Reengineering Metrics Systems for Aircraft Sustainment Teams: A Metrics Thermostat for Use in Strategic Priority Management

by

Keith A. Russell

B.S., Electrical Engineering
United States Coast Guard Academy, 1988

Submitted to the Department of Aeronautics and Astronautics and the Technology and Policy Program in Partial Fulfillment of the Requirements for the Degrees of

Master of Science in Aeronautics and Astronautics

and

Master of Science in Technology and Policy

at the
Massachusetts Institute of Technology
December 2000
[February 2001]

Signature of Author: ____________
Department of Aeronautics and Astronautics
Technology and Policy Program
December 15, 2000

Certified by: ____________ 01/04/2001
John R. Hauser
Kirin Professor of Marketing, Sloan School of Management
Thesis Supervisor

Certified by: ____________
Wesley L. Harris
Professor of Aeronautics and Astronautics
Thesis Supervisor

Accepted by: ____________
Wallace E. Vander Velde
Professor of Aeronautics and Astronautics
Chair, Committee on Graduate Students

Accepted by: ____________
Daniel Hastings
Director
Technology and Policy Program

- This page intentionally left blank -

Reengineering Metrics Systems for Aircraft Sustainment Teams: A Metrics Thermostat for Use in Strategic Priority Management

by

Keith A. Russell

Submitted to the Department of Aeronautics and Astronautics and the Technology and Policy
Program on December 15, 2000
in Partial Fulfillment of the Requirements for the Degree of Master of Science in Aeronautics
and Astronautics and Master of Science in Technology and Policy

ABSTRACT

We explore the selection of metrics for the United States Air Force weapon system sustainment team empirically with emphasis placed on the incentive, structural and predictive implications of metrics.

We define the term "metric" to include measures that employees impact through their efforts. We believe that even in a not-for-profit organization such as the Air Force, by putting emphasis (or weight) on a performance metric, the organization establishes inherent incentive structures within which employees will act to maximize their best interests. However, we believe that not-for-profit organizations differ from for-profit ones in their inherent structure since profit becomes cost and several mission-oriented outcome variables share a fundamental importance in achieving the organizations goals. We seek an understanding of the structural composition of Air Force sustainment's metrics systems that, when coupled with a method for practical selection of a high-quality set of metrics (and weights), will align the incentives of employees with the interests of the organization.

The empirical study is grounded in emerging theoretical work, which uses our above definition of a metric to purpose a theoretical metrics feedback construct called the Metrics Thermostat. System structure is explored through common correlation and regression analysis as well as more sophisticated structural equation modeling and systems dynamics techniques used to explore potential feedback loops.

The F-16 is used as a case study for this problem, and the metrics systems are considered from the front-line base-level point of view of Air Force active duty, Air National Guard and Air Force Reserve bases worldwide. 96 low-level metrics, covariates and outcomes were examined for 45 F-16 bases for a period of five years. Outcome importance was determined through personal interviews and internal archival documentation.

Key observations from the dataset to date include:

- The metrics, covariates and outcomes in the study are very interrelated.
- The primary indicator of overall performance is Command (ACC, USAFE, etc.)
- Increased Fix Rate *increases* Utilization, but increased Utilization *decreases* Fix Rate.
- Cannibalization Rate is associated with higher Fix Rates but lower Mission Capability, Flying Scheduling Effectiveness, and Aircraft Utilization.
- Active duty Mission Capability is predicted well from the dataset such that:
    - Active duty commands have higher mission capability.
    - Mission Capability is slightly higher in cool moist climates.
    - Increased Aircraft Utilization, Repeat Discrepancies and Flying Scheduling Effectiveness are all associated with higher Mission Capability.
    - Increased Break Rates and Unscheduled (engine) Maintenance are associated with lower Mission Capability.

The model appears to be valid for peacetime actions only.

Thesis Supervisor: John R. Hauser
Title: Kirin Professor of Marketing, Sloan School of Management

Acknowledgements

I would first like to thank Professor Dan Frey without whom I may not have ever attended MIT. Also, I am indebted to Professor Wes Harris who believed enough in me to make me a part of the Lean Sustainment Initiative. My research would never have been possible were it not for the generosity of the United States Coast Guard who gave me, in essence, a two-year sabbatical and for the interest of the United States Air Force Material Command and their personnel who taught me the Air Force system from the ground up.

For the day-to-day work, I am eternally grateful to my thesis advisor, Professor John Hauser. Forget for a moment his world-class technical competence and guidance. He provided nothing but praise and always instilled confidence and excitement in the project. Every time I was feeling down about our research, I knew I could look forward to our Monday meetings, and he would answer to all of my doubts and fears. There are few men of his quality. I was truly fortunate to have him as an advisor.

Along those lines, I would be remiss not to mention Jeff Moffitt. A fellow graduate student and military man, Jeff put in many hours teaching me the theory behind the statistics, a task I could not have undergone myself.

Of course, there are countless other students I have met and made friends with along the way. I believe it is the incredibly high caliber of the MIT student that makes MIT the singular experience it is. And, there are countless MIT staff members whose help in hundreds of small ways I could not have done without. It is they, I believe, who actually run the school.

But most of all, I would like to offer thanks to my family. To my mom, my dad, my brothers, and my in-laws: thank you for providing entertainment (golf or otherwise) and providing support to my immediate family when I couldn't be there. To my three sons, Connor, Sean and Brendan: thank you for making me laugh and smile and for reminding me every day that this project is not the most important thing in the world. And, most of all, thank you to my wife, Michele, who supported me in every way while I was here. Without your assistance I would not have made it through the program. Without your teachings, I would not be here to begin with. She is the prize that awaits me as I put the final ink to this page.

- This page intentionally left blank -

Table of Contents

Chapter 5 Understanding the Metrics

Chapter 6 Analysis and Results

Chapter 7 Conclusions and Recommendations

Appendices

Figures and Tables

Chapter 1: *Introduction*

1-1 *Motivation:*

Metrics have long been popular in assessing organizational behavior and attempting to maximize organizational output. Despite the fact that much of the work done in this field is associated with for-profit firms, not-for-profit firms, public firms like the United States Air Force, have traditionally embraced the idea that metrics can help maximize their output. As such, the Air Force has historically committed a significant amount of resources toward measuring performance and potential indicators of performance.

Many aspects of the public organization are similar to their counterparts in private firms. Perhaps because of this similarity, one particular sub-organization in the Air Force, the Air Force aircraft sustainment community, has recently being challenged to meet the performance-for-cost accomplishments of their private counterparts. In their attempts to do so, there is the temptation of the public organization to imitate the actions of their private counterpart. In fact, the recent establishment of methods like lean metrics systems and balanced scorecards are reemerging in popularity among particular Air Force sub-organizations. However, lost in these approaches is the understanding that the *overall* Air Force system is, at least in part, different from the private firm.

The Air Force is different from the typical private firm in other ways as well. For example, the Air Force may be more complex in size, structure and mission than most or all for-profit organizations. Enlarged structures increase the potential for sub-optimization. Also, as a government agency and, in particular, a military organization, the Air Force must operate under a complex set of rules, many of which are established out of their control at the highest levels of the Executive and Legislative branches of the United States government. Often, these rules do not allow the Air Force sustainment community to adapt as readily as their for-profit equivalents.

So, the question is:

> To what extent can the Air Force apply state-of-the-art private firm management philosophies to their operations?

To propose a limited answer to this question, the purpose of this study, in the context of a case study of the base-level metrics system of the F-16 aircraft, is twofold:

- To qualitatively explore the current state of the Air Force sustainment community's goals, objectives and metrics system, and to provide recommendations for areas where their current system does not match that of state-of-the-art theoretical systems; and
- To quantitatively explore historical base-level metrics system data for the F-16, to provide feedback as to the system structure of the F-16 sustainment system by construction and evaluation of predictive models, and to gain some insight as to the applicability of these models for Air Force use.

1-2 *Thesis Overview*

To this end, this work is organized as follows:

Chapter 2 begins with some background information in regard to the F-16 sustainment system to give a flavor for the sustainment system process as a whole. Here, we also discuss the genesis for this research idea as founded in MIT's Lean Sustainment Initiative. This genesis uncovered many qualitative observations in regard to Air Force sustainment's current goals, objectives, and metrics system. These ideas are presented as well.

Chapter 3 provides a brief review of other work conducted in this field, provides several definitions for what a metric is (and provides one for use in this work), and delves into the theory behind the Metrics Thermostat, a modern theoretical adaptive control mechanism for using metrics to maximize profit.

Chapter 4 discusses the methodology used on the F-16 data set. It provides a map that shows how we selected the system (and metrics) to be studied and what steps we took and methods we chose for analysis of the data set.

Chapter 5 provides an in-depth consideration of each of the metrics we initially chose to consider including strategic priority (high-level metric), low-level metric, covariate, and outcome definitions. Chapter 5 also provides a careful handling of the databases; their characteristics, strengths and weaknesses; since most of the data variables were from electronic databases and since these databases varied in their treatment of the data.

Chapter 6 shows our analysis and results to date, and Chapter 7 summarizes our key learnings and indicates directions for future research.

Chapter 2: Background

2-1 The United States Air Force F-16 Sustainment System

2-1-1 Sustainment and the F-16

The words enormous and complex fall short in an attempt to describe the United States Air Force sustainment system, and Air Force sustainment of the F-16 is virtually a twenty-four hour-per-day seven day-per-week global operation.

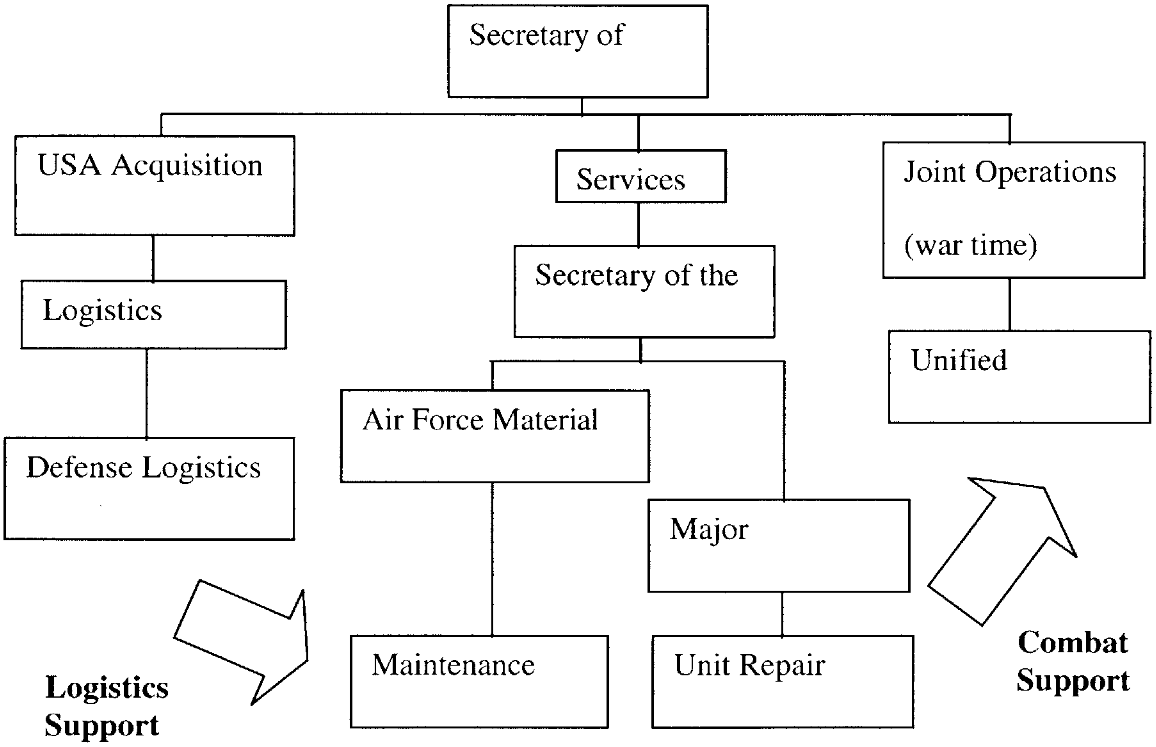
At the heart of the system, one finds the Air Combat Command (ACC), a primarily U. S. based operational organization and Major Command (MAJCOM). They provide the nuclear forces for the U.S. Strategic Command, the theater air forces for five unified commands: the U.S. Joint Forces Command, U.S. Central Command, U.S. Southern Command, U.S. European Command and U.S. Pacific Command. Further, they provide resources for the air defense forces for the North American Aerospace Defense Command. In terms of size, ACC is made up of approximately 90,100 active-duty personnel and 11,300 civilian personnel. Around 63,700 Air National Guard (ANG) and Air Force Reserve Command (AFRC) personnel are transferred to ACC in times of war. At the time of this writing, ACC possessed 1,021 aircraft. An additional 763 ANG and AFRC aircraft join ACC when mobilized. United States Air Forces Europe (USAFE) and Pacific Air Forces (PACAF) resources supplement ACC as needed (Air Combat Command, 2000).

During peacetime, front-line maintenance is conduced at over fifty fighter wings in Europe, the United States and the Pacific Region. During times of war, operations have the potential to span to almost any geographic location. In terms of complexity, the Air Force sustainment system spans government and civilian agencies both under and outside the direct control of the Secretary of the Air Force, only joining together at the level of the Secretary of Defense (Raymond, 1999). The Defense Logistics Agency (DLA), for example, under the United States Department of Acquisition and Technology and not under the direct control of the Secretary of the Air Force, provides logistical support to Air Force Commands. Since DLA does not report directly to the Secretary of the Air Force or any subcommand therein, many Air Force subcomponent operators regard DLA more as a supplier than as a part of their sustainment system. Likewise, many DLA subcomponent operators regard Air Force sustainment as a customer.

F-16 maintenance is performed at numerous locations by one of two entities depending on the level of maintenance to be conducted: Maintenance Repair and Overhaul facilities (MRO) (maintenance depots) and field units. Both entities fall under the management of the Secretary of the Air Force. The government or commercially run depot performs high-level aircraft repairs such as aircraft modifications, engine overhauls, and major airframe inspections. These repairs and inspections are designed to keep the weapons system healthy throughout the life expectancy of the aircraft. Field units perform less complex and specialized repairs designed to keep the weapons system operational on a more short-term (day-to-day or month-to-month) basis. This is not to say that field maintenance is not demanding. On the contrary, field maintenance may be as simple as refueling an F-16 or as complex as repairing a composite fiber structure.

Depot maintenance is under the oversight of the Air Force Material Command while field-level maintenance falls under the major command to which the unit is assigned (ACC, PACAF, USAFE, Guard or Reserve). During times of war, aircraft in the major commands change operational command or CHOP to a joint command.

Figure 2-1 – F-16 Logistics Structure



(Raymond, 1999)

For obvious reasons, field units are co-located with operational units. As the war fighters fly their various missions, field-level maintenance divisions are on-site to keep the aircraft in top flying order.

2-1-2 F-16 Performance-Based Metrics

The F-16's performance-based metrics system is as complex as the sustainment process itself. The primary maintenance database, called REMIS (for Reliability and Maintainability Information System), compiles performance data relating to the maintenance of the aircraft. However, sustainment goes well beyond maintenance, and separate data sources, some electronic and others not, are used to compile data for maintenance personnel, supply, supply personnel, and financials. Most often, any individual Air Force entity will control and/or use only one of these data sets. Further compounding the problem of data reliability, many of these data sets are major command or even agency specific. For example, one office controls the Air Combat Command data while another office controls the Pacific Area Forces data. Plus, within specified boundaries, each major command has the flexibility to decide which data sets they will track and to create data set definitions. In one database, for example, sortie utilization rate is defined as the number of sorties flown divided by the number of chargeable aircraft. In a second database it is defined as the number of sorties flown divided by the number of on-hand aircraft. In a third database, it may not be present at all.

To illustrate once again the enormous size and complexity of the Air Force sustainment system, consider a civilian comparison: A study by LaFountain (1999) with a similar objective observed 16 product development programs at Xerox over 57 metrics and covariates. This study examines data for over fifty geographic locations (programs) over a similar number of metrics and covariates. However, in constructing a time-series, each metric potentially holds sixty pieces of data (one piece for each month between January 1995 to December 1999). The multiple sources for this data are discussed in further detail in Chapter 5.

2-1-3 The Lean Sustainment Initiative & Goals, Objectives & Metrics

MIT's Lean Sustainment Initiative (LSI) was established in an effort to find the best ways to maintain both commercial and military aircraft. Through extensive work with the Air Force Material Command and others, LSI established three primary thrusts: Goals, Objectives and Metrics; Best Sustainment Practices; and System Characterization. This work is a product of the first thrust, Goals, Objectives and Metrics (GOM). LSI divided the GOM research into two major phases. In the first phase, we focused on understanding and characterizing the Air Force's system of goals, objectives and metrics. Through this characterization, we were able to compare the Air Force GOM system to more archetypical systems incorporating contemporary GOM best practices. It was this comparison that led to a list of qualitative recommendations for how the Air Force's GOM system could be changed to better reflect state-of-the-art GOM practices. The second phase of GOM is an ongoing project to identify and research quantitatively those specific and potentially high-payoff areas discovered qualitatively in phase one. The goal of these follow-on empirical studies is to provide Air Force sustainment with more system-specific recommendations for improving their GOM system. The primary body of this work is as the first of the Phase two studies. However, as the first study, it also includes a description of the work done in phase one. This will provide both a record of and flavor for the state of the current Air Force Metrics system that has lead to this and future work:

2-2 USAF Sustainment Goals, Objectives and Metrics

2-2-1 Overview

The Air Force has a comprehensive and integrated mission and vision statement. According to their vision, the mission of the Air Force is, "to defend the United States and protect its interests through aerospace power (United States Air Force, 2000)." In accordance with organizational theory, the mission and vision statements outline who, organizationally, the Air Force believes they are and what their organization purposes to do.

In successive organizational structures flowing down the Air Force chain of command, one can find linked mission and vision statements. For example, the Air Force Material Command's mission is, "to develop, deliver and sustain the best products for the world's best Air Force (Air Force Material Command, 2000)." Furthermore, this mission is directly linked to active goals. Five such goals exist in the case of AFMC:

- To satisfy its customers' needs in war and peace,
- To enable its people to excel,
- To sustain technological superiority,
- To enhance the excellence of its business practices, and
- To operates quality installations (Air Force Material Command, 2000).

These progressive series of linked vision and mission statements along with supporting goals and objectives act in accordance with current management practice (e.g., see Thompson, 1996).

However, more often than not, LSI's phase one GOM analysis was unable to uncover direct relationships between these elements and Air Force performance metrics.

2-2-2 Qualitative Metric Analyses

Thus, metrics became the focus of phase one research. Further qualitative analysis of the Air Force metrics system suggested areas where their system strayed from current strategic management philosophy. As one guideline, we compared Hauser's (1998) metric pitfalls to the Air Force sustainment community's metrics system to gauge their system's conformity with present-day metrics principles. We discovered:

1. Some metrics currently being used were highly fragmented. For example, the Air Force Material Command employs no less than three separate metric systems; each collecting unconnected measures of performance and two of which AFMC metrics specialists cannot even determine the use for. For a second example, consider the F-16 project. The F-16 sustainment team is broken down into two functions: the maintenance team and the supply team. For the most part, the maintenance team collects a comprehensive set of maintenance metrics about how the F-16 performs. Similarly, the supply team collects a comprehensive set of supply metrics about how the F-16 supply system performs. Neither maintenance nor supply collect metrics in regard to how their workforces affect F-16 performance, and supply only keeps limited information in regard to cost and performance. These and other metrics are

available through various other entities, but little evidence exists to suggest sustainment teams consider them when gauging F-16 performance.

2. Some metrics lack internal consistency. For example, the Air Combat Command Director of Logistics Quality Performance Measures Users' Guide (1995) defines Sortie Utilization Rate as the number of sorties flow divided by the number of authorized or chargeable aircraft at a geo-location. However, the REMIS database calculates Sortie Utilization Rate as the number of sorties flown divided by the number of actual aircraft at a geo-location. This seemingly minute difference changes the meaning of the metric from one that measure performance based on allowable resources to one that measures performance based on available resources, a substantial difference.

3. Some metrics do not appear to be well tied to measures of successful performance in order to gauge accountability. For example, a mainstay of the sustainment community's performance metric system is the Mission Capable Rate metric. On-site visits, telephone conversations, data base research, monthly briefing reviews, official reports and written correspondence all consistently suggested that this metric holds a position of great importance in management's gauging of F-16 performance. This held true across almost all management levels and major commands. The metric can be calculated very accurately and it serves to give management an idea of how often (as a percentage of time) their weapon systems are ready to perform. However, the leverage this metric has in determining overall success of the weapon

system is uncertain. Is success best described as the amount of calendar-time a weapon system is available for use (as overuse of Mission Capable Rate would suggest); or is better described as the amount of times, when called upon, the system was able to execute the assigned mission? Shouldn't mission criticality play a part in determining the level of success or failure of the system? If so, Mission Capable Rate somewhat misses the mark. This makes Mission Capable Rate a very quantifiable and easy to measure metric. However, it may lack the predictive power or leverage of some less quantifiable one.

4. Little evidence was found to indicate that the metrics currently in-place are used as a diagnostic devices to get to root causes (one of the goals of this study).

5. Little evidence was found to indicate that the sensitivity of the metrics on overall system-wide performance is well known (another goals of this study) (Russell, 2000).

These issues, particularly numbers four and five, are revisited in qualitative form in chapters 6 and 7.

- This page intentionally left blank -

Chapter 3: *Theory*

3-1 *Overview*

The theory for this work is grounded in prior research conducted at the Sloan School of Management at the Massachusetts Institute of Technology by Professor John Hauser, Burt David LaFountain, and Arpita Majumder and ongoing work being conducted by Jeff Moffitt (Hauser, 2000, LaFountain, 1999, and Majumder, 2000). Section 3-2 below provides a brief overview of the conceptual and mathematical underpinnings for this work. However, emphasis in this work is placed on the methodology (section 3-3) we used to apply the metrics thermostat concepts to the F-16 problem. Refer to John Hauser's work, "Metric Thermostat" currently under review at the *Journal of Product Innovation Management* for a more in-depth theoretical treatment.

3-2 *Theory*

3-2-1 What is a Metric?

A metric is often defined as something that can be precisely measured, but this definition may mislead modern organizations into misuse of their metric systems. A precisely measured metric may be precisely wrong where a harder to measure metric may be vaguely right. Perhaps management wants to know how productive their sales force is. They may be precisely able to measure the number of telephone calls sales people make each day (a precise but less accurate measure of productivity). Alternately, they may choose to conduct a survey of telephone customer satisfaction (a less precise but, perhaps, more representative metric for worker productivity). So, the value of a metric can be determined by two characteristics: its measurement precision and its association to its target concept.

Organizations use metrics in a variety of ways. Metrics can be used to indicate outcomes: "How often are our aircraft mission capable? How long did it take us to ship that part?" This view of a metric, in essence that it is a noisy indicator of output (the agency theory view), suggests that, excluding the costs to collect metrics a firm can increase the level of output by adding more metrics that indicate output.

Alternately, one might think of a metric as a noisy measure of effort: "How hard did our employees work conducting cannibalizations this month?" Again, this approach leads the organization to adding metrics indefinitely to better control the actions of employees. Together, systems of metrics lead management toward ideas about causality: "Is our mission capability down because we are cannibalizing more parts?" Management can use the metrics as decision aids: "Allocate $10 million extra to supply."

However, what if metrics are something more? What if metrics provide signals to employees on how to act? If employees are rewarded based on their performance as measured by a set of metrics, they will seek to maximize their own benefit based on the metrics. Then, organizations need neither measure effort nor output. They simply set the types and weights of the metrics to correspond with maximum desired output. This is the Baker (1992) Gibbons (1996) definition of a metric, as it will be used in obtaining the metrics thermostat equation below:

3-2-2 Theory Formulation

Metrics Thermostat theory combines elements of classic agency theory and utility theory in an attempt to predict the best weights an organization can place on individual metrics in order to maximize organizational success.

3-2-2-1 Notation and Assumptions

An organization rewards teams (and individuals) based on the team's ability to produce several levels of some set of metrics. To produce these levels, the team must choose a set of actions $a_1, a_2, \ldots, a_k$ that are in their own best interest in gaining rewards. These actions have an associated cost as a function of the actions, $c(a_1, a_2, \ldots, a_k)$. The team knows (and carries) the costs, but the costs are not necessarily evident to management. The actions a_k can be decomposed into similarly unobservable efforts e_i^a for each metric m_i. By designating the current operating efforts as e_i^0 and any incremental efforts to change this point as e_i, the cost to the team becomes $c(e_1^a, e_2^a, \ldots, e_n^a) = c(e_1^0 + e_1, e_2^0 + e_2, \ldots, e_n^0 + e_n) \rightarrow c^0(e_1, e_2, \ldots, e_n)$.

The team acts (with effort) to gain reward by incrementally changing the metrics, and management measures these metric changes $\tilde{m}_i$ with some error such that $\tilde{m}_i = m_i(e_i^a) + error_i$

where m_i^0 are the current operating points and the $error_i$ are zero mean normally distributed variables with variances σ_i^2.

Management places a weight on each metric. The team's total reward is based on their ability to incrementally increase the weighted linear sum of the metrics $rewards = rewards(m_1^0, m_2^0, \ldots, m_n^0) + w_1 (\tilde{m}_1 - m_1^0) + w_2 (\tilde{m}_2 - m_2^0) + \ldots + w_n (\tilde{m}_n - m_n^0)$. Representing all constants as w_o, one gets:

(3.1) $$rewards = w_o + w_1 \tilde{m}_1 + w_2 \tilde{m}_2 + \ldots + w_n \tilde{m}_n$$

where w_o is the base reward (salary, perhaps), the $\tilde{m}_i$ are metrics and the w_i are incremental changes in weight the organization can chose to place on the corresponding metric. Of course, most organizations do not pay employees based on a set of metrics (although many sales forces pay on commission). Instead, management signals employees what the organization believes is important by establishing pay raises, providing bonuses and giving other incentives based on the employees' (and teams') ability to maximize these metrics.

In an attempt to maximize *rewards*, the team will likely act to avoid risk and will place more effort on less risky metrics. If the team displays constant risk aversion, their utility function can be represented as:

(3.2) $$u(x) = 1 - e^{-rx}$$

where r represents the team's risk aversion constant. (We assume the organization, on the other hand has no aversion to risk as is, as such, risk neutral.). A larger r indicates more aversion to risk.

The actions of the team lead to gross profit π as a function of effort: $\pi(e_1^a, e_2^a, \ldots, e_n^a)$. In a private firm, monetary profit is, within some range of ethical and legal bounds, the ultimate goal. For a public organization (like the USAF), the profit construct is analogous to one or more desired outcomes (mission capability, for example, or aircraft utilization). Recently, however, government agencies have been increasingly directed to include reduced cost as a desired output.

