waste, not to reduce performance. But program managers need a tool that can clearly show the trade-offs between cost and performance in order to demonstrate the performance impact of cost-cutting measures and to avoid cutting more deeply into performance than they intend.

However, it is difficult to accurately track the LCC of a single weapon system because so many support facilities (e.g., repair, training) are shared and support several weapon systems, and many costs are relatively fixed. The model we present in this paper tracks the LCC of multiple operating units of a weapon system (e.g., multiple squadrons of aircraft). The cost model incorporates start-up (fixed) costs such as acquisition and maintenance facilities, as well as spare inventory pools for major components. Operations and maintenance costs, personnel and training costs, as well as disposal costs are also included in the model.

Investment and operating expenses are related to operational availability (Ao) through a stochastic model that considers variability in operational tempo (Op-tempo), operating and maintenance costs, component reliability, and maintenance downtime. The model, which relates costs to performance, incorporates congestion effects and the impact of delays due to an insufficient investment in capacity. For example, a smaller investment in spare parts inventory may lead to reductions in Ao as weapon systems wait for depot repair of a component part.

We use our model to analyze the trade-offs between LCC and Ao across a range of input factors that represent differences between (1) acquisition program approaches, (2) depot maintenance characteristics, and (3) squadron operations. Some factors are under the control of decision-makers, such as spare inventory levels, while others are exogenous, such as the price of petroleum, oil, and lubricant (POL). The intent of including exogenous factors is to give an idea of the degree of leverage a decision-maker may have in affecting LCC or Ao, given the impact of variables beyond his or her control.

Input factors that are varied include the mean time between failures (MTBF) of major components, Op-tempo, POL cost, depot repair turnaround time (DTAT), and preventive maintenance (for depot overhaul) turnaround time (PMTAT). Each of these factors is varied over several levels, creating an analysis problem too large for a full-factorial experiment. Instead, we used a Nearly-Orthogonal Latin Hypercube (NOLH) design, which allows a detailed, if not exhaustive, analysis of the way these input variables impact the outcome criteria.

In many cases, decision-makers involved in planning and operations for a weapon system are concerned about more than just average LCC or average Ao, but in addition, they want to understand the impact of variability in costs and performance. For example, a decision-maker may wish to know the probability that LCC exceeds a given budget (which we call *budget risk* [BR]) or the probability that Ao falls below a certain planning threshold (which we call *readiness risk* [RR]; Kang, Doerr, & Sanchez, 2006; Kang, Doerr, Apte, & Boudreau, 2010). To analyze the impact of variance in the input factors on risk, we conducted post hoc analyses using Monte Carlo simulation.

To perform the post hoc analyses, we conducted a factorial experiment on three key factors, which the main analysis indicated had an impact on mean outcomes but which are also under the control of decision-makers. Results of the post hoc analyses showed the impact that factors under the control of decision-makers can have on budget and readiness risk, potentially even late in the program.

II. Case Study

We have developed a hypothetical case involving fighter aircraft, the F-XX, and its acquisition, operation, and maintenance and have created a companion spreadsheet model to estimate the LCC and Ao. We briefly describe the case in the next section. More details of this F-XX case study are described in Kang and Doerr (2012).

A. The Case and the Spreadsheet Model

A total of 96 new fighter aircraft, F-XX, will be acquired and divided into eight squadrons. The F-XX program life cycle is estimated to be 30 years. The manning requirements are as follows:

Pilots and Ground Support Personnel (per squadron)

- 17 Pilots
- 4 Ground Support Officers
- 16 Non-commissioned Officers (NCOs)
- 176 Enlisted

Headquarters Personnel

- 2 One Commanding Officer (CO) and one Executive Officer (XO) (both are pilots)
- 1 Administration Officer (non-pilot)
- 2 NCOs
- 4 Enlisted