3-2-2-2 Case I: One Sustainment Team

The team will attempt to maximize output based on their aversion to risk and desire for rewards in that their maximum reward is their total rewards minus their total costs. If the measurement errors are uncorrelated and the team is constantly risk averse, they will attempt to maximize the certainty equivalent (*c.e.*) such that:

(3.3) $$c.e \approx w_o + w_1 m_1 + w_2 m_2 + w_n m_n - c^0(e_1, e_2, \ldots, e_n) - \tfrac{1}{2} r\, w_1^2\, \sigma_1^2 - \tfrac{1}{2} r\, w_2^2\, \sigma_2^2 - \ldots - \tfrac{1}{2} r\, w_n^2\, \sigma_n^2$$

The organization can attempt to maximize output (profit) based on their recognition of the team's aversion to risk by setting the constant w_o (the base salary) and the incremental changes in metric weights $w_1, w_2, \ldots, w_n$. The organizations output (profit) will be the difference between the total output (profit) and the amount of base wages and bonuses they pay the workers. To ensure employees do not leave the organization for greater *rewards* in some other firm, the organization will choose *rewards* $\geq W_o$ such that the total *rewards* are greater than or equal to the wages employees could earn elsewhere (W_o) for comparable effort. To maximize net output (profit), then, the firm simply maximizes gross output (profit) minus minimum rewards (W_o) minus the certainty equivalent (*c.e.*) of the team:

(3.4) $$max\ net\ output = \pi - W_o - c.e.$$

Agency theory suggests we can maximize equation 3.3 to determine the optimal incremental efforts e_i^* that describe the optimal actions a_k^*, substitute these results into equation 3.4, and determine the optimal incremental weights w_i^* (For a more complete mathematical treatment, refer to Hauser (2000) and Gibbons (1997)):

(3.5) $$w^*_i = \frac{\left(\dfrac{\partial \pi}{\partial e_i{}^0} \Big/ \dfrac{\partial m_i}{\partial e_i{}^0} \right)}{\left[1 + \left(r \dfrac{\partial^2 c^0}{\partial e_0{}^{o2}} \right) \left\{ \sigma_i \Big/ \left(\dfrac{\partial m_i}{\partial e_i{}^o} \right) \right\}^2 \right]}$$

Three terms of equation 3.6 provide observable features about the organizations endeavor to set an optimal weight for w_I^*. In particular:

Term 1: The Leverage Term: $\left(\dfrac{\partial \pi}{\partial e_i{}^o} \Big/ \dfrac{\partial m_i}{\partial e_i{}^o} \right)$

This numerator term suggests that metrics with high marginal effects on output should be weighted more heavily than metrics with low marginal effects on output. If fix rate affects mission capability more than cannibalization rate, then the Air Force should weight fix rate more than cannibalization rate (for this dimension of weight).

Term 3: The Noise-to-Signal Ratio: $\underline{\left\{\sigma_i \Big/ \left(\frac{\partial m_i}{\partial e_i^{o}}\right)\right\}^2}$

This denominator term represents the noise in the metric divided by the scale on the signal. A precise metric will have a low noise-to-signal ratio suggesting to the organization that they should increase the weight on the metric.

Term 4: The Risk/Cost Term: $\left(r\frac{\partial^2 c^{o}}{\partial e_i^{o2}}\right)$

This final term (in the denominator) represents risk aversion and the scale on cost. The organization should reduce the weight they place on metrics that require riskier investments by team efforts.

Terms 2 and 3: The Precision-to-Noise Tradeoff: $\dfrac{\left(\frac{\partial \pi}{\partial e_i^{0}} \Big/ \frac{\partial m_i}{\partial e_i^{0}}\right)}{\left\{\sigma_i \Big/ \left(\frac{\partial m_i}{\partial e_i^{o}}\right)\right\}^2}$

If one considers the leverage and noise-to-signal portions of the equation, the tradeoff between using precise measurements (those which measure without noise) and correct measurements (those which best describe the construct to be measured) becomes evident. The best metric has both.

3-2-2-3 Case II: Management Across Multiple Teams

Organizations contain many project teams, and they are not always likely to set metric weights for every individual project or team they have. Furthermore, depending on the nature of the team's work, the optimal metrics weights may differ from one team to another. The previous section models the metrics thermostat for one team. Hauser (2000) shows how this approach can be expanded (mathematically) for multiple teams within an organization such that:

$$\textbf{(3.6)} \quad w_{ij}^{*} = \frac{\beta_{ij} / \alpha_{ij}}{1 + 2\left[\dfrac{E\left[rewards_{ij}\right] - c.e.^{o}{}_{ij}}{E\left[rewards^{o}{}_{ij}\right]} \right]}$$

where the i subscripts represent the individual metrics 1 to I, the j subscripts represent the individual teams 1 to J, $\beta_{ij} \equiv \partial \pi_j / \partial e_{ij}^{o}$, and $\alpha_{ij} \equiv \partial m_{ij} / \partial e_{ij}^{o}$. The term in brackets in the denominator is defined as the Risk Discount Factor (RDF) and can be empirically measured through survey questionnaires such as that found in LaFountain (1999).

3-2-2-4 Case III: An Empirically Measurable Form

Many organizations (like the USAF) have multiple teams working on similar projects such that the ratio β_{ij} / α_{ij} and the operating point m_{ij}^{o} do not vary significantly across projects. In this specialized case, Hauser (2000) shows that the numerator of equation 3.6 reverts to a simple multiple regression coefficient in which observed outcomes (profits) are regressed on the metrics (and covariates):

$$\textbf{(3.7)} \quad \tilde{\pi}_j = const' + \sum_{i=1}^{n} \lambda_i \tilde{m}_{ij} + \sum_{g=1}^{G} \mu_g v^g{}_j + error'_j$$

where $\tilde{\pi}_j$ represents profit over all projects as a random variable, *const'* represents something like the baseline profit, $\lambda_i = \beta_{ij} / \alpha_{ij}$, $\tilde{m}_{ij}$ represents all metrics over all projects, $v^g{}_j$ represents those metrics (henceforth called covariates) outside the teams control (such as resource availability, weather, etc.), μ_g represents the weights on those covariates, and *error'* represents a zero mean, normal random variable. Traditionally, the goal of regression has been to identify those metrics that influence profit across firms. One key difference in application of the metrics thermostat is that this regression is used within one particular firm in an attempt to identify incremental improvements in weights rather than one-time overall optimization.

So, if RDF is constant around the operating point, and all teams have similar leverage (β_{ij} / α_{ij}) profiles, the weight for each metric m_i for the organization (or division of the organization *d*) is:

3.8 $$\hat{w}^{d}{}_{i} = \frac{\hat{\lambda}_i}{1+2RDF_i}$$

If an organization can determine the amount of leverage a metric exerts and the amount of risk aversion a team has, they can use this equation to determine the amount of weight to place on each metric.

RDF has been shown to be empirically measurable through responses of team members to survey questions. Past studies (LaFountain (1999), Majumder (2000)) suggest that RDF levels typically fall between 0.2 and 0.6 and that they have small effects on the relative weightings between metrics within a measurement system. This work concentrates on further exploration of leverage, exploration of the structural dynamics of an aircraft sustainment team as relating to their metrics, and an exploratory analysis of future methods of determining leverage and weights for systems (like those in the Air Force) with strong feedback loops.

3-2-2-5 Finding the Optimal Weight

One underlying assumption of this theory is that approximations are valid in a hyperplane surrounding the organization's initial operating point. In executing one iteration of measurements, equation 3.8 does not yield an optimum metric weighting scheme. Instead, it provides a mechanism that will, in one iteration, push an organizations weighting scheme towards the optimum. Additional iterations act to constantly adjust the system toward optimal; hence, the thermostat metaphor.

Hauser (2000) provides a seven-step process for practical application of the metrics thermostat for private (profit-seeking) firms with product teams with similar metric leverage profiles. Adapting this approach for an outcome-based organization, the research or firm should:

1. Identify a set of projects that follow a similar culture.
2. Identify the metrics by which the firm is managed.
3. Obtain measures for the metrics, covariates, and profit.
4. Use multiple regression to obtain estimates of leverage (λ_I) for each metric.
5. Use surveys to determine the Risk Discount Factor (RDF_i) for each metric.
6. Use equation 3.8 to calculate the increase or decrease in weight($\hat{w}^d{}_i$) for each metric. Change the weight on that metric accordingly.
7. Periodically repeat steps 3 through 6 to provide further adjustment. The optimum is reached when $\hat{w}^d{}_i = 0$, but periodic monitoring ensures the system can adjust to environmental changes.

- This page intentionally left blank -

Chapter 4: Methodology and Application

4-1 Methodology Overview

The Metrics Thermostat was originally intended for use in setting weights for product development teams. In order to adapt the thermostat for use in Air Force sustainment, adaptations of the seven-step methodology presented in chapter 3 were required as follows:

4-1-1 Changes in Step 3: Profit Versus Outcome:

As previously discussed in section 3-2, the concept of profit was expanded to include other forms of outcome. While many Air Force sustainment sub-communities (like Air Force depots, Defense Logistics Agency, etc.) are increasingly turning to measures of profit as success, profit is not their overarching goal. At the operational level, the analogy to profit may be Mission Capability (how often an aircraft is ready to fly), Utilization (how often an aircraft actually does fly), or some other construct.

4-1-2 Additional Step 3a: Determining the System Structure:

Multiple non-profit oriented output constructs may influence each other resulting in complex relationships between system metrics. Presumably, a private firm aims to maximize long-term profit. However, in a public organization (like the Air Force) there may be tradeoffs between optimizing, for example, Utilization and Flying Scheduling Effectiveness. Furthermore, outputs (so-called dependent variables) may greatly influence input metrics (so-called independent variables). For example, Utilization (traditionally thought of as a dependent variable) may induce aircraft breakage (a traditionally thought of independent variable). An understanding of these relationships and their role in defining the overall structure of the sustainment system is important if one is to later infer metric leverage relationships. To this end, thorough analysis of correlations and regression weights will allow hypotheses formulation about the causal loop structures inherent in the system. These theoretical findings can then be compared with field-level (operator) judgments.

4-1-3 Changes in Step 4: Using Regression to Find Leverage:

Multiple non-profit oriented output constructs may influence each other also resulting in a change in how leverage is measured. When the public firm considers the causal feedback loops present, outcome trade-offs may occur. Regression may not be able to capture the effects these loops have on leverage. So, alternative approaches (like causal modeling) are discussed.

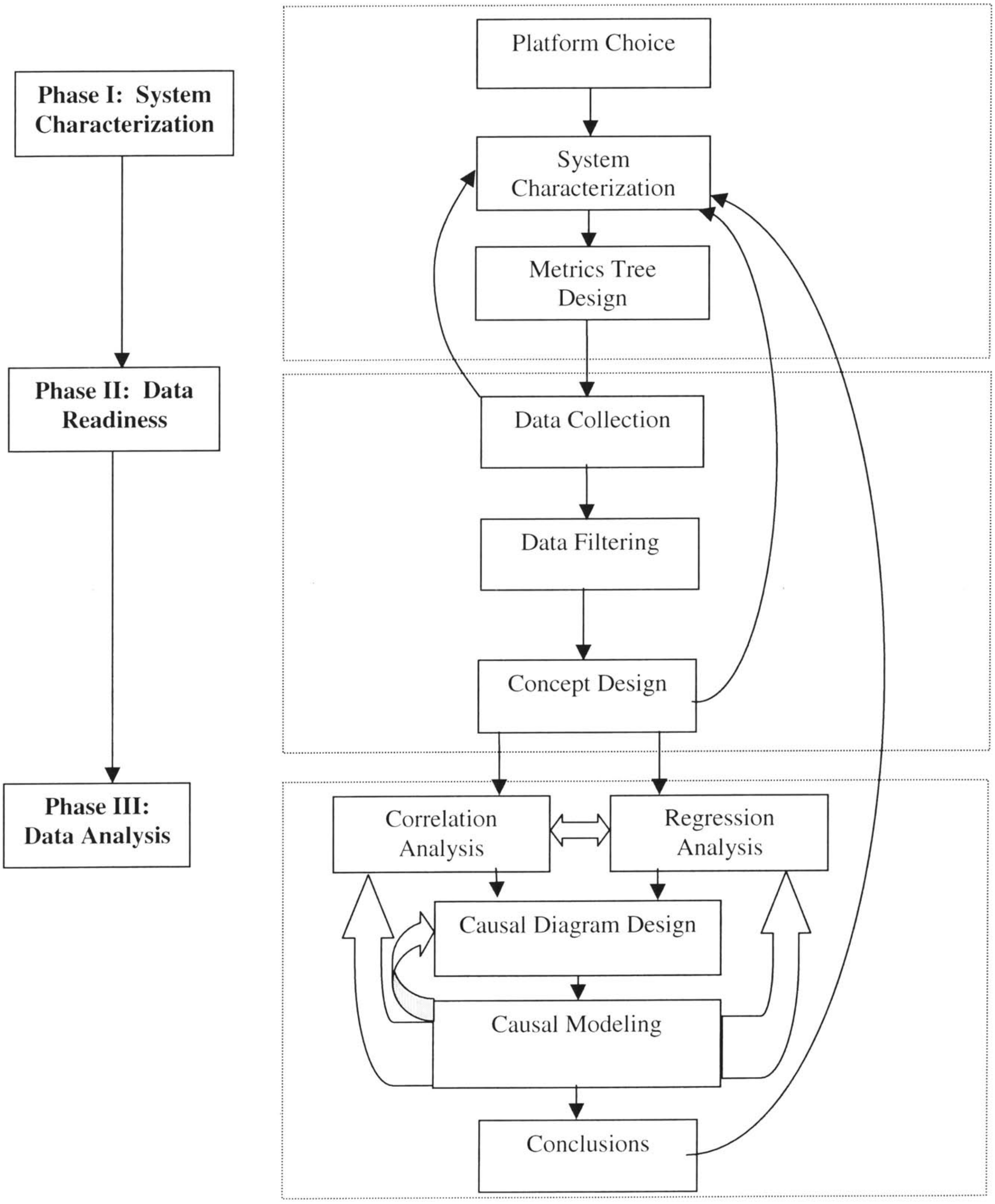
4-1-4 Overview

When applying the leverage theory to an actual data set (and particularly a large data set) one must consider several practical matters, and identification of the leverage part of the equation (from data acquisition to conclusion) becomes convoluted. As an example, consider the fact that the F-16 data sample contains more than 240,000 bits of collected information (80 low-level variables * 12 months/year * 5 years * 50 bases). Obviously, it is not practical to manually screen each information bit for both internal consistency and for consistency with bits of information in all other variables. Other techniques must be used. Additionally, as described in the theory section of this chapter (above), the varied techniques of determining leverage and system structure (correlation, correlation with regression residuals, time series regression, and causal modeling) each have strengths and weaknesses based on their underlying assumptions. For these and other reasons, special techniques are required to ensure the vigor of the data set and ultimate conclusions. Figure 4-1 depicts a graphical representation of the general process we followed. The narrative accompanying figure 4-1 suggests a linear research process. However, it does so only in an effort to describe the elements of the process used. In reality, the process followed was a great deal more iterative (as suggested by figure 4-1).

4-2 System Characterization

The first task was to find a suitable stage to test the theory in application. Early on in the project, we decided to focus our attention on a popular Air Force weapon system. Air Force weapon systems provided us with a breadth of personnel, maintenance, supply and cost data focused on a group of product teams with one common goal, namely the sustainment of the weapon system. The specific weapon system we were to choose must have an ample volume of strategic data to allow significant analysis. Furthermore, it should be found in number across major commands of the Air Force. To improve our statistical fidelity, we desired a platform with large numbers of geo-locations and a long history of uninterrupted operations. Finally, we wished to choose a platform with high potential to yield long-term results valuable to the Air Force.

Figure 4-1 - Methodology for Theory Application



4-2-1 Platform of Choice: The F-16

The F-16 weapon system excelled in each of these areas. First, it has a long historical performance record for the Air Force. Second, Air Combat Command, European Air Forces, Pacific Air Forces, the Air National Guard, and the Air Force Reserve fly the F-16 at over fifty commands across the United States, Europe and the Pacific region (refer to table 4-1). Third, many F-16 historical performance data measures are available for one-month intervals back three, five, and sometimes ten or more years. Much of this data is electronic and not highly classified by the Air Force making it readily transferable to this project. Finally, since the F-16 has been such a mainstay for Air Force fighter wing operations, we believe any recommendations we provide will have the potential for major impact on Air Force operations.

Table 4-1 – F-16 Bases (modeled)

Base Name	Location	Base Name	Location
SHAW	Sumter, North Carolina	DULUTH	Duluth, MN
CANNON	Clovis, NM	KELLY	San Antonio, TX
NELLIS	Las Vegas, NV	KIRTLAND	Albuquerque, NM
MOODY AFB GA	Valdosta, GA	BURLINGTON	Burlington, VT
MT HOME	Mountain Home, ID	TUCSON	Tucson, AZ
HILL AFB UT	Ogden, UT	MCENTIRE	Columbia, SC
LUKE	Phoenix, AZ	HANCOCK FIELD	Syracuse, NY
AVIANO	Aviano, Italy	ATLANTIC CITY	Atlantic City, NJ
SPANGDAHLEM	Trier, Germany	SPRINGFIELD ANG OH	SPRINGFIELD, OH
HOMESTEAD	Dade County, FL	TOLEDO-EXPRESS	TOLEDO-EXPRESS, OH
LUKE	Phoenix, AZ	HULMAN	Terre Haute, IN
CARSWELL	Fort Worth, TX	CAPITAL ANG ILL	Peoria, IL
HILL AFB UT	Ogden, UT	SIOUX CITY	Sioux City, IO
ANDREWS	MD	DANNELLY	Montgomery, AL
JOE FOSS	Sioux Falls, SD	FT SMITH	Fort Smith, AR
TRUAX	Madison, WI	BYRD FLD ANG RICH VA	Richmond, VA
HECTOR	Fargo, ND	KUNSAN	Kunsan, South Korea
GREAT FALLS	Great Falls, MT	MISAWA	Misawa, Japan
BAER	Fort Wayne, IN	OSAN	Osan, South Korea
SELFRIDGE	Mount Clemens, MI	EIELSON	Eielson Field, AK
DES MOINES	Des Moines, IA	FRESNO AIR TERM	Fresno, CA
TULSA	Tulsa, OK	ELLINGTON	Houston, TX
BUCKLEY	Denver, CO		

4-2-2 System Characterization

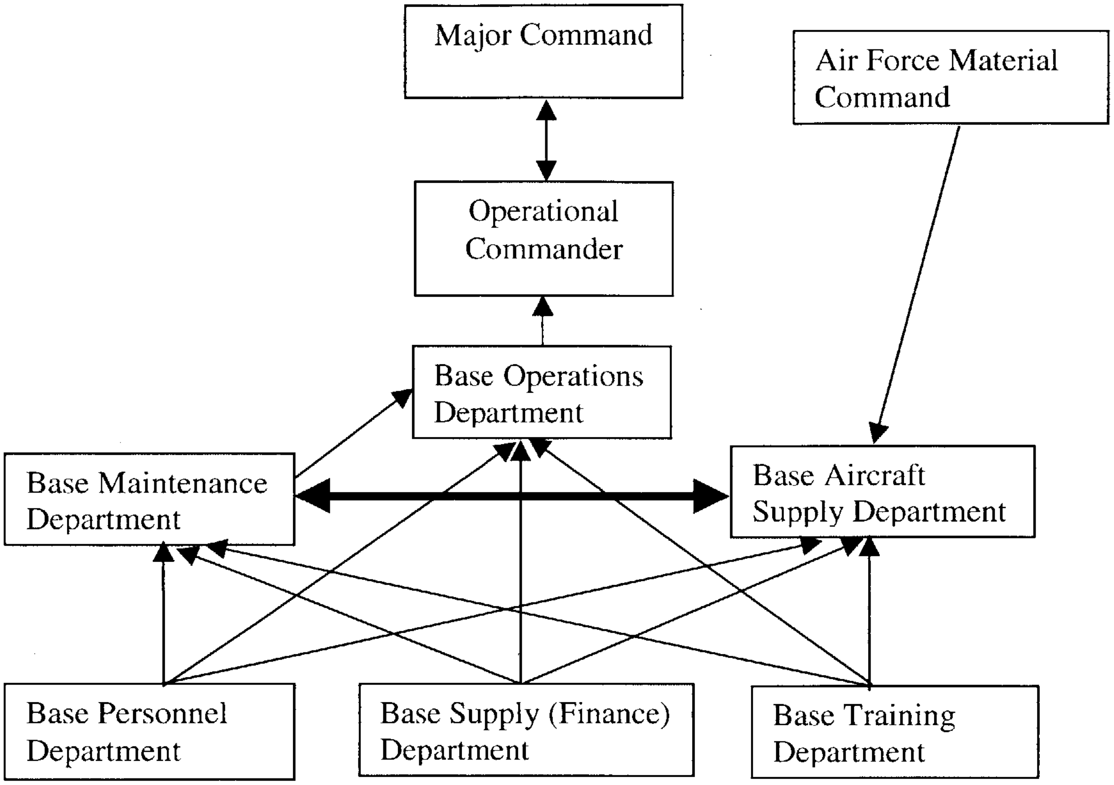
Having decided on the F-16, the next step was to extract a hypothesis describing the operation of the local F-16 sustainment community, in essence to answer the questions:

(1) What constitutes F-16 performance? What are the Strategic Priorities?

(2) What drives F-16 performance? What are the enabling metrics?

We initiated this learning process via numerous telephone interviews, on-site visits and written correspondence with the major stakeholders in F-16 sustainment, operations and oversight communities. It quickly became evident that to effectively operate the F-16, Air Force personnel were required to coordinate actions and priorities across multiple inter-command departments and across major commands on a daily basis. Major Commands oversee (and often directly task) Operational (base level) Commanders in their completion of F-16 missions. To conduct this tasking, Operational Commanders want F-16s delivered on time and capable of performing tasked missions. It is the job of the Fighter Wing Maintenance Department (base level) to provide these aircraft and, in addition, to maintain the health of the maintenance department to be able to respond effectively in case of times of war. To do so, the maintenance department relies on Air Force personnel and training departments to provide adequate personnel in number and know-how. Maintenance also requires adequate logistics support from both the Fighter Wing Supply Department and Air Force Material Command and adequate funding support from multiple internal financial organizations (see figure 4-2).

Figure 4-2 – F-16 Local Logistics Support Structure



Air Force sustainment at the base level can be thought of as a lose combination of the Fighter Wing Supply Department with the Fighter Wing Maintenance Department. For the purpose of this study, it is our view that these two organizations work together to meet the needs of their immediate customer, the Fighter Wing Operations Department and their successive customer, the Major Commander. It is because of these assumptions that, for this study, we built strategic priorities from the point of view of the Major Commander (ACC, USAFE, PACAF, Reserve and Guard), the director of the operational commanders.

Further research uncovered common operating trends over all Major Commands. We discovered that each command takes many operating cues from the Air Combat Command. Due to this fact and since the Reserve and Guard components fall under ACC during times of war, we decide that the strategic priorities of our model should resemble the strategic priorities of ACC.

ACC attempts to maintain integrity with its parent command, the U. S. Air Force. To do so, they have nested their mission statement and goals (strategic priorities) under the U. S. Air Force vision (see figure 4-3 and accompanying text). Notice in that text that, unlike the conventional private firm, the goals of the Air Force (as stipulated) are not all profit driven.

Figure 4-3 – Air Combat Command Strategic Management Nesting

The Air Force Vision Statement:

Air Force people building the world's most respected air and space force–Global Power and Reach for America.

The Air Combat Command Mission Statement:

> *Air Combat Command Professionals providing the world's best combat air forces–delivering rapid, decisive and sustainable airpower–anytime, anywhere.*

Air Combat Command Goals:

- PEOPLE are our most precious resource. Successful mission accomplishment hinges on creating an environment where our people can thrive. Our objectives flow from our responsibility to promote professional growth and the Core Values ensure individual and family health and safety, and improve retention and quality of life.

- MISSION is the direct measurement of how well we are able to deliver aerospace power. Objectives should address issues needed to maintain or improve ACC's delivery of combat airpower.

- EFFICIENCY enhances mission accomplishment. Our objectives are geared towards more effective operations, prudent stewardship of resources, increased capabilities and delivery of rapid, decisive combat airpower (Air Combat Command, 2000).

ACC's goals (strategic priorities) are echoed in fighter wing mission statements both inside and outside ACC. In designing a set of strategic priorities for our F-16 sustainment system model, we took elements from ACC priorities and base-level priorities and combined them such that they closely map to the maintenance and supply departments that support F-16 sustainment. Thus, we focused on six strategic priorities that we believe describe F-16 base-level sustainment:

- Strategic Priority 1 – Maintenance Efficiency: the amount of time and effort expended on weapons system repair functions. This priority recognizes that maintenance resources are scarce, and allocation of these resources is critical to maximizing overall success of the sustainment plan.

- Strategic Priority 2 - Repair Responsiveness: the ability of the repair team to meet customer needs. This priority recognizes that maintenance actions must be aligned with operational priorities. The end customer, as far as maintenance is concerned, is the war fighter. So the goal of the maintenance team is to provide aircraft that meet the timing, training and capability needs of aircrews.

- Strategic Priority 3 – Maintenance Personnel: base commanders have little influence over the numbers and qualifications of personnel they employ. Instead, personnel are assigned by skill code and skill level relative to the number of aircraft assigned to a geo-locations and the mission assigned.

- Strategic Priority 4 – Supply Efficiency: the time and effort waiting and spent on supply. Like maintenance resources, supply resources are scarce. This priority attempts to quantify the availability of supply resources.

- Strategic Priority 5 – Supply Responsiveness: the ability of the supply system to meet customer needs. Just as one can think of the customer of the maintenance system as the war fighter, one can think of the customer of the supply system as the maintenance system. Maintenance can only do their job if adequately supplied. This priority attempts to gauge the ability of the supply system to support the maintenance system keeping in mind that actions of the maintenance system affect the supply system as well.

- Strategic Priority 6 – Supply Personnel: just as with maintenance personnel, assignment of supply personnel is largely out of the hands of base commanders. Here again, personnel are assigned by skill code and skill level relative to the number of aircraft assigned to a geo-location and the mission assigned.

4-2-3 Selecting Causal Variables: The Metrics Tree Design

Hypothetically, successful execution of the strategic priorities would result in successful mission accomplishment. Furthermore, execution of strategic priorities could be explained by a set of low-level metrics. So, our next task was to determine what variables might best measure mission accomplishment and what variables might best explain successful execution of strategic priorities. As an initial baseline, we turned to the Air Force sustainment community. Our first clues came from the Air Combat Command Director of Logistics Quality Performance Measures Guide. This Air Force publication outlines and defines twenty-five aircraft related metrics that the Air Force believes are important enough for geo-locations to report on a recurring basis (USAF ACC, 1995). Next, we studied multiple major commander calls for monthly briefings. These briefings contain information regarding the historical status of the F-16s under a major commander's control. Each is tailored to the desires of the individual commander. So, they are likely to contain information that specific commanders deem as important. For example, the Air National Guard compiles a monthly report tracking thirty variables for over twenty-five geo-locations (Girald, 1998).

Our analysis of the monthly briefs for different major commanders suggests that, in general, commanders of differing commands are interested in similar F-16 metrics. It also suggests that, when considering a particular weapons system like the F-16, commanders are primarily interested in outcome-based, causal maintenance-based and causal supply-based metrics. For example, in the Girald brief cited above, of the thirty variables reported, ten could be categorized as outcome-based, three maintenance-based (causal), and four supply-based (causal). I believe this suggests that commanders are primarily interested in the scorecard as opposed to the reasons why the score is as it is. Furthermore, this suggests a potential lack of attention on the personnel-related strategic priorities, cost outcomes, operating environment covariates, etcetera. This approach may make sense for the operational commander since these three factors (and others) are often greatly out of her control. Personnel are allocated on a per-plane basis, budget is formulated based on flying hours assigned and environment is what it is. Still, the metrics system model of interest for this project should attempt to explain the overall performance of the F-16 above and beyond command-level interests and therefore should include all relevant factors. Unfortunately, since the major commands are less interested in some of these variables, they are less likely to collect metrics for them. Some, we were able to piece together from other Air Force sources. Others, such as climate data, required us to poll non-military sources. Still others were not available. In the end, we chose to create a hybrid metrics "tree" that includes those variables the Air Force bases feel are important as well as all other available variables we feel may help explain F-16 performance dictated, of course, by availability.