The personnel costs are based on the DoD standard composite pay that includes standard benefits (housing, food, medical, etc., not including re-enlistment bonuses, combat pay, etc.). (See http://www.defenselink.mil/ comptroller/rates/fy2013/ 2013_k.pdf.) All F-XX personnel will require both basic and advanced levels of training. The manpower annual turnover rate is estimated to be 20%, and additional personnel must be trained due to attrition. The cost for non-pilot basic training is estimated to be $2,000 per week per person, and advanced training is estimated to be $3,000 per week per person. Pilot training costs $11,000 per week per person for both basic and advanced training. Required training times for pilots and ground maintenance personnel and headquarters personnel are as follows:

Pilots and Ground Personnel Training Requirements

Officer	Basic	Advanced
Pilot	36 weeks	12 weeks
Ground	12 weeks	2 weeks
NCO	12 weeks	2 weeks
Enlisted	24 weeks	24 weeks

Headquarters Personnel Training Requirements

Basic Admin Training (Officers, NCOs, enlisted):	10 weeks
Advanced Admin Training (Officers and NCOs):	3 weeks

Management of spare parts will be on a one-for-one exchange at the squadron level (organizational level, or O-level). It takes one day to swap the failed component with a spare part, if the part is available. Otherwise, the aircraft will be grounded until a ready-for-issue (RFI) spare part becomes available. An average waiting time for an RFI spare part is assumed to be 50% of the depot repair turnaround time. A failed component is sent to the contractor-managed depot for repair. The depot turnaround time is estimated to be 40 days. Each aircraft will go through preventive maintenance (overhaul) every five years, which takes an average of three months.

Each squadron's activity has start-up fixed costs, which are incurred at $10,000,000 per activity prior to squadron activation. Additionally, operating variable costs, which are estimated at $5,000,000 per year per O-level activity, are incurred for each year that a squadron is operational.

In this study, we consider the six major components shown in Table 1. The MTBFs and the unit costs for the components are included in the table. To make the model more realistic, we may need to add some more components, yet not too many. As shown in Kang and McDonald (2010) in the case of light armored vehicles, generally in any major weapon system, a small number of components contribute to majority of the parts cost.

Table 1. The MTBF and the Unit Cost of the Six Major Components

Component Name	MTBF	Unit Cost
Auxiliary Power Unit	250	$100,000
Generator	400	$ 250,000
Radar	1000	$ 400,000
Avionic Computer	1000	$ 500,000
Landing Gear	500	$ 400,000
Engine	500	$ 2,000,000

Each aircraft is expected to fly an average of 40 hours per month, and the cost for POL is estimated to be $2,000 per flying hour. Each copy of the F-XX has an average unit cost of $50 million. Support equipment costs are $20,000 per aircraft. These one-time costs are incurred when the F-XXs are phased into the squadrons. The expected salvage value of each aircraft at the end of the life cycle is estimated to be $5 million, which is 10% of the procurement unit cost. An annual capital discount rate of 2% is used to compute the present value of the LCC. (See http://www.whitehouse.gov/omb/circulars/a094/a094.html for guidance for the capital discount rate.)

We have developed a spreadsheet model to compute the life cycle cost and the Ao of this F-XX case. A sample screenshot of the user-interface page of the model is shown in Figure 1.

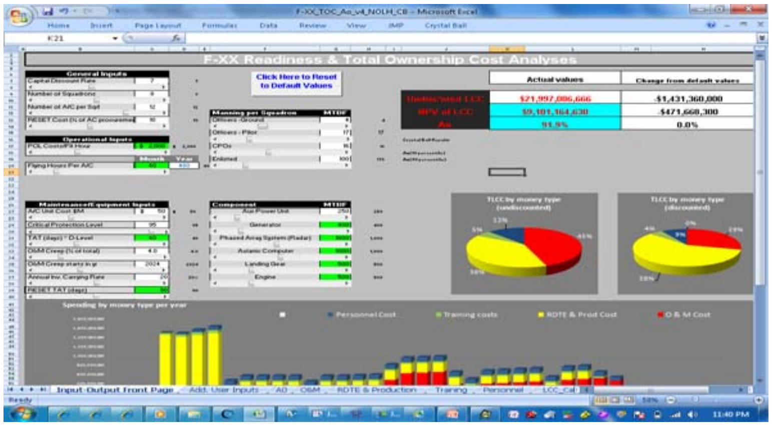


Figure 1. A Sample Screenshot of the F-XX Life Cycle Cost and Readiness Spreadsheet User-Interface Page

B. The Significant Factors

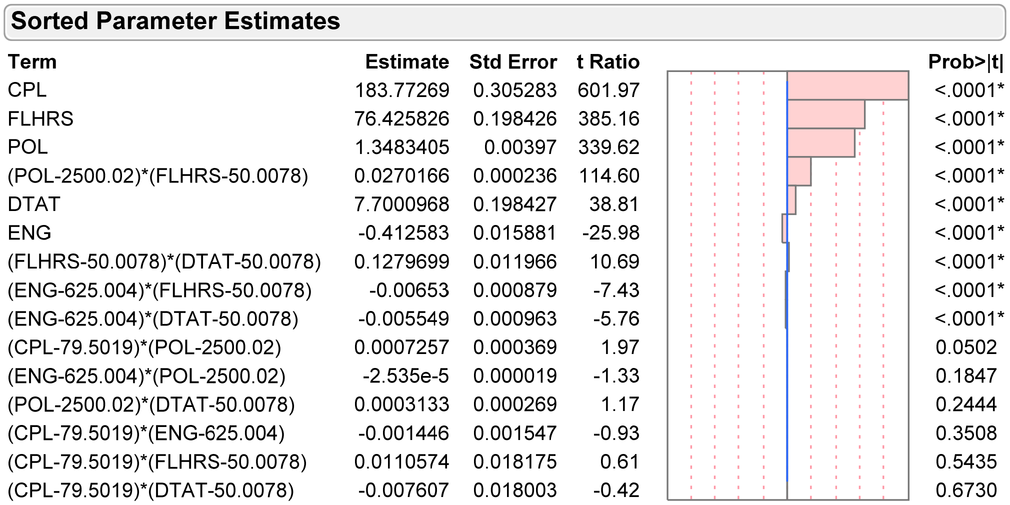
We considered the six major components (auxiliary power unit [APU], engine, landing gear, avionic computer, radar, and generator) shown in Table 1. When any of these components fails, the faulty part is removed from the aircraft, a spare is installed, and the faulty part is sent to the repair facility. After the repair is complete, the repaired part becomes a spare and is sent to the spare pool. When a critical part fails and a spare is not available, the aircraft will be non-operational and grounded until a spare becomes available. The components listed in Table 1, with the exception of the APU, are considered critical.

We have chosen the following 11 factors to identify significant factors for the readiness and life cycle cost of the program:

- MTBFs: six components' mean time between failures (or reliabilities),
- CPL: critical protection level for spare parts (fill rate or service level),
- FLHRS: monthly flight hours (operational tempo),
- POL: cost of POL,
- DTAT: depot corrective maintenance turnaround time, and
- PMTAT: preventive maintenance (or RESET) turnaround time.

We used an NOLH with 257 runs (Cioppa & Lucas, 2007). This design is capable of handling up to 29 factors without increasing the number of scenarios (Kleijnen, Sanchez, Lucas, & Cioppa, 2005; Sanchez, 2006). We have developed a macro written in Visual Basic that computes the life cycle cost and the operational availability for each scenario.

We fit regression meta-models of the life cycle cost as a function of the 11 main effects, and two-way interaction of the 11 input factors, using the JMP® software package (SAS Institute, 2008). After noticing the impact on several non-significant factors, we picked five significant factors for further analysis: CPL, ENG (MTBF of engine), POL, FLHRS, and DTAT. Then we fit regression meta-models of the LCC as a function of these five main effects and two-way interaction of these five input factors. The results are shown in Figure 2.



Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
CPL	183.77269	0.305283	601.97	<.0001*
FLHRS	76.425826	0.198426	385.16	<.0001*
POL	1.3483405	0.00397	339.62	<.0001*
(POL-2500.02)*(FLHRS-50.0078)	0.0270166	0.000236	114.60	<.0001*
DTAT	7.7000968	0.198427	38.81	<.0001*
ENG	-0.412583	0.015881	-25.98	<.0001*
(FLHRS-50.0078)*(DTAT-50.0078)	0.1279699	0.011966	10.69	<.0001*
(ENG-625.004)*(FLHRS-50.0078)	-0.00653	0.000879	-7.43	<.0001*
(ENG-625.004)*(DTAT-50.0078)	-0.005549	0.000963	-5.76	<.0001*
(CPL-79.5019)*(POL-2500.02)	0.0007257	0.000369	1.97	0.0502
(ENG-625.004)*(POL-2500.02)	-2.535e-5	0.000019	-1.33	0.1847
(POL-2500.02)*(DTAT-50.0078)	0.0003133	0.000269	1.17	0.2444
(CPL-79.5019)*(ENG-625.004)	-0.001446	0.001547	-0.93	0.3508
(CPL-79.5019)*(FLHRS-50.0078)	0.0110574	0.018175	0.61	0.5435
(CPL-79.5019)*(DTAT-50.0078)	-0.007607	0.018003	-0.42	0.6730

Figure 2. Sorted Parameter Estimates from JMP Analysis for Life Cycle Cost

As shown in Figure 2, CPL, FLHRS, and the POL cost are the major factors that affect the LCC. Also, the two-way interaction between FLHRS and POL has significant impact on the LCC. It is intuitively correct since as the POL cost and the flight hours increase at the same time; there is an accelerated impact on the increase of the life cycle cost. DTAT and ENG, and other two-way interaction factors, are not as critical as far as the LCC is concerned.

We also conducted the same regression meta-model analysis for Ao. PMTAT is by far the most significant factor, with FLHRS and DTAT also statistically significant.

The previous analyses helped to identify the critical factors for controlling the LCC and Ao across the range of significant inputs we varied. The bi-criterion problem faced by a decision-maker is to use the information provided by a model similar to ours to reduce LCC, without causing an unintentionally severe impact on Ao. Rather than looking across all factors as they vary, the decision-maker faces a particular scenario and must make decisions about whether, and how much, to vary a particular parameter. To provide an idea of how our model might be used to assist in such a decision, we took DTAT, a factor identified as important for both LCC and Ao, and varied it across its range of likely values for a particular scenario (in this case, the mean values of all other input factors). Results are shown in Figure 3. Note that while Ao is linearly decreasing in DTAT, LCC is not linearly increasing. There are levels of increase in DTAT that would provide no significant cost reduction but would degrade performance.