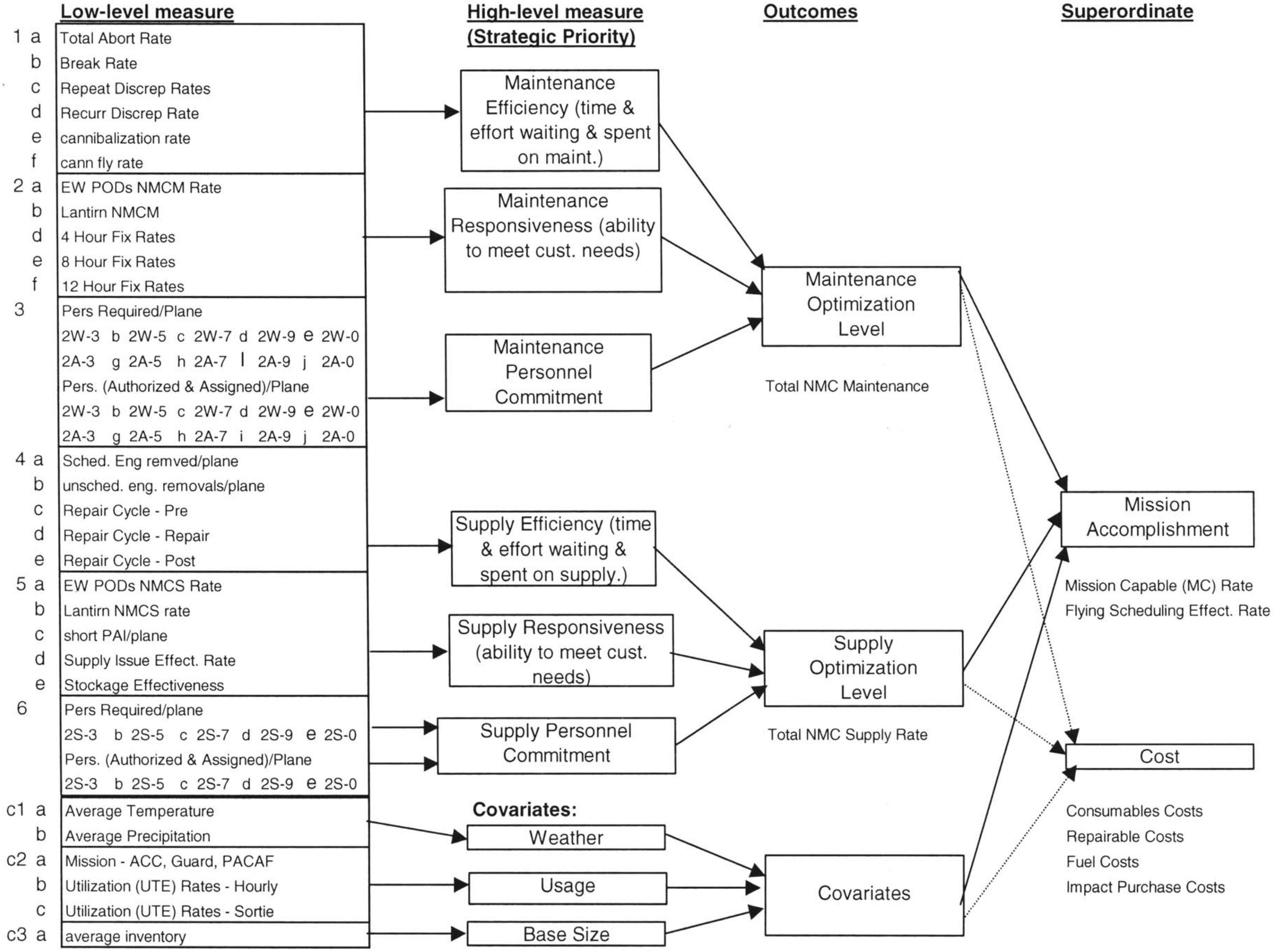
To this end, our initial goal was to collect as much potentially significant data as each pertained to a particular causal or outcome based strategic priority or a particular covariate we suspected might be causal. (We would have the opportunity later to weed out variables found to be less important). Table 4-2 lists the variables for which we initially collected data (by base by month for 1995 through 1999 to the extend available). Refer to Chapter 5 for a detailed definition of each metric.

With strategic priorities, outcomes (strategic metrics), and causal variables in place, we now had a hypothetical metric tree. The metrics tree concept establishes relationships between low-level metrics (or variables), strategic priorities and outcomes (strategic metrics). Low-level metrics and covariates are grouped together in an attempt to explain a strategic priority, and strategic priorities attempt to explain performance or outcome (strategic metrics). For example, one strategic priority for the F-16 is Repair Responsiveness, the ability for the repair team to meet customer needs. For our purposes, the customer for the maintenance team is the operations department. So, low-level metrics that make up this strategic priority must explain the ability of the repair team to provide working aircraft to the operations department (and air crews) capable of completing an assigned mission. Working from the list in Table 4-2, we designed the initial metrics tree shown in Figure 4-4.

Table 4-2 – Initial List of Low-level Metrics

Total Abort Rate	Break Rate
Repeat Discrepancy Rate	Recurring Discrepancy Rate
Cannibalization Rate	Cannibalization-Fly Rate
EW PODs NMCM Rate	Lantirn NMCM
4 Hour Fix Rate	8 Hour Fix Rate
12 Hour Fix Rate	Repair Cycle – Pre
Maintenance Personnel Required (10 fields)	Repair Cycle – Repair
Maintenance Personnel Authorized (10 fields)	Repair Cycle – Post
Maintenance Personnel Assigned (10 fields)	EW PODs NMCS Rate
Supply Personnel Required (10 fields)	Lantirn NMCS rate
Supply Personnel Authorized (10 fields)	Supply Issue Effectiveness Rate
Supply Personnel Assigned (10 fields)	Shortages of Primary Aircraft per Plane
Scheduled. Engines Removed per Plane	Stockage Effectiveness Rate
Unscheduled Engines Removed per Plane	Weather Cancellations
Average Temperature	Average Precipitation
Mission – ACC, Guard, PACAF	Aircraft Utilization Rates – Hourly
Utilization (UTE) Rates – Sortie	Average Inventory
Total Not Mission Capable Maintenance Rate	Mission Capable Rate
Total Not Mission Capable Supply Rate	Flying Scheduling Effectiveness Rate
Consumables Costs	Repairables Costs
Fuel Costs	Impact Purchase Costs

Figure 4-4 – The Metrics Hierarchy Tree: Metric, Covariate and Outcome Relationships



4-3 Data Readiness

4-3-1 Data Collection Challenges

We obtained data from a variety of sources. First and foremost, our maintenance and performance data came from the Air Force electronic historical data capture program called REMIS, the Reliability and Maintainability Information System. REMIS provides historical maintenance and performance data for many of the Air Force's weapons systems, including the F-16, across all major commands. Most data is available on a monthly basis. We initially ran a REMIS query for a ten-year period covering 1989 through 1999. However, data availability for many key metrics was unavailable before 1995 since the Air Force overhauled its measurement system at that time. So, we ultimately settled on a model with a five-year period of data covering 1995 through 1999. Data for the supply, cost, personnel and weather-related categories came from a variety of sources, and it is the variability of these sources that made data capture extraordinarily difficult. Major commands customized many of these data sets to meet their particular needs. So, when we collected, for example, Supply Issue Effectiveness data, we had to ensure ACC used the same definition for Supply Issue Effectiveness as did USAFE, PACAF, the Guard and the Reserve.

Another data collection challenge occurred when one or more major command decided independently to collect data on time scales other than monthly (quarterly or yearly, for example). Also, frequently one or more command did not collect a data set for a particular variable at all.

4-3-2 Data Filtering Challenges

Not all data came in as expected. Since the Air Force periodically moves assets from one base to another, some of our base data sets were empty for long historical time periods because the F-16 did not always reside there. We chose to eliminate any base that had less than a two-year F-16 history or was not currently flying the F-16 at the end of 1999. Three Air National Guard bases (the 125th, the 156th and the 173rd) and one Air Combat Command base (the 23rd) fit at least one of these descriptions, and all data for those four bases were eliminated from our final study. Furthermore, we eliminated numerous key-type and omission errors through visual inspection of scatter plots and utilization of Cooks Distance statistics.

Another filtering challenge came in the form of incompatible periodicity of data. REMIS, the source of most of our maintenance and supply data, capture and report data monthly. UMD, MDS and other data systems, the source of most of our personnel and cost data, only capture historical data on an annual basis. Unfortunately, the Metrics Thermostat regression model requires data input on a consistent time scale. That is, in the final analysis, annual data cannot be correlated with monthly data. Our choice was a difficult one: if we model without the annual data, we would be limiting our model primarily to the maintenance, supply, covariate and outcome fields; disregarding altogether the effects of cost and personnel on the success of the F-16. On the other hand, if we were to convert the monthly data to annual data, we would reduce the number of data points per metric by a factor of twelve resulting in a significant reduction in the model's power. In the end, we attempted a hybrid approach that endeavored to keep the best features of both possible techniques: in the early analysis, we converted the annual data to monthly data. Of course, all months in the year were reported to be the same. However, it allowed us to take advantage of the more precise maintenance and supply metric fields to help establish a set of purified metrics

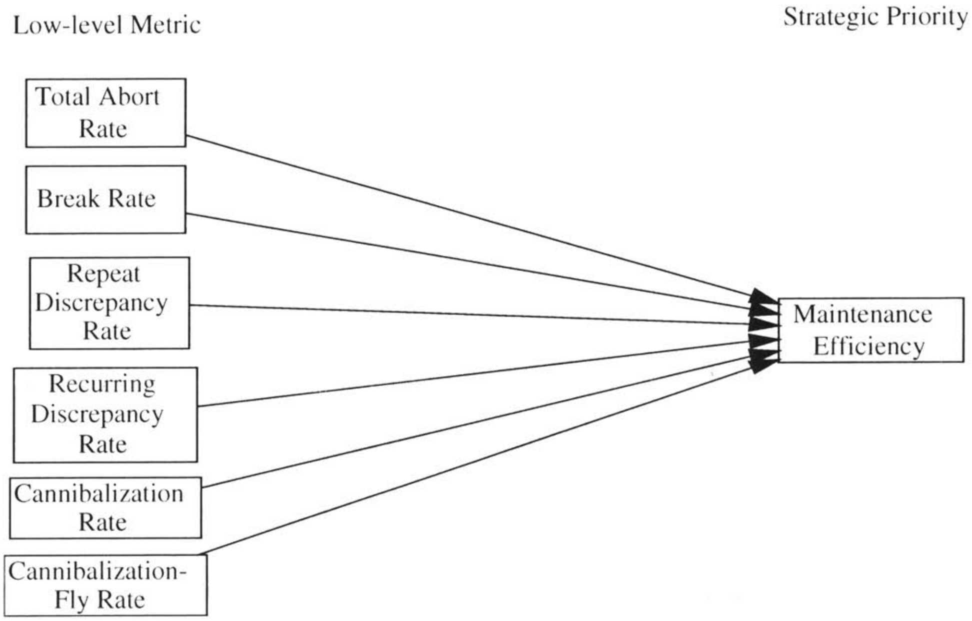
4-3-3 Concept Design and Data Purification

The filtered and "filled" metrics were now ready for purification, that is, reallocation into new conceptual frameworks based on reliability. Originally, each set of metrics purposed to explain a strategic priority. In reality, these metrics were predictors of some concept that supported a strategic priority. Some were good predictors. Others were not as good. So, we began grouping metrics together in an effort to describe concepts that could explain strategic priorities. Figure 4-5 shows one such potential combination:

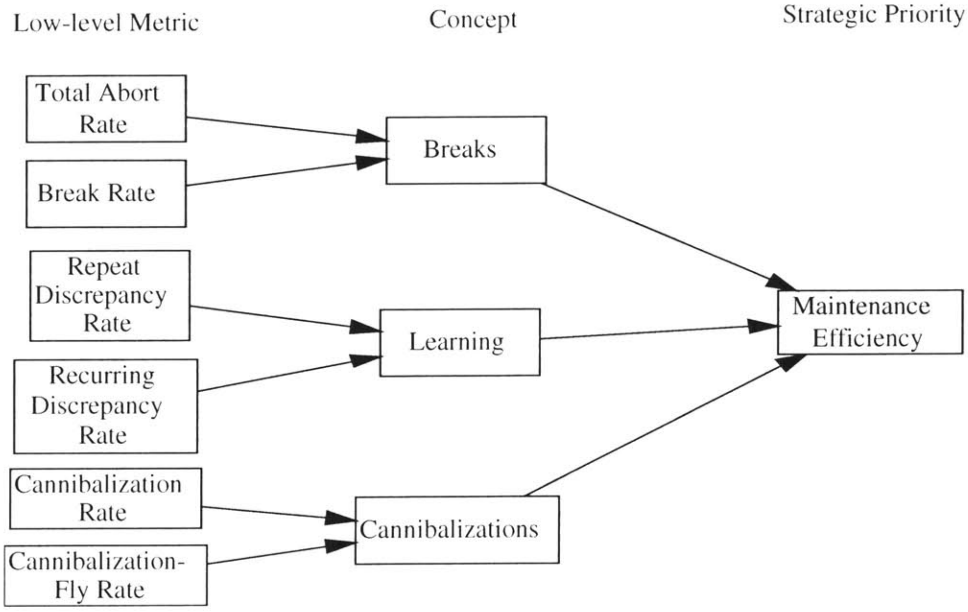
Each set of low-level metrics purposes (with some error) to describe the concept. The set of all concepts are then used to explain performance. To determine which metrics belonged together in describing particular concepts, we conducted a reliability analysis using Cronbach's Alpha. These data were then used in final analysis.

Figure 4-5 – Conceptualizing the Low-Level Metrics

Before Conceptualization:



After Conceptualization



4-4 *Data Analysis*

Before discussing the various techniques used to explore leverage, it is worth revisiting our initial assumptions in regard to metrics. Remember, a metric is defined as something that can be precisely measured. However, the construct the metric proposes to measure may or may not precisely map to the metric itself. The organization chooses a set of metrics from which to make management decisions. However, these metrics need not be noisy indicators of performance. Nor need they be noisy indicators of worker efforts. Instead, a system of metrics is considered to be an incentive system that workers will attempt to maximize given their preferences of reward delay and reward risk. Recall that in this light, the optimal weight an organization can place on a metric can be shown to be a combination of leverage (how much the metric supports an outcome) and risk (how much the team discounts the metric). This work will concentrate on the leverage portion of the equation and leave for further study the question of risk.

So, how does one proceed?

4-4-1 Regression Analysis

In the traditional sense of the metrics thermostat, the regression weights of metrics regressed onto outcomes represent leverage. This approach will be used as a baseline.

4-4-2 Causal Loop Hypothesis and Causal Modeling

As discussed earlier, we suspect that the Air Force sustainment system contains multiple feedback loops. To test for these loops, hypothetical system structure causal loop diagrams will be constructed using correlation coefficients, regression coefficients, and operator system knowledge. Validity of these loops and the predictive value of the feedback systems constructed will be explored through causal modeling. Causal modeling allows hypothesis testing of restrictive models (our model) against unrestrictive ones. Unlike conventional analysis, causal modeling reports low Chi-squared values and high significance probabilities when there is little evidence to suggest the restrictive model differs from the unrestrictive model (Arbuckle, 1999).

4-5 Potential Theoretical and Methodological Weaknesses

As previously stated, metrics thermostat theory has not previously been applied to public organizations, and so the relationships between metric regression weights and leverage are somewhat unclear. In addition, the data sample of metrics, covariates and outcomes obtained contains time-series data. On one hand, this allows for increased flexibility in determining causal relationships (left for further study). However, in straight regression analysis, time dependent components of the data may affect reported coefficient weights. Furthermore, the assumption of constant risk aversion may be less correct in a time series where management has, over time, changed implied metric weights. Finally, it is impractical to conduct a survey to extract "soft" metric data for a five-year time series.

The data itself came packaged in monthly bits and annual bits.

- This page intentionally left blank -

Chapter 5: Understanding the Metrics

5-1 Definitions

5-1-1 Understanding the Metrics

In general, Air Force sustainment activities are broken down into two categories: maintenance activities and supply activities. This Air Force-chosen breakdown follows the traditional functional breakout of the weapon system maintenance and supply responsibilities and can be seen in a dissection of Air Force sustainment's top performance indicator, Not Mission Capable time (NMC or NMCT). Air Force sustainment splits the NMC metric into two parts: Not Mission Capable Maintenance time (NMCM or NMCMT) and Not Mission Capable Supply time (NMCS or NMCST). Our review of base commander monthly briefings, personal contact with both commanders and data analysts and personal experience strongly suggest that NMCM and NMCS are the metrics most used by Air Force command and control personnel for system failure problem identification. In other words, when aircraft are excessively NMC, management personnel first look to see if the problem lies in maintenance or supply. High-level management may use these metrics to place outcome responsibility on the maintenance organization, the supply organization or both; sometimes to aid in targeting system malfunctions but often as if to suggest maintenance and supply are competing paradigms.

Under the two main metrics lay dozens of supporting metrics. The shear breadth and scope of these suggest the Air Force sustainment system pays very close attention to both maintenance and supply. However, perhaps due once again to the internal structure of the Air Force, sustainment activities tend to focus on a limited set of maintenance and supply metrics. For example, while most would agree that personnel and cost play significant roles in weapon systems sustainment, one must go beyond the Air Force sustainment community to find systemic and regular use of personnel and cost as metrics. Unlike a for-profit company, an Air Force base has very little influence in determining how many sustainment personnel they employ, what the skill levels of these personnel are or how much money they can spend on their operations. Instead (and in general), base commanders are assigned personnel and operating funds. Then it is their duty to manage these personnel and funds to produce the best result possible. Such an arrangement suggests a great deal of potential for suboptimization below the Major Command (MAJCOM) level.

As described in more detail in Chapter 4, this metrics thermostat model exploits metrics from the functional divisions listed above (namely maintenance, supply, personnel and cost) and combines them in a way that best describes the strategic priorities of the MAJCOMs (namely a commitment to personnel, sustainment efficiency and sustainment effectiveness) in an effort to ultimately map to mission success. With this in mind, we collected data for the following defined metrics, each categorized in one of six strategic priorities or three high-level covariates, the one we believe it best supports. In later analysis, the metrics are compared to each other and reallocated to a high-level metric with common functional inputs keeping in mind their effect on producing a potential outcome (total not mission capable time due to maintenance, for example) or a superordinate outcome (total mission capability, for example).

5-1-1-1 Strategic Priority 1 – Maintenance Efficiency

We define Maintenance Efficiency as the amount of time and effort expended on weapons system repair functions. This priority recognizes that maintenance resources are scarce, and allocation of these resources is critical to maximizing overall success of the sustainment plan.

Low-level Metric 1(a) – Total Abort Rate

$$\text{Total Abort Rate}=\frac{Number\_of\_air\_aborts + Number\_of\_ground\_aborts}{Number\_of\_sorties\_flown + Number\_of\_ground\_aborts} * 100$$

Database: REMIS

Units: percentage of aborts/flight

Potential Indicator of:

- Time and effort wasted attempting to complete mission.
- Inability to meet customer needs.

Discussion: Aircrew members are assigned aircraft with a mission objective in mind. From the time that the maintenance team assigns an aircraft to a pilot, the possibility exists that the mission will be aborted for any of a variety of reasons: weather, maintenance, aircrew issues, etcetera. If this occurs, an abort is recorded, and the Total Abort Rate is defined as the number of air aborts plus the number of ground aborts divided by the number of sorties plus the number of ground aborts at a geo-location per month as a percentage. Aborted missions represent waste since significant resources are committed before the mission and lost sorties must be rescheduled. Abort Rate also represents a failure to support the war fighter (customer) in that aircrew resources are used up. Furthermore, some time critical missions (such as a wartime mission) may never have the opportunity to be rescheduled; they may be lost altogether.

Low-level Metric 1(b) – Break Rate

$$\text{Break Rate}=\frac{Number\_of\_sorties\_resulting\_in\_broken\_aircraft}{Number\_of\_sorties\_flown}*100$$

Database: REMIS

Units: percentage of breaks/flight

Potential Indicator of:

- Weapon system reliability.
- Weapon system utilization.

Discussion: After demanding sorties, many F-16 aircraft return from their missions unable to fly again until unscheduled maintenance actions are performed. The Break Rate is defined as the number of sorties resulting in such returns divided by the total number of sorties flown in a month as a percentage by geo-location. The Break Rate is a primary indicator of the reliability of the weapons system and it has the potential to be an indicator of excessive load-levels placed on that system. Interestingly enough, many maintenance managers theorize that excessively low levels of utilization (not using the aircraft enough) can cause Break Rates to increase just as high utilization levels do.

Low-level Metric 1(c) – Repeat Discrepancy Rate

$$\text{Repeat Discrepancy Rate}=\frac{Number\_of\_repeat\_discrepancies}{Number\_of\_reported\_discrepancies}*100$$

Database: REMIS

Units: percentage or repeats/discrepancy

Potential Indicator of:

- Weapon system maintainability.
- Weapon system utilization.
- Workforce aptitude.

Discussion: Sometimes, after a maintenance corrective action has been taken, the maintenance problem reemerges on the next sortie or attempted sortie. This occurrence is called a repeat discrepancy. The Repeat Rate is the total number of repeat discrepancies divided by the total number of reported discrepancies for a distinct geo-location per month as a percentage. Air Force management believes that this rate is an indicator of the complexity of the weapons system, the level of the operations tempo (utilization) and the ability of the workforce.

Low-level Metric 1(d) – Recurring Discrepancy Rate

$$\text{Recurring Discrepancy Rate} = \frac{Number\_of\_recurring\_discrepancies}{Number\_of\_reported\_discrepancies} * 100$$

Database: REMIS

Units: percentage of recurs/discrepancy

Potential Indicator of:

- Weapon system maintainability.
- Weapon system utilization.
- Workforce aptitude.

Discussion: Similar to the Repeat Rate, the Recur Rate tracks reemerging discrepancies from the time of the initial discrepancy through the subsequent, third and fourth sorties. It is defined as the number of recurring discrepancies divided by the total number of reported discrepancies for a distinct geo-location per month as a percentage.

Low-level Metric 1(e) – Cannibalization Rate

Cannibalization Rate= $\frac{Number\_of\_cannibalizations}{Number\_of\_sorties\_flown} * 100$

Database: REMIS

Units: percentage of cannibalizations/flight

Potential Indicator of:

- Base supply effectiveness.
- Depot supply effectiveness.
- Maintenance efficiency.

Discussion: When a part is needed for one aircraft but it is unavailable from supply, maintenance managers will often elect to take the part off of another (typically otherwise broken) aircraft to meet the supply need. Such an action is called a cannibalization. Cannibalization Rate is defined as the number of cannibalizations made divided by the total number of sorties flown for a distinct geo-location per month as a percentage. Maintenance managers have a great deal of discretion in determining whether or not to cannibalize because each cannibalization comes with a maintenance efficiency loss, the extra time to uninstall and reinstall an extra part. Factors that affect this decision include time to wait for a new part, time to cannibalize and mission criticality. Many maintenance managers believe that cannibalizations result in higher workloads and lower outcomes. Others believe that judicious cannibalization can lead to increased productivity. The cross-purposes and cross-indications involved in cannibalization make this metric difficult to classify.

Low-level Metric 1(f) – Cannibalization Fly Rate

Cannibalization-Fly Rate= $\frac{Number\_of\_cannibalizations}{Number\_of\_hours\_flown} * 100$

Database: REMIS

Units: percentage of cannibalizations/hour flown

Potential Indicator of:

- Base supply effectiveness.
- Depot supply effectiveness.
- Maintenance efficiency.

Discussion: An alternate method of calculating cannibalization, Can-Fly Rate is defined as the number of cannibalizations divided by the number of hours flown for a distinct geo-location per month as a percentage.

5-1-1-2 Strategic Priority 2 - Repair Responsiveness

Repair Responsiveness is the ability of the repair team to meet customer needs. This priority recognizes that, maintenance actions must be aligned with operational priorities. The end customer, as far as maintenance is concerned, is the war fighter. So the goal of the maintenance team is to provide aircraft that meet the timing, training and capability needs of aircrews.

Low-level Metric 2(a) – Electronic warfare POD NMCM Rate

Electronic Warfare PODs NMCM Rate =

$$\frac{AWM\_rate(week\_1) + AWM\_rate(week\_2) + \ldots AWM\_rate(last\_week\_in\_the\_month)}{Number\_of\_weekly\_rates\_sampled}$$

Where AWM_rate=

$$\frac{Total\_number\_of\_Pods\_awaiting\_ma\text{int}ennance\_(snapshot)\_discrepancies}{Average\_number\_of\_EW\_Pods\_possessed}$$

Database: REMIS

Units: percentage of average time broken/month

Potential Indicator of:

- Base maintenance effectiveness.
- Utilization.

Discussion: An electronic warfare Pod (EW Pod) is a piece of avionics equipment encased in an aerodynamic shell that attaches to the exterior of a weapon system such as the F-16. The purposes of the Pods vary. However, the availability of a Pod can be critical for particular F-16 mission accomplishment. The Electronic Warfare POD not Mission Capable Maintenance time (EW Pod NMCM) is defined as the average number of Pods awaiting maintenance (AWM) (weekly snapshot) divided by the number of possessed Pods at any given geo-location. Weekly snapshots are combined and averaged to get the monthly rate. EW Pod availability is tracked so managers know how many Pods are available in case of war.

Low-level Metric 2(b) – LANTIRN NMCM Rate

LANTIRN Not Mission Capable Maintenance Rate =

$$\frac{AWM\_rate(week\_1) + AWM\_rate(week\_2) + \ldots AWM\_rate(last\_week\_in\_the\_month)}{Number\_of\_weekly\_rates\_sampled}$$

Where AWM_rate=

$$\frac{Total\_number\_of\_LANTIRN\_Pods\_awaiting\_ma\operatorname{int}ennance\_(snapshot)\_discrepancies}{Average\_number\_of\_LANTIRN\_Pods\_possessed}$$

Database: REMIS

Units: percentage of average time broken/month

Potential Indicator of:

- Base maintenance effectiveness.
- Utilization.

Discussion: The Low-Altitude Navigation and Targeting InfraRed for Night system (LANTIRN) is and EW Pod of particular interest to the Air Force for use during night F-16 operations. The LANTIRN NMCM Rate is calculated just like the EW Pod NMCM Rate excluding all except LANTIRN Pods.

Low-level Metric 2(c) – Four-Hour Fix Rate

Four Hour Fix Rate= $\frac{Number\_of\_aircraft\_repaired\_within\_4\_hours}{Number\_of\_aircraft\_that\_land\_broken} * 100$

Database: REMIS

Units: percentage of repairs/break

Potential Indicator of:

- Maintenance efficiency, speed of repair.
- Maintenance effectiveness in returning aircraft to next mission.
- Supply efficiency in speed of repair.
- Supply effectiveness in returning aircraft to next mission.

Discussion: Fix Rates are at the heart of determining mission capability since mission capability can be loosely defined by the rate at which weapon systems break against the rate at which they are fixed. The Four-Hour Fix Rate is defined as the number of broken aircraft returnable to flyable status within four hours divided by the number of aircraft broken (presumably by aircrews) at a geo-location per month as a percentage. This metric measures the ability of the maintenance team to respond to unscheduled maintenance events and provide mission-ready aircraft to the war fighter in a timely manner. During wartime, a fix that takes over four hours results in a lost sortie.

Low-level Metric 2(d) – Eight-Hour Fix Rate

$$\text{Eight Hour Fix Rate}=\frac{Number\_of\_aircraft\_repaired\_within\_8\_hours}{Number\_of\_aircraft\_that\_land\_broken}*100$$

Database: REMIS

Units: percentage of repairs/breaks

Discussion: Identical to the Four-Hour Rate except for the time period for repair.

Low-level Metric 2(e) – Twelve-Hour Fix Rate

$$\text{Twelve-Hour Fix Rate}=\frac{Number\_of\_aircraft\_repaired\_within\_12\_hours}{Number\_of\_aircraft\_that\_land\_broken}*100$$

Database: REMIS

Units: percentage of repairs/breaks

Discussion: Identical to the Four-Hour Rate except for the time period for repair.