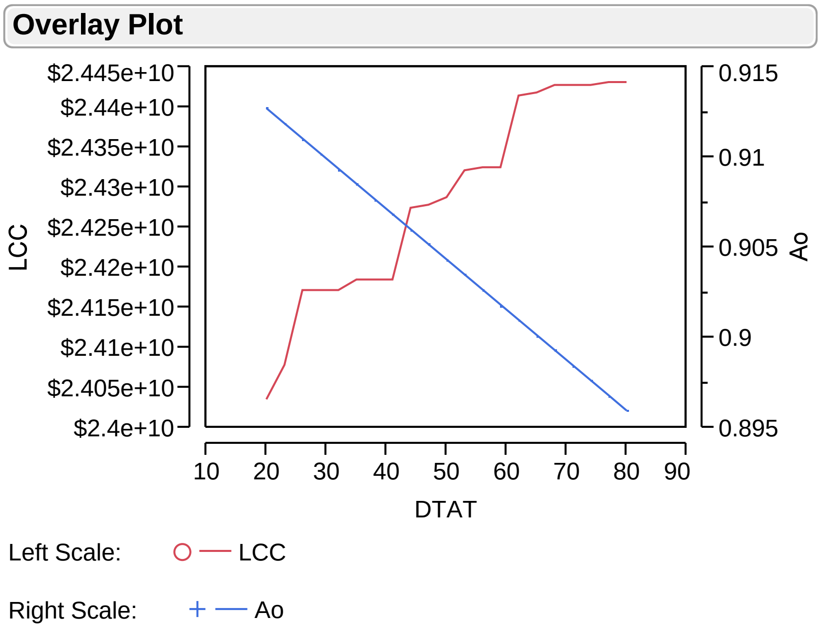


Figure 3. Depot Turnaround Time Impact on Bi-criterion Decision

III. Risk Analysis

Risk analysis focuses not upon the main outcomes of the expected LCC and Ao, but rather on the potential variability in those two metrics. Variability is important to assess for at least two reasons. First, the expected outcome may not be a reliable predictor. This is especially true of LCC. Program managers may be more interested in the probability that they will exceed their budget than the fact that the budget will be sufficient "on average." Second, the average outcome may not be especially relevant to operations. This is especially true of Ao since operations are planned assuming a particular level of readiness. Operational commanders may be more interested in knowing the probability that they will be able to execute a plan on a particular day rather than whether they would be able to execute the plan on average.

There are several potential risk metrics available to assess variability in Ao and LCC. We have selected two metrics relevant to the issues raised in the last paragraph. What we call *budget risk* (BR) is the percentage chance that LCC will exceed a given (cumulative) dollar budget. *Readiness risk* (RR) is the percentage chance that Ao will fail to achieve a given availability target.

The analysis of main outcomes indicated that cost—and, to a lesser extent, readiness—are determined in part by factors beyond the operational control of a program manager. POL and FLHRS (or Op-tempo) are both beyond his control, and except for expensive engineering change orders, improvements to engine MBTF are difficult to achieve, especially after a system is deployed. The risk analysis reported here investigated factors more easily controlled by a program manager. We intended to demonstrate that significant reductions in budget and operational risk can be obtained by manipulation of factors directly under the control of a program manager (even late in the life cycle of a weapon system—although our cost figures always refer to changes affecting the whole life cycle). In particular, we examined the effect of changes in PMTAT, DTAT, and CPL on the risk of exceeding a $20 billion budget ($20b-BR) and the risk of failing to achieve an Ao of 85% (85%-RR).

We varied our three independent variables in three levels in a 3x3x3 factorial design of experiments. At each level, the independent variable was modeled by a random variable. For DTAT, the three levels represented short, medium, and long turnaround times and were distributed by triangular distributions of the following (in days): T(10,20,40), T(20,40,80), and T(40,80,160). All three of these distributions had a coefficient of variation (CV) of 0.27. For PMTAT, the short, medium, and long turnaround times were distributed by uniform distributions of the following (in days): U(15, 105), U(22.5, 157.5), and U(37.5, 262.5). All three of these distributions had a CV of 0.43. For CPL, the three levels represented very high, high, and moderate fill rates and were distributed according to uniform distributions (in percentage) of the following: U(96.6, 99.5), U(91.25, 98.75), and U(80.75, 97.25). These distributions had a CV of 0.009, 0.023, and 0.054 (respectively), meaning that higher protection levels were also less variable.

Note that the levels selected for the independent variables are arbitrary and neither informed by historical data nor restricted carefully to provide a systematic analysis of the relationship between the independent variables and the outcomes. Therefore, the implications that can be drawn from our analysis are limited. However, our goal was merely to demonstrate (1) an approach to risk analysis, and (2) the impact that factors that can be changed by a program manager (even late in a program) can have on important program risks.

Marginal probabilities are reported in Table 2. Each cell in this table is the average across the 3x3=9 conditions of the other two factors. Results showed that readiness risk increases in PMTAT and DTAT and decreases in CPL. Budget risk increases in DTAT and decreases in CPL, although only modestly (spare parts are a small part of the overall budget). Budget risk is relatively unaffected by changes in PMTAT because our model did not include the cost associated with the extra time in computing LCC; the main impact of increasing PMTAT is that the weapon system is unavailable for longer periods.

It is worth noting that the magnitude of some of the reported changes was substantial. A 9% decrease in CPL (from 98% to 89%) resulted in a 23% decrease in readiness risk (from 31% to 8%). A 60% decrease in PMTAT (from an average of 112.5 days to an average of 45 days) resulted in a six-fold decrease in readiness risk (from 37% to 6%). On the other hand, only DTAT significantly reduced budget risk. A 75% decrease in DTAT (from an average of 80 days to an average of 20 days) reduced budget risk by half (from 16% to 8%).

Table 2. Marginal Probabilities of Readiness Risk and Budget Risk

	Marginal Probabilities					
	PMTAT		DTAT		CPL	
	85%-RR	$20b-BR	85%-RR	$20b-BR	85%-RR	$20b-BR
Low	6%	12%	9%	8%	31%	10%
Med	10%	12%	15%	11%	14%	12%
High	37%	11%	29%	16%	8%	13%

To examine interaction, we varied two factors at a time and examined the response surface of the marginal probabilities (marginal across the third factor) of each outcome. This gave us six potential graphs to draw. However, we omit the graphs involving budget risk and PMTAT because PMTAT has little impact on budget risk. Figure 4 shows readiness risk as a function of PMTAT and DTAT. As expected from the marginal results, readiness risk rises sharply as both turnaround times jointly increase. However, the function is clearly not monotonic, and there is a clear saddle point below the joint minimum, indicating that past a point, reductions in turnaround time would yield diminishing returns.

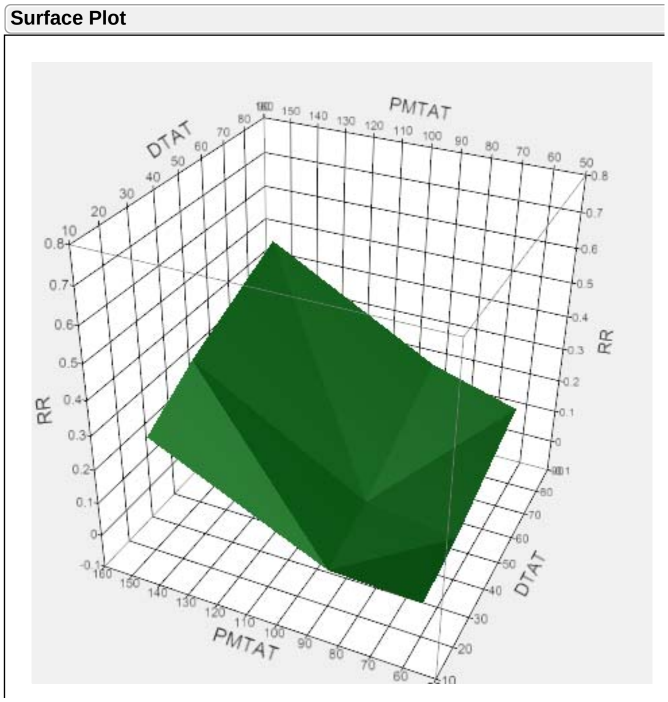


Figure 4. Readiness Risk as a Function of PMTAT and DTAT

Figure 5 shows readiness risk as a function of DTAT and CPL. Although less complex, the pattern is the same as that of Figure 4: a sharp non-linear increase in readiness risk as DTAT and CPL are jointly degraded (by increasing DTAT and decreasing CPL), a non-monotonic response surface, and diminishing marginal returns.

The graph of readiness risk as a function of PMTAT and CPL is similar to Figures 4 and 5 and is omitted. Instead, we present a contour plot (Figure 6) that clarifies something that the surface plots also suggest: that there are multiple ways to obtain a given level of readiness risk (as in the surface charts, intermediate points are interpolated). For example, one can obtain readiness risk as low as 15%, even with a PMTAT as high as 80 days, but only with very high (98%) CPL.