5-1-1-3 Strategic Priority 3 – Maintenance Personnel

As discussed earlier, base commanders have little influence over the numbers and qualifications of personnel they employ. Instead, personnel are assigned by skill code and skill level relative to the number of aircraft assigned to a geo-locations and the mission assigned. Five skill levels exist with level three representing the least experienced worker and level zero representing the most experienced worker (see Table 5-1):

Table 5-1 – Sustainment Skill Levels

Level	Description
3 LVL	Airman Basic, Airman, Airman First Class
5 LVL	Senior Airman, Staff Sergeant
7 LVL	Technical Sergeant, Master Sergeant
9 LVL	Senior Master Sergeant
0 LVL	Chief Master Sergeant

(Grey, 2000)

Two major aircraft sustainment skill codes exist: weapons systems specialization (W) or ammunitions specialization (A). An F-16 weapons system specialist would be used to maintain the F-16 itself while an ammunitions specialist would be charged with maintenance of munitions that fly on the F-16.

Finally, as discussed below in detail, three metrics describe the state of each skill-code skill-level combination: personnel requirements, personnel authorizations, and personnel assignments.

Low-level Metric 3(a) through 3(j) – Maintenance Personnel Required per Plane

Maintenance Personnel Required/Plane= $\dfrac{M\_pers\_theoretical - M\_pers\_funded}{Average\_aircraft\_inventory}$

Database: MDS

Units: people/plane

Potential Indicator of:

- Personnel funding commitment.
- Mission funding commitment.

Discussion: The F-16 was designed with a maintenance personnel complement in mind. However, due to budgetary constraints, it is not always possible for each base to be funded for its full complement. Maintenance personnel requirements represent funding shortages in the number of personnel in a given skill code and skill level at a geo-location. They are given by the number of personnel theoretically required to maintain all of the aircraft at the base minus the number of personnel funded to maintain all of the aircraft on the base. To normalize, we then divide this total by the number of aircraft on hand (Aircraft funded would be more correct. However, that number was in limited availability for this study.). With five skill levels and two skill codes, this represents ten potential metrics. However, several of these metric fields are zero since all bases have no requirements for particular skill-level skill-code combinations. Note: as the next two sets of metrics will show, just because a billet is funded does not mean it is filled. Also, note that bases with missions deemed to be more critical are more likely to be funded for personnel at a higher level. All personnel metrics are reported by year as opposed to by month.

Low-level Metric 3(k) through 3(t) – Maintenance Personnel Authorized/Plane

$$\text{Maintenance Personnel Authorized/Plane}=\frac{M\_personnel\_funded}{Average\_aircraft\_inventory}$$

Database: MDS and UMD

Units: people/plane

Potential Indicator of:

- Personnel funding commitment.
- Mission funding commitment.

Discussion: Constrained by funds available, Air Force manpower specialists compare base requirements and mission criticality from base to base and across MAJCOMs to decide at what level each base is funded for personnel. Maintenance personnel authorized represents this funding level for a given skill code and skill level at a geo-location. To normalize, we then divide this total by the number of aircraft on hand (Again, aircraft funded would be more correct.). With five skill levels and two skill codes, this represents ten potential metrics. Again, several of these metric fields are zero since all bases have no requirements for particular skill-level skill-code combinations.

Low-level Metric 3(u) through 3(ad) – Maintenance Personnel Assigned/Plane

$$\text{Maintenance Personnel Assigned/Plane}=\frac{M\_personnel\_assigned}{Average\_aircraft\_inventory}$$

Database: UMD

Units: people/plane

Potential Indicator of:

- Personnel resource commitment.

- Mission resource commitment.

Discussion: Personnel are not always assigned on a one-to-one ratio with personnel funded. Even if the funding exists, actual assignments are constrained by many factors including hiring pipelines and training pipelines. Maintenance personnel assigned represents the allocation of actual personnel for a given skill code and skill level at a geo-location. To normalize, we then divide this total by the number of aircraft on hand (Again, aircraft funded would be more correct.). With five skill levels and two skill codes, this represents ten potential metrics. Again, several of these metric fields are zero since all bases have no requirements for particular skill-level skill-code combinations.

Thus, thirty potential metrics exist for maintenance personnel, encoded as follows:

Table 5-2 – Maintenance Personnel Metrics

	Personnel Required	**Personnel Authorized**	**Personnel Assigned**
3 – Level Weapons	R_W_3	Au_W_3	As_W_3
5 – Level Weapons	R_W_5	Au_W_5	As_W_5
7 – Level Weapons	R_W_7	Au_W_7	As_W_7
9 – Level Weapons	R_W_9	Au_W_9	As_W_9
0 – Level Weapons	R_W_0	Au_W_0	As_W_0
3 – Level Munitions	R_A_3	Au_A_3	As_A_3
5 – Level Munitions	R_A_5	Au_A_5	As_A_5
7 – Level Munitions	R_A_7	Au_A_7	As_A_7
9 – Level Munitions	R_A_9	Au_A_9	As_A_9
0 – Level Munitions	R_A_0	Au_A_0	As_A_0

5-1-1-4 Strategic Priority 4 – Supply Efficiency

Supply Efficiency represents the time and effort waiting and spent on supply. Like maintenance resources, supply resources are scarce. This priority attempts to quantify the availability of supply resources.

Low-level Metric 4(a) – Scheduled Engine Removal (per Plane) Rate

$$\text{Scheduled Engine Removals Rate} = \frac{Number\_of\_scheduled\_engine\_removals}{Number\_of\_aircraft\_possessed}$$

Database: REMIS

Units: removals/plane

Potential Indicator of:

- Maintenance efficiency in on-time engine removal.
- Supply efficiency in spare engine availability.

Discussion: Engine maintenance plays a large role in determining the success of an aircraft weapons system and has been identified by the Air Force a lead contributor in degraded performance. REMIS does track how many engines were removed on schedule. However, it does not automatically convert this raw number into a rate. So, we devised the Scheduled Engine Removal Rate (SERR): the number of scheduled engines removed divided by the number of aircraft on hand at a given geo-location per month. This rate may help indicate the ability of the supply and maintenance teams to maintain a schedule of maintenance.

Low-level Metric 4(b) – Unscheduled Engine Removal (per Plane) Rate

Unscheduled Engine Removal Rate=$\dfrac{Number\_of\_unscheduled\_engine\_removals}{Number\_of\_aircraft\_possessed}$

Database: REMIS

Units: removals/plane

Potential Indicator of:

- Maintenance inefficiency in on-time engine removal.
- Supply efficiency in engine's ability to perform.

Discussion: The number of unscheduled engine removals divided by the number of aircraft possessed by geo-location, Unscheduled Engine Removal Rate is similar in formulation to the Scheduled Engine Removal Rate. Unscheduled Engine Removal Rate may help indicate the maintenance teams inability to follow a maintenance schedule due, perhaps in part, to the supplied engines inability to remain on wing for its allotted lifetime. Note that the true cause of the engine's inability to meet its specified lifetime may be a combination of maintenance and/or supply issues.

Low-level Metric 4(c) – Pre-Repair Cycle Time

Pre-Repair Cycle Time=$\dfrac{Total\_days\_in\_level\_2\_pre\_repair}{Number\_items\_repaired}$

Database: MAJCOM specific from Synergy

Units: days

Potential Indicator of:

- Local supply queuing time.
- Manning and ability of local repair teams.

- Local supply pipeline time.
- Break Rates.

Discussion: While the primary function of base maintenance teams is to maintain base weapon systems, they spend a significant portion of their efforts repairing parts for later use on those weapon systems. For many less specialized or time-critical repairs, the Air Force chooses to repair on-site rather than ship to a repair facility. Repairs of this nature are called two-level repairs. When a two-level repairable part is broken, it is sent to a local repair facility for repair. While there, it is classified by one of three status indicators: Pre-Repair, Repair or Post-Repair. Repairables in Pre-Repair are broken but not yet being repaired. This might occur, for example, if there are not enough personnel available to fix the part. Pre-Repair Cycle Time is then the sum of the time (in days) that all parts are in Pre-Repair divided by the total number of parts repaired per month by geo-location.

Low-level Metric 4(d) – Repair Cycle Time

$$\text{Repair Cycle Time}=\frac{Total\_days\_in\_level\_2\_repair}{Number\_items\_repaired}$$

Database: MAJCOM specific from Synergy

Units: days

Discussion: Repairables in Repair are being refurbished by the local repair team, and Repair Cycle Time is then the sum of the time (in days) that all parts are in Repair divided by the total number of parts repaired per month by geo-location. Otherwise, Repair Cycle Time is identical to Pre-Repair Cycle Time.

Low-level Metric 4(e) – Post-Repair Cycle Time

$$\text{Post-Repair Cycle Time}=\frac{Total\_days\_in\_level\_2\_post\_repair}{Number\_items\_repaired}$$

Database: MAJCOM specific from Synergy

Units: days

Discussion: Repairables in Post-Repair have been refurbished by the local repair team and await delivery back to "ready-for-issue" status. Post-Repair Cycle Time is then the sum of the time (in days) that all parts are in Post-Repair divided by the total number of parts repaired per month by geo-location. Otherwise, Post-Repair Cycle Time is identical to Repair Cycle Time.

5-1-1-5 Strategic Priority 5 – Supply Responsiveness

Supply Responsiveness is the ability of the supply system to meet customer needs. Just as one can think of the customer of the maintenance system as the war fighter, one can think of the customer of the supply system as the maintenance system. Maintenance can only do their job if adequately supplied. This priority attempts to gauge the ability of the supply system to support the maintenance system keeping in mind that actions of the maintenance system affect the supply system as well.

Low-level Metric 5(a) – Electronic Warfare PODs NMCS Rate

Electronic Warfare PODs NMCS Rate=

$$\frac{AWS\_rate(week\_1)+AWS\_rate(week\_2)+\ldots AWS\_rate(last\_week\_in\_the\_month)}{Number\_of\_weekly\_rates\_sampled}$$

Where AWS_rate=

$$\frac{Total\_number\_of\_Pods\_awaiting\_\sup ply\_(snapshot)\_discrepancies}{Average\_number\_of\_EW\_Pods\_possessed}$$

Database: REMIS

Units: percentage of average time broken/month

Potential Indicator of:

- Base supply effectiveness.
- Utilization.

Discussion: Analogous to the EW Pod NMCM Rate, this metric covers supply time. EW Pod NMCS Rate is defined as the average number of Pods awaiting parts (AWP) (weekly snapshot) divided by the number of possessed Pods at any given geo-location. Weekly snapshots are combined and averaged to get the monthly rate.

Low-level Metric 5(b) – LANTIRN NMCS Rate

LANTIRN Not-Mission Capable Supply Rate=

$$\frac{AWS\_rate(week\_1)+AWS\_rate(week\_2)+\ldots AWS\_rate(last\_week\_in\_the\_month)}{Number\_of\_weekly\_rates\_sampled}$$

Where AWS_rate=

$$\frac{Total\_number\_of\_LANTIRN\_Pods\_awaiting\_\sup ply\_(snapshot)\_discrepancies}{Average\_number\_of\_LANTIRN\_Pods\_possessed}$$

Database: REMIS

Units: percentage of average time broken/month

Potential Indicator of:

- Base supply effectiveness.
- Utilization.

Discussion: The LANTIRN NMCM Rate is calculated just like the EW Pod NMCS Rate excluding all except LANTIRN Pods.

Low-level Metric 5(c) – Unit's Shortage of Primary Aircraft Assigned (PAI) per Plane

$$\text{PAI Shortage/Plane} = \frac{\#\_of\_aircraft\_authorized - \#\_of\_aircraft\_on\_hand}{\#\_of\_aircraft\_authorized}$$

Database: REMIS and local MAJCOM sources

Units: planes/plane

Potential Indicator of:

- Mission criticality.
- Supply effectiveness.
- Fiscal commitment.

Discussion: Units are staffed for and budgeted for a chargeable amount of aircraft. However they frequently operate with more or less than authorized. The Air Force tracks how many aircraft are short (or surplus) for each geo-location. To normalize this number for locations with large numbers of aircraft against locations with small number of aircraft, the Unit Short Primary Aircraft Inventory is defined as the number of authorized aircraft at a geo-location minus the number of actual aircraft at that location divided by the number of authorized aircraft at the location averaged for the month. A negative number indicates the unit had a windfall of aircraft and a positive number indicates the unit had a shortage. REMIS does not track the number of aircraft authorized. So, that portion of this metric was derived from several local sources.

Low-level Metric 5(d) – Supply Issue Effectiveness

$$\text{Supply Issue Effectiveness} = \frac{Line\_items\_issued}{Line\_items\_issued + Line\_items\_backordered} * 100$$

Database: SBSS

Units: percentage of items/item

Potential Indicator of:

- Logistics customer support.
- Anticipation of customer needs.

Discussion: The base is not funded to supply each and every part. On the contrary, each base must decide which critical or highly used components they will stock constrained by funding. Supply Issue Effectiveness is a measure of the base's ability to anticipate the needs of maintenance personnel and is defined as the number of parts issued divided by the number of parts issued and the number of parts backordered (desired but not available on base) as a percentage by month and geo-location.

Low-level Metric 5(e) – Stockage Effectiveness

$$\text{Stockage Effectiveness} = \frac{Line\_items\_issued}{items\_issued + items\_backordered - items\_bo\_4w} * 100$$

Database: SBSS

Units: percentage of items/item

Potential Indicator of:

- Logistics customer support.
- Anticipation of customer needs.

Discussion: For a variety of reasons, some parts require long lead times to procure. Over the long term (and in general terms), when base supply orders a part it becomes the Defense Logistics Agency's (DLA) responsibility to supply that part. However, not every part is delivered in a timely manner. In an effort to differentiate base supply shortcomings and DLA supply issues, Stockage Effectiveness was established. Stockage Effectiveness is defined as the number of parts issued divided by the number of parts issued plus the number of parts backordered minus the number of parts backordered for over four weeks as a percentage by month and geo-location.

5-1-1-6 Strategic Priority 6 – Supply Personnel

Just as with maintenance personnel, assignment of supply personnel is largely out of the hands of base commanders. Here again, personnel are assigned by skill code and skill level relative to the number of aircraft assigned to a geo-locations and the mission assigned. The same five skill levels exist in supply as they exist in maintenance (see Table 5-1).

Unlike maintenance codes, supply codes exist in only one generic "supply" category (S). No records were obtainable in regard to aviation-specific supply personnel, so data exists for general supply personnel only.

Also, as in maintenance, three metrics describe the state of each skill-code skill-level combination: personnel requirements, personnel authorizations, and personnel assignments.

Refer to the discussion section of the complimentary maintenance personnel metric for a more complete explanation of each metric below:

Low-level Metric 6(a) through 6(e) – Supply Personnel Required per Plane

$$\text{Supply Personnel Required/Plane} = \frac{S\_pers\_theoretical - S\_pers\_funded}{Average\_aircraft\_inventory}$$

Database: MDS

Units: people/plane

Potential Indicator of:

- Personnel funding commitment.
- Mission funding commitment.

Low-level Metric 6(f) through 6(j) – Supply Personnel Authorized/Plane

$$\text{Supply Personnel Authorized/Plane} = \frac{S\_personnel\_funded}{Average\_aircraft\_inventory}$$

Database: MDS and UMD

Units: people/plane

Potential Indicator of:

- Personnel funding commitment.
- Mission funding commitment.

Low-level Metric 6(k) through 6(o) – Supply Personnel Assigned/Plane

$$\text{Supply Personnel Assigned/Plane} = \frac{S\_personnel\_assigned}{Average\_aircraft\_inventory}$$

Database: UMD

Units: people/plane

Potential Indicator of:

- Personnel resource commitment.
- Mission resource commitment.

Thus, fifteen potential metrics exist for supply personnel, encoded as follows:

Table 5-3 – Supply Personnel Metrics

	Personnel Required	**Personnel Authorized**	**Personnel Assigned**
3 – Level Supply	R_S_3	Au_S_3	As_S_3
5 – Level Supply	R_S_5	Au_S_5	As_S_5
7 – Level Supply	R_S_7	Au_S_7	As_S_7
9 – Level Supply	R_S_9	Au_S_9	As_S_9
0 – Level Supply	R_S_0	Au_S_0	As_S_0

5-1-2 Understanding the Covariates

Many factors that effect F-16 performance are either completely or at least somewhat out of base commanders' control. We call these factors covariates. While the line between what a metric is and what a covariate is may be blurred (based on the relative amount of control a base commander can effect on each item), the mathematics behind how both are treated in the model does not change. The primary motive behind breaking covariates out is to illustrate that management cannot control all factors.

5-1-2-1 Covariate 1 – Weather

Maintenance managers have often theorized that weather pattern changes affect both their ability to maintain a weapons system and the weapon system's likeliness to break.

Low-level Covariate 1(a) – Average Monthly Temperature

No formula.

Database: WorldClimate

Units: degrees Fahrenheit

Potential Indicator of:

- Break Rate
- Fix Rate

Discussion: Weapon systems are designed to operate in ranges of temperatures. If the temperature is too high or too low on a regular basis, system components may fail at increasing rates. Furthermore, sustainment workers are likely to be more efficient and effective working under moderate temperatures. Average Monthly Temperature is a monthly sum of the daily average temperature at a given geo-location divided by the number of days in the month.

Low-level Covariate 1(b) – Monthly Precipitation

No formula.

Database: WorldClimate

Units: inches

Potential Indicator of:

- Break Rate
- Fix Rate

Discussion: Precipitation tends to exacerbate both maintenance and operation of modern aircraft subsystems. Greater precipitation rates may indicate increasing system component failures. Furthermore, since some sustainment activities occur outside, sustainment workers are likely to be more efficient and effective working in less rainy environments. Monthly Precipitation is a sum (in inches) of all rain and snow for a given month at a given geo-location where snowfall is converted to inches of rain.

5-1-2-2 Covariate 2 – Mission

Each MAJCOM has a different mission, and each base within a MAJCOM possesses a unique part of that mission. So, it is reasonable to expect that successful mission completion may vary somewhat from geo-location to geo-location based on both the difficulty and engagement of the local mission.

Low-level Covariate 2(a) – Mission

No formula.

Database: USAF general information (no database)

Units: nominal

Potential Indicator of:

- Mission type

- Mission difficulty

Discussion: F-16's are operated by several major commands including the Air Combat Command, the Air National Guard, the Training Command, the Pacific Air Forces, the United States Air Forces Europe and the Air Force Reserve. It may be that distinct commands have policies and/or mission elements that alter mission effectiveness or that mission effectiveness is measured differently from one command to the next. This metric explores potential correlations between performance and command. Each geo-location is assigned a number (as shown in table 5-4 below) that describes the MAJCOM it is associated with:

Table 5-4 - Numerical Command Identifiers

Command	**Numerical Identifier**
Air Combat Command	1
Training Command	2
United States Air Forces Europe	3
Air Force Reserve	4
Air National Guard	5
Pacific Air Forces	6

Low-level Covariate 2(b) – Hourly Utilization Rate

Hourly Utilization Rate= $\dfrac{Number\_of\_hours\_flown}{Aircraft\_on\_hand}$

Database: REMIS

Units: hours/aircraft

Potential Indicator of:

- Overuse/underuse
- Mission criticality

Discussion: Each unit has a "programmed" or scheduled amount of F-16 flight hours to fly each month. However, due to changing operational requirements, budgeting constraints, maintenance issues, weather issues and other unforeseeable events, units often stray significantly from their programmed aircraft utilization. For our study, the Hourly Utilization Rate is defined as the number of hours all geographically co-located F-16s fly in a month divided by the number of on-hand F-16's for the geo-location. In the typical Air Force definition, Utilization Rates are based on chargeable, not on-hand, aircraft. Due data availability constraints, our rates are based on actual or on-hand aircraft.

Low-level Covariate 2(c) – Sortie Utilization Rate

$$\text{Sortie Utilization Rate}=\frac{Number\_of\_sorties\_flown}{Aircraft\_on\_hand}$$

Database: REMIS

Units: sorties/aircraft

Potential Indicator of:

- Overuse/underuse
- Mission criticality

Discussion: Similar in concept to Hourly Utilization Rate, for our study Sortie Utilization Rate is defined as the number of sorties all geographically co-located F-16s fly in a month divided by the number of on-hand F-16's for the geo-location. Again, we have modified the denominator of the metric for reasons of data availability.

5-1-2-3 Covariate 3 – Base Size

Low-level Covariate 3(a) – Average Inventory

No formula.

Database: REMIS

Units: number of aircraft

Potential Indicator of:

- Economies of Scale (efficiency and effectiveness)

Discussion: Economists have long recognized the advantages of (somewhat) larger organizations in completing tasks more efficiently and/or effectively than their smaller counterparts. Average Inventory attempts to measure base size by capturing the amount of aircraft actually at a given geo-location (averaged per month).

5-1-3 Understanding the Outcomes

Just as the lines between metrics and covariates are blurred, so are the lines between metrics and outcomes. An outcome is generally regarded as a measure of mission completeness. It is the end goal of the sustainment team. However, outcomes, like covariates, can affect each other as well as provide feedback to strategic priorities and low-level metrics.

5-1-3-1 Outcome 1 - Mission Accomplishment

Outcome 1(a) – Mission Capable Rate

Mission Capable Rate= $\frac{1-NMCM-NMCS-NMCB}{Possessed\_hours}*100$

Database: REMIS

Units: percentage

Potential Indicator of:

- Sustainment's readiness over time.

Discussion: Perhaps the most pervasive and traditional measure of a weapon system's performance, Mission Capable Rate is defined (quite narrowly) as the total number of "ready to perform" aircraft hours a unit possesses in a month divided by the total number of aircraft hours a unit possesses in a month as a percentage. For example, if a unit had three F-16s, one of which was capable for 20 days, one for 27 and one for 30 in a thirty-day month, the unit's Mission Capable Rate would be:

$$\frac{(20+27+30)*24hrs/day}{3aircraft*24hrs/day*30days}=\frac{1848}{2160}=85.5\%$$

This metric is the traditional yardstick from which base commanders have judged F-16 performance. It is an accurate and easily collectible (highly measurable) metric. Unfortunately, in recent years, its power in predicting F-16 performance (its leverage) has come under scrutiny. Mission capability measures the hours for which aircraft are available to complete their mission. It does not, however, measure how well the maintenance team meets the flying requirements (flight schedule) of the war fighter. The Utilization Rate metric was designed to meet this shortfall. Still, complicating the performance question more, war fighter missions come with a broad range of criticalities and time constraints. For example, for a wartime mission, both the operation of and the timely availability of the F-16 are extremely important. For a peacetime training mission, operation and availability can be traded off and are both less important than in times of war. Even the Utilization Rate metric fails to fully capture this side of performance. NMC is further broken up as described in outcomes 1(b) and 1(c) below:

Outcome 1(b) – Total Not Mission Capable Maintenance Rate (TNMCM)

$$\text{Total Not Mission Capable Maintenance Rate}=\frac{NMCM\_hours + NMCB\_hours}{Possessed\_hours}*100$$

Database: REMIS

Units: percentage

Potential Indicator of:

- Maintenance's readiness over time.

Discussion: Aircraft are said to be NMC for one of three reasons: they are awaiting maintenance (NMCM), they are awaiting parts or supply (NMCS) or they are awaiting both maintenance and supply (NMCB). The total NMCM time (TNMCM) includes both NMCM and NMCB. The TNMCM Rate is the number of hours all aircraft at a particular geo-location are in an NMCM or NMCB status divided by the total aircraft hours possessed in the month (# days/month*24 hours/day*# aircraft possessed) as a percentage.

Outcome 1(c) – Total Not Mission Capable Supply Rate (TNMCS)

Total Not Mission Capable Supply Rate= $\frac{NMCS\_hours + NMCB\_hours}{Possessed\_hours} * 100$

Database: REMIS

Units: percentage

Potential Indicator of:

- Supply's readiness over time.

Discussion: Returning to the definition of NMC, Not Mission Capable Supply time (NMCS) is the amount of time an aircraft is grounded due to a supply shortage. The NMCS Rate is the number of hours all aircraft at a particular geo-location are in an NMCS or NMCB status divided by the total aircraft hours possessed in the month (# days/month*24 hours/day*# aircraft possessed) as a percentage.

Outcome 1(d) – Flying Scheduling Effectiveness (FSE)

Flying Scheduling Effectiveness= $\frac{Total\_sorties\_scheduled - Total\_deviations}{Total\_sorties\_scheduled} * 100$

Database: REMIS

Units: percentage

Potential Indicator of:

- Ability to meet needs of operations department.

Discussion: An alternate method of measuring mission success, Flying Scheduling Effectiveness measures the ability of a base to meet its mid-term operational requirements. A flight schedule is posted in advance, and any deviations from that schedule are counted against effectiveness.

5-1-3-2 Outcome 2 – Cost

The Air Force, unlike private companies, does not operate for profit. Furthermore, due to the nature of government funding, military aircraft operate with a (relatively) fixed budget. Funding is allocated on a per-flight-hour assigned basis. That is, for each geo-location where the F-16 operates, the base commander receives a fixed amount of money for each F-16 flight-hour "programmed." For example, if Shaw Air Force Base is funded for 60 F-16s at 300 hours per F-16 per year, Shaw receives $59,472,000 ($3304/flight-hour* 60 aircraft*300 flight-hours/aircraft) annually to maintain and fly their aircraft. Notice that this funding is based on funded aircraft and programmed flight-hours, not assigned aircraft and actual flight hours. Furthermore, it is really only a partial cost of ownership of the F-16. It does not include costs to operate the base, design and manufacture costs or maintenance and operational personnel costs. It does include (refer to table 5-5):

Table 5-5 - F-16 Funding Costs by Classification

F-16 Funding Classifications:	**Cost Per Flight Hour**
Fuel (AVPOL)	$563
Maintenance Support Division (MSD-consumable supply)	$2353
Materials Support Division (GSD-repairable supply)	$388
Total	$3304

Shaw will most likely fly its F-16s for more or less than the 1800 flight-hours programmed (in this example, 60 aircraft*300 hours/aircraft), and, many times, they will possess either more or less aircraft than they are funded for. Notwithstanding this, they (in general) still received $59,470,000.

What they spend is another issue. While base commanders try to spend up to but not over their budgets, many factors may prevent them from doing this. Therefore, spending may be an important driver of F-16 behavior:

Outcome 2(a) – Consumable Cost per Plane

Consumable Cost per Plane= $\frac{Total\_consumable\_\cos ts}{Average\_inventory}$

Database: SBSS

Units: dollars

Potential Indicator of:

- Supply Fix Rate
- Utilization

Discussion: The total number of dollars spent (per year) per geo-location for consumable items. Consumables include small relatively inexpensive aircraft subsystem support items (usually part of the weapon system).

Outcome 2(b) – Repairable Cost per Plane

Repairable Cost per Plane= $\frac{Total\_repairable\_\cos ts}{Average\_inventory}$

Database: SBSS

Units: dollars

Potential Indicator of:

- Supply Fix Rate
- Utilization

Discussion: The total number of dollars spent (per year) per geo-location for repairable items. Repairables include large reusable (repairable) relatively expensive aircraft subsystem support items (usually part of the weapon system).

Outcome 2(c) – Fuel Cost per Plane

Fuel Cost per Plane= $\frac{Total\_fuel\_\cos ts}{Average\_inventory}$

Database: SBSS

Units: dollars

Potential Indicator of:

- Utilization

Discussion: The total number of dollars spent (per year) per geo-location for fuel. With stable fuel prices, this metric may help indicate aircraft utilization.

Outcome 2(d) – Impact Cost per Plane

Impact Cost per Plane= $\frac{Total\_impact\_\cos ts}{Average\_inventory}$

Database: SBSS

Units: dollars

Potential Indicator of:

- Level of civilian operations

- Utilization

Discussion: The total number of dollars spent (per year) per geo-location for impact purchases. Impact purchases occur with a credit card. So, they may be an indicator of aircraft usage away from military operating bases or a weak indicator of utilization.

5-2 Data Sources

As of 05 July 2000, AFMC's Corporate Data Repository System Data System Assignment Directory contained 395 distinct data collection programs. Some provided inputs and/or outputs to others. However most provided subsets of information either overlapping or inaccessible from other data systems (AFMC, 2000). Just a few of these, involved in the collection of data for this study, are described below:

5-2-1 Reliability and Maintainability Information System (REMIS)

Functional Operator: United States Air Force Material Command (AFMC)

Used by: MAJCOM-level through base level for daily maintenance management through long-term reliability and maintainability management.

Description: REMIS receives weapons system maintenance information in detailed and summary format from CAMS, CAMS for airlift (g081), Integrated Maintenance Data System (IMDS), and depot and contractor technology repair centers by direct on-line input and file transfer protocol via the Defense Information System Network (DISN). Taking inputs from CAMS and other databases, REMIS purposes to be one-stop shopping for all reliability and maintainability metrics for USAF weapon systems. In this regard, I found REMIS to be exceptionally useful for finding maintenance metrics and marginally useful in finding supply metrics. Unfortunately, REMIS falls short in providing financial (cost) and personnel data associated with reliability and maintainability (AFMC, 2000).

5-2-2 Standard Base Supply System (SBSS)

Functional Operator: United States Air Force Material Command (AFMC)

Used by: base level across MAJCOMs

Description: SBSS is an automated electronic inventory control program that standardizes equipment, supplies and base aviation fuels accounts throughout the air force. It provides historical information in regard to weapon systems cost breakdowns (AFMC, 2000).

5-2-3 Core Automated Maintenance System (CAMS)

Functional Operator: United States Air Force Material Command (AFMC)

Used by: Base-level personnel across MAJCOMs for data entry and maintenance management.

Description: CAMS is the Air Force base-level automated maintenance information management system. It supports all aircraft, communications-electronics, and support equipment maintenance activities at 93 active duty bases worldwide, 118 Air National Guard and Air Force Reserve sites, and several NATO bases. A legacy system, CAMS was the first automated system installed, taking the place of manual maintenance data collection systems. CAMS automates aircraft history, aircraft scheduling and aircrew debriefing processes. It provides a common interface for entering base-level maintenance data into other standard logistics management systems, particularly REMIS. CAMS data is retrieved at the base level or uploaded to REMIS for retrieval at the MAJCOM level. Unfortunately, not all MAJCOMs enter data into CAMS in the same way, leaving the REMIS database sparsely or inaccurately populated when analyzing data across MAJCOMs. Furthermore, CAMS provides little or no personnel and financial data to REMIS (AFMC, 2000).

5-2-4 Unit Manning Document (UMD)

Functional Operator: MAJCOM level (Directorate of Personnel (DP))

Used by: MAJCOM level (Directorate of Personnel) to base-level

Description: The UMD is designed to provide MAJCOM personnel managers with accurate automated personnel data. The Air Force is careful to differentiate between personnel data and manpower data. The UMD provides personnel data. Personnel data are information packets regarding the actual location of personnel (assigned personnel) against personnel authorization levels (the quantity funded).

5-2-5 Manpower Data System (MDS)

Functional Operator: HQ USAF/XP (Strategic Planning Directorate)

Used by: HQ USAF/XP (Strategic Planning Directorate)

Description: The MDS is designed to provide headquarters-level managers with accurate automated manpower authorization data. As the name implies, the MDS provides manpower data. Manpower data are information packets regarding the number of personnel theoretically required (the quantity needed to properly execute a systemic task) against personnel authorization levels (the quantity funded) (USAF Electronic Systems Center, no date).

5-2-6 ACC-203 Report

Functional Operator: HQ USAF (contracted to civilian provider "Synergy")

Used by: MAJCOM-level (Maintenance, Policy and Procedures Branch)

Description: USAF bases not only maintain the F-16 through direct maintenance of the weapon system. They also perform the maintenance of on-hand weapon system supplies (repairables). Each base is required to track several data fields in regard to their ability to conduct these supply-type repairs. They report this data via the ACC-203 report to

Synergy, a civilian contractor, who collects the data for dissemination at the MAJCOM level. MAJCOM supply, planning and measurement staffs handle this data differently from one MAJCOM to the next, but they do typically aggregate it into comparable supply metrics with the goal of understanding and correcting the health of the base-level and the MAJCOM-level aviation supply system. Three such aggregated and comparable supply metrics reported via the ACC-203 are: PRE Repair Cycle Time (the amount of time a part awaits repair), REPAIR Cycle Time (the amount of time a part is in repair), and POST Repair Cycle Time (the amount of time a part awaits return to "ready for issue"). MAJCOM supply analysts typically judge the health of a base's supply repair system on the average amount of time a repairable spends in all three of these queues (shorter times indicating healthier more successful operation).

5-2-7 WorldClimate

Functional Operator: Civilian

Used by: N/A

Description: WorldClimate is a web-based data system that collects and aggregates climatological data from a variety of sources. Sources for WorldClimate include the Global Historical Climatology Network, version 1; The Global Historical Climatology Network, version 2 beta; NCDC TD 9641 Clim 81 1961-1990 Normals; and NCDC Cooperative Stations.

Chapter 6: Analysis and Results

6-1 Overview

This chapter presents an overview of the preliminary analyses conducted with the F-16 data. Accrediting the breath and scope of the data, the amount and types of data analysis possible are extensive. Thus, the suggestions herein are exploratory in nature and not intended to be definitive. In all cases, future study is warranted.

6-2 Purification and Correlation of Low-Level Metrics

Initial exploration of the F-16 sustainment data revealed that the low-level metrics, as originally mapped to strategic priorities, possessed relatively low internal reliability. We used Cronbach's Alpha reliability analysis statistics to measure the reliability of the grouped low-level metrics converted to standardized form (the metric minus the mean of the metric all divided by the standard deviation of the metric). Originally, Alpha reported relatively low values suggesting the opportunity to regroup low-level metrics into improved or "purified" high-level metrics for further analysis. This regrouping typically involved a tradeoff between selecting high alphas and eliminating potentially valuable low-level metrics from the model. Table 6-1 lists the "purified" metrics we decided on along with their associated Alphas and common cases (N):

Table 6-1 - Purified Metrics and Alphas

High-Level Concept	Concept Type	Supporting Low-Level Metric	Method	α	N
Base Size	Metric	• Average Inventory	Single	N/A	N/A
Maintenance Personnel/Plane	Metric/ Covariate	• Authorized • Assigned	Sum & Sum Averaged*	.982	217
Supply Personnel/Plane	Metric/ Covariate	• Authorized • Assigned	Sum & Sum Average*	.992	184
Break Rate	Metric	• Abort Rate • Break Rate	Averaged Sum	.431	2467
Fix Rate	Metric	• 4-hour Fix rate • 8-Hour Fix Rate • 12-Hour Fix Rate	Averaged Sum	.999	1878
Supply Costs/Plane	Metric/ Outcome	• Consumable Costs/Plane • Repairable Costs/Plane	Averaged Sum	.7646	172
Aircraft Utilization Rate	Metric/ Outcome	• Hourly Utilization/Plane • Sortie Utilization/Plane	Averaged Sum	.870	2691
Cannibalization Rate	Metric	• Cannibalizations/Hour • Cannibalizations/Sortie	Averaged Sum	.969	2592
Base Supply Effectiveness	Metric	• Issue Effectiveness • Stockage Effectiveness	Averaged Sum	.754	1916
Repeat Discrepancies	Metric/Cov	• Repeat Discrepancy Rate	Single	N/A	N/A
Base Repair Effectiveness	Metric	• Pre-Repair Cycle Time • Repair Cycle Time • Post-Repair Cycle Time	Added	N/A	N/A
EW POD NMCT	Metric/ Covariate	• EW Pod NMCM • EW POD NMCS	Averaged Sum	.7519	630
Scheduled Maintenance Rate	Metric	• Scheduled Engine Removal Rate	Single	N/A	N/A
Unscheduled Maintenance Rate	Metric/ Covariate	• Unscheduled Engine Removal Rate	Single	N/A	N/A
Aircraft Shortages	Metric/ Covariate	• Shortages of Primary Aircraft Assigned/Plane	Single	N/A	N/A
Weather- Temperature	Covariate	• Average Monthly Temp.	Single	N/A	N/A
Weather- Precipitation	Covariate	• Average Monthly Precipitation	Single	N/A	N/A
Total NMCM	Outcome	• NMCM Rate	Single	N/A	N/A
Total NMCS	Outcome	• NMCS Rate	Single	N/A	N/A
Time Mission Capable	Outcome	• Mission Capable Rate	Single	N/A	N/A
Flying Scheduling Effectiveness	Outcome	• Flying Scheduling Effectiveness	Single	N/A	N/A
Variable Costs/Plane	Metric/Cov	• Fuel Costs/Plane	Single	N/A	N/A
Metrics Dropped		• LANTIRN POD NMCM • LANTIRN POD NMCS • Impact Costs/Plane • Authorized Inventory • Maintenance Pers. Rqd • Supply Pers. Rqd.	N/A	N/A	N/A

* Maintenance and supply personnel data were aggregated (summed) from five subtotals of personnel classified by skill level (as described in Chapter 5) to get authorized and assigned personnel. Then, these low-level metrics were summed and averaged to get the purified high-level metric.

The F-16 data enjoyed three distinct advantages over typical social science-type data sets. First, due to the Air Force's expansive commitment to collecting data and cataloging it electronically, 2700 cases were available in the data set. Secondly, the Air Force sustainment community appears to be very particular about data definitions. This may have had the effect of eliminating additional potential noise in the data and ensuring uniform scaling for data submitted by multiple data-entry personnel. Finally, based on the definitions of the metrics, the level of the metric leaves very little room for interpretation. It may be that these three factors combined to bring about the high Alpha levels this data set depicts.

Appendix 2 displays a correlation matrix (with n-values and significance levels) for all purified metrics. Table 6-2 shows the correlations for purified metrics on outcome variables:

Table 6-2 – Metric and Covariate Correlations on Outcome

		supply costs/plane	not-mission-capable-maintenance-rate	not-mission-capable-supply-rate	total mission capable rate	aircraft utilization rate	flying scheduling effectiveness
supply costs/plane	**Correlation**	1	-.290(**)	-0.096	.215(*)	.282(**)	-0.197
	Sig. (2-tailed)	.	0.001	0.28	0.014	0.001	0.086
	N	129	129	129	129	129	77
not-mission-capable-maintenance-rate	**Correlation**	-.290(**)	1	.617(**)	-.938(**)	-.384(**)	0.029
	Sig. (2-tailed)	0.001	.	0	0	0	0.212
	N	129	2151	2148	2149	2151	1814
not-mission-capable-supply-rate	**Correlation**	-0.096	.617(**)	1	-.759(**)	-.237(**)	-0.03
	Sig. (2-tailed)	0.28	0	.	0	0	0.202
	N	129	2148	2149	2148	2149	1812
total mission capable rate	**Correlation**	.215(*)	-.938(**)	-.759(**)	1	.338(**)	0.026
	Sig. (2-tailed)	0.014	0	0	.	0	0.273
	N	129	2149	2148	2154	2151	1815
aircraft utilization rate	**Correlation**	.282(**)	-.384(**)	-.237(**)	.338(**)	1	-.090(**)
	Sig. (2-tailed)	0.001	0	0	0	.	0
	N	129	2151	2149	2151	2153	1816
flying scheduling effectiveness	**Correlation**	-0.197	0.029	-0.03	0.026	-.090(**)	1
	Sig. (2-tailed)	0.086	0.212	0.202	0.273	0	.
	N	77	1814	1812	1815	1816	1816
base size	**Correlation**	.195(*)	-.353(**)	-.226(**)	.298(**)	.238(**)	-.119(**)
	Sig. (2-tailed)	0.027	0	0	0	0	0
	N	129	2151	2149	2154	2153	1816
maintenance personnel/plane	**Correlation**	0.118	.176(*)	.214(**)	-.209(**)	-0.104	0.044
	Sig. (2-tailed)	0.19	0.02	0.004	0.006	0.17	0.655
	N	124	174	174	173	174	106
supply personnel/plane	**Correlation**	-.446(**)	.545(**)	.439(**)	-.550(**)	-.440(**)	0.074
	Sig. (2-tailed)	0	0	0	0	0	0.452
	N	124	174	174	173	174	106
break rate	**Correlation**	0.172	0.016	0.024	-0.043	-.204(**)	-.160(**)
	Sig. (2-tailed)	0.066	0.489	0.294	0.055	0	0
	N	115	1984	1982	1984	1984	1716
fix rate	**Correlation**	.451(**)	-.575(**)	-.383(**)	.519(**)	.359(**)	-.229(**)
	Sig. (2-tailed)	0	0	0	0	0	0
	N	84	1490	1488	1490	1490	1331
cannibalization rate	**Correlation**	.401(**)	-.113(**)	.122(**)	0.023	0.041	-.210(**)
	Sig. (2-tailed)	0	0	0	0.299	0.063	0
	N	126	2097	2096	2097	2098	1774
base supply effectiveness	**Correlation**	-.225(*)	-.083(**)	-.203(**)	.131(**)	-0.012	-0.001
	Sig. (2-tailed)	0.029	0.001	0	0	0.651	0.967
	N	94	1519	1519	1518	1520	1196
repeat discrepancy rate	**Correlation**	-0.171	-.247(**)	-.220(**)	.240(**)	.093(**)	.095(**)
	Sig. (2-tailed)	0.173	0	0	0	0	0
	N	65	1834	1833	1834	1834	1545
base repair effectiveness	**Correlation**	-.579(*)	.335(**)	.322(**)	-.285(**)	-.295(**)	.244(**)
	Sig. (2-tailed)	0.048	0	0	0	0	0
	N	12	224	225	225	225	218
EW POD NMCT rate	**Correlation**	-0.008	.217(**)	.227(**)	-.224(**)	-.108(*)	0.03
	Sig. (2-tailed)	0.961	0	0	0	0.013	0.508
	N	37	525	525	524	525	492
scheduled maintenance rate	**Correlation**	0.061	-.131(**)	-.104(**)	.126(**)	.103(**)	-0.035
	Sig. (2-tailed)	0.517	0	0	0	0	0.151
	N	114	1943	1943	1944	1945	1653

Table 6-2 – Metric & Covariate Correlations on Outcome (cont.)

		supply costs/plane	**not-mission-capable-maintenance-rate**	**not-mission-capable-supply-rate**	**total mission capable rate**	**aircraft utilization rate**	**flying scheduling effectiveness**
unscheduled maintenance rate	**Correlation**	0.041	.063(**)	0.018	-.076(**)	.099(**)	-.126(**)
	Sig. (2-tailed)	0.667	0.006	0.421	0.001	0	0
	N	114	1943	1943	1944	1945	1653
aircraft shortages/plane	**Correlation**	0.22	.116(**)	.140(**)	-.139(**)	.221(**)	.074(*)
	Sig. (2-tailed)	0.097	0.001	0	0	0	0.042
	N	58	818	818	817	819	758
temperature (average)	**Correlation**	0.153	0.018	.083(**)	-.053(*)	.186(**)	-0.038
	Sig. (2-tailed)	0.083	0.414	0	0.015	0	0.109
	N	129	2151	2149	2154	2153	1816
precipitation (average)	**Correlation**	0.01	-.084(**)	-.055(*)	.058(**)	.134(**)	-.054(*)
	Sig. (2-tailed)	0.911	0	0.01	0.007	0	0.022
	N	129	2151	2149	2154	2153	1816
variable costs/plane	**Correlation**	.586(**)	-.477(**)	-0.157	.397(**)	.566(**)	-0.178
	Sig. (2-tailed)	0	0	0.076	0	0	0.122
	N	129	129	129	129	129	77

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

Many significant correlations exist.

6-3 Exploring System Structure

6-3-1 The Structural Equation Model

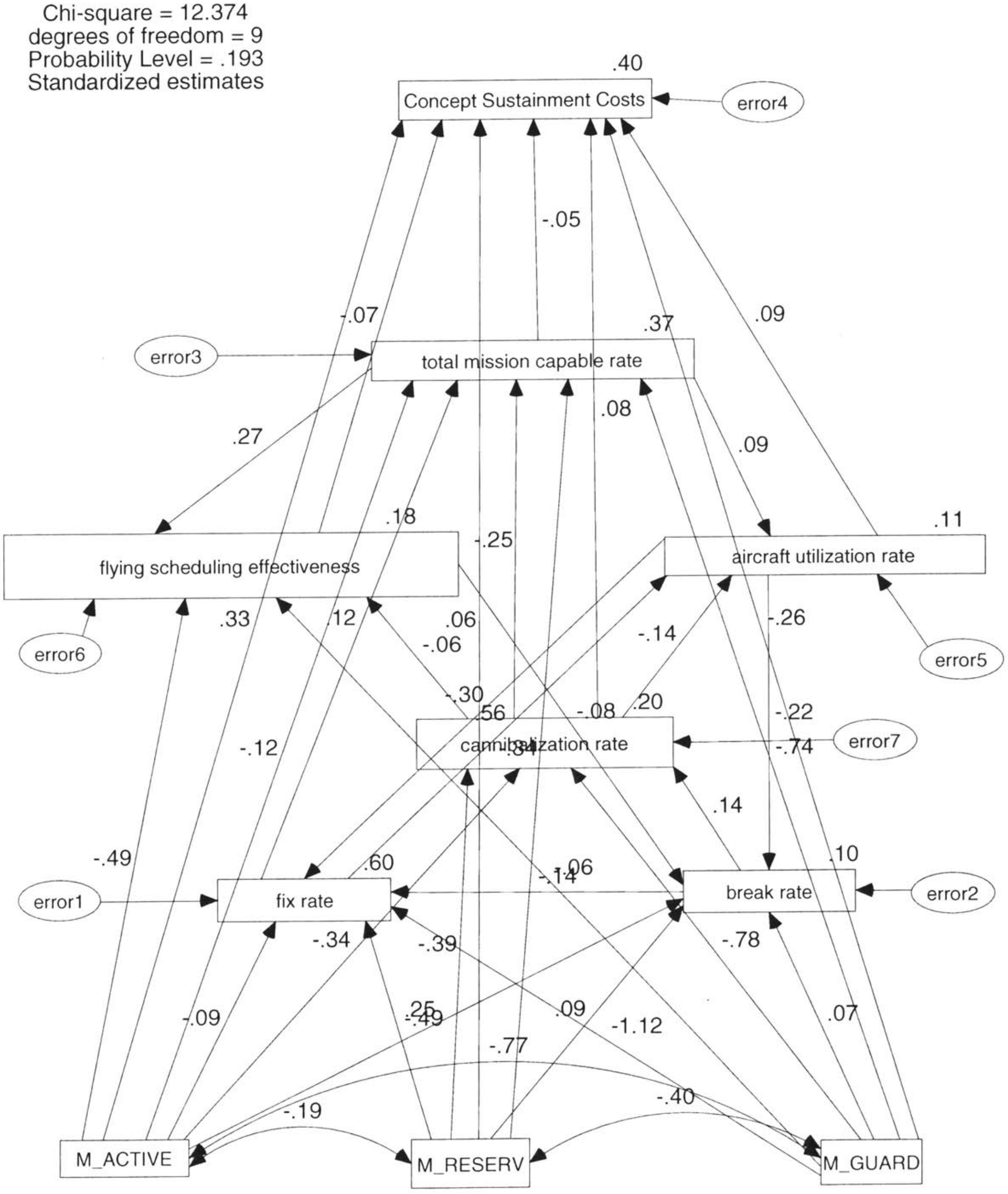
In the absence of an overriding profit outcome metric, the correlations matrix suggested that the metrics, covariates and outcomes were much more interrelated than initially believed. Furthermore, it provided some insight as to where to begin in making hypotheses in regard to the interrelationships present in the Air Force sustainment system. We adopted the technique of causal modeling to explore these interconnectivities and, through numerous iterations, decided on the following structural equation model (figure 6-1) to attempt to represent the high-level processes and interactions present in the USAF sustainment system. Since cost was reported annually and all other data were reported monthly, one simplifying assumption about the data was made: cost remained constant on a yearly basis. Remember also that costs represent data for the cost per plane for consumables and repairables only, and that each base is allocated a budget they must ultimately use to target annual costs.

Though the model seems complex, it has nine degrees of freedom, a Chi-square of 12.374 and reports a significance level of .193. Each straight single-headed arrow represents a predictive characteristic from some single variable to the variable the arrow points to. Each curved double-headed arrow represents an allowance for one exogenous variable to co-vary with another exogenous variable. In our model, each degree of freedom represents a restriction on the model. Unlike other traditional methods of analysis, in structural equation modeling the Chi-square statistic is an overall measure of how the unrestrained model (one where no limiting structural assumptions have been made) compares to the restrained model (our model). If the null hypothesis is correct, both the restrained model and unrestrained model represent maximum likelihood estimates of the corresponding population values. Thus, if the unrestrained model is not significantly different from the restrained model, the Chi-square statistics is low, its significance is high and the restrained model is preferred over the unrestrained model since the standard errors are reduced. In our case, a significance level of .193 suggests that the evidence against the null hypothesis is not significant at any traditional level of confidence.[1]

---

[1] As stated above and as opposed to traditional models, a good structural equation model has a high significance level. To determine the significance level for a model, AMOS (the structural equation model software we used) creates a fully specified model, that is, a model in which every variable is connected to every other variable exhausting all possible degrees of freedom. Our model (figure 6-1) represents a lesser-specified subset of the fully specified model with nine degrees of freedom. In determining our model's significance level, AMOS compares our model to the fully specified model. The significance level is a measure of the probability that the two models differ. As in our case, a high significance level indicates little evidence to suggest our model is significantly different from

Figure 6-1 – Structural Equation Model: Base Sustainment



---

the fully specified model. Thus, we can conclude that our model portrays as much information as could be gleemed from a fully saturated model, and there is no model (with these variables) that does better. This does not mean that the model is unique. Rather, it means that we cannot reject it as a description of the data. This is why this modeling technique is based in large part on the modeler's qualitative understanding of the system (and data) being modeled.

For recursive models such as this one, one must ensure the model is "stable." For some sets of regression weights, the infinite series of linear dependencies will converge. Others will not. A stability index can be calculated from the estimated regression weights. An unstable system will have a stability index with an absolute value greater than 1. The stability index for this model is 0.186.

The model reports results in standardized form. The estimates reported along single-headed arrows represent regression weights. The estimates reported along double-headed arrows represent correlations. The estimates reported on the top right corner of each endogenous variable (each predicted variable) report the squared multiple correlation for that variable as predicted by the other variables chosen to predict it in the model. The model is organized from bottom to top by hypothetical causality. The variables at the bottom have the purest input to the model (pure exogenous variables), the variables in the middle provide levels of input and outcome, and the variable at the top has only outcome characteristics (a pure endogenous variable). At the bottom of the model are three exogenous "dummy" variables representing three divisions for F-16 bases: active duty bases, reserve bases and guard bases. Due to data limitations and in order to eliminate unnecessary complexity in the structural equation model, this set of three mission identifiers was constructed out of the original set of six with active duty bases incorporating ACC, PACAF, USAFE and training commands. Working from bottom to top, one next finds three primarily causal variables; fix rate, break rate and cannibalization rate. Then, further up in the top third of the model one gets to three causal and outcome-type variables: flying scheduling effectiveness, aircraft utilization rate and total mission capable rate. Finally, sustainment costs sit at the top of the model.

6-3-2 Structural Equation Model: Tabular Form

Table 6-3 – Structural Model: Tabular Regression Weights

```
Regression Weights:           Estimate    S.E.     C.R.    Standard Est.
-------------------           --------   -------  -------  -------------

BRK_RTE <----- M_ACTIVE         0.466     0.123     3.796     0.253
FIX_RATE <---- M_ACTIVE        -0.222     0.125    -1.778    -0.088
MC_RATE <----- M_ACTIVE        -0.272     0.121    -2.246    -0.120
CAN_RATE <---- M_ACTIVE        -0.776     0.137    -5.678    -0.343
FIX_RATE <---- M_RESERV        -1.923     0.135   -14.273    -0.490
MC_RATE <----- M_RESERV        -1.201     0.142    -8.453    -0.341
CAN_RATE <---- M_RESERV        -1.365     0.146    -9.325    -0.389
FIX_RATE <----- M_GUARD        -2.581     0.124   -20.801    -1.121
MC_RATE <------ M_GUARD        -1.537     0.141   -10.905    -0.744
FSE_RATE <----- M_GUARD        -0.129     0.079    -1.639    -0.058
CAN_RATE <----- M_GUARD        -1.599     0.133   -12.011    -0.776
FSE_RATE <---- M_ACTIVE        -1.215     0.086   -14.132    -0.495
BRK_RTE <----- M_RESERV         0.263     0.131     2.014     0.092
BRK_RTE <------ M_GUARD         0.120     0.120     0.996     0.072
SUSTCOST <----- M_GUARD        -0.487     0.115    -4.215    -0.256
SUSTCOST <---- M_ACTIVE         0.677     0.110     6.156     0.325
SUSTCOST <---- UTIL_RTE         0.083     0.018     4.508     0.086
SUSTCOST <---- FSE_RATE        -0.059     0.017    -3.494    -0.070
SUSTCOST <---- CAN_RATE         0.074     0.018     4.079     0.080
SUSTCOST <---- M_RESERV         0.206     0.121     1.700     0.064
SUSTCOST <----- MC_RATE        -0.042     0.020    -2.076    -0.045
MC_RATE <----- FIX_RATE         0.105     0.032     3.276     0.117
CAN_RATE <----- BRK_RTE         0.176     0.026     6.792     0.143
UTIL_RTE <----- MC_RATE         0.088     0.026     3.449     0.093
FSE_RATE <----- MC_RATE         0.290     0.028    10.247     0.268
MC_RATE <----- CAN_RATE        -0.255     0.019   -13.322    -0.254
BRK_RTE <----- UTIL_RTE        -0.186     0.023    -7.970    -0.217
FSE_RATE <---- CAN_RATE        -0.061     0.026    -2.307    -0.056
UTIL_RTE <---- CAN_RATE        -0.132     0.024    -5.505    -0.139
BRK_RTE <----- FSE_RATE        -0.063     0.018    -3.425    -0.085
FIX_RATE <----- BRK_RTE        -0.186     0.026    -7.144    -0.135
UTIL_RTE <---- FIX_RATE         0.479     0.031    15.479     0.563
FIX_RATE <---- UTIL_RTE        -0.352     0.029   -12.044    -0.300
```

Table 6-4 – Structural Model: Tabular Intercepts

```
Intercepts:       Estimate     S.E.      C.R.
-----------       --------   -------   -------
   FIX_RATE         1.695     0.121    14.049
    MC_RATE         1.121     0.127     8.831
   UTIL_RTE         0.073     0.020     3.585
    BRK_RTE        -0.209     0.118    -1.773
    SE_RATE         0.458     0.070     6.573
   CAN_RATE         1.317     0.131    10.061
   SUSTCOST         0.106     0.109     0.965
```