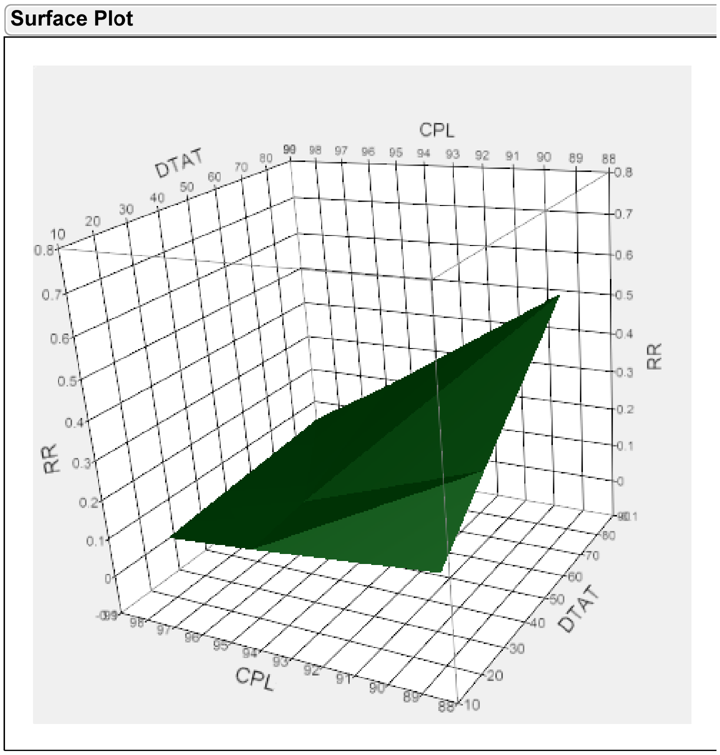


Figure 5. Readiness Risk as a Function of CPL and DTAT

Finally, Figure 7 presents a graph of budget risk as a function of DTAT and CPL. Although it is also non-linear and non-monotonic, it is clear from the graph that the effect of changes to DTAT is far more powerful than changes to CPL in reducing budget risk.