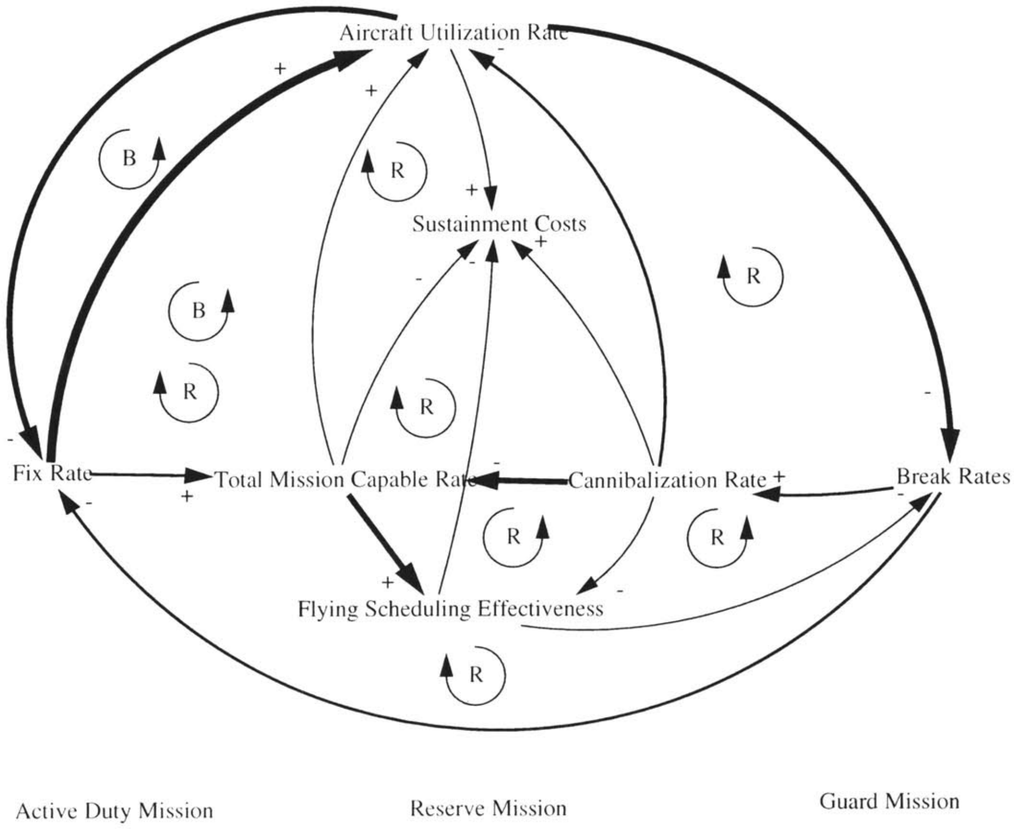
Table 6-5 – Structural Model: Squared Multiple Correlations

```
Squared Multiple Correlations:    Estimate
------------------------------    --------
                      FSE_RATE      0.177
                      UTIL_RTE      0.107
                      CAN_RATE      0.204
                      FIX_RATE      0.602
                       BRK_RTE      0.102
                       MC_RATE      0.371
                      SUSTCOST      0.401
```

6-3-3 Simplified Form

A hybrid of the structural form model and the tabular form model is the dynamic model. The dynamic model keeps the graphical look of the structural model but displays only the sign of the causal hypotheses standardized regression weights. Regression weight magnitude is indicated by arrow width. Though all three models are conceptually identical, the dynamic model is, perhaps, the most useful in attempts to understand the structural dynamics present in the system (see figure 6-2):

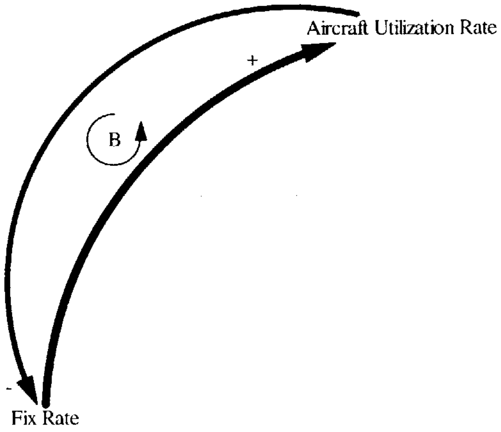
Figure 6-2 – Structural Dynamic Model for Base Sustainment



6-3-3-1 Understanding the Loops: an Illustrated Example

To the untrained eye, the dynamic model still appears little more than a conglomeration of variables with multiple feedback structures resulting in indeterminate conclusions. However, this model can be taken apart loop-by-loop (as will be done in chapter 7 for all loops present), and each loop can be examined individually to determine the potential effect it has on overall system performance. Each of the multiple "Bs" and "Rs" displayed inside the model in figure 6-2 represent one of these individual feedback loops. In traditional systems dynamics notation, the

"Bs" represent "balancing" feedback loops, or ones that provide negative feedback, and the "Rs" represent "reinforcing" feedback loops, or ones that provide positive feedback. (Note that positive feedback does not always increase output in the model. Rather, it can increase cannibalization or break rate, for example.) Some of the loops are easy to see. Others are more hidden in the model. Some loops describe well-know system structure, and others, as chapter 7 will reveal, suggest structures not clearly understood to date. To illustrate by example, consider the simple loop described below (extracted from figure 6-2), one we call the Resource-Use Penalty loop:



As intuition would confirm, this loop suggests a system structure where increased rates of aircraft fixes allow utilization per plane to *increase* as represented by the positive arrow from fix rate to aircraft utilization rate. Also, and perhaps less intuitively, the model suggests that increased utilization results in a *decreased* fix rate as evidenced by the negative arrow from aircraft utilization rate to fix rate. Based on the strength of the coefficients (shown in figure 6-1 and table 6-3 and represented by the width of the arrow here) and the direction of the action (either positive or negative), these two phenomena combine to form a strong balancing feedback loop where fixes allow increased use, but increased use reduces the rate at which aircraft can be fixed. The loop is balancing because it has an odd number of negative paths (arrows).

6-4 Regression Analysis

The structural model can be loosely thought of as a set of regressions nested together. One shortfall of the structural model is that it reports deviations from less-specified models. It gives little evidence to suggest whether a model is truly correct, only that it is better than some less-specified model. All models are (in some sense) "wrong," but many "wrong" models are useful. Conversely, many more correct models are of little use. In addition, the structural equation model relies heavily on researcher insight into the system to make initial hypotheses in regard to how the system operates. Plus, since structural models are extremely limited in complexity due to stability problems associated with multiple feedback loops, in-depth analysis of some of the less prominent high-level metrics collected for this study were necessarily left out. For these reasons, it is advantageous to explore the outcomes in a more traditional sense using standard regression analysis.

6-4-1 Purified Metrics Regressed on Outcomes

Table 6-6 displays the regression coefficients of the purified metrics covariates and outcomes on the outcomes in standardized form. Once again, cost remained constant on a yearly basis so as not to conflict with the causal model. It is worthwhile to note again that the regression models include metric, covariate and outcome variables not present in the structural model. This may explain some of the differences between the two models.

Table 6-6 – Regressions of Purified Metrics on Outcomes

Measures	*supply costs/plane*		not-mission-capable-maintenance-rate		not-mission-capable-supply-rate		*total mission capable rate*		*aircraft utilization rate*		*flying scheduling effectiveness*	
	Coeff.	sig.	Coeff.	sig.	Coeff.	sig.	Coeff.	sig.	Coeff.	sig.	Coeff.	sig.
supply costs/plane			0.041	.052					0.081	.000	-0.120	.000
NMCM												
NMCS												
MC Rate									0.095	.000	0.299	.000
utilization rate	0.082	.005	-0.090	.000			0.083	.002			0.083	.015
FSE	-0.100	.000	-0.144	.000	-0.105	.000	.140	.000	0.046	.018		
base size			-0.173	.000	-0.142	.000			0.100	.000	-0.055	.042
maintenance pers.												
supply pers.												
break rate			0.047	.049	0.064	.038	-0.055	.046	-0.195	.000	-0.117	.001
fix rate	-0.066	.036			-0.100	.003						
cann. rate	0.073	.003	0.087	.000	0.276	.000	-0.150	.000	-0.129	.000		
supply effect												
repeat discrep.			-0.041	.014	-0.054	.009	0.034	.071			0.149	.000
base repair effect												
EW POD NMCT												
scheduled maint.												
unsched. maint.			0.124	.000			-0.115	.000	0.054	.003		
aircraft shortages												
temperature	-0.100	.000	0.102	.000	0.069	.007	-0.085	.000	0.167	.000	-0.114	.000
precipitation	0.087	.000	-0.076	.000	-0.069	.001	0.054	.004	0.044	.019		
variable costs												
Active Duty	0.329	.000	-0.719	.000	-0.659	.000	**1.355**	.000	0.703	.000	-1.354	.000
Guard	-0.818	.000	0.616	.000	0.178	.026	**0.322**	.000			-0.282	.002
Reserve												
Adjusted R-square	.347	.000	.568		.366		.468		.351		.235	
Intercept							-0.441					

Note: The bold coefficients in column eight table 6-6 are those that do not agree (in sign) with the causal model. The italicized variables listed in column one and row one are those that the regression model has in common with the structural model.

Additionally, although it was not initially considered an outcome variable, the high R-squared in the structural model (and the multiple high correlations in the correlations matrix) suggests an analysis of fix rate as described by the other high-level metrics (table 6-7 below):

Table 6-7 – Regressions of Purified Metrics on Fix Rate

Measures	*fix rate*	
	Coeff.	sig.
supply costs/plane		
NMCM		
NMCS		
MC Rate		
utilization rate		
FSE		
base size	0.181	.000
maintenance pers.		
supply pers.		
break rate	-0.187	.000
fix rate		
cann. rate	0.077	.000
supply effect		
repeat discrep.		
base repair effect		
EW POD NMCT		
scheduled maint.		
unsched. maint.		
aircraft shortages		
temperature	-0.133	.000
precipitation		
variable costs		
Active Duty	**0.966**	.000
Guard	-0.836	.000
Reserve		
Adjusted R-square	.672	
Intercept	.123	

Only two coefficients, the one for the dummy variable Active Duty Mission regressed on Total Mission Capable Rate *and* Fix Rate, do not agree (in sign) with the coefficients found for the structural model. The reason for this is unknown and warrants further future investigation but may be due to the differences in input variables between the regression and structural models.

So far, all of the analyses have been conducted with data from 1995 through 1998. Now, we can use the 1999 data to determine how closely these models are able to "predict" future outcomes. Both the regression models and the causal model are best at predicting fix rate and mission capable rate as evidenced by their relatively higher R-square value. (This is not surprising as one might guess that utilization rate, break rate, and flying scheduling effectiveness are related to variables outside those found in the model.) Since cost data is only available monthly, a monthly prediction of cost is unattainable. Figures 6-3 and 6-4 show that the linear and causal models are similar in what they predict:

Figure 6-3 – Fix Rate 1999 Predicted Value: Linear and Causal

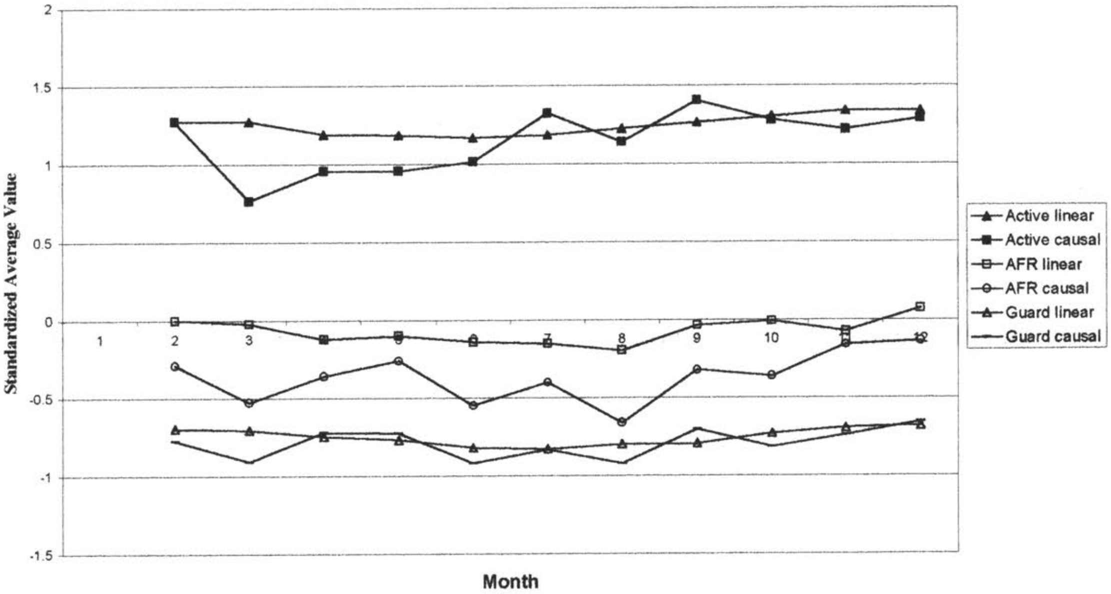
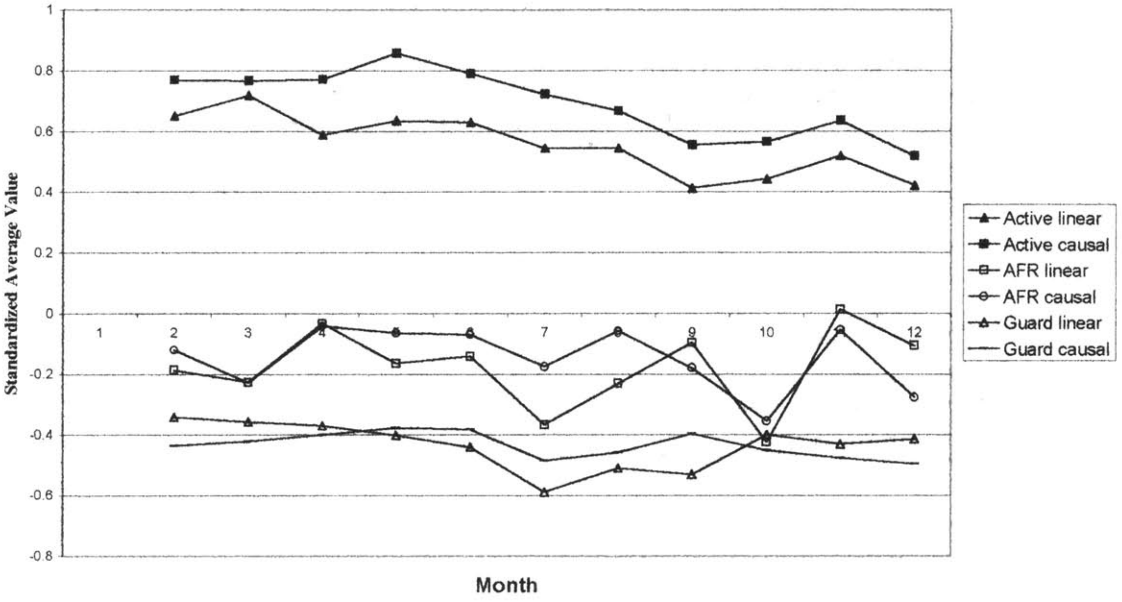


Figure 6-4 - MC Rate 1999 Predicted Value: Linear and Causal



Unfortunately, while both models suggest the differences in mission associated with fix rate, they leave a bit to be desired when attempting to predict additional factors causing actual 1999 fix rates. Furthermore, actual fix rates in 1999 were consistently higher than predicted as suggested by figure 6-5. The mission capable models, on the other hand, shows more promise, especially in predicting a rate for active duty aircraft. Still, the causal model predicts mission capability will be consistently higher than it actually is (refer to figures 6-6 and 6-7). This constant shift is puzzling. It may be that the shift is due to some factor (variable change) present in 1999 that is not modeled in the causal model making it somewhat under-specified. This theory could be explored by producing fit plots similar to the one in figure 6-7 for the years 1995 through 1998. If the causal model had no constant shift for these years, it would suggest the model is under-specified. If, however, the shift existed for these years, we know our fit could be better. For now, this is left for further investigation.

Figure 6-5 - Actual Fix Rate versus Predicted Fix Rate

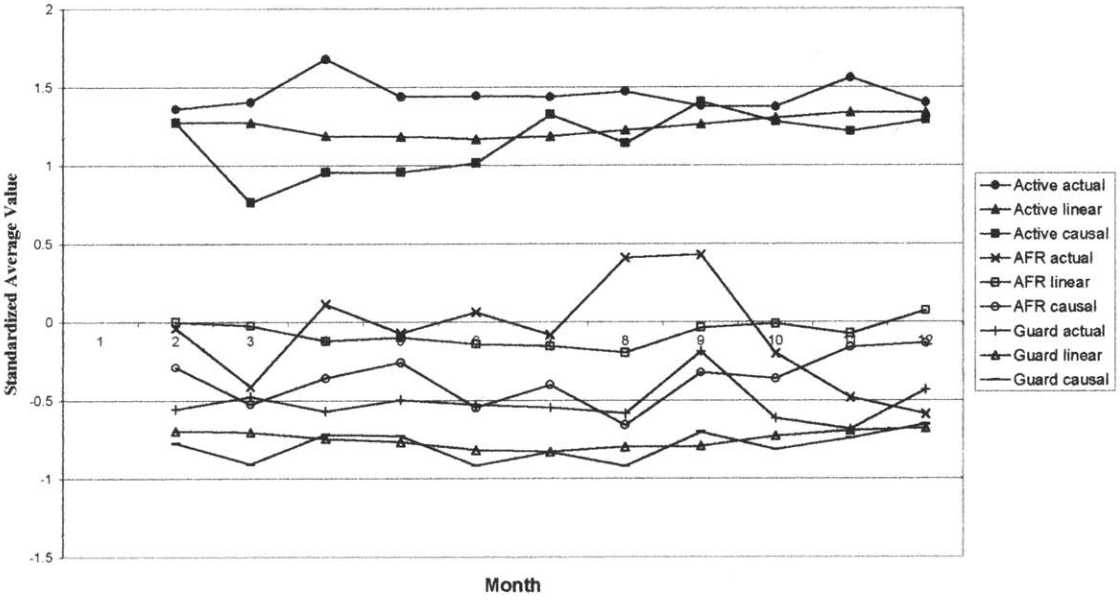


Figure 6-6 – Actual MC Rate versus Predicted MC Rate

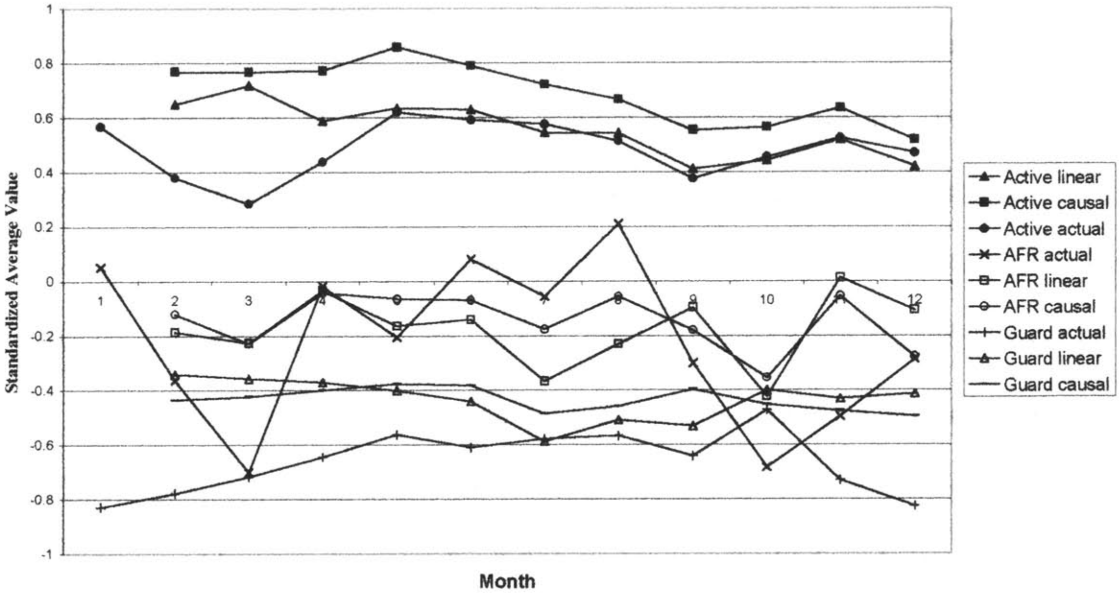
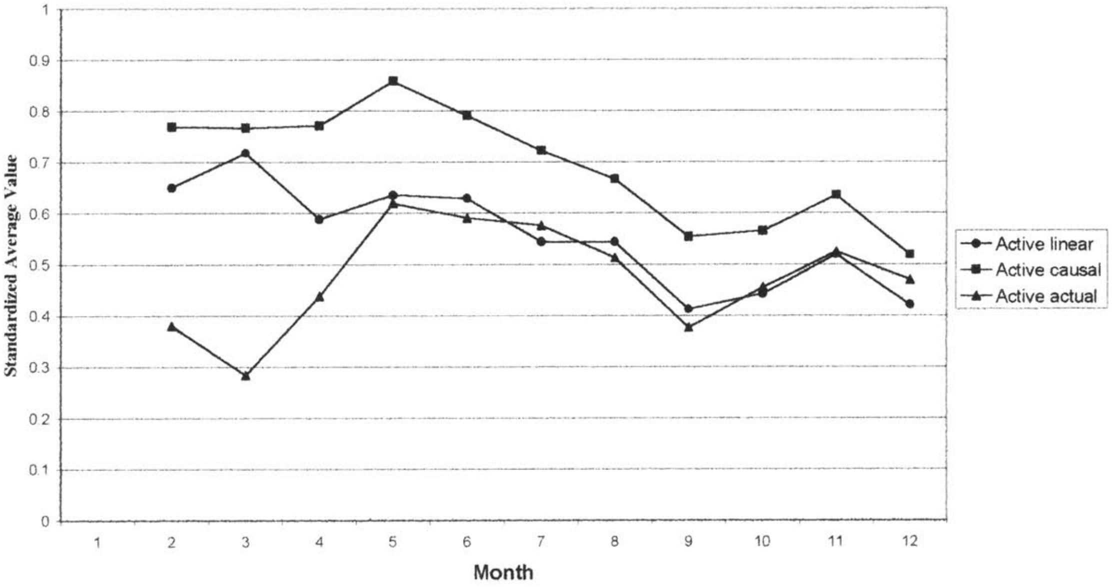


Figure 6-7 – Actual v. Predicted MC Rate – Active Duty Only



- This page intentionally left blank -

Chapter 7: Conclusions and Recommendations

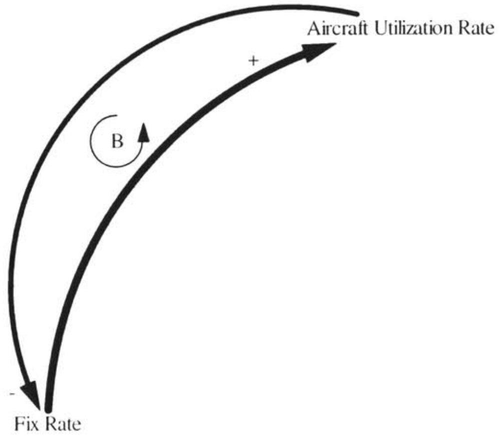
7-1 Conclusions

7-1-1 The Dynamic Model

Though the dynamic model needs further analysis before is can be used to predict outcomes, for now, it is at least somewhat useful in predicting how, perhaps, several outcomes relate to and are affected by one another. In general, the model suggests that the leading factor in performance is mission type as indicated by major command.

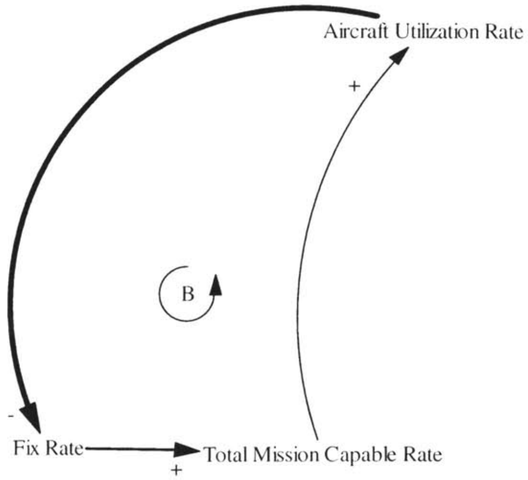
Figure 6-2 suggests several feedback loops, and each is reproduced below for direct analysis. These conclusions hold for all mission types. Of course, all observations are exploratory.

7-1-1-1 Resource-Use Penalty:



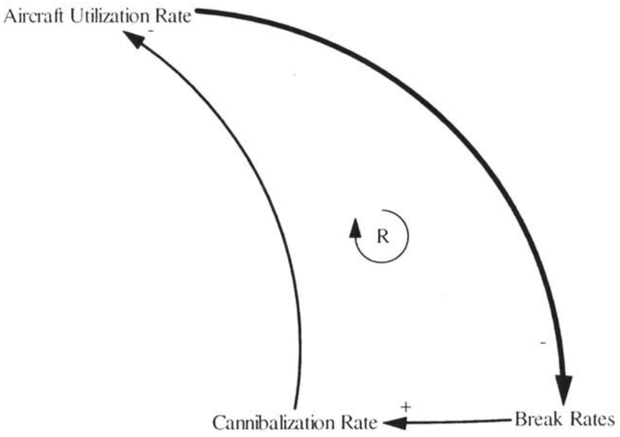
One might imagine that increased rates of aircraft fixes will allow utilization per plane to increase. Perhaps less intuitively, the model suggests that increased utilization takes time and resources from the repair team and causes the fix rate to decrease. The model suggests that these two phenomena combine to form a strong balancing feedback loop where fixes allow increased use, but increased use reduces the rate at which aircraft can be fixed.

7-1-1-2 The Mission Capability Penalty:



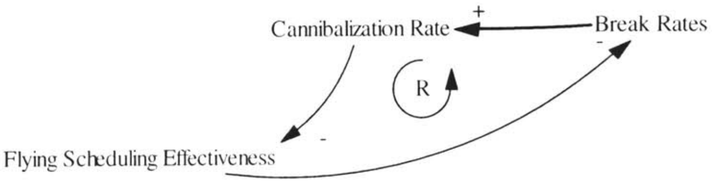
Similarly, as fix rates improve, total mission capable rates improve and utilization goes up. However, the model suggests that the same fix rate penalty is paid in the form of this balancing feedback loop.

7-1-1-3 Breaks and Canns 1:



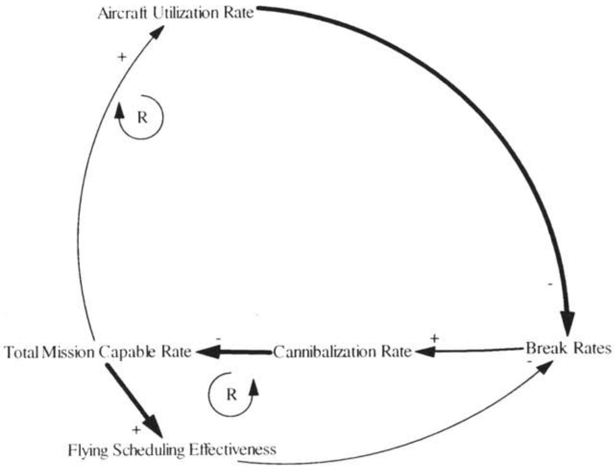
The model is top level in nature and does not explain why aircraft break. (This is left for future work.) However, it does suggest what happens *when* aircraft break. As one might suppose, the model suggests that increased breaks lead to increased cannibalizations. Cannibalization has several effects. The one shown in this reinforcing feedback loop is that utilization per plane is reduced. This effect is balanced by the fact that reduced utilization reduces the opportunity for breaks to occur.

7-1-1-4 Breaks and Canns 2:



Similarly, breaks cause adherence to the schedule to be reduced, and, again, reductions in schedule adherence reduce the opportunity for breaks as less aircraft are (presumably) being flown.