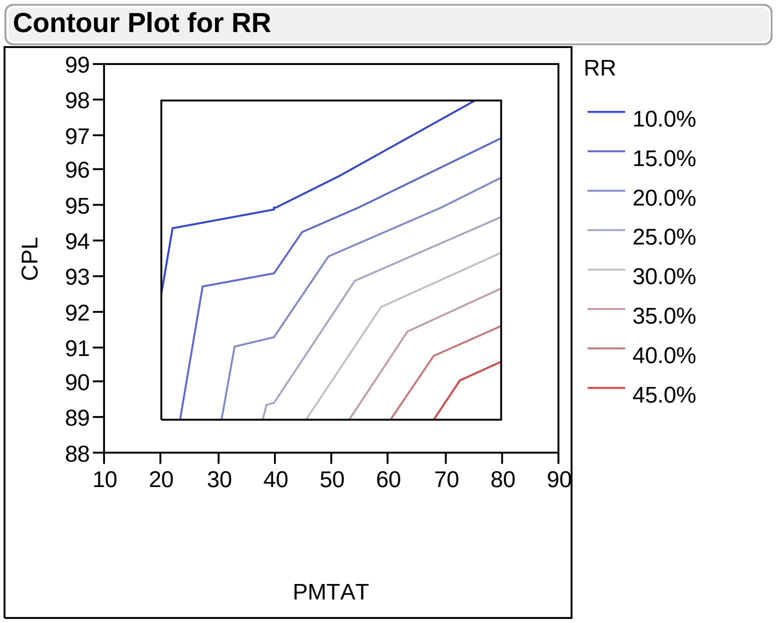


Figure 6. Readiness Risk as a Function of CPL and PMTAT

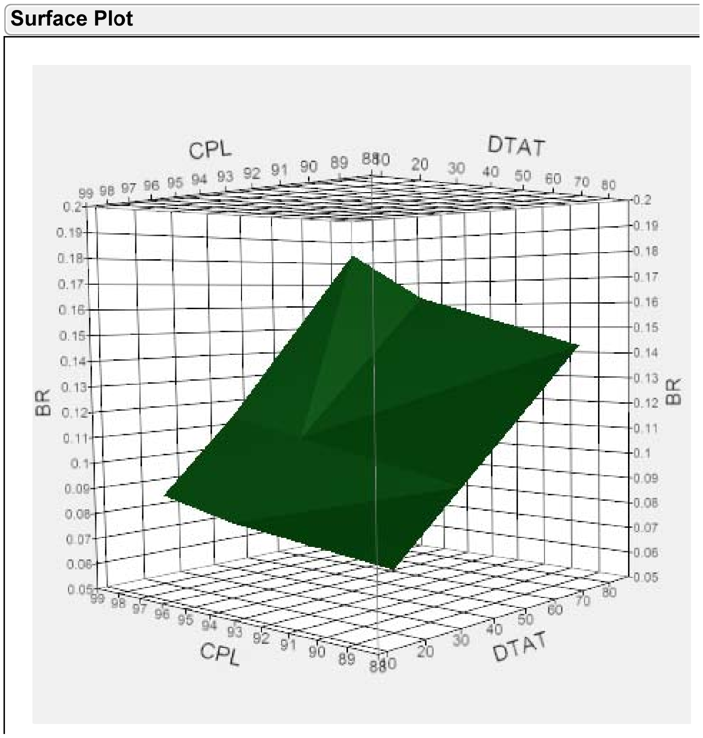


Figure 7. Budget Risk as a Function of CPL and DTAT

IV. Summary

In summary, we first presented a methodology to identify significant factors that affect readiness and life cycle cost for a weapon system, using a fighter aircraft program as an example. We then demonstrated a method of examining the joint impact of maintenance and sparing on readiness and budget risk. The impact is interactive, and highly non-linear. We have also shown that while factors beyond the control of a program manager, such as POL and FLHRS, may be critical factors in (average) Ao and life cycle cost, factors within the control of a program manager may still affect a great deal of the risk involved in those metrics.

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Human Resources

- Indefinite Reenlistment
- Individual Augmentation
- Learning Management Systems
- Moral Conduct Waivers and First-term Attrition
- Retention
- The Navy’s Selective Reenlistment Bonus (SRB) Management System
- Tuition Assistance

Logistics Management

- Analysis of LAV Depot Maintenance
- Army LOG MOD
- ASDS Product Support Analysis
- Cold-chain Logistics
- Contractors Supporting Military Operations
- Diffusion/Variability on Vendor Performance Evaluation
- Evolutionary Acquisition
- Lean Six Sigma to Reduce Costs and Improve Readiness

- Naval Aviation Maintenance and Process Improvement (2)
- Optimizing CIWS Lifecycle Support (LCS)
- Outsourcing the Pearl Harbor MK-48 Intermediate Maintenance Activity
- Pallet Management System
- PBL (4)
- Privatization-NOSL/NAWCI
- RFID (6)
- Risk Analysis for Performance-based Logistics
- R-TOC AEGIS Microwave Power Tubes
- Sense-and-Respond Logistics Network
- Strategic Sourcing

Program Management

- Building Collaborative Capacity
- Business Process Reengineering (BPR) for LCS Mission Module Acquisition
- Collaborative IT Tools Leveraging Competence
- Contractor vs. Organic Support
- Knowledge, Responsibilities and Decision Rights in MDAPs
- KVA Applied to AEGIS and SSDS
- Managing the Service Supply Chain
- Measuring Uncertainty in Earned Value
- Organizational Modeling and Simulation
- Public-Private Partnership
- Terminating Your Own Program
- Utilizing Collaborative and Three-dimensional Imaging Technology

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