7-1-1-5 Breaks and Canns 3 and 4:

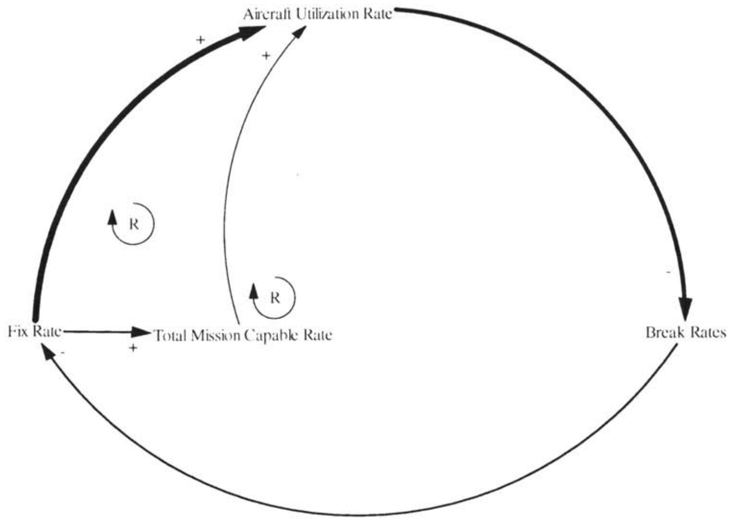


Two similar cannibalization effects can be seen in the model in two reinforcing feedback loops through mission capable rate. All totaled, the model detects four feedback mechanisms that reduce break rate: reductions in mission capability, reductions in flying scheduling effectiveness, reductions in utilization per plane, and increases in cannibalization. The first three are, effectively, reductions in outcome and, as so, are undesirable. The fourth suggests, on the surface, that increases in cannibalization will reduce break rates. This is true only to the extent that increased cannibalization rates reduce mission capability, flying scheduling effectiveness and aircraft utilization per plane.

Notice, then, that cannibalizations have negative effects on the three major outcomes. Still, referring back to figure 6-2 one can see that cannibalization does have a positive effect on fix rate due to the feedback mechanism present in section 7-1-1-2. This increased fix rate may lead maintenance managers to believe that cannibalizations have positive outcome effects. However, this study suggests that cannibalizations are, at least, overused in the base-level F-16 sustainment process. Note that a review of the correlation matrix (table 6-2) confirms these findings in that cannibalizations are associated with increased costs, no perceptible overall mission capability improvements, no perceptible utilization improvements, and decreased flying scheduling effectiveness.

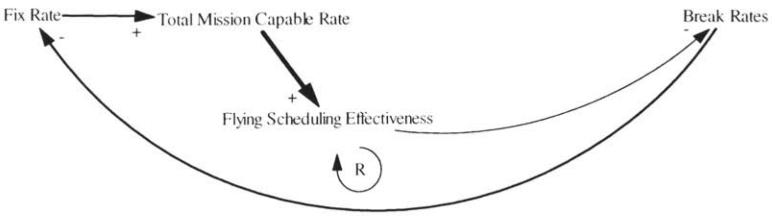
Also, as cannibalizations increase, the not-mission-capable maintenance rate falls, but it is offset by an almost identical rise in the not-mission-capable supply rate. The result is the net zero significant gain in total mission capable rate. Still, one could successfully argue that cannibalizations are used to maintain falling mission capable rates in the aftermath of unusually high break rates. This interpretation may also be true since cannibalizations correlate positively with break rates and the model does not suggest overall causality of break rates.

7-1-1-6 Fixes and Breaks 1 & 2:



As the break rate increases, the model suggests that the fix rate is reduced. That is, the ability of the sustainment team to repair particular aircraft is diluted (in time) by their limited resources being spread too thin. Reductions in fix rate suggest reductions in mission capability and utilization per plane. As more aircraft are broken, one would guess that the utilization burden is spread on fewer planes (since the denominator of the utilization per plane metric is *total* planes not *available* planes) and the overall break rate is further increased.

7-1-1-7 Fixes and Breaks 3:



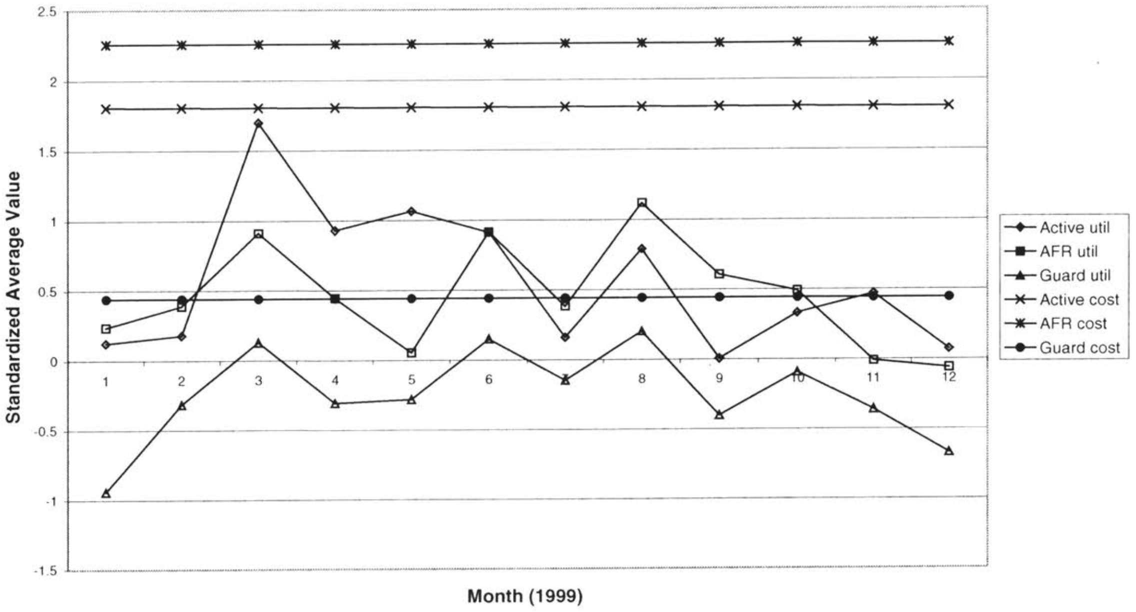
The same logic holds for fix and break rate effects on flying scheduling effectiveness.

7-1-1-8 Predictions of the Causal Model

Due, in part, to the limitations encountered during causal modeling, the causal model is limited (by number of variables due to increasing complexity) in its ability to fully predict many variables. As figures 6-3 and 6-4 suggest, it follows the predictions of the linear model but with less predictive resolution. The causal model does perceive the differences in outcome between major commands particularly well, though.

Still, the raw data suggests that, for whatever reason, active duty commands are consistently more costly per plane (for supply costs); and, as would be expected, these increased costs go along with higher mission capable rates, fix rates, break rates and cannibalization rates. The AFR bases rank second in these categories and the Guard bases rank third. When it comes to scheduling effectiveness, however, the Guard bases are most successful. These observations are provided not to judge command performance against one another. Rather, together, they suggest that mission type may be a surrogate variable for some deeper cause (like budget, for example) that differs between major commands. Further research is necessary to address this hypothesis.

Figure 7-1 – Utilization and Cost by Mission



7-1-2 The Linear Model

While the linear model (tables 6-6 and 6-7) does not explain feedback structure like the recursive model, it has the ability to explain particular outcomes in more depth:

7-1-2-1 General Observations

In all except one case, the regressions and the causal model were both able to predict general trends in monthly outcome when compared to the 1999 data, but further work is needed to refine these models. In one case (mission capability - discussed in detail below) both models were able to predict with some accuracy the 1999 monthly outcomes. Like the causal model, in the case of the supply cost, utilization per plane, flying scheduling effectiveness and fix rate regressions, the primary indictor of performance was mission as indicated by major command. Also like the causal model, active duty commands signal outcome performance with higher coefficients for cost per plane (for supply costs), and they have higher mission capable rate-to-mission and fix rate-to-mission coefficients. Again, when it comes to scheduling effectiveness, the Guard bases display the highest mission-related coefficients. Also, the linear model coefficients match the coefficients in the causal model with only three exceptions (noted in bold in table 6-6 and 6-7).

7-1-2-2 Mission Capability Predictions

Unlike the causal model and other regression models that show only general trend predictions, the mission capable regression appears to predict the actual 1999 mission capable data extraordinarily well from May 1999 through December 1999. Besides the mission indicator dummy variables, the regression has eight predictor variables. Two clear covariates, temperature and precipitation, suggest that cooler moister climates are associated with slight increases in the sustainment team's ability to provide mission capable aircraft. Three other small factors; utilization, break rate and repeat discrepancy rate; are also greatly out of the control of the sustainment team. Increased breaks are associated with slight decreases in mission capability. However, increased repeat discrepancies are associated with slight increases in mission capability giving rise to the speculation that learning plays a role in the ability of the sustainment team to succeed. Increases in utilization per plane are associated with slight increases in mission capability. Flying scheduling effectiveness plays a more significant role (standardized coefficient of 0.14, sig. 0.00) in associations with increased mission capability, but, like utilization, due to the potential for strong feedback components between these variables, a cause-effect relationship is best left to the causal model. Most interestingly, though, are two high leverage variables that the sustainment team can partially control: cannibalization rate and unscheduled (engine) maintenance. As cannibalizations and unscheduled maintenance increase, mission capability drops (standardized coefficient -0.15 & -0.12, sig. 0.00 & 0.00 respectively). A prediction for January is not listed since some of the predictor variables were not available, and the reason for the model's departure from the actual 1999 data for February March and April is unknown. However, when this analysis was presented to AFMC personnel, they pointed out that this period of time was associated with the NATO air attack on Yugoslavia, an action the active duty USAF contributed to significantly. Further research uncovered that on March 24, 1999, NATO launched an attack on Yugoslavia, which included, among other things, bombing runs by American aircraft. One could hypothesize that the ramp-up, attack and ramp-down from military action in February, March and April changed the USAF sustainment structure, and that our mission capability model is incapable of detecting this wartime change. Furthermore, this finding supports the concern regarding the differences between maximizing mission capability during peacetime and wartime.

7-2 Recommendations

Two competing models were presented in this study: a simple regression model and a causal model. The causal model is most promising for explanation due to its ability to incorporate feedback while the regression model is best at predicting due to its ability to handle more variables than the causal model. When set to the task of predicting unknown data, both the causal and regression models were able to make remarkably accurate mission capable predictions for bases under the ACC, PACAF and USAFE commands. This is particularly true if one believes the models to be valid for peacetime operations only.

The data set had several potential variables from which to draw. However, in the end, the maintenance data were the ones most fully populated. So, not surprisingly, it was these data that provided many of the insights gleamed by this study. This study should not be construed to conclude that the other variables from sources other than REMIS (like supply issue effectiveness, for example) do not affect mission performance of the F-16. Rather, study to date is inconclusive, and we hope further analysis and perhaps a future more complete data set will improve this model and improve its ability to predict other outcome variables both inside and outside ACC, PACAF and USAFE.

Using the metrics thermostat theory, this study set out to provide a set of initial weights from which Air Force Sustainment could adjust employee rewards to maximize outcomes. However, chapters 6 and 7 are careful not to provide any such weights. We believe it would be premature, at this time, to suggest any explicit weights. Rather, the direction (signs) of the coefficients provides valuable insight into the structure of the Air Force sustainment process.

Though this study was limited to the F-16, it may have application for other Air Force fighter aircraft, other Air Force weapon systems, or as broad ranging as for military aircraft in other services at the discretion of the Air Force.

I believe the Air Force, as a not-for-profit public organization, can benefit from the metrics thermostat, a for-profit tool. That is, the thermostat model appears adaptable for systems where cost is a constraint and profit may or may not exist as an output. However, several potential issues and challenges still exist for successful implementation into USAF sustainment. First, though the USAF (and the U. S. military in general) relies heavily on non-monetary incentives, their systems of incentives may differ significantly from those used in the commercial sector. Chan (1999) conducted research with the U. S. Army Research, Development and Engineering Center (RDEC) under the Missile Command (MICOM) in an attempt to quantify the impact of non-monetary incentives there. However, I believe significant research is still necessary to fully understand the impact the USAF sustainment community's non-monetary incentive system might have on application of the Metrics Thermostat.

Second, the Air Force sustainment system is so complex and operates at so many levels that proper application of the thermostat at any one level might still leave behind some sub-optimized performance. It may take many years of research for one to adequately understand the system as a whole. On this issue I give council for patience. The system's vast complexity speaks directly to the dire need for such research to be conducted and ensures the benefit that even a little understanding of the system can bring. It is my hope that the research conducted in conjunction with this paper will provide, at least, a little understanding and benefit, and, in doing so, serve as an early step toward the ultimate goal of system-wide understanding.

- This page intentionally left blank -

BIBLIOGRAPHY

1. Air Force Material Command (2000), *Air Force Material Command Fact Sheet* [Online], Available: http://www.afmc.wpafb.af.mil/HQ-AFMC/PA/library/afmcfact.htm [05 July 2000].

2. Air Force Material Command (2000), *Data System Assignment Directory* [Online], Available: http://www.afmc-pub.wpafb.af.mil/MSG/EN/CDRS/ [05 July 2000].

3. Arbuckle, James and Wothke, Werner (1999), *AMOS 4.0 User's Guide*, Chicago, IL: SmallWaters Corporation.

4. Baker, George (1992), "Incentive Contracts and Performance Measurement," *Journal of Political Economy*, 100, 598-614.

5. Barra, Ralph (1989), "Motorola's Approach to Quality," *Journal for Quality and Participation*, 12, 1, 46-50.

6. Chan, Christine W. Y. (1999), "Measuring Non-Monetary Incentives Using Conjoint Analysis," M.Eng. thesis, Electrical Engineering and Computer Science Departments, MIT, Cambridge, MA (June).

7. Gibbons, Robert (1997), "Incentives and Careers in Organizations," in D. Kreps and K. Wallis (Eds.) *Advances in Economic Theory and Econometrics*, Cambridge, UK: Cambridge University Press, 1-37.

8. Girald, E (1998), *Fiscal Year 1998 Air National Guard F-16 statistics,* Excel file. Air National Guard.

9. Grey, Stephen (2000), *Request for F-16 Maintenance Data* [Electronic mail document], Washington DC: Author [18 July 2000].

10. Hauser, John R. and Clausing (1988), "The House of Quality," *Harvard Business Review*, 1, 63-73.

11. Hauser, John R. and Gerald Katz (1998), "Metrics: You Are What You Measure!" *European Management Journal*, 16, 5, 516-528.

12. Hauser, John R. (2000), "Metrics Thermostat," Massachusetts Institute of Technology, Sloan School of Management Working Paper 1-28.

13. LaFountain, Burt D. (1999), "An Empirical Exploration of Metrics for Product Development Teams," S.M. thesis, Mechanical Engineering Department, MIT, Cambridge, MA (January).

14. Mackey, Wayne A., and John C. Carter (1994), "Measure the Steps to Success," *IEEE Spectrum*, 31, 6, 33-38.

15. Majumder, Arpita (2000), "Strategic Metrics for Product Development at Ford Motor Company," S.M. thesis, Engineering and Management, MIT, Cambridge, MA (June).

16. Massachusetts Institute of Technology, Center for Technology, Policy and Industrial Development's Lean Sustainment Initiative (2000), *Goals, Objectives And Metrics Task Progress Report,* Cambridge, MA: Author (August).

17. McGrath, Michael E. and Michael N. Romeri (1994), "From experience: The R&D Effectiveness Index: A Metric for Product Development Performance," *Journal of Product Innovation Management,* 11, 213-220.

18. Raymond, Neil (1999), *Sustainment Overview*. Vienna, VA: GRC International presentation.

19. Russell, Keith (2000), *An F-16 Metrics Thermostat* [PowerPoint presentation], Cambridge, MA: Author [17 May 2000].

20. Thompson, Arthur A. Jr., and A. J. Strickland (February 1996), "Strategic Management: Concepts & Cases," *The Strategic Management Process: An Introduction* [Online], 9, 2, Available: http://live.looksmart.com/cgi-bin/framer?http://www.csuchico.edu/mgmt/strategy/module1/index.htm Site/Path/File [27 June 2000].

21. United States Air Force Air Combat Command (2000), *Air Combat Command Strategic and Master Plan FY2000*, Washington, DC: Author.

22. United States Air Force Air Combat Command Director of Logistics (1995), *Air Combat Command Director of Logistics Quality Performance Measures (L-QPM) Users Guide*, Langley AFB, VA: Author.

23. United States Air Force (2000), *America's Air Force Vision* [Online], Available: http://www.af.mil/vision/ [27 June 2000].

24. USAF Electronics Systems Center: Technology Transfer (2000) *Alphabetical Listing of Programs.* Available: http://www.hanscom.af.mil/Orgs/O_Orgs/XR/TechX/Programs/Programs.listing.html [27 June 2000].

Appendix 1: Metric Formulas

Total Abort Rate= $\frac{Number\_of\_air\_aborts + Number\_of\_ground\_aborts}{Number\_of\_sorties\_flown + Number\_of\_ground\_aborts} * 100$

Break Rate= $\frac{Number\_of\_sorties\_resulting\_in\_broken\_aircraft}{Number\_of\_sorties\_flown} * 100$

Repeat Discrepancy Rate= $\frac{Number\_of\_repeat\_discrepancies}{Number\_of\_reported\_discrepancies} * 100$

Recurring Discrepancy Rate= $\frac{Number\_of\_recurring\_discrepancies}{Number\_of\_reported\_discrepancies} * 100$

Cannibalization Rate= $\frac{Number\_of\_cannibalizations}{Number\_of\_sorties\_flown} * 100$

Cannibalization-Fly Rate= $\frac{Number\_of\_cannibalizations}{Number\_of\_hours\_flown} * 100$

Electronic Warfare PODs NMCM Rate =

$$\frac{AWM\_rate(week\_1) + AWM\_rate(week\_2) + ...AWM\_rate(last\_week\_in\_the\_month)}{Number\_of\_weekly\_rates\_sampled}$$

Where AWM_rate=

$$\frac{Total\_number\_of\_Pods\_awaiting\_ma\text{int}ennance\_(snapshot)\_discrepancies}{Average\_number\_of\_EW\_Pods\_possessed}$$

LANTIRN Not Mission Capable Maintenance Rate =

$$\frac{AWM\_rate(week\_1)+AWM\_rate(week\_2)+\ldots AWM\_rate(last\_week\_in\_the\_month)}{Number\_of\_weekly\_rates\_sampled}$$

Where AWM_rate=

$$\frac{Total\_number\_of\_LANTIRN\_Pods\_awaiting\_ma\text{int}ennance\_(snapshot)\_discrepancies}{Average\_number\_of\_LANTIRN\_Pods\_possessed}$$

Four-Hour Fix Rate= $\frac{Number\_of\_aircraft\_repaired\_within\_4\_hours}{Number\_of\_aircraft\_that\_land\_broken}*100$

Eight-Hour Fix Rate= $\frac{Number\_of\_aircraft\_repaired\_within\_8\_hours}{Number\_of\_aircraft\_that\_land\_broken}*100$

Twelve-Hour Fix Rate= $\frac{Number\_of\_aircraft\_repaired\_within\_12\_hours}{Number\_of\_aircraft\_that\_land\_broken}*100$

Maintenance Personnel Required/Plane= $\frac{M\_pers\_theoretical-M\_pers\_funded}{Average\_aircraft\_inventory}$

Maintenance Personnel Authorized/Plane= $\frac{M\_personnel\_funded}{Average\_aircraft\_inventory}$

Maintenance Personnel Assigned/Plane= $\frac{M\_personnel\_assigned}{Average\_aircraft\_inventory}$

Scheduled Engine Removals Rate=$\frac{Number\_of\_scheduled\_engine\_removals}{Number\_of\_aircraft\_possessed}$

Unscheduled Engine Removal Rate= $\frac{Number\_of\_unscheduled\_engine\_removals}{Number\_of\_aircraft\_possessed}$

Pre-Repair Cycle Time=$\frac{Total\_days\_in\_level\_2\_pre\_repair}{Number\_items\_repaired}$

Repair Cycle Time=$\frac{Total\_days\_in\_level\_2\_repair}{Number\_items\_repaired}$

Post-Repair Cycle Time=$\frac{Total\_days\_in\_level\_2\_post\_repair}{Number\_items\_repaired}$

Electronic Warfare PODs NMCS Rate=

$$\frac{AWS\_rate(week\_1)+AWS\_rate(week\_2)+\ldots AWS\_rate(last\_week\_in\_the\_month)}{Number\_of\_weekly\_rates\_sampled}$$

Where AWS_rate=

$$\frac{Total\_number\_of\_Pods\_awaiting\_\sup ply\_(snapshot)\_discrepancies}{Average\_number\_of\_EW\_Pods\_possessed}$$

LANTIRN Not-Mission Capable Supply Rate=

$$\frac{AWS\_rate(week\_1)+AWS\_rate(week\_2)+\ldots AWS\_rate(last\_week\_in\_the\_month)}{Number\_of\_weekly\_rates\_sampled}$$

Where AWS_rate=

$$\frac{Total\_number\_of\_LANTIRN\_Pods\_awaiting\_\sup ply\_(snapshot)\_discrepancies}{Average\_number\_of\_LANTIRN\_Pods\_possessed}$$

PAI Shortage/Plane= $\frac{\#\_of\_aircraft\_authorized - \#\_of\_aircraft\_on\_hand}{\#\_of\_aircraft\_authorized}$

Supply Issue Effectiveness= $\frac{Line\_items\_issued}{Line\_items\_issued + Line\_items\_backordered} * 100$

Stockage Effectiveness= $\frac{Line\_items\_issued}{items\_issued + items\_backordered - items\_bo\_4w} * 100$

Supply Personnel Required/Plane= $\frac{S\_pers\_theoretical - S\_pers\_funded}{Average\_aircraft\_inventory}$

Supply Personnel Assigned/Plane= $\frac{S\_personnel\_assigned}{Average\_aircraft\_inventory}$

Supply Personnel Assigned/Plane= $\frac{S\_personnel\_assigned}{Average\_aircraft\_inventory}$

Average Temperature=historical daily average temperature (°Fahrenheit) for the month

Average Precipitation=historical daily average rainfall (inches) for the month

Mission =

Table XX: Numerical Command Identifiers

Command	**Numerical Identifier**
Air Combat Command	1
Training Command	2
United States Air Forces Europe	3
Air Force Reserve	4
Air National Guard	5
Pacific Air Forces	6

$$\text{Hourly Utilization Rate}=\frac{Number\_of\_hours\_flown}{Aircraft\_on\_hand}$$

$$\text{Sortie Utilization Rate}=\frac{Number\_of\_sorties\_flown}{Aircraft\_on\_hand}$$

$$\text{Mission Capable Rate}=\frac{1-NMCM-NMCS-NMCB}{Possessed\_hours}*100$$

$$\text{Total Not Mission Capable Maintenance Rate}=\frac{NMCM\_hours+NMCB\_hours}{Possessed\_hours}*100$$

Where Possessed_hours= $24 hours/day*\#\_days/month*\sum\#\_of\_aircraft\_possessed$

Total Not Mission Capable Supply Rate= $\frac{NMCS\_hours + NMCB\_hours}{Possessed\_hours} * 100$

Where Possessed_hours= $24 hours / day * \#\_days / month * \sum \#\_of\_aircraft\_possessed$

Flying Scheduling Effectiveness= $\frac{Total\_sorties\_scheduled - Total\_deviations}{Total\_sorties\_scheduled} * 100$

Consumable Cost per Plane= $\frac{Total\_consumable\_\cos ts}{Average\_inventory}$

Repairable Cost per Plane= $\frac{Total\_repairable\_\cos ts}{Average\_inventory}$

Fuel Cost per Plane= $\frac{Total\_fuel\_\cos ts}{Average\_inventory}$

Impact Cost per Plane= $\frac{Total\_impact\_\cos ts}{Average\_inventory}$

Appendix 2:

Pure Standardized High-Level Metric Correlations		Concept Basesize	Concept Maintenance Personnel per Plane	Concept Supply Personnel per Plane	Concept Break Rate	Concept Fix Rate	Concept Maintenance Novice Resources per Plane	Concept Maintenance Worker Resources per Plane	Concept Learning by Doing	Concept Sustainment Costs	Concept Marginal Utilization of Aircraft	Concept Cannibalization Rate
Concept Basesize	**Pearson Correlation**	1	-.133(**)	-.555(**)	.072(**)	.450(**)	.591(**)	-.360(**)	.233(**)	.381(**)	.264(**)	.378(**)
	Sig. (2-tailed)	.	0	0	0.001	0	0	0	0	0	0	0
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept Maintenance Personnel	**Pearson Correlation**	-.133(**)	1	.582(**)	-.050(*)	-.226(**)	.328(**)	.931(**)	.070(**)	0.038	-.086(**)	-0.026
	Sig. (2-tailed)	0	.	0	0.02	0	0	0	0.001	0.076	0	0.235
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept Supply Personnel	**Pearson Correlation**	-.555(**)	.582(**)	1	-.085(**)	-.638(**)	-.498(**)	.772(**)	-.267(**)	-.431(**)	-.344(**)	-.297(**)
	Sig. (2-tailed)	0	0	.	0	0	0	0	0	0	0	0
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept Break Rate	**Pearson Correlation**	.072(**)	-.050(*)	-.085(**)	1	-0.021	.046(*)	-.064(**)	.126(**)	.153(**)	-.189(**)	.192(**)
	Sig. (2-tailed)	0.001	0.02	0	.	0.326	0.031	0.003	0	0	0	0
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept Fix Rate	**Pearson Correlation**	.450(**)	-.226(**)	-.638(**)	-0.021	1	.510(**)	-.416(**)	.318(**)	.420(**)	.293(**)	.294(**)
	Sig. (2-tailed)	0	0	0	0.326	.	0	0	0	0	0	0
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept Maintenance Novice	**Pearson Correlation**	.591(**)	.328(**)	-.498(**)	.046(*)	.510(**)	1	-0.023	.376(**)	.489(**)	.301(**)	.320(**)
	Sig. (2-tailed)	0	0	0	0.031	0	.	0.287	0	0	0	0
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept Maintenance Worker	**Pearson Correlation**	-.360(**)	.931(**)	.772(**)	-.064(**)	-.416(**)	-0.023	1	-.050(*)	-.116(**)	-.191(**)	-.143(**)
	Sig. (2-tailed)	0	0	0	0.003	0	0.287	.	0.021	0	0	0
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept Learning by Doing	**Pearson Correlation**	.233(**)	.070(**)	-.267(**)	.126(**)	.318(**)	.376(**)	-.050(*)	1	.645(**)	.117(**)	.262(**)
	Sig. (2-tailed)	0	0.001	0	0	0	0	0.021	.	0	0	0
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept Sustainment Costs	**Pearson Correlation**	.381(**)	0.038	-.431(**)	.153(**)	.420(**)	.489(**)	-.116(**)	.645(**)	1	.205(**)	.349(**)
	Sig. (2-tailed)	0	0.076	0	0	0	0	0	0	.	0	0
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept Marginal Utilization of	**Pearson Correlation**	.264(**)	-.086(**)	-.344(**)	-.189(**)	.293(**)	.301(**)	-.191(**)	.117(**)	.205(**)	1	0.038
	Sig. (2-tailed)	0	0	0	0	0	0	0	0	0	.	0.077
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept Cannibalization Rate	**Pearson Correlation**	.378(**)	-0.026	-.297(**)	.192(**)	.294(**)	.320(**)	-.143(**)	.262(**)	.349(**)	0.038	1
	Sig. (2-tailed)	0	0.235	0	0	0	0	0	0	0	0.077	.
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept	**Pearson Correlation**	-.043(*)	0.026	0.037	-0.019	0.011	-0.015	0.038	0	0.007	-0.014	-0.026

Appendix 2:

Pure Standardized High-Level Metric Correlations		Concept Basesize	Concept Maintenance Personnel per Plane	Concept Supply Personnel per Plane	Concept Break Rate	Concept Fix Rate	Concept Maintenance Novice Resources per Plane	Concept Maintenance Worker Resources per Plane	Concept Learning by Doing	Concept Sustainment Costs	Concept Marginal Utilization of Aircraft	Concept Cannibalization Rate
Base Reapir Effectivenes	**Sig. (2-tailed)**	0.047	0.221	0.086	0.379	0.609	0.488	0.081	0.995	0.733	0.522	0.233
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept Maintenance Management	**Pearson Correlation**	-.537(**)	.703(**)	.948(**)	-.091(**)	-.601(**)	-.405(**)	.884(**)	-.210(**)	-.316(**)	-.307(**)	-.250(**)
	Sig. (2-tailed)	0	0	0	0	0	0	0	0	0	0	0
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept Base Supply Effectivenes	**Pearson Correlation**	0.023	-.104(**)	-.042(*)	0.026	.046(*)	0.001	-.125(**)	-0.001	-.062(**)	-0.006	-.105(**)
	Sig. (2-tailed)	0.295	0	0.049	0.226	0.033	0.967	0	0.978	0.004	0.793	0
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept Supply Novice	**Pearson Correlation**	.400(**)	.416(**)	-.324(**)	-0.033	.393(**)	.859(**)	.105(**)	.205(**)	.289(**)	.242(**)	.252(**)
	Sig. (2-tailed)	0	0	0	0.123	0	0	0	0	0	0	0
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept Supply Worker	**Pearson Correlation**	-.564(**)	.563(**)	.998(**)	-.080(**)	-.646(**)	-.527(**)	.764(**)	-.266(**)	-.429(**)	-.350(**)	-.301(**)
	Sig. (2-tailed)	0	0	0	0	0	0	0	0	0	0	0
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept Supply Management	**Pearson Correlation**	-.556(**)	.359(**)	.935(**)	-.088(**)	-.624(**)	-.606(**)	.565(**)	-.328(**)	-.506(**)	-.338(**)	-.325(**)
	Sig. (2-tailed)	0	0	0	0	0	0	0	0	0	0	0
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Single POD NMCM Standardize	**Pearson Correlation**	-.110(**)	0.037	.134(**)	-0.024	-.072(**)	-.105(**)	.080(**)	-.067(**)	-.075(**)	-.068(**)	-0.017
	Sig. (2-tailed)	0	0.082	0	0.26	0.001	0	0	0.002	0.001	0.002	0.427
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Single LANTIRN NMCM	**Pearson Correlation**	-0.02	0.029	.051(*)	0.014	-.066(**)	-0.013	0.034	-0.041	-.048(*)	0.002	0.016
	Sig. (2-tailed)	0.356	0.184	0.017	0.512	0.002	0.551	0.111	0.059	0.025	0.93	0.463
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Single Scheduled Engine	**Pearson Correlation**	.073(**)	-.074(**)	-.153(**)	0.039	.135(**)	.101(**)	-.114(**)	.068(**)	.100(**)	.095(**)	.102(**)
	Sig. (2-tailed)	0.001	0.001	0	0.073	0	0	0	0.002	0	0	0
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Single POD NMCS Standardize	**Pearson Correlation**	-.056(**)	-0.008	-0.016	.047(*)	.050(*)	0.005	-0.004	-0.011	-0.013	0.006	.058(**)
	Sig. (2-tailed)	0.009	0.711	0.454	0.028	0.02	0.805	0.858	0.62	0.532	0.776	0.007
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Single LANTIRN NMCS	**Pearson Correlation**	0.031	0.01	-0.014	0.018	0.012	0.032	-0.001	0.01	0.008	-0.012	.053(*)
	Sig. (2-tailed)	0.145	0.632	0.513	0.416	0.586	0.136	0.952	0.646	0.695	0.586	0.014
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Single Aircraft	**Pearson Correlation**	0.004	.140(**)	.096(**)	.057(**)	-.061(**)	-0.002	.165(**)	.078(**)	.086(**)	.132(**)	0.039
	Sig. (2-tailed)	0.85	0	0	0.008	0.005	0.92	0	0	0	0	0.068

Appendix 2:

Pure Standardized High-Level Metric Correlations		**Concept Basesize**	**Concept Maintenance Personnel per Plane**	**Concept Supply Personnel per Plane**	**Concept Break Rate**	**Concept Fix Rate**	**Concept Maintenance Novice Resources per Plane**	**Concept Maintenance Worker Resources per Plane**	**Concept Learning by Doing**	**Concept Sustainment Costs**	**Concept Marginal Utilization of Aircraft**	**Concept Cannibalization Rate**
Shortage	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Single	**Pearson Correlation**	.130(**)	-.094(**)	-.075(**)	-.096(**)	-.068(**)	-.043(*)	-.075(**)	0.004	.062(**)	.186(**)	.106(**)
Temperature	**Sig. (2-tailed)**	0	0	0	0	0.001	0.047	0	0.84	0.004	0	0
Standardize	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Single	**Pearson Correlation**	-.063(**)	-.055(*)	-.056(**)	.095(**)	0.035	-0.008	-.043(*)	.123(**)	.114(**)	.134(**)	.078(**)
Precipitation	**Sig. (2-tailed)**	0.004	0.011	0.01	0	0.108	0.694	0.045	0	0	0	0
Standardize	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Single	**Pearson Correlation**	-.377(**)	.196(**)	.567(**)	0.012	-.484(**)	-.441(**)	.362(**)	-.208(**)	-.259(**)	-.381(**)	-.110(**)
TNMCM	**Sig. (2-tailed)**	0	0	0	0.566	0	0	0	0	0	0	0
Standardize	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Single	**Pearson Correlation**	-.222(**)	.204(**)	.403(**)	0.028	-.313(**)	-.267(**)	.320(**)	-.093(**)	-.089(**)	-.234(**)	.120(**)
TNMCS	**Sig. (2-tailed)**	0	0	0	0.194	0	0	0	0	0	0	0
Standardize	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Single	**Pearson Correlation**	.308(**)	-.214(**)	-.510(**)	-.044(*)	.444(**)	.371(**)	-.361(**)	.181(**)	.212(**)	.335(**)	0.022
Mission	**Sig. (2-tailed)**	0	0	0	0.04	0	0	0	0	0	0	0.302
Capable	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Single	**Pearson Correlation**	-.202(**)	.110(**)	.232(**)	-.135(**)	-.190(**)	-.276(**)	.226(**)	-.140(**)	-.213(**)	-.082(**)	-.197(**)
Flying	**Sig. (2-tailed)**	0	0	0	0	0	0	0	0	0	0	0
Scheduling	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Single Cost	**Pearson Correlation**	.402(**)	.131(**)	-.445(**)	.057(**)	.487(**)	.638(**)	-.075(**)	.410(**)	.590(**)	.415(**)	.336(**)
of Gas per	**Sig. (2-tailed)**	0	0	0	0.008	0	0	0.001	0	0	0	0
Plane	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Single Cost	**Pearson Correlation**	.211(**)	.268(**)	-.187(**)	-0.035	.285(**)	.482(**)	.111(**)	.167(**)	.296(**)	.133(**)	.188(**)
of Impact	**Sig. (2-tailed)**	0	0	0	0.105	0	0	0	0	0	0	0
Purchases	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160

** Correlation is sig. at the 0.01 level

* Correlation is sig. at the 0.05 level

Appendix 2:

Pure Standardized High-Level Metric Correlations		Concept Base Reapir Effectiveness	Concept Maintenance Management Resources per Plane	Concept Base Supply Effectiveness	Concept Supply Novice Resources per Plane	Concept Supply Worker Resources per Plane	Concept Supply Management Resources per Plane	Single POD NMCM Standardized	Single LANTIRN NMCM Standardized	Single Scheduled Engine Removal Rate Standardized	Single POD NMCS Standardized	Single LANTIRN NMCS Standardized
Concept Basesize	Pearson Correlation	-.043(*)	-.537(**)	0.023	.400(**)	-.564(**)	-.556(**)	-.110(**)	-0.02	.073(**)	-.056(**)	0.031
	Sig. (2-tailed)	0.047	0	0.295	0	0	0	0	0.356	0.001	0.009	0.145
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept Maintenance Personnel	Pearson Correlation	0.026	.703(**)	-.104(**)	.416(**)	.563(**)	.359(**)	0.037	0.029	-.074(**)	-0.008	0.01
	Sig. (2-tailed)	0.221	0	0	0	0	0	0.082	0.184	0.001	0.711	0.632
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept Supply Personnel	Pearson Correlation	0.037	.948(**)	-.042(*)	-.324(**)	.998(**)	.935(**)	.134(**)	.051(*)	-.153(**)	-0.016	-0.014
	Sig. (2-tailed)	0.086	0	0.049	0	0	0	0	0.017	0	0.454	0.513
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept Break Rate	Pearson Correlation	-0.019	-.091(**)	0.026	-0.033	-.080(**)	-.088(**)	-0.024	0.014	0.039	.047(*)	0.018
	Sig. (2-tailed)	0.379	0	0.226	0.123	0	0	0.26	0.512	0.073	0.028	0.416
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept Fix Rate	Pearson Correlation	0.011	-.601(**)	.046(*)	.393(**)	-.646(**)	-.624(**)	-.072(**)	-.066(**)	.135(**)	.050(*)	0.012
	Sig. (2-tailed)	0.609	0	0.033	0	0	0	0.001	0.002	0	0.02	0.586
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept Maintenance Novice	Pearson Correlation	-0.015	-.405(**)	0.001	.859(**)	-.527(**)	-.606(**)	-.105(**)	-0.013	.101(**)	0.005	0.032
	Sig. (2-tailed)	0.488	0	0.967	0	0	0	0	0.551	0	0.805	0.136
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept Maintenance Worker	Pearson Correlation	0.038	.884(**)	-.125(**)	.105(**)	.764(**)	.565(**)	.080(**)	0.034	-.114(**)	-0.004	-0.001
	Sig. (2-tailed)	0.081	0	0	0	0	0	0	0.111	0	0.858	0.952
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept Learning by Doing	Pearson Correlation	0	-.210(**)	-0.001	.205(**)	-.266(**)	-.328(**)	-.067(**)	-0.041	.068(**)	-0.011	0.01
	Sig. (2-tailed)	0.995	0	0.978	0	0	0	0.002	0.059	0.002	0.62	0.646
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept Sustainment Costs	Pearson Correlation	0.007	-.316(**)	-.062(**)	.289(**)	-.429(**)	-.506(**)	-.075(**)	-.048(*)	.100(**)	-0.013	0.008
	Sig. (2-tailed)	0.733	0	0.004	0	0	0	0.001	0.025	0	0.532	0.695
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept Marginal Utilization of	Pearson Correlation	-0.014	-.307(**)	-0.006	.242(**)	-.350(**)	-.338(**)	-.068(**)	0.002	.095(**)	0.006	-0.012
	Sig. (2-tailed)	0.522	0	0.793	0	0	0	0.002	0.93	0	0.776	0.586
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept Cannibalization Rate	Pearson Correlation	-0.026	-.250(**)	-.105(**)	.252(**)	-.301(**)	-.325(**)	-0.017	0.016	.102(**)	.058(**)	.053(*)
	Sig. (2-tailed)	0.233	0	0	0	0	0	0.427	0.463	0	0.007	0.014
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept	Pearson Correlation	1	0.037	0.015	-0.02	0.039	0.014	0.005	-0.016	-0.002	-0.035	0.024

Appendix 2:

Pure Standardized High-Level Metric Correlations		Concept Base Reapir Effectiveness	Concept Maintenance Management Resources per Plane	Concept Base Supply Effectiveness	Concept Supply Novice Resources per Plane	Concept Supply Worker Resources per Plane	Concept Supply Management Resources per Plane	Single POD NMCM Standardized	Single LANTIRN NMCM Standardized	Single Scheduled Engine Removal Rate Standardized	Single POD NMCS Standardized	Single LANTIRN NMCS Standardized
Base Reapir Effectivenes	Sig. (2-tailed)	.	0.09	0.479	0.364	0.071	0.511	0.801	0.467	0.942	0.1	0.274
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept Maintenance Management	Pearson Correlation	0.037	1	-.121(**)	-.246(**)	.949(**)	.831(**)	.128(**)	.046(*)	-.154(**)	-0.011	-0.011
	Sig. (2-tailed)	0.09	.	0	0	0	0	0	0.033	0	0.612	0.611
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept Base Supply Effectivenes	Pearson Correlation	0.015	-.121(**)	1	-0.025	-0.041	-0.032	-0.01	-.050(*)	0.013	-0.013	-0.008
	Sig. (2-tailed)	0.479	0	.	0.236	0.054	0.133	0.636	0.019	0.543	0.547	0.694
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept Supply Novice	Pearson Correlation	-0.02	-.246(**)	-0.025	1	-.366(**)	-.439(**)	-.079(**)	-0.024	.064(**)	0.011	0.015
	Sig. (2-tailed)	0.364	0	0.236	.	0	0	0	0.269	0.003	0.623	0.474
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept Supply Worker	Pearson Correlation	0.039	.949(**)	-0.041	-.366(**)	1	.930(**)	.134(**)	.051(*)	-.154(**)	-0.017	-0.014
	Sig. (2-tailed)	0.071	0	0.054	0	.	0	0	0.017	0	0.423	0.503
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept Supply Management	Pearson Correlation	0.014	.831(**)	-0.032	-.439(**)	.930(**)	1	.144(**)	.050(*)	-.143(**)	-0.01	-0.016
	Sig. (2-tailed)	0.511	0	0.133	0	0	.	0	0.02	0	0.649	0.449
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Single POD NMCM Standardize	Pearson Correlation	0.005	.128(**)	-0.01	-.079(**)	.134(**)	.144(**)	1	0.005	-0.002	.567(**)	-0.01
	Sig. (2-tailed)	0.801	0	0.636	0	0	0	.	0.812	0.933	0	0.649
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Single LANTIRN NMCM	Pearson Correlation	-0.016	.046(*)	-.050(*)	-0.024	.051(*)	.050(*)	0.005	1	0.031	-.063(**)	.234(**)
	Sig. (2-tailed)	0.467	0.033	0.019	0.269	0.017	0.02	0.812	.	0.145	0.003	0
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Single Scheduled Engine	Pearson Correlation	-0.002	-.154(**)	0.013	.064(**)	-.154(**)	-.143(**)	-0.002	0.031	1	0.024	0.014
	Sig. (2-tailed)	0.942	0	0.543	0.003	0	0	0.933	0.145	.	0.265	0.528
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Single POD NMCS Standardize	Pearson Correlation	-0.035	-0.011	-0.013	0.011	-0.017	-0.01	.567(**)	-.063(**)	0.024	1	-0.037
	Sig. (2-tailed)	0.1	0.612	0.547	0.623	0.423	0.649	0	0.003	0.265	.	0.089
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Single LANTIRN NMCS	Pearson Correlation	0.024	-0.011	-0.008	0.015	-0.014	-0.016	-0.01	.234(**)	0.014	-0.037	1
	Sig. (2-tailed)	0.274	0.611	0.694	0.474	0.503	0.449	0.649	0	0.528	0.089	.
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Single Aircraft	Pearson Correlation	0.01	.149(**)	-.101(**)	-0.025	.097(**)	.079(**)	0.001	.045(*)	0.003	0.03	0.024
	Sig. (2-tailed)	0.635	0	0	0.246	0	0	0.95	0.035	0.877	0.163	0.263

Appendix 2:

Pure Standardized High-Level Metric Correlations		Concept Base Reapir Effectiveness	Concept Maintenance Management Resources per Plane	Concept Base Supply Effectiveness	Concept Supply Novice Resources per Plane	Concept Supply Worker Resources per Plane	Concept Supply Management Resources per Plane	Single POD NMCM Standardized	Single LANTIRN NMCM Standardized	Single Scheduled Engine Removal Rate Standardized	Single POD NMCS Standardized	Single LANTIRN NMCS Standardized
Shortage	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Single Temperature Standardize	Pearson Correlation	-0.04	-.067(**)	-0.023	-.067(**)	-.065(**)	-.105(**)	-.054(*)	0.001	-0.009	-.060(**)	0.017
	Sig. (2-tailed)	0.06	0.002	0.276	0.002	0.002	0	0.012	0.981	0.681	0.005	0.443
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Single Precipitation Standardize	Pearson Correlation	-0.024	-0.033	-0.032	-.081(**)	-.051(*)	-0.031	-0.031	-0.021	-0.013	0.038	0.005
	Sig. (2-tailed)	0.268	0.128	0.143	0	0.018	0.146	0.151	0.326	0.541	0.078	0.816
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Single TNMCM Standardize	Pearson Correlation	0.032	.533(**)	-.068(**)	-.342(**)	.572(**)	.570(**)	.195(**)	0.031	-.123(**)	-0.001	0.011
	Sig. (2-tailed)	0.138	0	0.002	0	0	0	0	0.149	0	0.975	0.601
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Single TNMCS Standardize	Pearson Correlation	0.023	.411(**)	-.175(**)	-.217(**)	.408(**)	.382(**)	.144(**)	0.037	-.096(**)	0.039	0.014
	Sig. (2-tailed)	0.294	0	0	0	0	0	0	0.088	0	0.067	0.526
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Single Mission Capable	Pearson Correlation	-0.029	-.497(**)	.105(**)	.302(**)	-.516(**)	-.495(**)	-.183(**)	-0.036	.118(**)	-0.015	-0.02
	Sig. (2-tailed)	0.172	0	0	0	0	0	0	0.098	0	0.497	0.348
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Single Flying Scheduling	Pearson Correlation	0.022	.259(**)	0	-.139(**)	.236(**)	.200(**)	0.002	-0.003	-0.032	-0.016	-.061(**)
	Sig. (2-tailed)	0.302	0	0.983	0	0	0	0.923	0.891	0.135	0.465	0.005
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Single Cost of Gas per Plane	Pearson Correlation	-0.011	-.335(**)	-.070(**)	.509(**)	-.456(**)	-.522(**)	-.096(**)	-0.018	.150(**)	.049(*)	0.022
	Sig. (2-tailed)	0.624	0	0.001	0	0	0	0	0.401	0	0.023	0.315
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160
Single Cost of Impact Purchases	Pearson Correlation	0.023	-.106(**)	-0.026	.531(**)	-.204(**)	-.299(**)	-0.03	-.049(*)	.123(**)	0.035	-0.015
	Sig. (2-tailed)	0.286	0	0.235	0	0	0	0.163	0.023	0	0.108	0.472
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160	2160

** Correlation is sig. at the 0.01 level

* Correlation is sig. at the 0.05 level

Appendix 2:

Pure Standardized High-Level Metric Correlations		Single Aircraft Shortage per Plane Standardized	Single Temperature Standardized	Single Precipitation Standardized	Single TNMCM Standardized	Single TNMCS Standardized	Single Mission Capable Standardized	Single Flying Scheduling Effectiveness Standardized	Single Cost of Gas per Plane Standardized	Single Cost of Impact Purchases per Plane
Concept Basesize	Pearson Correlation	0.004	.130(**)	-.063(**)	-.377(**)	-.222(**)	.308(**)	-.202(**)	.402(**)	.211(**)
	Sig. (2-tailed)	0.85	0	0.004	0	0	0	0	0	0
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept Maintenance Personnel	Pearson Correlation	.140(**)	-.094(**)	-.055(*)	.196(**)	.204(**)	-.214(**)	.110(**)	.131(**)	.268(**)
	Sig. (2-tailed)	0	0	0.011	0	0	0	0	0	0
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept Supply Personnel	Pearson Correlation	.096(**)	-.075(**)	-.056(**)	.567(**)	.403(**)	-.510(**)	.232(**)	-.445(**)	-.187(**)
	Sig. (2-tailed)	0	0	0.01	0	0	0	0	0	0
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept Break Rate	Pearson Correlation	.057(**)	-.096(**)	.095(**)	0.012	0.028	-.044(*)	-.135(**)	.057(**)	-0.035
	Sig. (2-tailed)	0.008	0	0	0.566	0.194	0.04	0	0.008	0.105
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept Fix Rate	Pearson Correlation	-.061(**)	-.068(**)	0.035	-.484(**)	-.313(**)	.444(**)	-.190(**)	.487(**)	.285(**)
	Sig. (2-tailed)	0.005	0.001	0.108	0	0	0	0	0	0
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept Maintenance Novice	Pearson Correlation	-0.002	-.043(*)	-0.008	-.441(**)	-.267(**)	.371(**)	-.276(**)	.638(**)	.482(**)
	Sig. (2-tailed)	0.92	0.047	0.694	0	0	0	0	0	0
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept Maintenance Worker	Pearson Correlation	.165(**)	-.075(**)	-.043(*)	.362(**)	.320(**)	-.361(**)	.226(**)	-.075(**)	.111(**)
	Sig. (2-tailed)	0	0	0.045	0	0	0	0	0.001	0
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept Learning by Doing	Pearson Correlation	.078(**)	0.004	.123(**)	-.208(**)	-.093(**)	.181(**)	-.140(**)	.410(**)	.167(**)
	Sig. (2-tailed)	0	0.84	0	0	0	0	0	0	0
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept Sustainment Costs	Pearson Correlation	.086(**)	.062(**)	.114(**)	-.259(**)	-.089(**)	.212(**)	-.213(**)	.590(**)	.296(**)
	Sig. (2-tailed)	0	0.004	0	0	0	0	0	0	0
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept Marginal Utilization of	Pearson Correlation	.132(**)	.186(**)	.134(**)	-.381(**)	-.234(**)	.335(**)	-.082(**)	.415(**)	.133(**)
	Sig. (2-tailed)	0	0	0	0	0	0	0	0	0
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept Cannibalization Rate	Pearson Correlation	0.039	.106(**)	.078(**)	-.110(**)	.120(**)	0.022	-.197(**)	.336(**)	.188(**)
	Sig. (2-tailed)	0.068	0	0	0	0	0.302	0	0	0
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept	Pearson Correlation	0.01	-0.04	-0.024	0.032	0.023	-0.029	0.022	-0.011	0.023

Appendix 2:

Pure Standardized High-Level Metric Correlations		Single Aircraft Shortage per Plane Standardized	Single Temperature Standardized	Single Precipitation Standardized	Single TNMCM Standardized	Single TNMCS Standardized	Single Mission Capable Standardized	Single Flying Scheduling Effectiveness Standardized	Single Cost of Gas per Plane Standardized	Single Cost of Impact Purchases per Plane
Base Reapir Effectivenes	Sig. (2-tailed)	0.635	0.06	0.268	0.138	0.294	0.172	0.302	0.624	0.286
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept Maintenance Management	Pearson Correlation	.149(**)	-.067(**)	-0.033	.533(**)	.411(**)	-.497(**)	.259(**)	-.335(**)	-.106(**)
	Sig. (2-tailed)	0	0.002	0.128	0	0	0	0	0	0
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept Base Supply Effectivenes	Pearson Correlation	-.101(**)	-0.023	-0.032	-.068(**)	-.175(**)	.105(**)	0	-.070(**)	-0.026
	Sig. (2-tailed)	0	0.276	0.143	0.002	0	0	0.983	0.001	0.235
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept Supply Novice	Pearson Correlation	-0.025	-.067(**)	-.081(**)	-.342(**)	-.217(**)	.302(**)	-.139(**)	.509(**)	.531(**)
	Sig. (2-tailed)	0.246	0.002	0	0	0	0	0	0	0
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept Supply Worker	Pearson Correlation	.097(**)	-.065(**)	-.051(*)	.572(**)	.408(**)	-.516(**)	.236(**)	-.456(**)	-.204(**)
	Sig. (2-tailed)	0	0.002	0.018	0	0	0	0	0	0
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160
Concept Supply Management	Pearson Correlation	.079(**)	-.105(**)	-0.031	.570(**)	.382(**)	-.495(**)	.200(**)	-.522(**)	-.299(**)
	Sig. (2-tailed)	0	0	0.146	0	0	0	0	0	0
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160
Single POD NMCM Standardize	Pearson Correlation	0.001	-.054(*)	-0.031	.195(**)	.144(**)	-.183(**)	0.002	-.096(**)	-0.03
	Sig. (2-tailed)	0.95	0.012	0.151	0	0	0	0.923	0	0.163
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160
Single LANTIRN NMCM	Pearson Correlation	.045(*)	0.001	-0.021	0.031	0.037	-0.036	-0.003	-0.018	-.049(*)
	Sig. (2-tailed)	0.035	0.981	0.326	0.149	0.088	0.098	0.891	0.401	0.023
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160
Single Scheduled Engine	Pearson Correlation	0.003	-0.009	-0.013	-.123(**)	-.096(**)	.118(**)	-0.032	.150(**)	.123(**)
	Sig. (2-tailed)	0.877	0.681	0.541	0	0	0	0.135	0	0
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160
Single POD NMCS Standardize	Pearson Correlation	0.03	-.060(**)	0.038	-0.001	0.039	-0.015	-0.016	.049(*)	0.035
	Sig. (2-tailed)	0.163	0.005	0.078	0.975	0.067	0.497	0.465	0.023	0.108
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160
Single LANTIRN NMCS	Pearson Correlation	0.024	0.017	0.005	0.011	0.014	-0.02	-.061(**)	0.022	-0.015
	Sig. (2-tailed)	0.263	0.443	0.816	0.601	0.526	0.348	0.005	0.315	0.472
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160
Single Aircraft	Pearson Correlation	1	-0.023	.104(**)	.044(*)	.066(**)	-.057(**)	0.038	.170(**)	-.048(*)
	Sig. (2-tailed)	.	0.294	0	0.041	0.002	0.008	0.076	0	0.025

Appendix 2:

Pure Standardized High-Level Metric Correlations		Single Aircraft Shortage per Plane Standardized	Single Temperature Standardized	Single Precipitation Standardized	Single TNMCM Standardized	Single TNMCS Standardized	Single Mission Capable Standardized	Single Flying Scheduling Effectiveness Standardized	Single Cost of Gas per Plane Standardized	Single Cost of Impact Purchases per Plane
Shortage	N	2160	2160	2160	2160	2160	2160	2160	2160	2160
Single Temperature Standardize	**Pearson Correlation**	-0.023	1	.278(**)	0.018	.083(**)	-.052(*)	-0.033	-0.014	-.062(**)
	Sig. (2-tailed)	0.294	.	0	0.413	0	0.015	0.122	0.525	0.004
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160
Single Precipitation Standardize	**Pearson Correlation**	.104(**)	.278(**)	1	-.084(**)	-.055(*)	.059(**)	-.052(*)	.107(**)	-.145(**)
	Sig. (2-tailed)	0	0	.	0	0.01	0.007	0.016	0	0
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160
Single TNMCM Standardize	**Pearson Correlation**	.044(*)	0.018	-.084(**)	1	.609(**)	-.912(**)	0.027	-.424(**)	-.218(**)
	Sig. (2-tailed)	0.041	0.413	0	.	0	0	0.214	0	0
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160
Single TNMCS Standardize	**Pearson Correlation**	.066(**)	.083(**)	-.055(*)	.609(**)	1	-.752(**)	-0.028	-.237(**)	-.114(**)
	Sig. (2-tailed)	0.002	0	0.01	0	.	0	0.194	0	0
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160
Single Mission Capable	**Pearson Correlation**	-.057(**)	-.052(*)	.059(**)	-.912(**)	-.752(**)	1	0.024	.361(**)	.199(**)
	Sig. (2-tailed)	0.008	0.015	0.007	0	0	.	0.262	0	0
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160
Single Flying Scheduling	**Pearson Correlation**	0.038	-0.033	-.052(*)	0.027	-0.028	0.024	1	-.175(**)	-.076(**)
	Sig. (2-tailed)	0.076	0.122	0.016	0.214	0.194	0.262	.	0	0
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160
Single Cost of Gas per Plane	**Pearson Correlation**	.170(**)	-0.014	.107(**)	-.424(**)	-.237(**)	.361(**)	-.175(**)	1	.380(**)
	Sig. (2-tailed)	0	0.525	0	0	0	0	0	.	0
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160
Single Cost of Impact Purchases	**Pearson Correlation**	-.048(*)	-.062(**)	-.145(**)	-.218(**)	-.114(**)	.199(**)	-.076(**)	.380(**)	1
	Sig. (2-tailed)	0.025	0.004	0	0	0	0	0	0	.
	N	2160	2160	2160	2160	2160	2160	2160	2160	2160

** Correlation is sig. at the 0.01 level

* Correlation is sig. at the 0.05 level